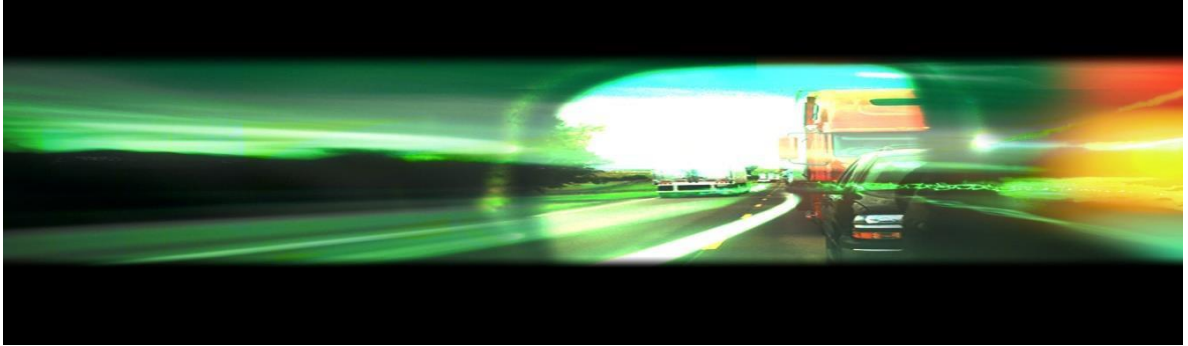


Developing a Smartphone Based Warning System Application to Enhance the Safety at Work Zones

Final Report



TranLIVE

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May 2016

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1. Report No. TranLIVE/TSU/16/06	2. Government Accession No.	Recipient's Catalog No.	
4. Title and Subtitle Developing a Smartphone Based Warning System Application to Enhance the Safety at Work Zones		5. Report Date May 2016	
		6. Performing Organization Code TranLIVE/TSU/16/06	
7. Author(s) Ruksana Rahman, Fengxiang Qiao, Qing Li, and Lei Yu		8. Performing Organization Report No. TranLIVE/TSU/16/06	
		10. Work Unit No. (TRAIS)	
9. Performing Organization Name and Address Innovative Transportation Research Institute Texas Southern University 3100 Cleburne Avenue Houston, TX 77004		11. Contract or Grant No. DTRT12GUTC17/KLK900-SB-003	
		13. Type of Report and Period Covered Research Report 01/01/12 - 05/31/16	
12. Sponsoring Agency Name and Address Tier 1 University Transportation Center TranLIVE Office of the Assistant Secretary for Research and Technology U.S. Department of Transportation 1200 New Jersey Avenue, SE Washington, DC 20590		14. Sponsoring Agency Code	
		15. Supplementary Notes 100% matching fund from Texas Southern University	
16. Abstract Collisions in the work zone have always been a contributing factor to compromising safety on urban roadways. The National Highway Traffic Safety Administration (NHTSA) and the State Transportation Authorities have implemented many safety countermeasures to reduce forward collisions in work zones. However, due to the complexity of traffic in a work zone, traditional countermeasures often fail to prevent crashes. In this study, a smartphone-based warning system application was developed, which provides different types of warning messages, including sound, visual, and voice, to alert drivers for a hazardous traffic situation. Meanwhile, the effectiveness of the warning system application in different part of a work zone was investigated by two driving simulator tests. The study of safety at work zones was divided into two phases, Phase A and Phase B. For each Phase, different twenty- four subjects were recruited to measure their driving behaviors that are affected by different types of smartphone- based warning messages, in terms of headway distance, headway time, speed, and acceleration/deceleration. Results show that voice messages works the most effective to instruct drivers to control their speed smoothly and keep sufficient headway time and braking distance, while driving through a work zone. These driving simulator-based studies found that the smartphone-based warning system is effective in reducing both vehicle-to-vehicle crashes and worker fatalities. It is recommended that such a low-cost and effective smartphone application should be tested in real road conditions with similar safety measures to those employed in this report.			
17. Key Words Work Zone, Advance Warning Area, Activity Area, Forward Collision, Fatality, Driving Simulator, Smartphone.		18. Distribution Statement No restriction. This document is available to the publication through the National Technical Information Service, 5285 Port Royal Road, Springfield, Virginia 22161 www.ntis.gov	
19. Security Classify (of this report) Unclassified	20. Security Classify (of this page) Unclassified	21. No. of Pages 103	22. Price

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ACKNOWLEDGMENT

The authors would like to thank the participants of the driving simulator tests for this research and the graduate research assistants at Texas Southern University (TSU) in providing technical assistants on data analysis. Also the authors would like to express thanks to all personnel who have directly or indirectly contributed to this project or have provided various assistances.

ABSTRACT

Collisions in the work zone have always been a contributing factor to compromising safety on urban roadways. The National Highway Traffic Safety Administration (NHTSA) and the State Transportation Authorities have implemented many safety countermeasures to reduce forward collisions in work zones. However, due to the complexity of traffic in a work zone, traditional countermeasures often fail to prevent crashes. As such, smart warning systems can be applied to notify motorists about the upcoming conditions in work zones. In this study, smartphone-based warning systems were designed to investigate (Phase-A) effectiveness in notifying users about the presence of a work zone and reducing forward collisions through advanced warning area and (Phase-B) the potential to reduce worker fatalities in activity areas. The smartphone-based warning system app was designed by using MIT App Inventor 2. In Phase-A, four different warning messages were generated (visual, sound, male voice and female voice) to alert drivers. Driving simulator tests with twenty-four participants with one hundred and twenty rounds through work zones were conducted to investigate the impacts of smartphone-based warnings on performance measures such as headway distance, headway time, speed, and acceleration/deceleration.

In Phase B, three different warning message systems (sound, male voice and female voice) were designed to alert drivers. Driving simulator tests were conducted with twenty-four participants in ninety-six rounds of driving in a work zone to investigate the impacts of smartphone-based warning messages on performance measures speed, speed variation, acceleration, and brake reaction distance. In Phase-A, the statistically analyzed results show that, with the help of voice (either female or male) warnings regarding

forward collisions, acceleration and speed were reduced, and the headway time and braking distance increased. The headway distance was increased a certain distance; after that, it gradually decreased. Moreover, participants found the notification system to be user friendly and felt that it helped to avoid rear-end crashes in work zones. In Phase-B, the statistically analyzed results showed that, with the assistance of sound and voice (either female or male) warning messages, drivers could effectively reduce their speeds. Meanwhile, such warning systems can also reduce the brake reaction distance and increase the headway time and headway distance. Overall, no statistically significant difference between the male and female voice were found. Thus, voice warning from either a male or female voice is the best option to reduce forward collision and worker fatalities.

These driving simulator-based studies found that the smartphone-based warning system is effective in reducing both vehicle-to-vehicle crashes and worker fatalities. It is recommended that such a low-cost and effective smartphone application should be tested in real road conditions with similar safety measures to those employed in this paper.

EXECUTIVE SUMMARY

This research is proposed to develop and test a smartphone-based warning system to reduce both forward collision and worker fatalities work zones. More specifically, a smartphone application was developed, which is able to provide different types of warning system to alert drivers. The smartphone-based warning system app was designed by using MIT App Inventor 2. Four types of warning messages, including visual, sound, male voice, and female voice, were designed to alert drivers on forward collisions in the advanced warning area of a work zone, and three types of warning messages, including sound, male voice, and female voice, to alert drivers on the presence of construction works in the activity area of a work zone. The effectiveness of the smartphone-based warning messages was tested in a driving simulator environment.

A smartphone-based warning system application was developed, which is dedicated to provide Safe Forward Collision Warning (SFCW) and Safe Worker to Driver (SWD) warning by drivers' own smartphones. This developed system is an Android-based application that can be easily downloaded onto any compatible smartphone in the current global market. In this study, the smartphone had the pre-installed application that can detect if a work zone is ahead based on the geo-location position of the phone. Warning messages including sound and voice prompts will be triggered to alert the driver once the geo-location and driving direction of motorist match.

There are two phases in the driving simulator tests. While Phase A was to investigate the impacts of the smartphone-based SFCW messages on drivers' driving behaviors, Phase B was dedicated to enhance the safety of workers in a work zone, namely SWD messages. For each phase, different twenty-four subjects were recruited to test their

driving behaviors affected by different types of the smartphone-based warning messages, in terms of headway time, headway distance, speed, and acceleration/deceleration.

These driving simulator-based studies found that the smartphone-based warning system is effective in reducing both vehicle-to-vehicle crashes and worker fatalities. It is recommended that such a low-cost and effective smartphone application should be tested in real road conditions with similar safety measures to those employed in this study.

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CHAPTER 1**INTRODUCTION****1.1 Background of Research**

Since the invention of the wheel, we have progressed a long way in developing efficient and safe road transportation systems that serve human mobility needs. However, road transportation-related human fatalities, economic loss, and environmental impacts are staggeringly high. According to the Fatality Analysis Reporting System (FARS), each year, more than 32,000 people lose their lives in the USA alone due to road accidents (FARS, 2014). Work-zone-related collisions and fatalities contribute significantly to this high number of fatalities. Ullman et al. (2004) calculated that road users find an active work zone in approximately one out of every hundred miles driven on the national highway system. Facts and Statistics Injuries and Fatalities (FHWA, 2014) reported that, in 2010, there were 87,606 work zone crashes nationwide and 37,476 related injury to drivers and workers. Unfortunately, on average, there was one injury caused every 14 minutes in 2010. According to the National Highway Traffic Safety Administration's (NHTSA)

Fatality Analysis Reporting System (FARS) report (2014), the trend for work-zone related accidents from 2002 to 2012 fell slightly from 2.76% to 1.81%, and the work-zone related accident percentage also decreased from 5.15% to 3.68%.

According to the latest report for the State of Texas (2014), 17,266 crashes occurred in 2013 within roadway construction and maintenance zones, resulting in 3,522 serious injuries and 115 fatalities. From the Center for Disease Control and Prevention report (CDC), 2014), the major causes of work zone fatalities are collisions between vehicles and vehicles, vehicles and infrastructures, and workers hit by oncoming vehicles.

In a work zone, crashes are often rear-end collisions. The major factors contributing to these collisions are the driver's failure to follow the work zone speed limit and lane merging warning messages. Pigman et al. (1990) and Schrock et al. (2004) found that the presence of large trucks that obstruct the view of other vehicles in narrow work zone areas can cause multi-vehicle collisions. Truck Crash Dangers (Fact Sheet, 2014) reported that, in 2011, a total of 530 fatal crashes occurred in work zone areas of construction, maintenance, or utility activity, and a total of 174 large trucks were involved in fatal work zone crashes in the U.S. Unfortunately, for aging urban areas with increased needs of periodic repairs and expansions of roadways, work-zone-related crashes could still be high (TxDOT, 2014).

In a typical work zone, warning signs are posted in an advance warning area to alert the oncoming traffic of the work zone ahead. The mandatory warning system includes static signs saying, "Work Zone Ahead," "Speed Limit XX," and "Left/Right Lane Closed." Radwan et al. (2009) reported that, in some cases, there are dynamic warning systems to further improve the traffic flow in work zone areas. However, these general safety measures often fail to guide a motorist correctly, as they do not take into consideration the various operational characteristics of oncoming vehicles and their relative positions near a work zone. Often larger vehicles, like trucks or buses, require more turning space to merge, and hence pose risks to other vehicles and workers. Also, vehicles behind such trucks become virtually blind to the exact position of a lane merge and the speed to follow, which may result in rear-end collisions. Garber et al. (2002) reported rear-end collisions as the most frequent crash type in the advance warning area of a work zone. Studies by Garber et al. (2002) and Nemeth et al. (1978) mentioned that

comparative crash analyses by Hall et al. (1989) and Roupail et al. (1988) found that rear-end crashes are more predominant in a work-zone than in a non-work zone.

Road construction workers are most vulnerable due to moving traffic in construction road zones. According to data from the USDOT (2014), more than 20,000 people experience work-related injuries in road construction zones each year. Mobility and safety research (2014) reported that, in the roadway construction worksites, most injuries and deaths of workers happen due to run-overs/back-overs (often by dump trucks), collisions between moving construction vehicles and equipment, and getting caught in between or struck by an object. According to Salem et al. (2006) and Akepati et al. (2011), the activity (work) area is the most hazardous crash location. For example, Garber et al. (2002) and Pigman et al. (1990) found that 70 percent and 80 percent of crashes respectively occurred in the activity area. The existing studies in work zones are inadequate to capture the impact of the great variability in length of each work zone component of different projects. However, whether or not activity area is indeed the most unsafe element of a work zone, more advanced safety measures are warranted.

Speed is referenced as the number-one contributing factor in work zone crashes. According to the USDOT reports (2010), approximately 31 percent of work zone fatalities occurred due to excessive speed. The Maryland State Highway Administration (2014) identified that speeding in the work zone area not only endangers drivers' lives but also puts the lives of roadside workers potentially at risk as they operate their vehicles recklessly. According to the Bureau of Labor Statistics and USDOT federal highway administration reports (2014), worker fatalities at road construction sites were 101 in

2008, 116 in 2009, 106 in 2010, 122 in 2011, 133 in 2012, and 105 in 2013. Over the 11 years from 2003 through 2013, Texas was ranked as the state with the most worker deaths in work zone at 131.

It is obvious that conventional static and dynamic warning signs may not be sufficient to prevent crashes in work zones. A more efficient and streamlined driver warning system could apply the Intelligent Transportation System (ITS) based connected vehicle technologies. USDOT reported (2014) that, with such technology, reliable and secure data are shared wirelessly using communication systems such as the high-speed 5.9 GHz dedicated short-range communications (DSRC). Maitipe et al. (2012) reported that another form of technology is Wi-Fi, used to offer a link through which vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communications can take place to prevent potential crashes. However, estimates from NHTSA (2014) and ITS (2014) committee reported that this technology will not come into use before 2017 and there have been significant challenges encountered in terms of the applicability and costs of such on-board warning systems. The application of a smartphone-based warning system could be another promising tool to provide warning messages to drivers.

1.2 Objectives of Research

The work-zone-related fatalities and current safety measures provided the motivation to define the scope and objectives of this research. The overall goal was to develop and test a smartphone-based warning system to reduce both forward collision and worker fatalities in work zones. More specifically, the objectives were to:

- develop a smartphone-based warning system to alert drivers in the driving simulator environment;
- test four types of warning messages (visual, sound, male voice, and female voice) to alert drivers about forward collisions in the advanced warning area of work zone, and three types of warning messages (sound, male voice, and female voice) to alert drivers about the presence of construction works in the activity area of work zone; and
- analyze the test results to compare the relative effectiveness of warning methods to reduce forward collisions and worker fatalities.

1.3 Outline of the Study

The remainder of this thesis includes the following chapters:

Chapter 2: presents a review of the connected vehicle technology concept and the existing studies on preventing the two different types of accident; i.e. forward collision accident in an advance warning area, worker-related accidents in an activity area.

