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Vehicle-to-Device (V2D) Communications: Readiness of the Technology and Potential Applications for People with Disability

FINAL REPORT

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16. Abstract

IEEE 802.11p was developed as an amendment to IEEE 802.11 for wireless access in vehicular environments (WAVE). While WAVE is considered the de facto standard for V2V communications, in the past few years a number of communications technologies have emerged that enable direct device-to-device (D2D) communications. Technologies like Bluetooth Smart, WiFi-Direct and LTE-Direct allow devices to communicate directly without having to rely on existing communications infrastructure (e.g., base stations). More importantly, these technologies are quickly penetrating the smartphones market.

The goal of this research is to conduct extensive simulation and experimental studies to assess the efficacies of utilizing D2D communications technologies in transportation scenarios focused around pedestrians and bicyclists. Specifically, we design, develop, and experiment with Smart Cone and Smart Cane systems to evaluate the readiness of D2D technologies to support transportation applications.

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1 INTRODUCTION

IEEE 802.11p was developed as an amendment to IEEE 802.11 for wireless access in vehicular environments (WAVE). While WAVE is considered the de facto standard for V2V communications, in the past few years a number of communications technologies have emerged that enable direct device-to-device (D2D) communications. Technologies like Bluetooth Smart, WiFi-Direct and LTE-Direct allow devices to communicate directly without having to rely on existing communications infrastructure (e.g., base stations). More importantly, these technologies are quickly penetrating the smartphones market.

The goal of this research is to conduct extensive simulation and experimental studies to assess the efficacies of utilizing D2D communications technologies in transportation scenarios focused around pedestrians and bicyclists. Specifically, we design, develop, and experiment with Smart Cone and Smart Cane systems to evaluate the readiness of D2D technologies to support transportation applications.

This report is organized into two major sections that explore the use of D2D technology to introduce new smart cone and smart cane systems.

2 SMART CONE SYSTEM

2.1 OVERVIEW

Often, work zones on highways require entering vehicles to reduce their speeds and make lane changes because of lane closures. At this time, traffic congestion and conflicts are caused by driver maneuvering at work zones and nearby highways sections. In this paper, we address traffic management strategies to resolve this problem at work zones.

Traffic management at work zones typically utilizes traffic signs installed ahead of the work zone. These signs provide warning and guidance information about the work zone, and they can support the drivers' decision-making process regarding speed and lane change. Many research studies performed evaluations of traffic flows and capacities in terms of operational efficiency at work zones [1-4]. Heaslip et al. [5] studied the change of capacity by types of work zones,

including the number of blocked lanes and blocked lane positions. Furthermore, crash occurrences at work zones were analyzed in terms of safety [6-9]. Zhu J. et al. [10] analyzed traffic safety performance at work zones using surrogate safety measures such as unstable deceleration and speed variance. In addition, Finley et al. [11] proposed management of speed limit. They analyzed drivers' behaviors by speed limit signs and presented strategies for speed management at work zones.

As such, traffic management at work zones can lead to safer and lighter traffic conditions to passing traffic at work zone areas. Recently, several research studies proposed intelligent work zone systems that strives to manage traffic flows at work zones. Iowa DOT [12] evaluated a speed control management tool that employs changeable message signs and suggested operational strategies. Lin et al. [13] analyzed the effectiveness of variable speed limit (VSL) using throughput, delay, and average speed. Minnesota DOT [14] proposed guidelines for intelligent work zone system selection and installation positions. They introduced traffic, vehicle, and environment responsive system using PVMS. This system provides various information including speed advisory, congestion advisory, and travel time information. The Transportation Research Board [15] developed a sensing methodology for intelligent and reliable hazardous events at work zones using vision techniques. Li et al. [16] studied PVMS installation position using entering vehicle speed at work zones.