Chapter 3: describes the experimental methods of this study (a) smartphone app development, (b) driving simulator tests with different warning methods, and (c) data collection.

Chapter 4: presents the analysis of test results to find the comparative effectiveness of various warning methods to reduce forward collisions and worker fatalities.

Chapter 5: summarizes the overall conclusions, recommendations, and future direction of this research.

CHAPTER 2**LITERATURE REVIEW**

In this chapter, a comprehensive literature review is performed to understand the current state of research performed to mitigate work-zone-related accidents and the potential application of the connected vehicle technology to address it. More specifically, this literature review will focus on 1) work-zone safety countermeasure research, 2) the background history of Connected Vehicle technology (V2V communication and V2I communication) and its potential applications, 3) existing research with the connected vehicle technology, 4) existing research with the smartphone, and 5) the use of the driving simulator.

2.1 Work-Zone Safety Countermeasure Research

Yang et al. (2014) mentioned in the Transportation Research Board Annual meeting that studies to minimize work-zone-related crashes could be tracked as far back as 1960. Most of these studies focused on analyzing crash data from various state and transportation organization sources to find causes and effects.

As a result, several factors related to both the environment and roads such as environmental conditions (rain, light condition, etc.), physical features of a work zone, and vehicle types and driver actions have been reported as key components.

Although these studies provide valuable insight into the causes of work zone accidents, they did not consider innovative measures to improve safety. To address these limitations, McAvoy et al. (2011) and Nelson et al. (2011) reported that driving- simulator-based studies employ useful methods to investigate work zone safety countermeasures and motorist driving behaviors.

For example, in a recent driving simulator study conducted by the Texas Transportation Institute (TTI), Nelson et al. (2011) demonstrated that a combination of iterative short warning signs and orange-colored barriers best impacted driver response, reduction in speed, and safe lane change behavior. Besides, many of recent driving simulator studies have focused on the impacts of V2I on drivers' driving performance, regarding safety in conflicting areas, such as work zones (Qiao, et al., 2016a; Qiao et al., 2016b; Qiao et al., 2016c), STOP sign intersection (Li et al., 2016a; Li et al., 2015b), signalized intersection with sun glare disturbance (Li et al., 2015a), and car following along local streets (Li et al., 2016b).

From all the demonstrations of real crash incidents and driving-simulator-based studies, it is observed that traditional safety warning systems can improve safety but not completely eliminate the risk. As such, it may be possible to further reduce the number of crash incidents by applying innovative safety countermeasures such as ITS. In recent years, the USDOT has conducted several applications of ITS technologies to ensure road

safety by creating smart work zones. Under ITS-based smart work zone processes and through state transportation agencies in Kentucky, Agent et al. (1999) tested a speed sensor-based traffic monitoring system in work zones. The collected data were processed via an onsite control system to assess the scenario and to generate warning messages (speed, delay, or route diversion), if necessary. Qiao et al. (2014) developed a Radio Frequency Identification (RFID)-based Drivers Smart Assistance System (DSAS), which helps a driver to take earlier action to decelerate with smoother speed profiles.

2.2 A Brief History of Connected Vehicle Technologies

Advancements of the information technology opened the scope of many potential applications in the transportation sector. ITS utilizes applications of advanced information technology to enhance safe driving conditions for motorists. The design and implementation of ITS have become one of the major focuses for government transportation agencies like the USDOT. ITS plays an important role in the connected vehicle technology by enabling information transfers among vehicles (V2V) and roadside infrastructures (V2I). The first cornerstone of this connected vehicle technology was laid when the Federal Communications Commission (FCC) started allocations of DSRC for testing the vehicle connectivity (Harding et al., 2014 and Zeng et al., 2012). DSRC was initially intended for transportation safety purposes. A comprehensive initiate

was started at 2002, when two consortiums were formed, the Vehicle Infrastructure Initiative (VII) and the Vehicle Safety Communications Consortium (VSCC), to coordinate activities among auto manufacturers, government agencies, and research institutions. Cooperative Intersection Collision Avoidance System (CICAS) is one of the many successful outcomes from these coordinated efforts. With time, applications of the connected vehicle technology were expanded in both utilizing new communications systems and applying different types of road scenarios. Figure 1 presents the history of the connected vehicle technology.

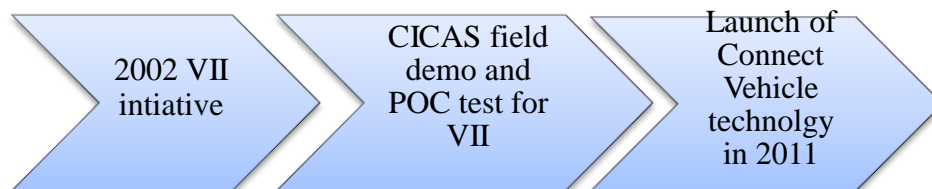


Figure 1 A brief history of connected vehicle technology

The USDOT Connected Vehicle Research Program (2011) laid out multiyear (2010-2015) pilot projects for different ITS initiatives. The year 2011 marked a milestone for the connected vehicle technology, as a safety pilot program was initiated to test this technology for real-world driving scenarios. Another study assessing the effects of connected vehicles on the road mobility was completed in 2013. In the proof of the

concept report, Kandarpa et al. (2013) reported that, depending on the outcome of these studies, more studies are envisioned for the near future by USDOT.

2.3 Connected Vehicle Technology and Its Potential

2.3.1 Connected vehicle technology

Reliable and secure data are shared wirelessly using high-speed 5.9 GHz DSRC. USDOT (2011) asserts that this technology is similar to Wi-Fi, offering a link through which V2V and V2I communication can take place to prevent potential crashes.

The basic feature of V2V is the “Here I am” concept and the application of DSRC to detect any presence of another vehicle in the collision range (300 to 500 meters). According to the GAO report (2013), this range is greater than that of the existing sensor-based collision avoidance range (150 meters). V2V technology generates three types of alert (visual, audible, and tactile) and seat vibration, motivating the driver to take the necessary steps to avert an imminent collision. Furthermore, DSRC with GPS makes the system cost-effective and issues a warning about the path history of vehicles present within a 360-degree radius of a vehicle.

In V2I technology, communication can be established between vehicles and roadside infrastructures. The real-time information regarding traffic situation (road

signal, speed limits, etc.) and hazardous conditions (work zone, curve, turns, etc.) are collected by infrastructures and is continuously distributed to vehicles as warnings or advisories.

In Figure 2, various components and their connectivity used in V2V technology is presented.

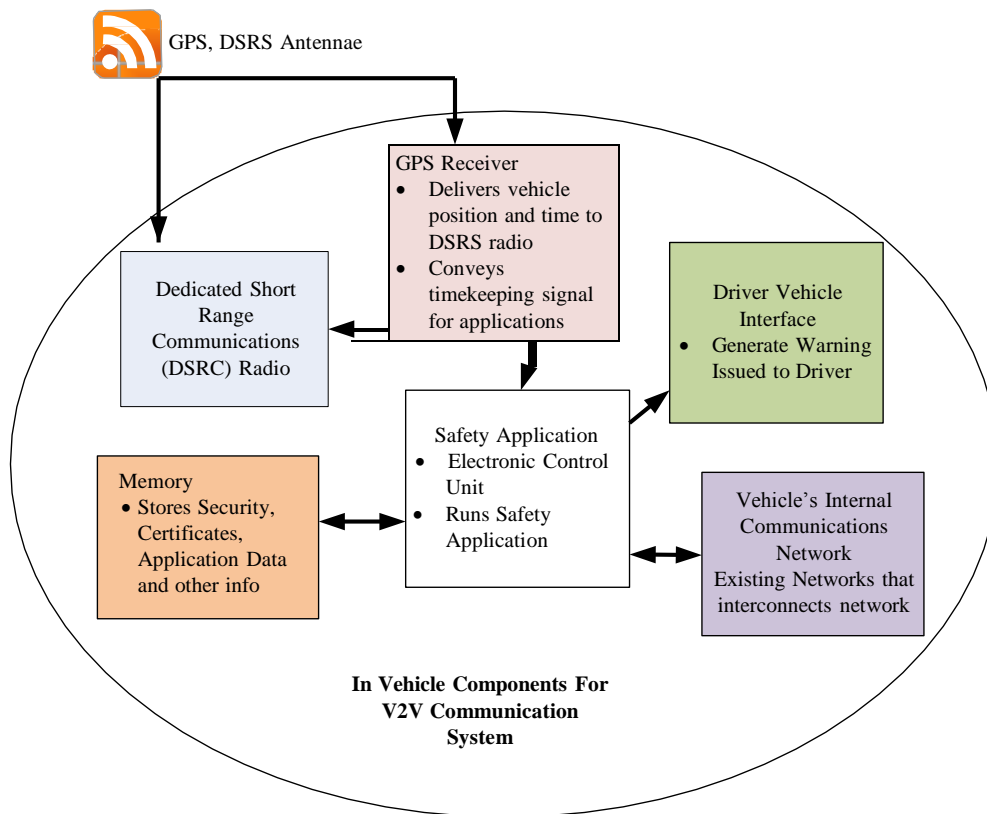


Figure 2 Components of V2V crash avoidance system

(Source: GAO 14-13, Intelligent Transportation System, Page No.14)

The DSRC system includes a cable and antenna for both sending and receiving data while GPS chips keep track of the concerned vehicle. All of the received data are analyzed in terms of

vehicle speed, position, and applied brake. With the help of the processed data, potential collisions are predicted. The collision predictions are conveyed to the vehicle driver via a driver- vehicle interface mechanism. Typically, drivers are alerted via sounds, light, or seat vibrations about an imminent collision.

2.3.2 Benefits in Terms of Safety, Mobility, and Other Areas

The potential benefits of the connected vehicle technology are manifold. The benefits in the three main sectors are described as follows.

Safety Benefits. As this technology constantly tracks cars in terms of their location, speed, direction, etc., each driver will be aware of the presence of another car in his/her collision zone. The advisory warning will inform drivers to take pre-emptive action to avoid crashes and prevent fatalities. According to a recent study by NHTSA, “These applications could potentially address about 75 percent of all crashes involving all vehicle types, or 81 percent of all vehicle crashes involving unimpaired drivers.” This technology will reduce rear-end collisions by generating the Forward-Collision warning (FCW) intended to inform the driver about the presence of a slower- moving vehicle ahead. Other similar safety feature includes blind-spot warning (BSW), electronic brake light (EBL), lane change control (LCW), do not pass warning (DNPW), etc.

Figure 3 depicts several safety applications currently in various stages of research and development, including conceptual, simulation, and field demonstrations. Two major mechanisms including V2V and V2I are used to communicate data to ensure safety.

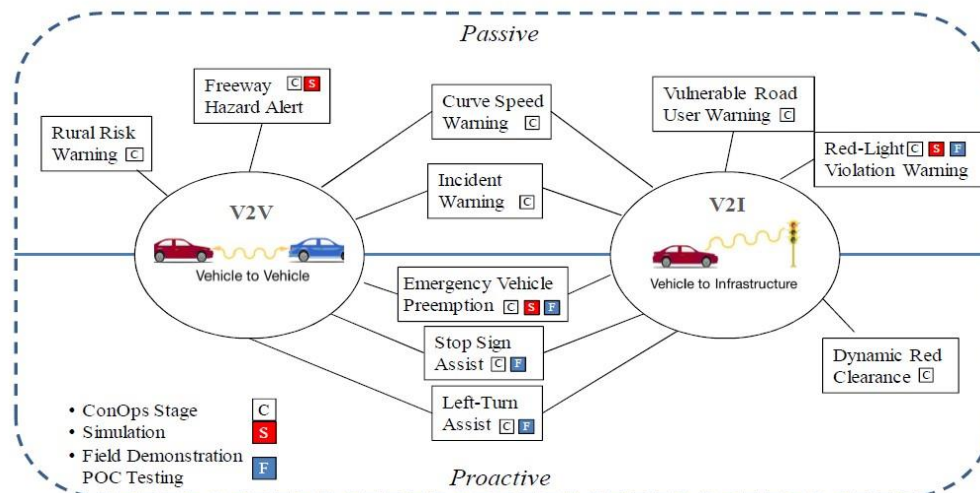


Figure 3 Summary of safety application with research activities

(Source: Report No. SWUTC/12/161103-1, Page no 26)

Safety applications include both situational awareness (passive) and active warning (proactive). For example, in passive mode, user advisories or message suggestions are generated to prepare the driver to take preventive action. While in proactive mode, urgent warnings are generated to alert the driver to take immediate action to avoid a crash/hazard.

In addition, this technology can also improve intersection-related collisions. For instance, when a vehicle has run a red light, other drivers with V2I installed will receive automatic collision advisory warnings until they achieve clearance of the intersection.

As the car can be tracked, insurance companies may have opportunities to provide a discount to drivers with safe driving habits.

Mobility Benefits. According to Gozalvez et al. (2014), the application of V2I technology will reduce road congestion, eventually improving the mobility of the roadways. This will guide drivers to alternate routes and help ease electronic toll collection. As the vehicles will be connected, reaction times and headway will be reduced. Thus, the capacity of the roadway will increase to reduce travel delay and traffic jams. The Lane capacity will increase, which will result in building fewer lanes and reducing related cost. Furthermore, accurate traffic-signal coordination will help to track the vehicle platoon. It will permit traffic managers to use a secure Wi-Fi connection to access traffic controllers without going to the field or stopping traffic.

Environmental and Cost Benefits. It has been found that wireless communication systems, including V2I, V2V, and P2V, are able to reduce vehicle emissions by improving drivers' driving behaviors (Li et al., 2015b). In particular, the vehicle emission reduction in some conflicting areas, such as work zones (Rahman, et al., 2015; Li et al., 2016c; Li et al., 2015c; Li et al., 2014; Qiao et al., 2014) and signalized intersections (Munni et al., 2015). Besides, the V2X technology will prevent road- weather-related accidents by providing drivers with real-time weather updates (icy roads, rain) and conditions of slippery pavement (Figure-4).

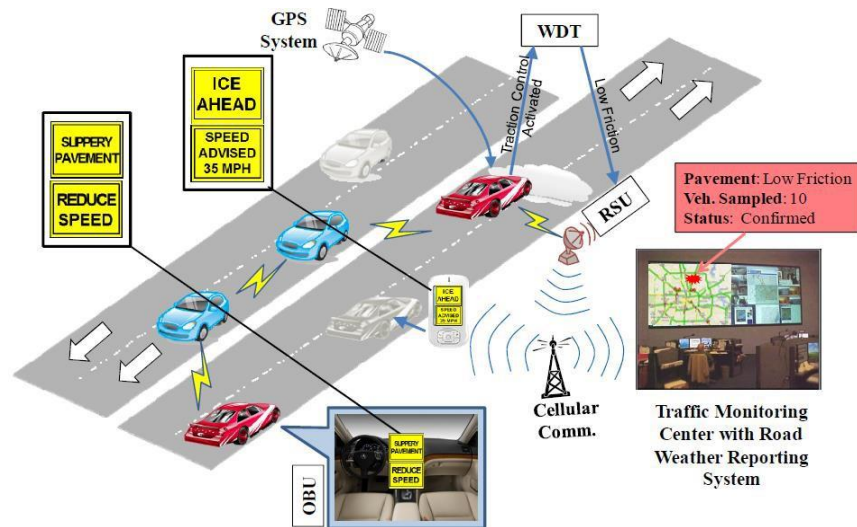


Figure 4 The concept of slippery pavement (Environmental Benefits) system

(Source: Report No. SWUTC/12/161103-1, Page no 71)

In broader terms, V2X technology covers both aspects of connected vehicle technology (V2V and V2I applications). The impact of V2X technologies may lessen the reliance on the costly inductive loop and video detection installation and maintenance. The introduction of this technology will create numerous jobs in the automotive, electronics and transportation industry.

Most importantly, people's lives will be spared from accidents, and our future generation will be able to live in a crash, congestion, and pollution-free world.

2.2.3 Deployment Scenarios

Successful pilot study is the precondition for the wide implementation of any new technology. To test the effectiveness and applicability of connected vehicles, USDOT is conducting two collaborative safety pilot deployments with ITS-JPO RITA, NHTSA, research institutes, and several automakers.

The first pilot study was conducted in August 2011 and examined how the 700 participating drivers handled the various advisory warning systems. These included in-car collision warnings, “do not pass” warnings, and alerts of sudden stops by a vehicle in front. ITE Journal publications (2013) indicated that an overwhelming majority of drivers (9 out of 10) would like to have the V2V features installed in their own vehicles to avoid crashes.

The second phase of the program (August 2012-2014) involved deployment of the safety pilot model of the V2X in the real world to evaluate the performance of vehicle wireless technology and how V2X can improve road safety. This pilot test is the largest real-road testing program, with 3,000 vehicles running in the public roads of Ann Arbor, Michigan. The finding (ITE Journal, 2011) from this major study is expected to be released in fall 2014 by NHTSA.

The outcome of these two studies (ITE Journal, 2011) will eventually help NHSTA to make a decision regarding the major rulemaking about whether the V2V technology should be mandated in newly manufactured vehicles from late 2013. US DOT, ITS (JPO) RITA, and NHTSA are trying to develop the concept of operations (ConOps) of transportation operations and management issues regarding this technology.

In a field demonstration, Maitipe et al. (2012) found that the DSRC-based V2I communication with V2V assistance can help to dynamically change work zone traffic environments and can handle much greater congestion lengths as compared to the previous system using the V2I-only communication without the V2V assistance. Liao et al. (2014) developed the concept of a V2V-based advisory system for the lane merging of vehicles in a work zone. This new system is planned for implementation as a standalone work zone queue warning system or as a cost-effective enhancement for a dynamic lane merges system.

2.2.4 V2I Strategy to Improve Traffic Safety for Workers

A significant amount of research has been completed in the area of safety associated with construction and maintenance work zones. Previous studies were focused on the proper use of traffic control devices, work activity scheduling, and personnel training for work zones. Qiao et al. (2012) revealed that the person-to-infrastructure (P2I) system can

notify drivers about workers crossing from the activity area, which entices them to reduce their driver speed.

2.3 Smartphone Based Research

University of Minnesota researcher Liao (2014) investigated smartphone applications that used GPS and Bluetooth technologies to generate the vibration with the audible message for visually impaired pedestrians to help warn them about the presence of the work zone ahead. In another study, Basacik et al. (2011) investigated the danger of using smartphones while driving by using a driving simulator. They found that, while drivers were using the smartphone to update their social media status or read or write messages, their speeds and time headway with the leading vehicle varied. Drivers were unable to maintain a central lane position and spend 40% to 60% of their time looking down at the smartphone. Rakha et al. (2014) conducted a study on smartphone applications to track greenhouse gas emissions and the fuel consumption of vehicles so that drivers can adjust their driving patterns to minimize emissions. Ren et al. (2013) developed a low-cost smartphone-based technology as an alternative to the current expensive collision warning system to detect the lead vehicle in order to minimize rear-end collisions. They used the Haar-like feature detector to identify the candidate vehicles' location by using the AdaBoost algorithm on the smartphone. The Internet-published

report (2013) mentioned that the App Inventor service for general public access was launched by MIT Center for Mobile Learning during the first quarter of 2012. When creating any app, it is recommended that creators use a device and developing computer connected to the same Local Area Network (LAN).

2.4 Applications of Driving Simulator

In recent years, transportation researchers have widely utilized driving simulators to investigate new technologies on road design, advanced vehicles feature, and driver/passengers safety. One of the major focuses on driving simulator tests is to investigate the response/reaction of drivers upon receiving a warning message on the imminent road hazard ahead. Li et al. (2015d) constructed the fuzzy logic-based lane-changing models in which drivers' socio-demographics are developed to enhance the practicality of lane-changing movements. In this research, the primary independent variables were drivers' socio-demographic factors, and the output variables were Lane-Changing Action Time (LCAT) and Lane-Changing Action Distance (LCAD). To demonstrate the effectiveness of this model in traffic simulation, the LCAT and LCAD were calculated at five geo-locations with different socio-demographic specifications. The outcome of these research indicated that the Drivers' Smart Advisory System (DSAS) messages were successful in notifying all drivers to prepare and change lanes

earlier, which thereby shortened the duration of time changing lanes. In the developed models, essential variables were educational background and age, while the influences of gender on the output variables are undistinguished. This finding specifies that drivers' driving behaviors and the application of the new technologies on roads are subject to their socio-demographic factors, which is consistent with the previous studies (Qiao et al., 2016d; Li et al., 2015e).

In another study, Li et al. (2013) developed a Person-to-Infrastructure (P2V) wireless communication system comprising two parts. The first part was communication between workers and the infrastructure (P2I), whereas the communication between the infrastructure and vehicles (I2V) was considered in the second one. This research was conducted with the DriveSafety DS-600c driving simulator in TSU. The main objective of this research was to investigate drivers' driving behaviors, considering factors such as lane change, deceleration, and stop distance for oncoming workers with and without the P2V communication system. The results showed that drivers change their lane approximate 130 meters earlier and decelerate 49 meters earlier in emergent situations. Furthermore, the posterior survey among drivers found that participants enjoy this technology and would like it to be implemented and adopted.

Santose et al. (2005) observed that young drivers have poor hazard anticipation skills compared with older, more experienced drivers, thereby leading to their over-

involvement in traffic crashes. Computer-based driver training programs have proved effective at training drivers in skills such as hazard perception, which was not taught in standard driver education courses. Although they have been successful in the evaluated cases on a simulator and in the field, to the best of our knowledge, no hazard anticipation training program has focused on teaching drivers to anticipate hazards in complex situations where anticipating the hazard requires more than one glance towards the hazard. Tracy et al. (2014) conducted a driving simulator study to evaluate the effectiveness of a training program, Road Aware (RA), when training drivers to scan for hazards in roadway scenarios where the anticipation of a hazard requires between one and three glances. The study involved 48 participants driving 18 scenarios on a simulator while their eye movements were recorded. The study's results suggest that RA training was effective in teaching young drivers to anticipate hazards and that the training effect was even larger for the complex situations requiring more than one glance. For low- complexity scenarios requiring one hazard anticipation glance, the RA participants made the correct glance 76% of the time compared to 58% for placebo participants, a difference of 17 percentage points. The difference increased to 28 percentage points for medium-complexity scenarios requiring two glances (63% RA, 35% placebo) and to 33 percentage points for high-complexity scenarios requiring three glances (42% RA, 9% placebo).

One of the major objectives of many driving simulator-based studies involves understanding how effectively drivers can follow warning messages. A recent study by Brittany et al. (2014) examined whether dynamic message signs (DMS) have an adverse effect on traffic flow and safety due to the traffic slowdown as a result of reading the safety message. Drivers' speed fluctuations in the proximity of two dynamic message signs with qualitative and quantitative contents on a highway and a freeway were analyzed. No statistically significant reduction in the speed of drivers to read the quantitative message in a highway with 55 mph (88.5 km/hr) speed limit was found. In correlation with the speed analysis, a majority of the subjects believed their speed reduction was insignificant. However, the average speed decreased by 2.6 mph (4.3 km/hr) to read the quantitative message on a sign mounted on the 65 mph (105 km/hr) freeway. Although the DMS was considered likely to impact the speed of fast drivers, they were found to safely operate as traffic management tools.

Ardehshiri et al. (2013) used a hybrid approach that incorporates a driving simulator in conjunction with a stated preference (SP) survey to analyze driver response behavior under real-time route guidance through DMS. It seeks to better understand factors affecting the route choice decisions by bridging some of the key gaps that limit the applicability of SP approaches. A 400 square kilometer network in the southwest of the Baltimore metro area is used for the driving-simulator-based analysis, with over 100

participants. The results illustrate that the cognitive loads experienced while driving, past exposure to DMS, information reliability of DMS, personal perceptions, and past experience are important determinants of driver response behaviors in the real world. Also, in addition to travel time, inertia and anchoring effects can significantly influence choice decisions. The study also illustrates that the decisions revealed in the simulator experiments at the individual level can diverge significantly from those stated in the SP questionnaire, highlighting the need to go beyond stated intent to analyze the effectiveness of information-based guidance strategies.

In summary, widespread applications of the driving simulator have confirmed that it is indeed an effective and powerful tool to study the roadway design, driving behaviors, and various safety issues when the massive collection of real-world data is technically difficult.

2.5 Summary of Literature Review

Due to aging U.S. roadways and infrastructures, the federal government and state agencies are allocating a greater portion of funds for the repair and maintenance of existing roadways as well as constructing new ones. Therefore, numbers of work zones are increasing, which causes increased risk for related fatalities and crashes to both drivers and workers. Currently, two types of warning systems are in place to guide

motorist through work zone areas. In most of the work zones, MUTCD static warning signs are posted to warn motorists about the existence of the work zone and its configurations. The main objective of this static sign is to entice reduction of speed for increased safety with little consideration of impacted mobility in the work-zone area. Alternatively, the dynamic work-zone merge systems are used in some work zone areas where traffic flow patterns vary greatly. This chapter reviewed traditional safety measures as well as newer technologies based on the connected vehicle concept (*i.e.* P2V system and DSAS system) implemented in work zone areas. Although there have been many pilot tests on connected vehicle technologies, the implementation of these methods is low due to the high cost and security issues. So there is potential to find newer technologies to implement the connected vehicle technology in cheaper and more reliable ways. Smartphone-based warning messages can be a suitable candidate to fill this gap to ensure safety in work zones.

CHAPTER 3

DESIGN OF THE STUDY

3.1. Methodology

Figure 5 illustrates this flow chart depicted the whole research framework of this thesis.

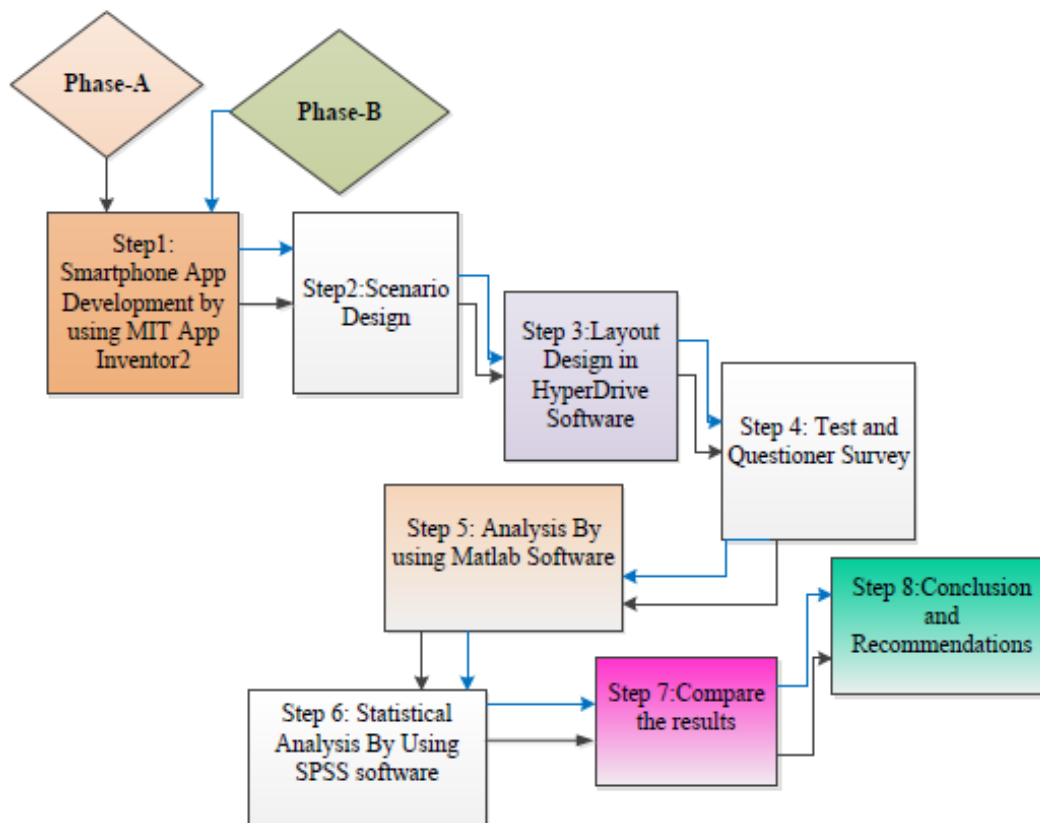


Figure 5 Research framework

3.2. Warning Message preparation with MIT APP Inventor

For this research study, two smartphone-based warning message apps, Safe Forward Collision Warning (SFCW) and Safe Worker to Driver (SWD), were developed with Massachusetts Institute of Technology (MIT) APP inventor2.

App Inventor2 is a cloud-based open-source web application originally provided by Google. The following steps were performed for the app development process.

3.2.1 Steps to Build up the Smartphone App:

The major steps to prepare the warning message app included the installation of MIT AI2 Companion app and configuration of relevant built-in functions.

Step 1: Installation of App Inventor Setup Software

MIT AI2 Companion app and QR code scanner were downloaded and installed on the smartphone used for this study.