Previous studies mostly presented advisory tools based on PVMS as intelligent techniques. However, such techniques have limitations because PVMS is aimed at unspecified individuals. Therefore, we are motivated to seek intelligent management strategies that support individual user-responsive systems to improve traffic conditions at work zones. In addition, such techniques should be analyzed scientifically and systematically to achieve better efficiency. This study proposes a smart cone system that intelligently manages traffic at work zones. The proposed smart cone system allows the real-time collection of traffic data, delivery of traffic information, and recommended drivers' maneuvering information at work zones. This system can provide user-responsive information to individual users using a crowd sensing application. Furthermore, this study conducts performance evaluation of the proposed smart cone system through a set of systematic simulation experiments.

2.2 OBJECTIVE AND SCOPE

The objective of this research is to present an overall architecture of the smart cone system and evaluate results of the system's performance using traffic simulation.

To accomplish the objectives, the following tasks are performed:

- Real-time traffic data collection of highway work zone.
- Architecture design of the smart cone system.
- Hardware and software selection of the smart cone system.
- Smart cone system application logic development
- Simulation and data analysis

2.3 SECTION ORGANIZATION

The rest of this section is organized as follows:

- Section 1 provides an overview of the proposed smart cone system, and the project objective and scope.
- Sections 2.4 and 2.5describe the whole architecture and the hardware of the smart cone system.
- Section 2.6 discusses the data collection of real-time traffic of the highway work zone.
- Sections 2.7, 2.8, and 2.9 documents the simulation-related information, including the simulation tools used in this study, and the configuration of the simulation environment.
- Sections 2.10 ans 2.11 evaluate the system performance using simulation under different market penetration rates.
- Section 4.1 summarizes our smart cone study and gives some suggestions about future work.
- Section 5 includes the list of references.

2.4 SYSTEM ARCHITECTURE

2.4.1 Overview

As soon as the smart cone is turned on, it automatically publishes its GPS coordinates to the cloud, where our computing engine is deployed, through 4G LTE. The computing engine will first pull the real-time traffic conditions, e.g., speed of upstream adjacent road segments based on the given smart cone coordinates. Then the real-time traffic conditions are used as input to our algorithm that determines the segmentation range of notification zones. Specifically, the range of three zones is computed; namely, red, yellow, and green. The suggestions to the drivers in the three identified zones vary from mere recommendations, to strong recommendations, to alerts. Also, another module of the cloud computing engine is in continuous listening mode to dynamically calculate the distance of the individual vehicles from the zone. Once a vehicle enters the green zone, the listener asynchronously activates the notification mode to the vehicle. The distance of the vehicle from the work zone is updated continuously. If the vehicle is in the green zone, a "recommendation" to start merging is published through an asynchronous push notification to the vehicle. This notification servers to inform the driver that the traffic congestion is likely to be avoided if the community of drivers cooperates with the provided push notifications, e.g., start merging. If the vehicle is in the yellow zone, the notification level becomes "strongly recommended." The community of drivers in that zone will also be notified that the traffic congestion will build up if they do not comply with the notifications. If the vehicle is in the red zone, the notification is escalated to an "alert." Besides, with the real-time details about the speed of upstream adjacent road segments of the construction zone, the notification may also contain the suggested speed in order to have smoother traffic flow.

2.5 HARDWARE SOLUTIONS

The hardware used in this study includes a Raspberry Pi 3, a USB GPS dongle, a USB 4G LTE dongle, a Linux server, and a construction cone. The Raspberry Pi 3 is used as the micro controller, which connects with the USB GPS dongle to get the real-time GPS coordinates of the construction cone, and connects with the USB 4G LTE dongle to publish the coordinates to the Internet for further processing. The Linux server is used as the local data center, which logs the collected data and performs other activities required to complete the workflow of the smart cone.

Figure 1 illustrates the overall system architecture. In the following, we detail the rationale behind using the hardware described above.