The following is the procedure to prepare the App inventor

- Get A Google account was set up,
- Start AppInventor at <http://ai2.appinventor.mit.edu/.com> was launched,
- AppInventor works was composed of three functions,
- Designer assets were compiled,
- Blocks editor-command for function execution was blocked, and

Emulator-virtual mobile device was launched

Step 2: Configuration of Built-in Functions to App Development

To start the app development, a new project was created through the Google account (Figure 6 and Figure 7) that was created in the previous procedure. The following procedure describes the development of the warning message app

- Dragged and dropped AppInventor components,
- Assigned appropriate name (In this study, “Safe worker”),
- Uploaded other assets (images, sounds) and named them, and
- Provided commands to assets to perform in the Blocks Editor

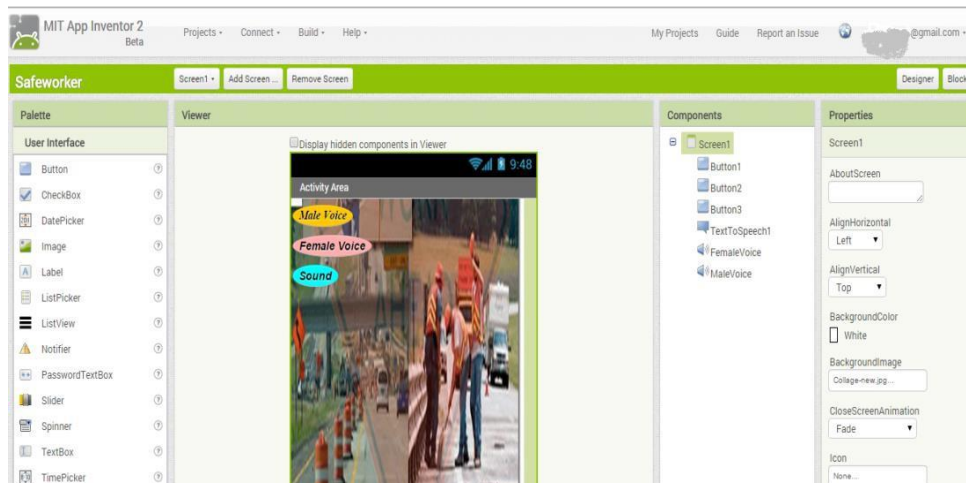


Figure 6 Snapshot of MIT App Inventor 2 Design Block



Figure 7 Snapshot of MIT App Inventor 2 Script Editor

Step 3: Uploading of developed in Smartphone:

After the app was developed in Google account, it was e-mailed as .apk file to the Smartphone to be used in the driving simulator study.

3.2.2 Proposed Smartphone-Based Worker Warning Message System

In this research, a smartphone-based SFCW in Phase A and Phase B “SWD” app was developed to deliver warning messages to drivers via their smartphones. This developed system is an Android-based application that can be easily downloaded onto any compatible smartphone in the current global market. In this study, the smartphone had the pre-installed application that can detect if a work zone is ahead based on the geo-location position of the phone. Warning messages including sound and voice prompts

will be triggered to alert the driver once the geo-location and driving direction of motorist match.

The communication between the driver's smartphone and the cloud-based ITS management server will be maintained via a Wi-Fi or phone network system or 5.9 GHz DSRC system. There will be a pool of warning messages that will be available once the app is downloaded. In the Phase-A study, four types of warning messages, including visual, sound, and male and female voice prompts were created, while in Phase-B, three types of warning messages, including sound, male voice, and female voice, were developed, and test runs were conducted to determine their comparative effectiveness.

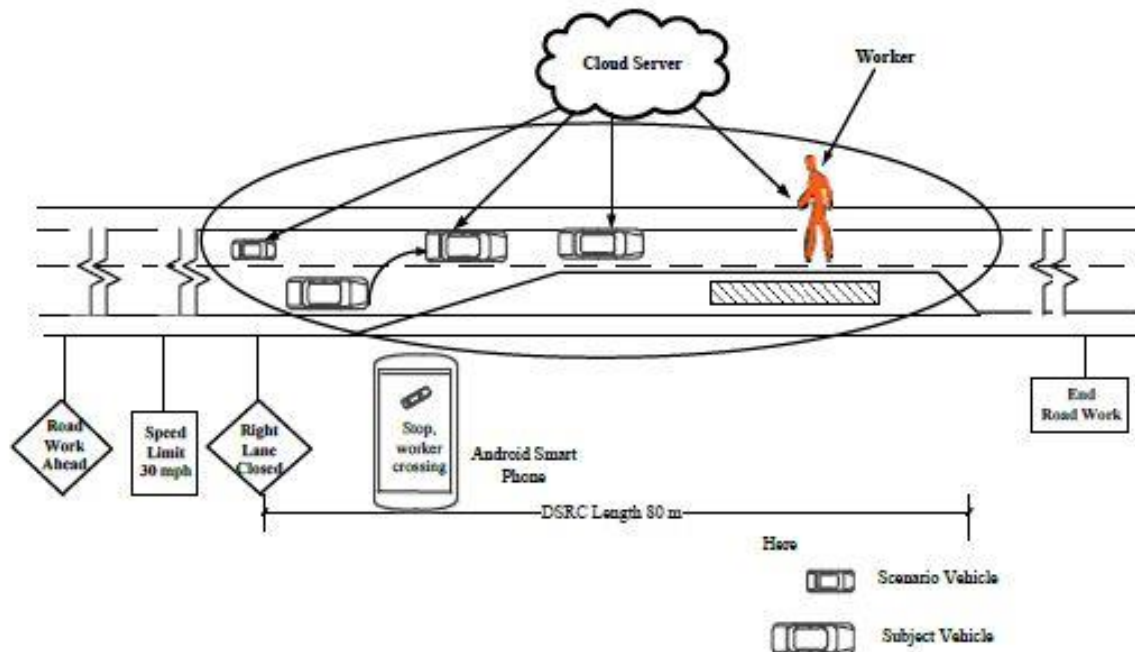


Figure 8. Conceptual framework of this research to transfer message

In Figure 8, A Wi-Fi communication system in the range of 80 m was used throughout the Phase-B study. For the Phase-A study, a 130 m range of communication system was used. For Phase-A, during tests when the subject vehicle was within this 130 m range, warning messages were generated to alert the driver about the presence of the truck through the Bluetooth communication, whereas for Phase-B, the subject vehicle was alerted when it reached the vicinity of the 80 m communication range through the Bluetooth communication between the subject vehicle and pedestrians.

3.3. Driving Simulator Test

In this study, the design and test of the subject warning system was conducted with a DriveSafety DS-600c simulator. This simulator was selected because of its advanced features of high performance, high fidelity, and fully integrated performance. It had the provisions of a multi-channel audio/visual system with 180°, 240°, 300°, and 360° wrap-around display options. It has the complete features of real automobile cabins; for example, a windshield, seats, a complete dashboard, a steering wheel, brakes, and acceleration systems. The participant can drive this simulator as a real-time automobile, and as such, data (up to 60 records per second) related to the acceleration, braking, velocity, and headway distances can be collected on a real-time basis.

3.3.1 Participants (Phase-A and Phase-B)

A total of 24 participants, including 12 females and 12 males with valid driver’s licenses, were selected for this test. The composition of participants followed the Houston’s demographics – gender, age, and educational level – as illustrated in Table 1 from the 2010 census. Table 1 illustrated the age and education distributions of the recruited drivers.

Table 1 Demographics of Subjects Based on 2010 Census Data in Houston

Subject	Gender*		Age				Education	
	Male	female	under 5	5 to 18	18 to 64	65+	High school+ Associate degree	Bachelor's degree or higher
Houston Statistics	49.80 %	50.20 %	26.90%	26.90%	57%	9%	74%	28.20%
Adjusted distribution	50%	50%	0%	0%	92%	8%	71%	29%
Number of participants	12	12	0	0	22	2	17	7

*The gender distribution was selected as 50% male and 50% female.

3.3.2 Test Procedure (Phase-A)

To familiarize the participants with the driving simulator, an adequate practice session time was arranged. This test was designed in such a way that each participant needed only 10 minutes to complete all five scenarios for the simulation. After the driving test, each participant filled in a

survey questionnaire regarding his/her simulator experience. The whole experiment process with the consent process and post-drive questionnaire took approximately 20 minutes. To reduce the motion sickness experienced in the simulator, the course of the urban roadway was designed in a way that participants only drove through a straight path with no stops. Figure 9 shows the placement of the smartphone in the driving simulator cab, and Figure 10 shows the subject in a practice test session.



Figure 9 Smartphone position view of driving simulator for Phase-A



Figure 10 Practice session for Phase-A

Each participant needed to drive through a total of five work zones with different

scenarios. This test was conducted in December 2014.

3.3.3 Scenario Design and Test Process (Phase-A)

The layout of the urban road work zone was prepared according to the Manual on Uniform Traffic Control Devices (MUTCD), with the right lane closed. According to the MUTCD 2009, a typical work zone is divided into four areas: the advance warning area, the transition area, the activity area, and the termination area. Figure 11 provides a standard setup of a typical work zone that is used in this research including four major zones.

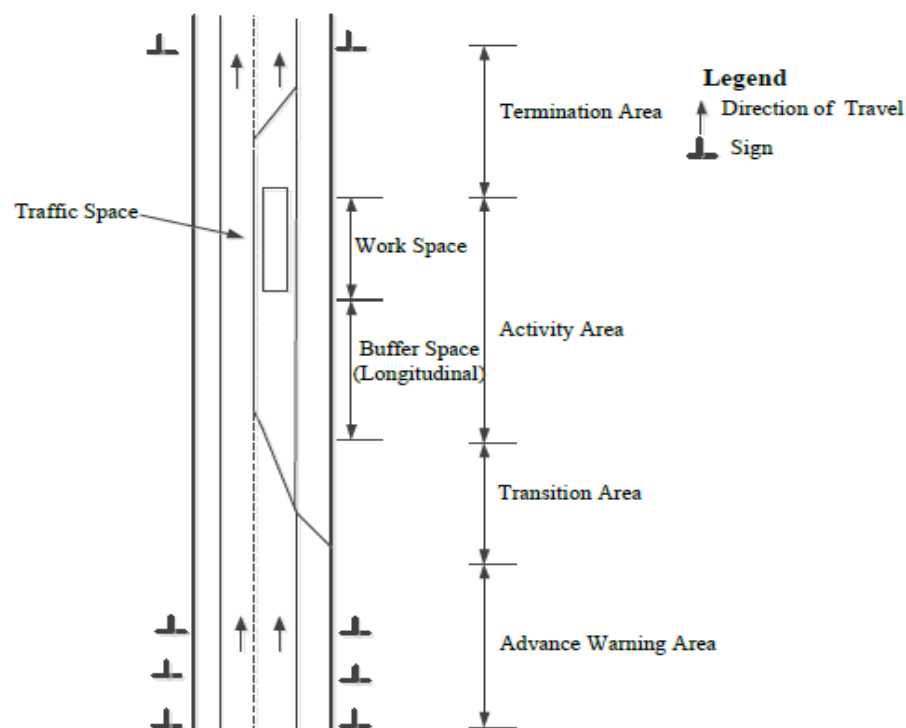


Figure 11 The typical work zone layout

Figure 12 showed the placement of signs and the smartphone warning location for the simulator tests. Car 2 is the subject vehicle, and Car 1 is indicated as a hard-braking vehicle. This scenario was created to reflect when Car 1 in the left lane made a hard brake due to an accident in the advance warning area where the subject vehicle (Car 2) was behind a truck. The driver of Car 2 was notified by the smartphone application about the accident.

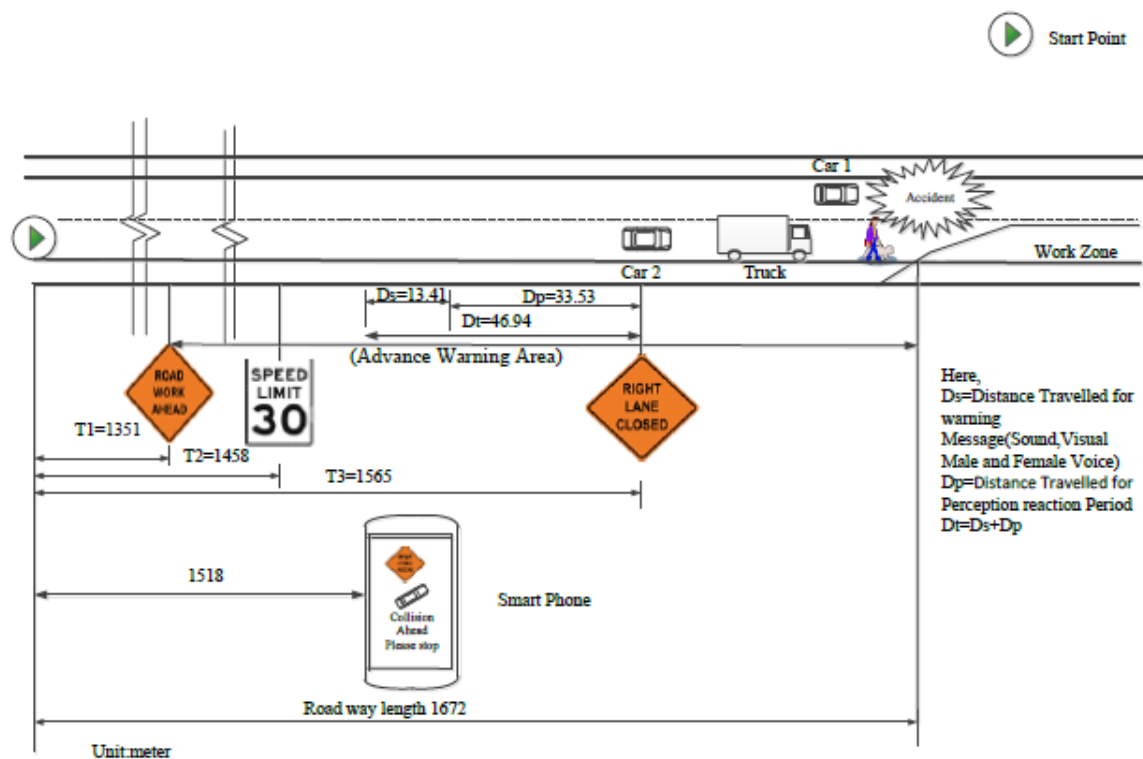


Figure 12 Placement of signs and smartphone warning location for simulator tests.

In this study, the effectiveness of warning messages for alerting drivers was tested in the advance warning area of an urban road work zone simulation.

In Figure 12 T1 (road work ahead), T2 (speed limit), and T3 (right lane closed)

indicate the placement of three static signs in the advance warning area based on MUTCD. A total of five scenarios were studied with a road length of 2,000 m. In Figure 10 (b), the subject was notified by a message via either sound, visual, male voice, or female voice notification that lasted for one second, with a posted speed limit of 30 mph (48 km/h or 13.41 m/s), the subject vehicle traveled a distance $D_s = 1 \times 13.41 = 13.41$ m. According to Chang et.al (1985) and Qiao et.al (2014), perception reaction is 2.5 sec for the 95th percentile. In this test, the reaction time used was 2.5 sec. Therefore, in that time, a subject vehicle traveled $D_p = 2.5 \times 13.41 = 33.528$ m. The total distance for lane preparation needed here was $D_t = D_s + D_p = 13.411 + 33.53 = 46.94$ m.