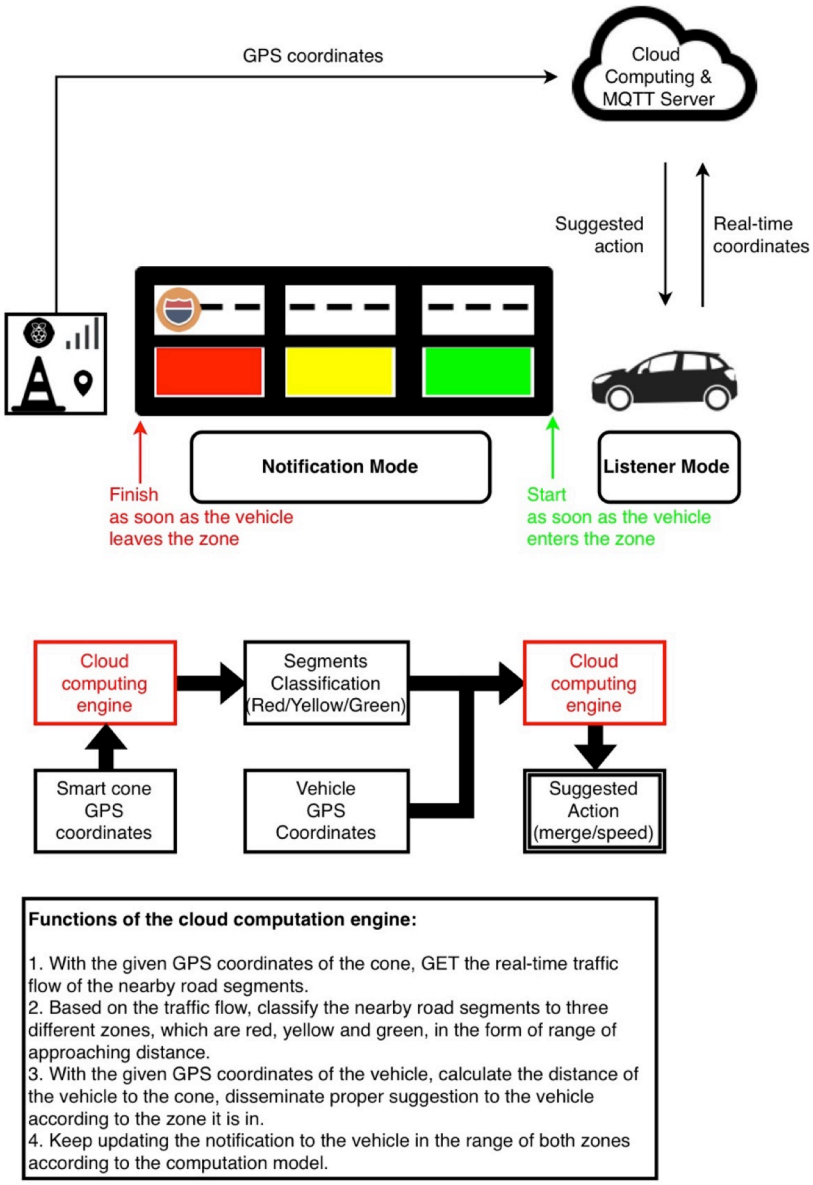


Figure 1: Overall System Architecture.

2.5.1 Micro Controller

The Raspberry Pi 3 is the third-generation Raspberry Pi, which has been updated since the Raspberry Pi 2 Model B. The most important updates that we are interested in are the introduction of the BCM43438 wireless LAN, and the on-board Bluetooth Low Energy (BLE) features. The wireless LAN capacity allows us to easily utilize Wi-Fi Direct communications. With the BLE capacity, we are able to make the Raspberry Pi a beaconing device, which is one of the candidate means to enable the Device to Device (D2D) communications between the smart cones and the vehicles. Another reason why we pick this device as the micro controller is its computational capacity (Quad Core 1.2GHz Broadcom BCM2837 64-bit CPU) as well as its compatibility of running a Debian-based Linux operating system.

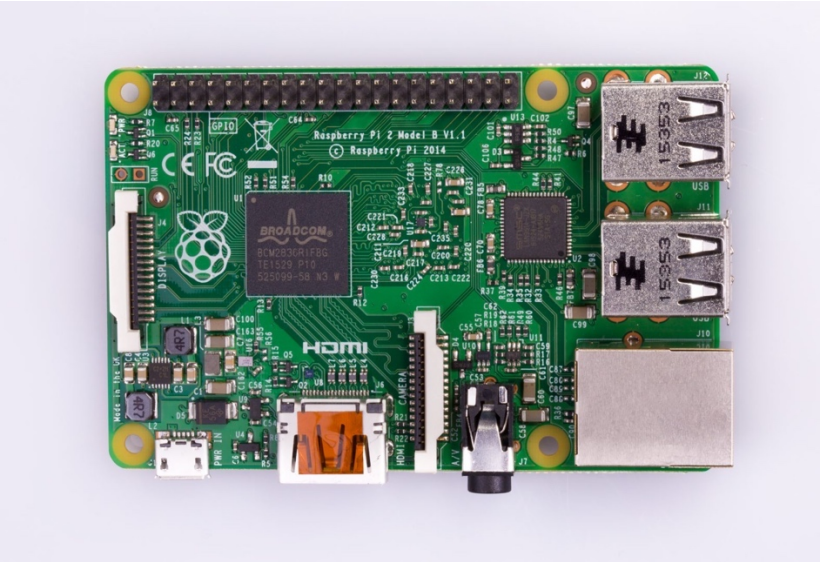


Figure 2: Raspberry Pi.

2.5.2 GPS

In order to provide GPS capacity to the microcontroller mentioned above, we connect a USB GPS locator shown in Figure . With this device, the microcontroller is able to publish the real-time GPS coordinates of the smart cone to the cloud for further computing.

Figure 3: GPS dongle.

2.5.3 Network Communication

In order to enable D2D communications between the smart cones and the vehicles, we evaluated the potential use of several communications technologies, including: Wi-Fi Direct, Bluetooth Beaconing, Dedicated Short-range communications (DSRC), and 4G LTE. Both Wi-Fi Direct and Bluetooth Beaconing provide local area networking. DSRC provides a two-way short-to-medium range wireless communications capacity specifically designed for vehicular communications, such as V2V. Contrary to the above three types of communications, 4G LTE may provide the device with Internet access ability, which may further improve the computing and processing through the use fog and cloud computing resources.

Figure 4: LTE dongle.

2.6 DATA COLLECTION

2.6.1 Overview

In order to properly build the proposed model (i.e., speed or area/point of lane merge) for our algorithm, we use the data collected from HERE.com, which provides real-time traffic through Representational State Transfer (RESTful) Application Programming Interfaces (APIs). The data provides detailed traffic conditions of the highway segments. We have successfully collected and analyzed empirical traffic measurements at highway work zones, although the data analyses are not included in this paper. Table I and Figure 5 provide the features of the collected data and a sample dataset, respectively.

TABLE I: FEATURES OF THE TRAFFIC FLOW RESPONSE

Features	Description
PBT	The base timestamp used for predictive calculations.
PC	Point location code for the flow item. This is the defined location code based on the TMC Tables.
LE	Length of the stretch of road in miles.
DE	Description of the point
QD	The TMC queuing direction of traffic in positive or negative notation.
CN	A number between 0.0 and 1.0 indicating the percentage of real time data included in the speed calculation.
TY	Type of the location reference.
SP	The average speed, capped by the speed limit, that current traffic is travelling. -1.0 indicates that the average speed could not be calculated. The unit is mile.
SU	The average speed, uncapped by the speed limit, that current traffic is travelling. -1.0 indicates that the average speed could not be calculated. The unit is mile.
FF	The free flow speed on this stretch of road.
JF	A number between 0.0 and 10.0 indicating the expected quality of travel. When there is a road closure, the Jam Factor will be 10. -1.0 indicates that a Jam Factor could not be calculated.