Therefore, for a safe lane-merge, the warning messages in the study were provided at 1,518 m. The created scenario in the driving simulator was sufficiently urgent, as the subject vehicle's front view was obstructed by the presence of a large truck. Each participant was instructed to drive during five scenarios, as shown in Table 2. Smartphone-based warnings, including "Collision ahead, please stop" were generated to notify the subject vehicle's driver about the presence of the stopped vehicles ahead, the view of which was obstructed by a truck. Table 2 illustrates the five different scenarios in the advance warning area.

Table 2 Description of Five Scenarios in Advance Warning Area

Scenario	Message Option	Content of Message in Smartphone
1. Base	No	None
2. Study	Visual	“Collision ahead, please stop.”
3. Study	Sound	One-second beep
4. Study	Male voice	“Collision ahead, please stop.”
5. Study	Female voice	“Collision ahead, please stop.”

At the beginning of the formal tests, each participant was asked to drive several rounds along the work zone areas so that they would become familiar with the operation of the simulator and the work zone environment. In this test, warnings to each participant were provided based on Table 2. Table 3 illustrates the 24 sequences of messages that were followed in the test. In each test scenario, the subject vehicle started travelling on the urban roadway at the point of 462 m with a speed of 40 mph while a heavy-duty truck drove at a speed of 30 mph at the 814 m in front of the subject vehicle. In the adjacent lane, Car 1, which is the test vehicle, started at the position of 888 m at a speed of 30 mph. Due to a sudden crash at the end of the advance warning area, Car 1 stopped at the location of 1,630 m. This forced the truck to stop at the location of 1,635 m.

Table 3 Different Sequences of Messages

Sequences No	Sequence of Messages				
	Base	Visual	Sound	Male	Female
1	Base	Visual	Sound	Male	Female
2	Base	Sound	Male	Female	Visual

3	Base	Male	Female	Visual	Sound
4	Base	Female	Visual	Sound	Male
5	Base	Visual	Sound	Female	Male
6	Base	Sound	Female	Male	Visual
7	Base	Male	Female	Sound	Visual
8	Base	Female	Visual	Male	Sound
9	Base	Visual	Female	Male	Sound
10	Base	Sound	Female	Visual	Male
11	Base	Male	Visual	Sound	Female
12	Base	Female	Sound	Visual	female
13	Base	Visual	Female	Sound	Male
14	Base	Sound	Male	Visual	Female
15	Base	Male	Visual	Female	Sound
16	Base	Female	Sound	female	Visual
17	Base	Visual	Male	Sound	Female
18	Base	Sound	Visual	Male	Female
19	Base	Male	Sound	Female	Male
20	Base	Female	Male	Visual	Sound
21	Base	Visual	Male	Female	Sound
22	Base	Sound	Visual	Female	Male
23	Base	Male	Sound	Male	Female
24	Base	Female	Male	Sound	Visual

3.3.4 Scenario Design (Phase-B)

To test the best message option from the smartphone, the layout of the urban road was created on the basis of the MUTCD with the right lane closed. Here, the TSU DS-160 Driving Simulator is presented in Figure 13.



Figure 13 TSU DS-160 Driving Simulator used for Phase-B

A scenario in Hyper-Driver software with the simulation environment is demonstrated in Figure 14. The worker's movement from the activity area of the simulated work zone in the DS-160 Driving Simulator is depicted in this Figure.



Figure 14 Worker comes out in Phase-B test

The path of the urban roadway was designed in such a way that participants only drove through a straight path with no stops. Thereby, it was possible to reduce the motion sickness from the simulator among the participants. The advance warning area is comprised of three parts: Part A (Construction ahead), Part B (Speed limit), and Part C (Right/left lane closed). In this test, the urban road speed limit was set to 40 mph. Specifically, the advance warning area started at 1,351 m and ended at 1,672 m, as shown in Figure 15. In the test, the urban road speed limit was set to 40 mph.

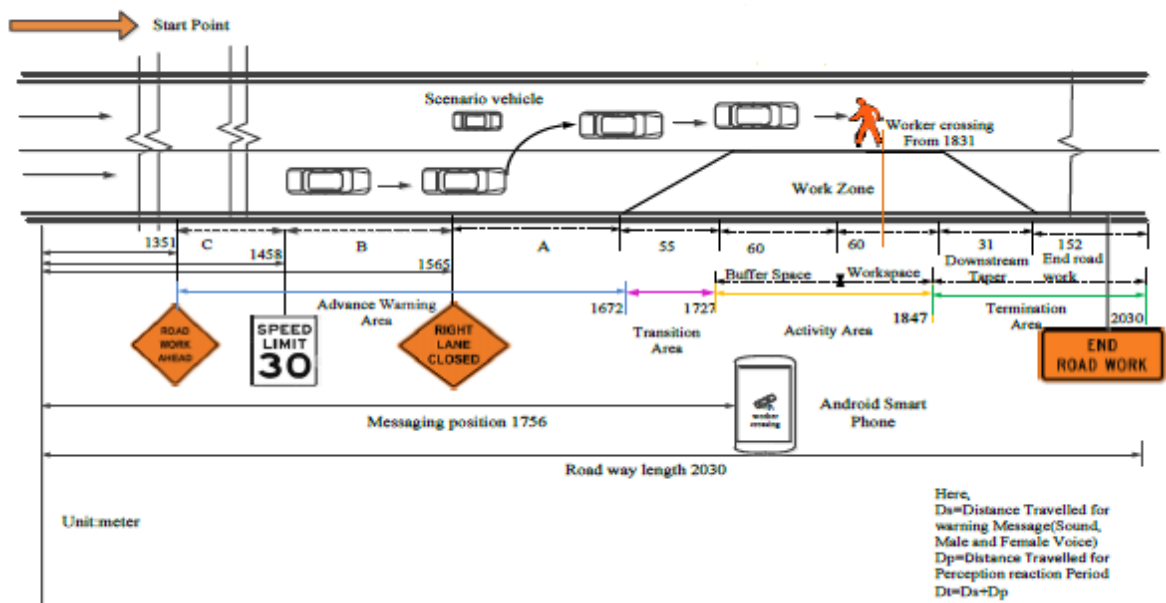


Figure 15 Illustration of smartphone-based advanced warning message system

The transition area starts immediately after the advance work area, which is to advise the driver to change the lane if any redirection is necessary. This area started at 1,672 m to

1,727 m. The activity area is the zone where actual roadway repair activities take place. In this layout, the activity area started at 1,727 m and ended at 1,847 m. A buffer space of 60 m (200 ft) and a work space of 60 m was considered. The termination area started at 1,847m and closed at 2,030 m.

3.3.5 Testing Process (Phase-B)

The test is designed to give three types of messages, sound, female voice, and male voice, through the smartphone about the worker crossing from the activity area in the work zone. The subject vehicle started from 780 m position and faced two situations: (a) a stalled vehicle at the advanced warning area at the merging point and (b) a worker crossing the road at 2mph in the activity area. A total of four scenarios were examined with a road length of 2,030 m. In Figure

15, the subject was notified by message via either a sound, visual notification, male voice, or female voice that lasted for one second, with a posted speed limit of 30 mph (48 km/h or 13.41 m/s), and the subject vehicle traveled a distance of $D_m = 1 \times 13.41 = 13.411$ m. According to the Texas Department of transportation (TxDOT), The stopping sight distance is the sum of the brake reaction distance and the braking distance where the perception reaction time also includes 2.5 sec. In this test, the design speed was 30 mph.

Therefore, the calculated stopping sight distance $D_{sd} = 110.3 + 86.4 = 200$ ft (61m). The

total distance for the stop here was $D_t = D_m + D_{sd} = 13.411 + 61 = 74.41$ m. Therefore, to ensure that the driver did not hit the worker, the warning messages in the study were provided at the position of $(1,831 - 74.41)$ m = 1,756 m.

Each participant was instructed to drive during four scenarios, as shown in Table 4. Smartphone-based warnings of “Stop, worker crossing” were generated to inform the subject vehicle’s driver about the worker crossing. Table 4 illustrates the four different scenario message preferences in the activity area.

Table 4 Different Scenarios with Different Message Options

Scenario	Option of Message	Message Overview in Smartphone
Base	No	None
Study	Sound	One second beep
Study	Male voice	“Stop, worker crossing”
Study	Female voice	“Stop, worker crossing”

Messages were randomized for this test, except for in the base scenario. There were exactly six sequences in this test followed by three combinations. To get the best results, these six sequences were repeated in Table 5 four times, which totals 24 sequences, as shown in Table 5.

Table 5 Different Sequence of Messages

Six sequences	Sequence of Messages			
1.	Base	Sound	Male	Female
2.	Base	Sound	Female	Male
3.	Base	Male	Female	Sound
4.	Base	Male	Sound	Female
5.	Base	Female	Sound	Male
6.	Base	Female	Male	Sound

The test was prepared in such a way that each participant needed only 10 minutes to finish all four scenarios for the simulation. After completing the driving test, each individual participant was asked to complete the survey questionnaire regarding his/her simulator experience. Overall, each participant needed about 25 minutes, including the consent process and post-drive questionnaire.

3.3.6 Data Collection and Analysis

In this research, for Phase-A and Phase-B, scenarios data were collected from the Hyperdrive software. The driving simulation scenario was built up based on traffic and road parameters as in the real-world study area, such as road types, number of lanes, and roadway length. Required triggers were placed in locations at the beginning of each different road type and the urban work zone, and static signs were set up. In the driving

simulator, the scenarios needed to work on Tiles, Scenario Tools, Entities, Static Entities and World Object Browser. Figure 16 shows a snapshot of the Hyper-Driver triggers and script windows.

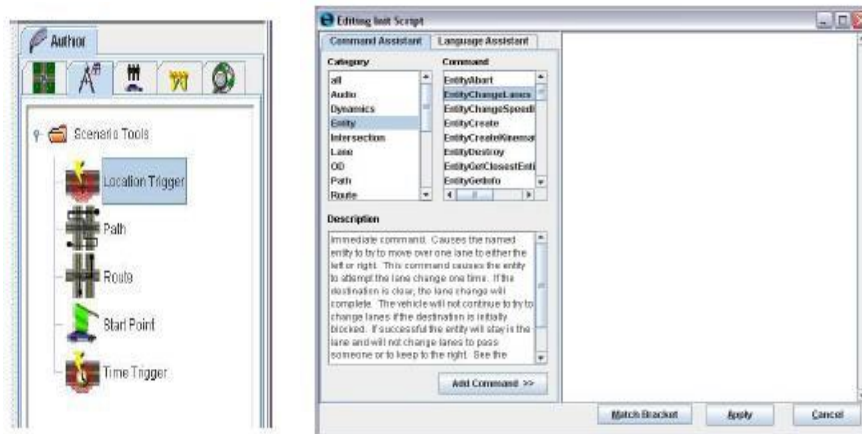


Figure 16 Triggers and Script editor in driving simulator

The script for each trigger was coded to control the whole scenario of the work zone. The driving simulation test was conducted with the second-by-second driving activity data. After finishing the driving simulator test, the data analysis was performed by using Matlab software.

CHAPTER 4**RESULTS AND DISCUSSION****4.1 Results of Phase-A**

The simulator-based driving performance of 24 participants for different scenarios was analyzed based on generated data from the Hyper-Driver software. In this analysis, four measures of effectiveness (MOE) were calculated to evaluate driver performance in the advance warning area:

- Headway time difference between the subject vehicle and the truck,
- Headway distance difference between the subject vehicle and the truck,
- Speed, and
- Acceleration/deceleration

Here for the purposes of comparative analysis, the MOE was used to evaluate the driving behavior of participants in different test scenarios. To examine the significance of these test results, the *paired-t test* by SPSS software was performed to compare participant driving performance.

4.1.1 Impact on Headway Time:

Figure 17 shows the headway time vs. the subject vehicle position. It clearly indicates that the base scenario had the worst safety performance compared with the other four scenarios. Without warning, the headway time between a subject vehicle and the truck was less than those for other scenarios. This graph illustrates that a voice message, both in male and female voice, resulted in a higher headway time than other modes of warning compared to the base case. In particular, a female voice resulted in the highest headway time. The male voice and the sound warning had the second and third largest headway time, respectively.

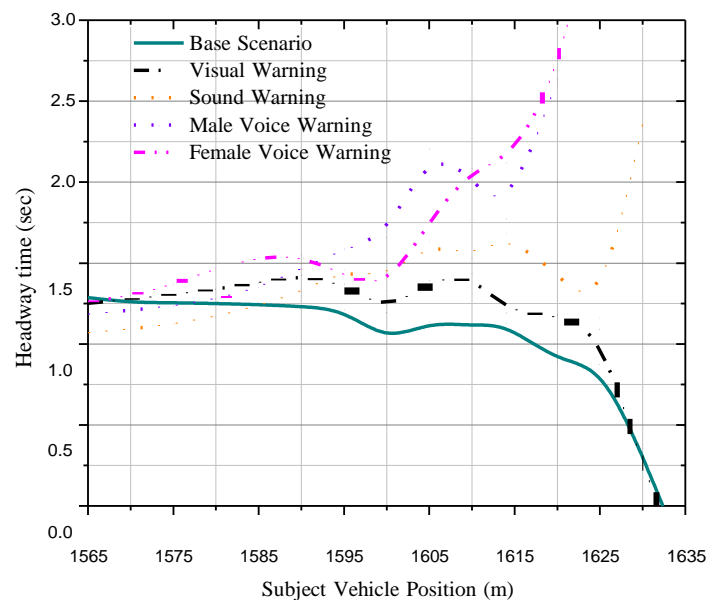


Figure 17 Comparison of different scenarios of headway time vs. subject vehicle position

In Figure 17, it is observed that, overall; the female voice warning had the greatest influence on participant driving behaviors. For example, after hearing the female warning message, the subject vehicles tried to make a lane change at 1,565 m, and some drivers applied the brake at a 1,580 m distance and others decelerated at 1,605 m. Similar driving behavior was observed with the male voice warning message.

The headway time difference between the base case and the voice warning (male and female) and the sound was found to be statistically significant with a 95% *paired-t Test* (P-value = 0.005, 0.000, and 0.134, respectively). However, there was no statistically significant difference found between the base case and the visual warning (*P-Value* = 0.48).