2017-07-26 00:00:30	4952	1.02974	Oakland Dr/Exit 75	-	0.9	TR	67.83	67.83	69.59	0.37182
2017-07-26 00:00:30	4953	1.46079	I-94-BR/US-131/Exit 74	-	0.88	TR	66.3	66.3	69.59	0.69493
2017-07-26 00:00:30	4954	1.90766	9th St/Exit 72	-	0.87	TR	62.91	62.91	70.21	1.52523
2017-07-26 00:00:30	4955	5.67259	CR-652/Exit 66	-	0.84	TR	64.55	64.55	70.21	1.18391
2017-07-26 00:00:30	4956	5.6371	M-40/Exit 60	-	0.9	TR	63.05	63.05	70.21	1.49608
2017-07-26 00:00:30	4957	3.99758	M-51/Exit 56	-	0.93	TR	62.73	62.73	70.21	1.56296
2017-07-26 00:01:30	4952	1.02974	Oakland Dr/Exit 75	-	0.9	TR	67.83	67.83	69.59	0.37182
2017-07-26 00:01:30	4953	1.46079	I-94-BR/US-131/Exit 74	-	0.88	TR	66.3	66.3	69.59	0.69493
2017-07-26 00:01:30	4954	1.90766	9th St/Exit 72	-	0.87	TR	62.91	62.91	70.21	1.52523
2017-07-26 00:01:30	4955	5.67259	CR-652/Exit 66	-	0.84	TR	64.55	64.55	70.21	1.18391
2017-07-26 00:01:30	4956	5.6371	M-40/Exit 60	-	0.9	TR	63.05	63.05	70.21	1.49608
2017-07-26 00:01:30	4957	3.99758	M-51/Exit 56	-	0.93	TR	62.73	62.73	70.21	1.56296

Figure 5: Sample Dataset of Collected Traffic Measurements on I-94.

2.7 TRAFFIC SIMULATION

2.7.1 Overview

Due to the difficulties such as safety and scalability, this study uses simulation in order to evaluate the performance of the proposed smart cone system. We start the simulation using VISSIM and then imported the same road network to SUMO for the simulation using Veins and OMNeT++ under 802.11p (DSRC/WAVE).

Simulation modules	
Veins	v4.6
Software	
SUMO	v0.30.0
OMNeT	v5.2.1
Operating system	
Ubuntu	16.04.4 LTS

2.8 SIMULATION TOOLS

2.8.1 SUMO (Simulation of Urban Mobility)

SUMO is an open source microscopic road traffic simulation package designed to handle large road networks (http://sumo.dlr.de/index.html). An important feature of SUMO is TraCI (Traffic Control Interface), which is an interface for coupling road traffic and network simulators. Through the API provided by TraCI, we are able to retrieve values of the simulation objects, such as vehicles, edge, etc. For example, in the suggestion algorithm of smart cone system, we use the API to retrieve the mean speed, and density of the edge, and further use the command changeLane and slowdown to manipulate the vehicles in the simulation in the real-time. Figure 6 shows part of the construction zone of our simulation in the graphic user interface (GUI) of SUMO.