4.1.2 Impact on Headway Distance

The headway distance was correlated with the severity level of potential conflicts. The higher the headway distance is, the lower the likelihood that the change would result in a conflict. From the headway difference vs. subject vehicle position plot in Figure 18, the base scenario had the headway distance that gradually decreased, indicating the worst safety performance. For a voice warning message (in both male and female voice) and sound warning, the headway distance increased at the points of 1,582, 1,587, and 1,595. These graphs indicated that headway distance increased (from position 1,565 to

1,590 m approximately) for sound and voice warning messages. It indicated that most participants were able to follow the warning message. Overall, the trends in headway distances indicate that drivers were able to keep a safe distance from the truck as a result of the sound and voice (both male and female) warnings.

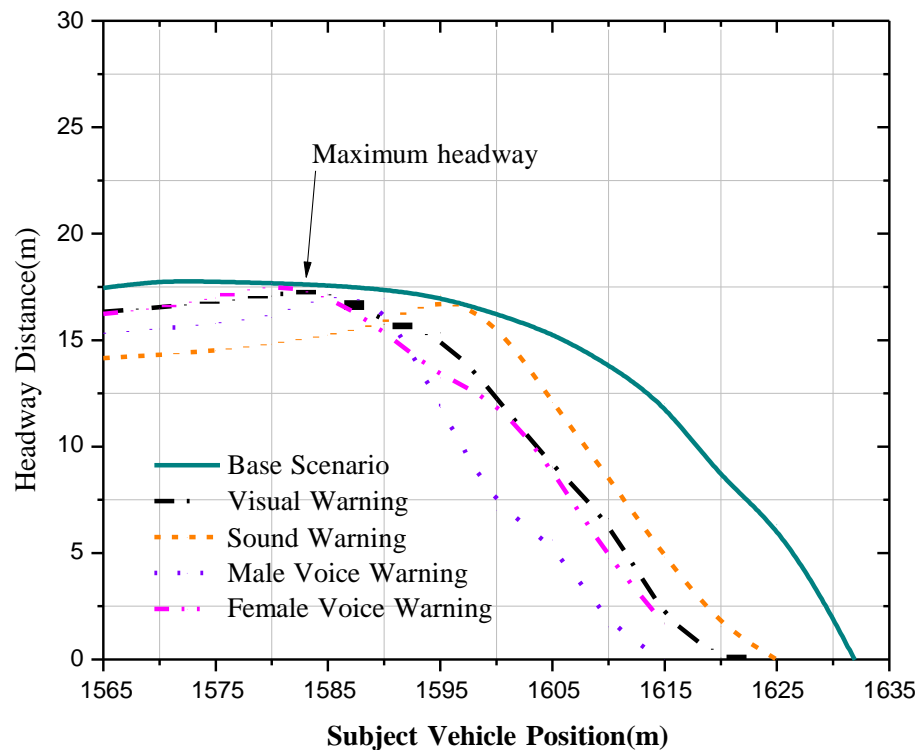


Figure 18 Comparison of headway distance vs. subject vehicle position scenarios

The difference in headway distance between the base case and the voice warning (male and female) was found to be statistically significant with the 95% *Paired-T Test* (P -value = 0.001 and 0.001, respectively). Similarly, a statistically significant difference existed between the base case and sound warning (P -value = 0.002). However, there was no statistically significant difference between the base case and the visual warning (P -value = 0.720).

4.1.3 Impact on Speed

In the work zone advance warning area, drivers are sometimes confused about adopting the posted speed limit. Potential speed difference is one of major causes of conflicts in an advance warning area. Speed is an effective surrogate measure for safety in a work zone area. The plotted graph in Figure 19 shows that the speed reduction was highest for the voice warning (male and female) among other scenarios.

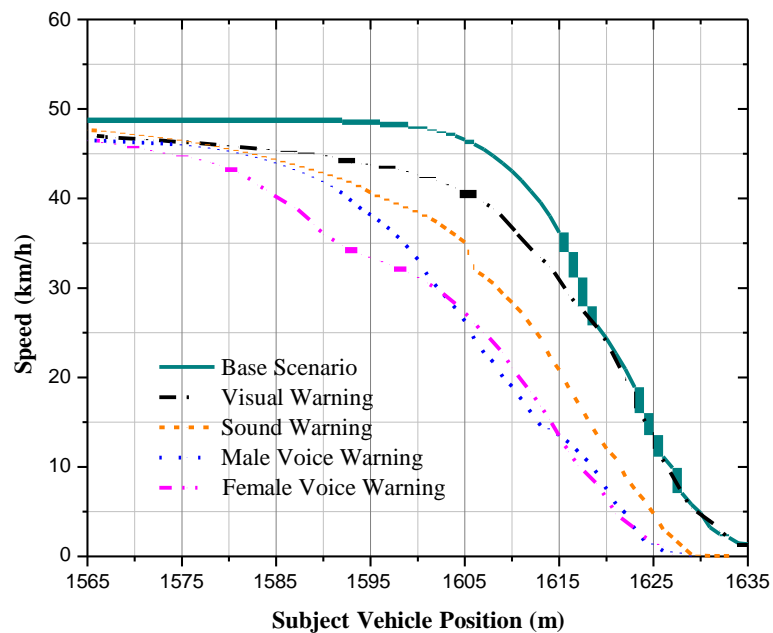


Figure 19 Comparison of speed vs. subject vehicle position scenarios

The comparison results between the 95% significant test P -values obtained from the base with the female and male voice option mode showed that there was a significant difference between the female and male voice mean speeds, whereas there was no difference between visual and sound warnings. The obtained P -values with 95%

confidence interval for the female and male message mode were a P -value of 0.002 and 0.004, respectively. For the message options of visual and sound, the corresponding P -values were 0.789 and 0.079, respectively. The comparative analysis results showed that the female and male voice had a mean speed of 30 km/h and 31 km/h, respectively, while the mean speed value of the base scenario was 46 km/h.

4.1.4 Impact on Acceleration/Deceleration

For a safety research, the acceleration and deceleration are effective performance measures as they indicate the potential severity of the conflict event. The deceleration was recorded to evaluate the driving performance of the participants in five scenarios. Figure 22 illustrates the acceleration distribution of vehicles in different test scenarios. This graph demonstrated that, among the five scenarios, the average of 24 participants' deceleration rate was similar. However, 3 people demonstrated maximum deceleration at 1,615 points. Among the other four study scenarios in Phase-A, even the fastest participants were able to start earlier deceleration with the voice warning.

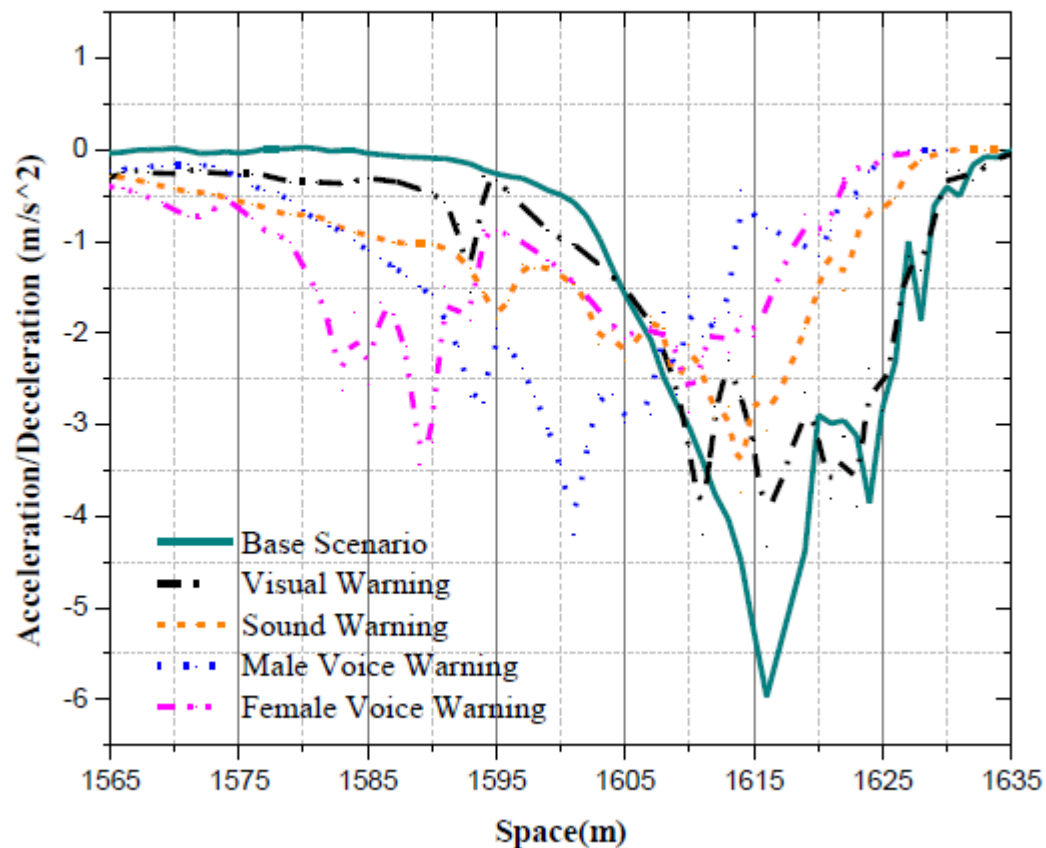


Figure 20 Comparison of acceleration rate vs. space diagram scenarios

The statistical difference between the maximum decelerations in the baseline scenario and in the study scenario for the voice (male and female) and the sound was significant (P -values = 0.000, 0.004 and 0.000, respectively). However, no significant differences were found in the case of the visual warning compared with the base scenario (P -values = 0.108).

This result indicated that the smartphone-based forward collision warning message contributed to the smoother driving behavior in the advance warning area of a work zone, thereby improving safety.

4.1.5 Brake Reaction Distance

From Figure 23, the effects of warning system are evident on the braking distance of the participants.

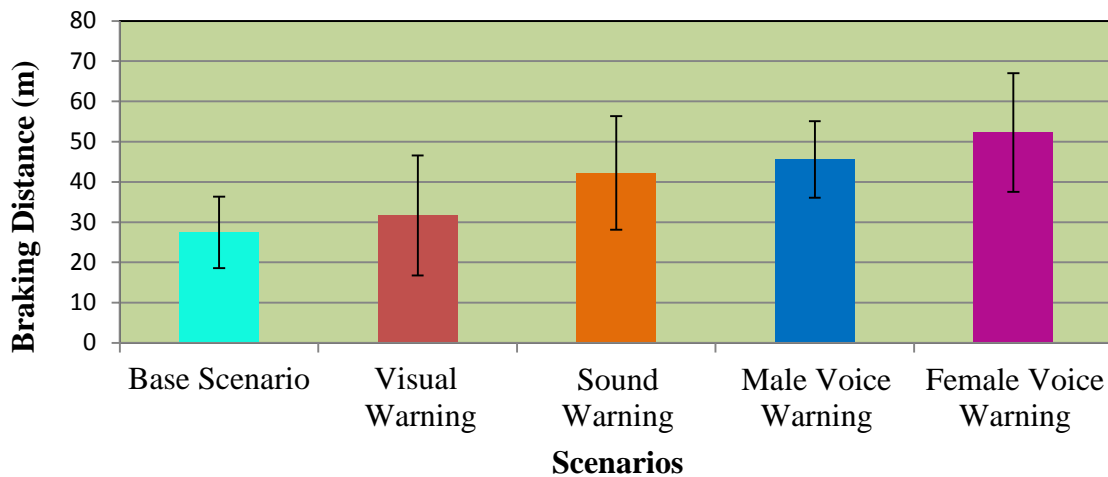


Figure 21 Comparison of brake reaction distance for different scenarios

With the help of the voice warning (both male and female), participants were able to apply the brake approximately 45-50 m behind the accident location in the advance warning area. Similarly, with a sound warning, participants were able to apply the brake earlier compared to both base and visual warnings. These test results indicated that the sound and the male voice and female voice warnings helped the participants to apply the brake before the subject vehicle come closer to the accident location.

Table 6 Mean and Standard Deviation for Five Scenarios

Brake Reaction	Base Scenario	Visual Warning	Sound Warning	Male Warning	Female Voice
Mean	27.45	31.70	42.23	45.59	52.24
SD	8.86	14.89	14.11	9.50	14.76

Table 6 presents the mean and standard deviation values for the test. The average value for the female voice warning was highest, but the standard deviation values were quite high. That means the participants' driving behavior was deviated with the female warning message. A similar pattern was also observed in the case of the visual warning message. The calculated *P*-values with 95% confidence interval for the female and male message options were a *P*-value of 0.000 and 0.000, respectively. Similar results were also observed for the sound warnings. For the message options of the visual warning, corresponding *P*-values was 0.142.

4.1.6 Post Questionnaire Survey Phase-A

The results from the post-test questionnaire revealed that 80% of the test participants indicated that the smartphone-based forward collision warning message would increase defensive driver driving. The survey results found that 75% of participants wanted to install this system on their smartphones, whereas 25% participants did not want to install this mobile application on their smartphones.

During the test, 60% of participants successfully followed the warning from the smartphone, while only 40% of subjects obeyed the traffic sign and speed limit on an urban street. 70% of drivers believed that the audio instruction/warning did not increase the workload of the driver, while 30% said it increased the workload. 75% of participants agreed that this warning alert successfully assisted them in stopping behind the large truck in the advance warning area. Among the four warning messages, 45% of participants liked the female voice warning, whereas only 2% liked the visual warning message. The percentages that liked the male voice and the sound warning were 40% and 13%, respectively. The survey results provided a good indication of the participant choice regarding the type of voice warnings.

4.2 Results of Phase-B

The simulator-based driving performance of twenty-four participants in different scenarios was analyzed based on the generated data from the Hyper-Driver software. In this analysis, four performance measures of effectiveness (MOE) were calculated to evaluate the driver performance in the activity area of the work zone. The performance measure indexes were speed, speed variations, acceleration, and braking distance.

4.2.1 Influence of Speed

The potential speed difference is one of major causes of conflict in an activity area. In Figure 24, the X-axis indicated the subject vehicle position and the Y-axis is the mentioned average speed of twenty-four participants in this study. When the message was provided at the point of 1,756 m, few differences were found between the study scenarios (sound, male and female voice) warnings and the base scenario. For the voice warning messages (male voice and female voice), the speed profile gradually decreased from the point 1,773 m to 1,814 m; after that point, the speed for this two scenario gradually increased.

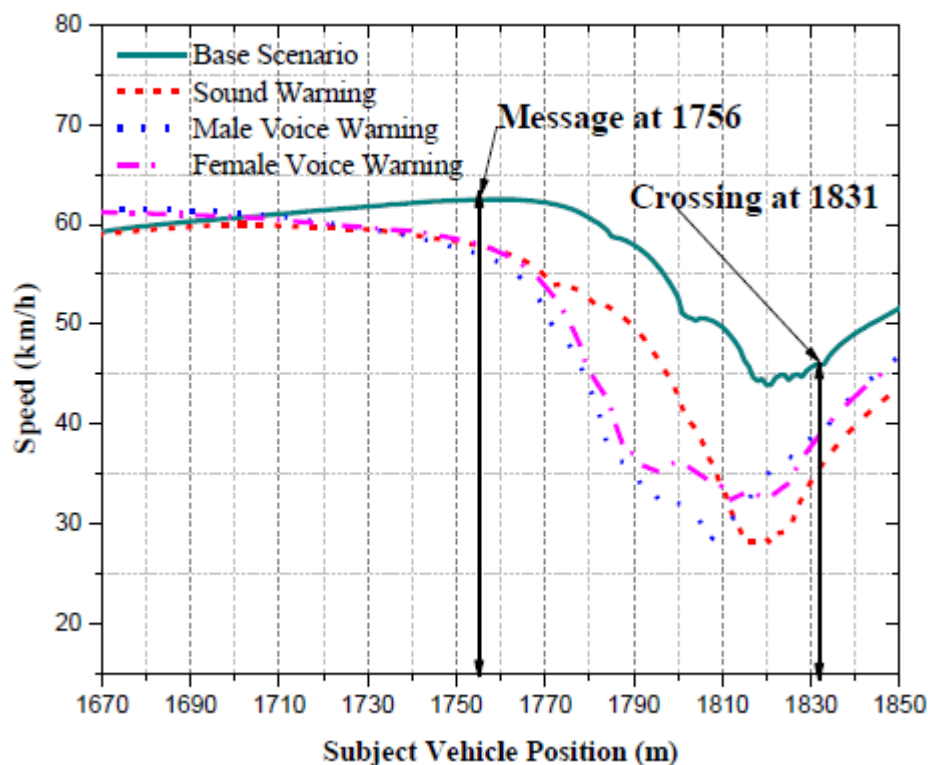


Figure 22 Comparison of speed vs. subject vehicle position in different scenarios

In addition, for the sound warning, the speed profile sharply decreased from point

1,779 m to 1,815 m and remained steady from 1,815 m to 1,824 m. For the sound and male and female voice warnings, the speed dropped from 60 km/h to 30 km/h. On the other hand, for the base scenario, the speed profile dropped 60 km/h to 45 km/h from 1,794 m to 1,831 m very close to the pedestrian crossing position. That implied that, without the smartphone warning, participants would be confused about adopting a safe speed in the activity area. Overall, the trends in the speed profile implied that drivers were able to maintain a good speed while they were travelling in the activity area as a result of sound and (male and female) voice messages.

The *Paired-t* test by the IBM SPSS statistical test was conducted to evaluate the statistical significance of various warning methods for the speed profile. In this *Paired-t* test, three subject vehicle positions (1,790, 1,810 and 1,831 m) in Table-7 were evaluated because of the existence of large differences of measures of speed. As a general guideline, if the *p*-value is less than 0.05 for 95% confidence interval, then the result would be considered statistically significant.

Table 7 Paired T-test Results for Speed at 1,790 m, 1,810 m, and 1,830 m

Pair at 1,790 m 1790 Point	Scenarios	Mean	N	SD	P value
Pair 1	Base	57.94	24	17.23	0.113
	Sound	49.74	24	14.7	
Pair 2	Base	57.94	24	17.23	0.001
	Male	35.27	24	17.23	

Pair 3	Base	57.94	24	17.23	0.002
	Female	37.11	24	22.73	
Pair at 1,810	Scenarios	Mean	N	SD	<i>P</i> value
Pair 1	Base	49.7	24	23.074	0.009
	Sound	33.7	24	14.83	
Pair 2	Base	49.7	24	23.074	0.001
	Male	29.84	24	16.00	
Pair 3	Base	49.7	24	23.07	0.003
	Female	33.73	24	13.64	
Pair at 1,831	Scenarios	Mean	N	SD	<i>P</i> value
Pair 1	Base	45.67	24	22.9	0.023
	Sound	34.23	24	10.74	
Pair 2	Base	45.67	24	22.9	0.128
	Male	38.59	24	9.27	
Pair 3	Base	45.67	24	22.9	0.109
	Female	37.84	24	9.29	

Overall paired t-test with a 95% confidence interval showed that, at the 1790 m position, voice warnings had a statistically significant effect (male, $p = 0.001$ and female, $p = 0.002$) on speed control. At the point of 1,810 m, all warnings had statistically significant speed reduction (Male, $p = 0.001$ and Female, $p = 0.003$, Sound, $p = 0.009$) compared with the base scenario. Interestingly, at the point of 1,830 m, the sound warning was statistically significant ($p = 0.023$). This indicates that, with the help of a voice warning (male and female), drivers could swiftly reduce the speed (within 50 m). Although the sound warning was effective, it was only effective after travelling distances longer than 50 m.

4.2.2 Speed Variations

The speed frequency distribution is another important indicator to identify the participants' speed at a specific point. In Figure 25 to 29, the plotted graph shows the frequency distribution of the speed at five different points in the activity area of work zone: 1,750 m (before message), 1,756 m (exact message providing position), 1,790 m, 1,810 m (two different locations after message providing), and 1,831 m (worker crossing position).

Speed Variations at 1,750 m (Before warning message). From Figure 25, it is observed that, at the 1,750 m position, the participants in the base scenario were predominantly at 50-60 km/h and 60-70 km/h speed frequency, respectively.

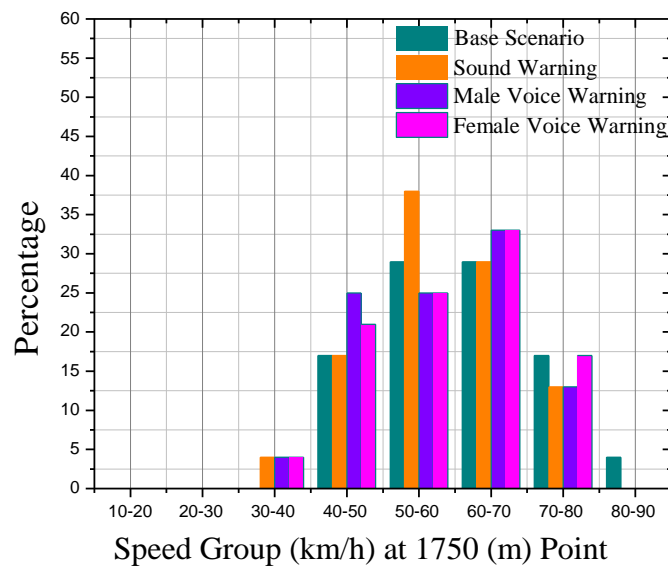


Figure 23 Comparison of different scenarios speed variation at 1,750 m

Similarly, for other scenarios including the male voice, female voice, and sound warning, participants were predominantly in the 50-60 km/h and 60-70 km/h speed range.

Speed Variations at 1,756 m (Warning message location). In Figure 26, speed frequency is plotted for the position 1,756 m, which was 75 m from the worker crossing position. In the base scenario, the highest speed frequency occurred at the speed range of 60-70 km/h.

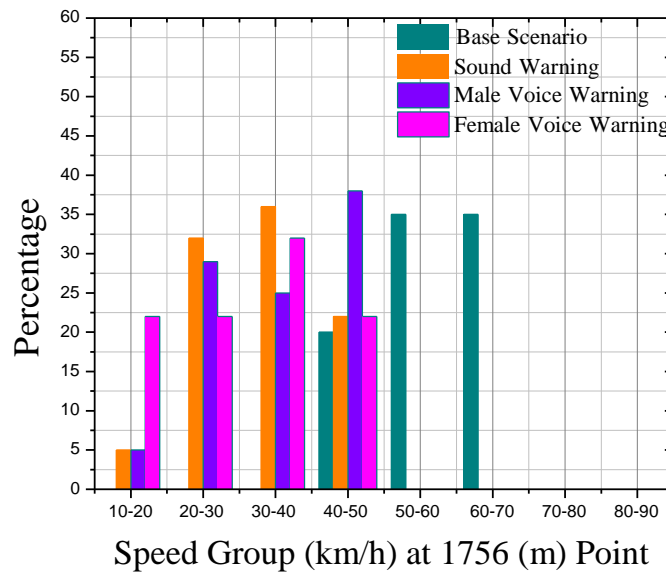


Figure 24 Comparison of different scenarios speed variation at 1,756 m

For the sound and female voice scenarios, the largest speed frequency speed values were in the speed range of 30-40 km/h, whereas for the male voice warning, the highest speed frequency value was 40-50 km/h.

Speed Variations at 1,790 m (After warning message). In Figure 27, at 1,790 m, the highest speed frequency for the base scenario was in the 50-60 km/h speed range. In the case of the sound warning, the largest speed frequency was observed in the speed range of 60-70 km/h. However, for the female voice warning, the highest speed frequency was observed at 10-20 km/h. With the male voice warning, the largest speed frequency occurred at 20-30 km/h. That means most of the participants were able to adopt a safe speed with the help of the voice warning message within the 41 m from the worker crossing position.

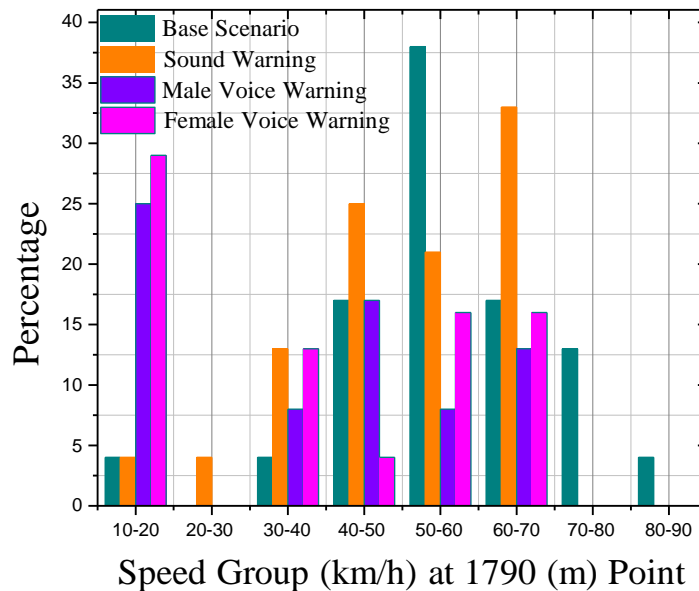


Figure 25 Comparison of different scenarios speed variation at 1,790 m

For the sound warning, maximum speed frequency was approximately 35%, with 10-20 km/h speed range. A similar speed pattern was also observed for the male voice warning.

Speed Variations at 1,810 m (After warning message). In Figure 28, at the 21 m back from worker crossing position, the voice warning (male and female) had the highest frequency in speed range, 30-40 km/h. Similarly, the participant with the assistance of sound warning maintained a speed range of 40-50 km/h.

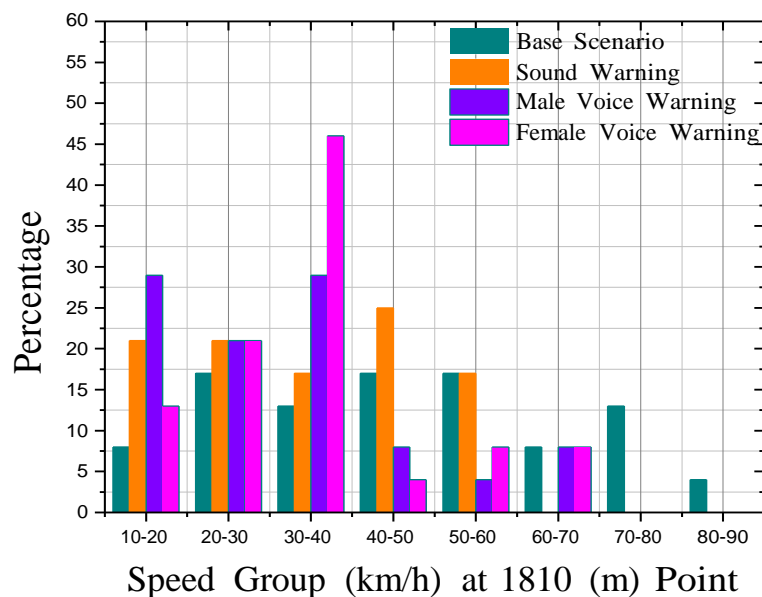


Figure 26 Comparison of different scenarios speed variation at 1,810 m

However, the base scenario speed frequency was varied in speed range 50-60 km/h and 70-80 km/h.

Speed Variations at 1,831 m (Worker crossing position). From Figure 29, at position 1,831 m, the base scenario had the highest frequency in the 20-30 km/h speed range. That implied that more than 25% people in the study struggled to adopt a safe speed when they approached the critical point.

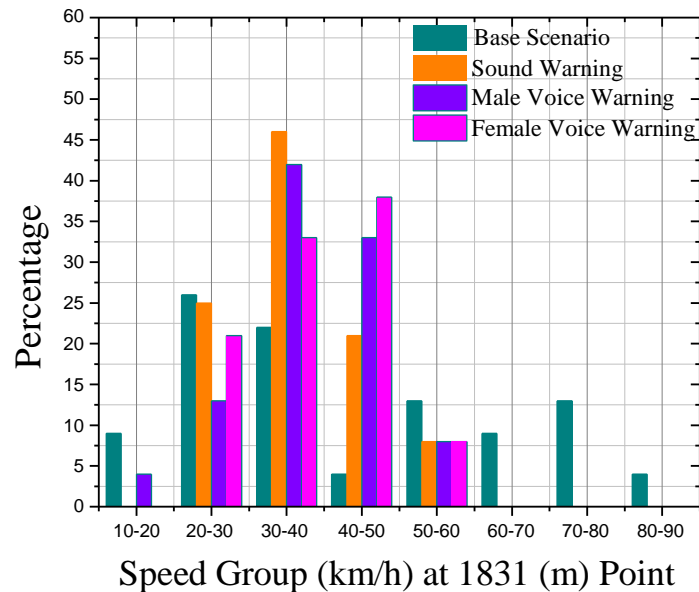


Figure 27 Comparison of different scenarios speed variation at 1,810 m

From the speed range analysis at various positions, it is observed that the base scenario speed frequencies were the highest at 50-60 km/h and 60-70 km/h. However, in the case of all warning messages, participants were able to slow down the speed and maintain safe distance from workers.

4.2.3 Acceleration/Deceleration

For safety research, acceleration and deceleration are realistic performance measures, since they indicate the potential severity of the conflict event. Figure 30 depicts the acceleration and deceleration distribution for this study from 1,756 m to 1,830 m.

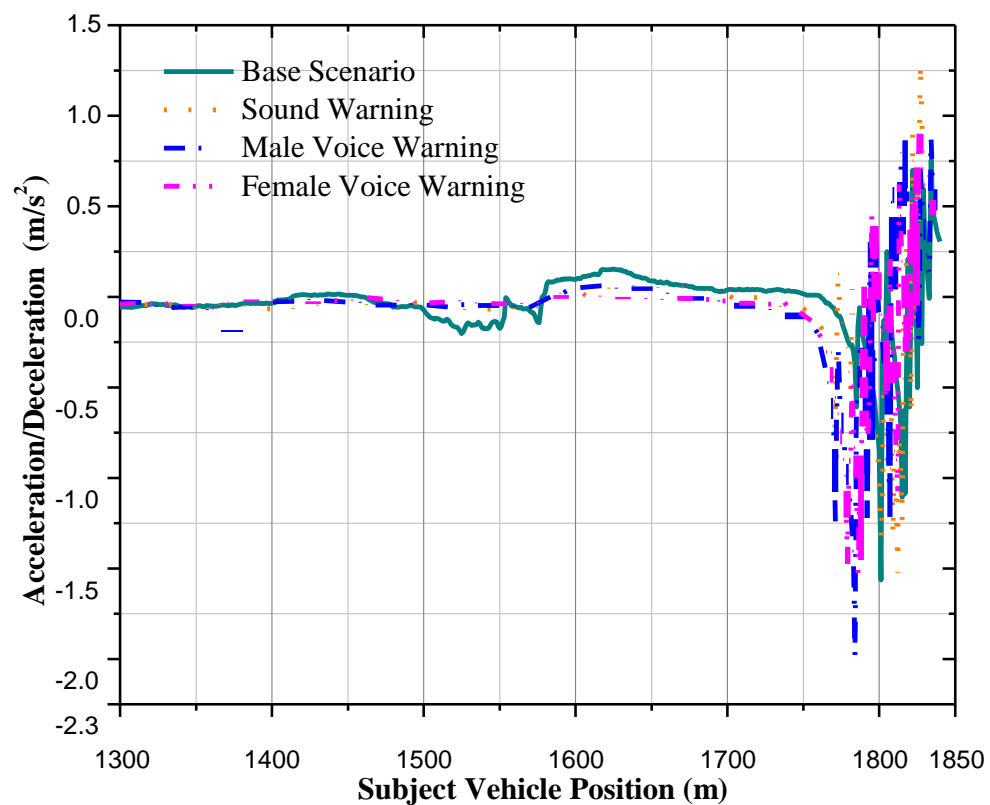


Figure 28 Comparison of acceleration vs. subject vehicle position in different scenarios

For The three study scenarios showed that, among the male voice, female voice, and sound warnings, participants decelerated earlier than the base scenario. In these three

scenarios, participants decelerated approximately from 1,773 m and accelerated from the 1,815 m position. However, the base scenario participants struggled to decelerate at this point, and their decelerations were very close to the worker crossing position at 1,831 m.

4.2.4 Brake Reaction Distance

The brake reaction distance is an important parameter to evaluate the performance of the warning in this test, which is to determine when the participants first applied the brake to slow their speed down. Figure 31 clearly showed that participants in this test first braked earlier for the voice (female and male) warning message in contrast to the base scenario.

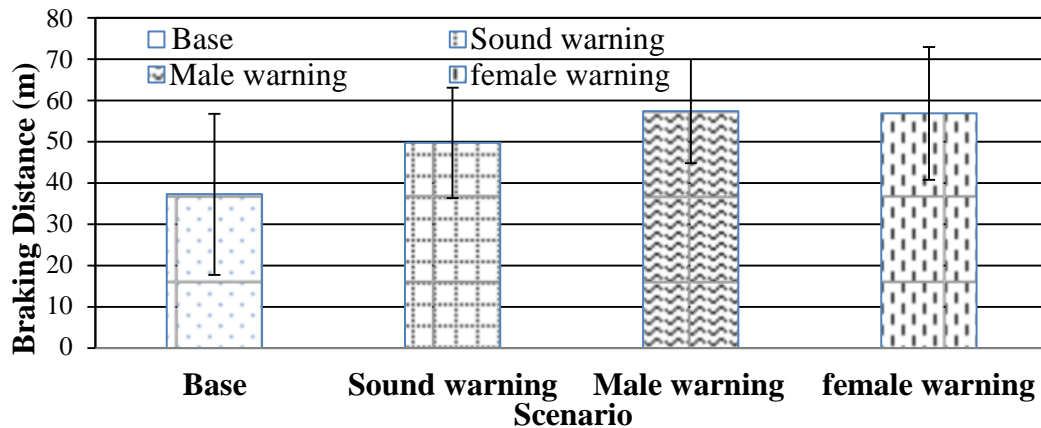


Figure 29 Comparison of brake reaction distance for different scenarios

Their average first brake distance for male voice, female voice, and sound warnings were approximately 58 m, 57 m, and 50 m, respectively. Furthermore, for the sound

warning message, the participants' brake response is better than the base warning message.

On the other hand, braking distance was the lowest for the base case among all scenarios. The average brake distance for base warning was 38 m. Standard deviation errors were very close for voice (female and male) and sound (Table 8) warning messages.

Table 8 Mean and Standard Deviation for Four scenarios

Brake reaction distance	Base	Sound	Male	Female
Mean	37.27	49.73	57.39	56.86
Standard Deviation	19.51	13.36	12.59	16.11

4.2.5 Safe Headway Distance and Headway time

The headway distance and headway time are further important safety indicators for this study. The analyzed comparison results in Figure 32 illustrated that with voice warning message (male and female), participants were able to keep a safe headway distance from the worker crossing 31 m and 30 m respectively.

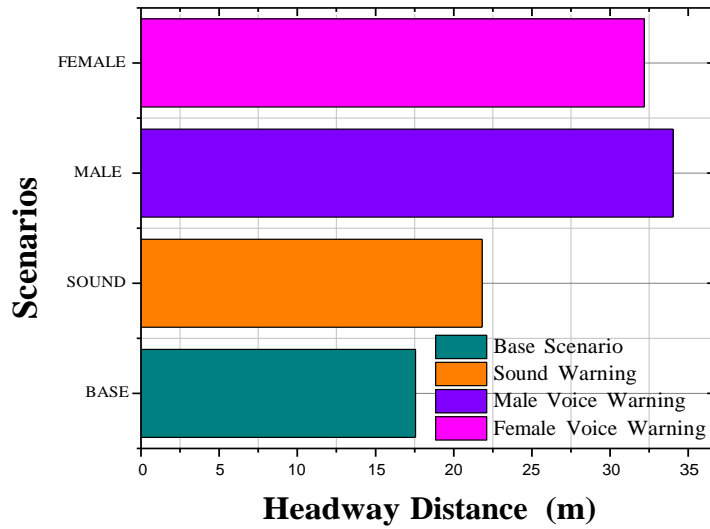


Figure 30 Headway distance in different scenarios

In Figure 33 indicated that, for the voice warning message (male and female), participants on average were maintain to increase their headway time 3 sec and 2.5 sec respectively, when compared with the base scenario.

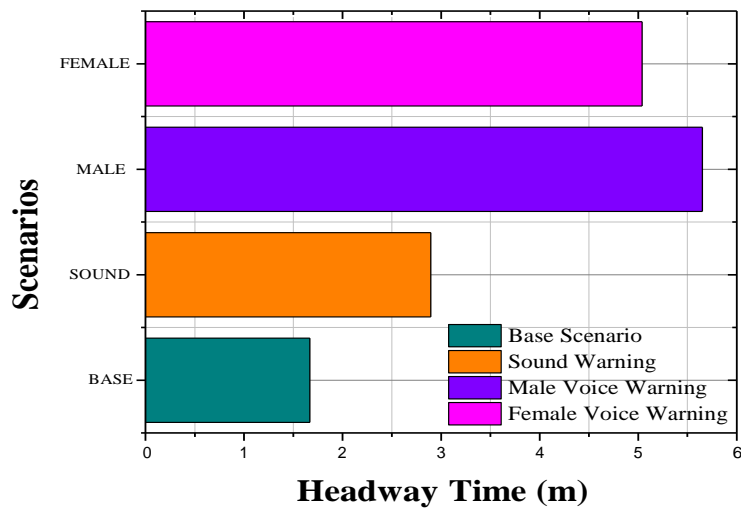


Figure 31 Headway time in different scenarios

Whereas for the sound, the average headway distance and headway time were quite shorter than the voice warning. However, for the base scenario, participants had the smallest headway distance and headway time, 17 m and 1.6 sec, respectively.

4.2.6 Post Questionnaire Survey Phase-B

Posterior questionnaire survey results reported that 85% of the test participants indicated that the smartphone-based warning message safe worker app in the activity area would increase defensive driver driving.

Eighty percent of participants were interested in installing this app on their smartphone, while only 20% participants did not express desire to install this mobile application onto their smartphones.

Seventy-five percent of drivers supported that the audio instruction/warning did not raise the workload of the driver, whereas only 25% mentioned that it increased the workload. Throughout the test process, smartphone warnings helped approximately 60% of participants, while only 40% of subjects obeyed the traffic sign and speed limit in an urban street. The highest percentage of participants, about 50%, liked the female voice, whereas only 10% liked the sound warning. Forty percent of participants chose the male voice. This survey result provided a clear view of the participant choice regarding the type of voice warning.

CHAPTER 5**CONCLUSIONS AND RECOMMENDATIONS**

In this research, a smartphone-based driver warning system was tested to avoid forward collision, in the advance-warning area of a work zone (Phase-A) and to ensure road workers' safety in the activity area of the work zone (Phase-B). The impact of the smartphone-based system on driving behaviors was tested in a driving simulator with 24 participants. The following conclusions can be drawn from statistical analysis of the data for the two phases of experiments:

5.1 Phase-A

Overall, the statistical results indicated that voice-based warning (both male and female) messages from a smartphone were the best option for enhancing the safety in the advance- warning area of work zones. Among the four warning methods, drivers could maintain the safe speed limit in the advanced warning area with the help of the voice warnings (male and female).

In terms of the headway time, voice (male and female) and sound warnings had a statistically significant impact on maintaining a safe headway distance from the vehicle ahead, compared with the base case scenario.

An important finding from the study was that the visual warning was rather distractive to keeping the driver's focus on the road ahead. In all four performance measures, distance headway time, speed, and deceleration/acceleration, a visual warning message deteriorated the driving behavior of participants even when compared with the base case scenario. This is suggestive that drivers should not at any time be visually distracted from the road conditions ahead.

Phase-A analysis results clearly showed that the SFCD app is capable of making the 18 m safe headway distance for drivers with assist of voice warning.

5.2 Phase-B

Both sound and voice-based (male and female) warnings helped drivers to maintain a safer speed and deceleration rate in the activity area of the work zone. From the speed frequency distribution at several locations, it was clearly observed that participants were able to maintain a safe speed with the assistance of the voice warning compared with the base warning message. Also, for the three scenarios, participants were able to start decelerating earlier than in the base scenario.

To ensure workers' safety, participant drivers were able to apply their first brake with the help of voice warning messages. This implies that the voice-based warning actually helps drivers to react quicker by applying brakes to avoid an accident.

Phase-B Analysis results indicated that the SWD app is capable of facilitating a 30 m safe distance for workers.

A very promising outcome of this study was that a significant majority (approx. 80%) of participants wanted to adopt a smartphone-based warning method in their everyday driving. Participants found the warning method to be a helpful guide and did not feel that such a warning system could increase the workload and stress while driving in work zone areas.

5.3 Recommendations

To completely investigate the full potential and applicability of smartphone-based warning methods, the following future research scopes are recommended.

While all in-lab tests are justified, large-scale real road tests can be conducted to validate the operations and impacts of the smartphone-based forward collision warning in a real-world work zone environment. In addition to the work zone study, the investigation of the smartphone-based warning can be extended to other aspects of road safety spots, such as pedestrian crossing, traffic lights, and curvy roads.

Simulator tests with more participants should be conducted with the random selection of warning messages from the smartphone. To investigate the adaptability of this technology, participants with broader demographic representations should be included.

APPENDIX

PHASE-A: QUESTIONNAIRE SURVEY FORM

Do you feel that the audio instruction/warnings increase the workload for the driver?

- Yes
- No

If yes, can you accept it?

- Yes
- No

Do you feel that this Forward Collision Warning is really effective for driving?

Please rate it:

Warning		Helpful	Not helpful
Voice warning	Female		
	Male		
Sounds	1-sec beep		
Visual			

Are you used to this type of warning message on the roadway?

- Yes
- No

<p>Which pattern of warning did you like most in this test?</p> <p style="margin-left: 40px;">(a) Voice warning Female</p> <p style="margin-left: 40px;">(b) Voice warning Male</p> <p style="margin-left: 40px;">(c) Sound</p> <p style="margin-left: 40px;">(d) Visual</p>
<p>Do you feel that you were informed of the potential accident situation during the test with the warning messages?</p> <p style="margin-left: 40px;"><input type="radio"/> Yes</p> <p style="margin-left: 40px;"><input type="radio"/> No</p>
<p>Which warnings did you give more attention to during the test?</p> <p style="margin-left: 40px;"><input type="radio"/> Traffic sign and speed limit</p> <p style="margin-left: 40px;"><input type="radio"/> Warning</p>
<p>Do you think the Forward Collision Warning can increase drivers' defensive driving awareness?</p> <p style="margin-left: 40px;"><input type="radio"/> Yes</p> <p style="margin-left: 40px;"><input type="radio"/> No</p>
<p>THANK YOU FOR PARTICIPATING IN THIS SURVEY</p>

PHASE-B: QUESTIONNAIRE SURVEY FORM

<p>Do you feel that the audio instruction/warnings increase the workload for the driver?</p> <p style="margin-left: 40px;"><input type="radio"/> Yes</p> <p style="margin-left: 40px;"><input type="radio"/> No</p> <p>If yes, can you accept it?</p> <p style="margin-left: 40px;"><input type="radio"/> Yes</p> <p style="margin-left: 40px;"><input type="radio"/> No</p> <p style="margin-left: 40px;">Do you feel that this Forward Collision Warning is really effective for driving?</p> <p style="margin-left: 40px;">Please rate it:</p>			
		Helpful	Not helpful
Voice warning	Female		
	Male		

Sounds	1-sec beep			
<p>Are you used to this type of warning message on the roadway?</p> <p><input type="radio"/> Yes</p> <p><input type="radio"/> No</p>				
<p>Which pattern of warning did you like most in this test?</p> <p>(a) Voice warning Female</p> <p>(b) Voice warning Male</p> <p>(c) Sound</p>				
<p>Do you feel that you know the hazard specially (Pedestrian presence) during the test with the message?</p> <p><input type="radio"/> Yes</p> <p><input type="radio"/> No</p>				
<p>Which warnings did you give more attention to during the test?</p> <p><input type="radio"/> Traffic sign and speed limit</p> <p><input type="radio"/> Warning</p>				
<p>Do you want to apply this warning system in your vehicle?</p> <p><input type="radio"/> Yes</p> <p><input type="radio"/> No</p>				
<p>THANK YOU FOR PARTICIPATING THIS SURVEY</p>				

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