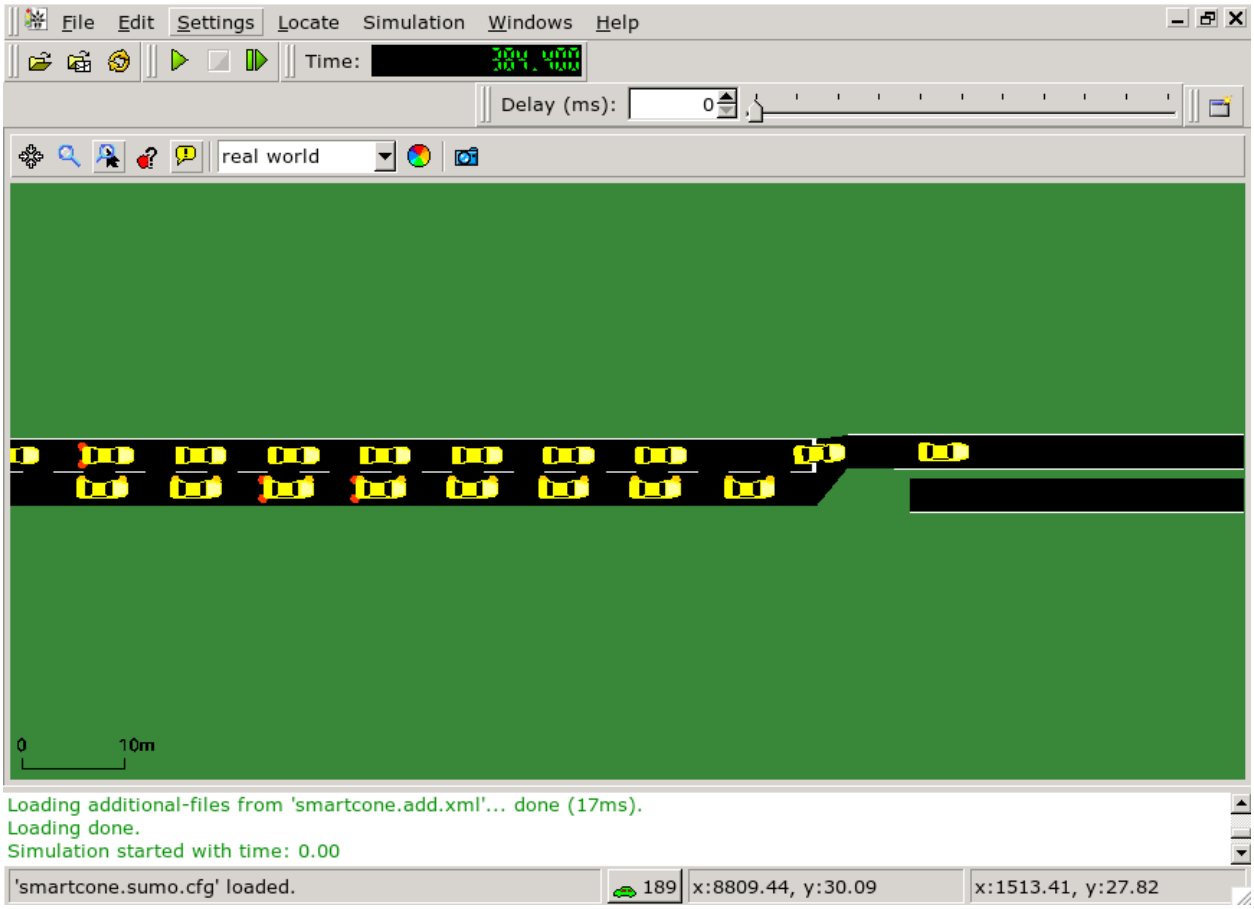


Figure 6: SUMO simulator and work-flow.

2.8.2 OMNeT++ (Objective Modular Network Tested in C++)

OMNeT++ is an extensible, modular, component-based C++ simulation library and framework that is primarily for building network simulators, such as wired and wireless communication networks, on-chip networks, queueing networks, etc. It also supports sensor networks, wireless ad-hoc networks, Internet protocols, performance modeling, photonic networks, etc. OMNeT++ runs on different operating systems including Windows, Linux, Mac OS, and Unix-like system. It has the GUI support for simulation execution. (https://www.omnetpp.org/intro) Besides, it also provides useful tools for result analysis, such as data plot. The Figure 7 shows the Eclipse-based Integrated Development Environment (IDE) of OMNeT++, and its Qtenv simulation GUI.

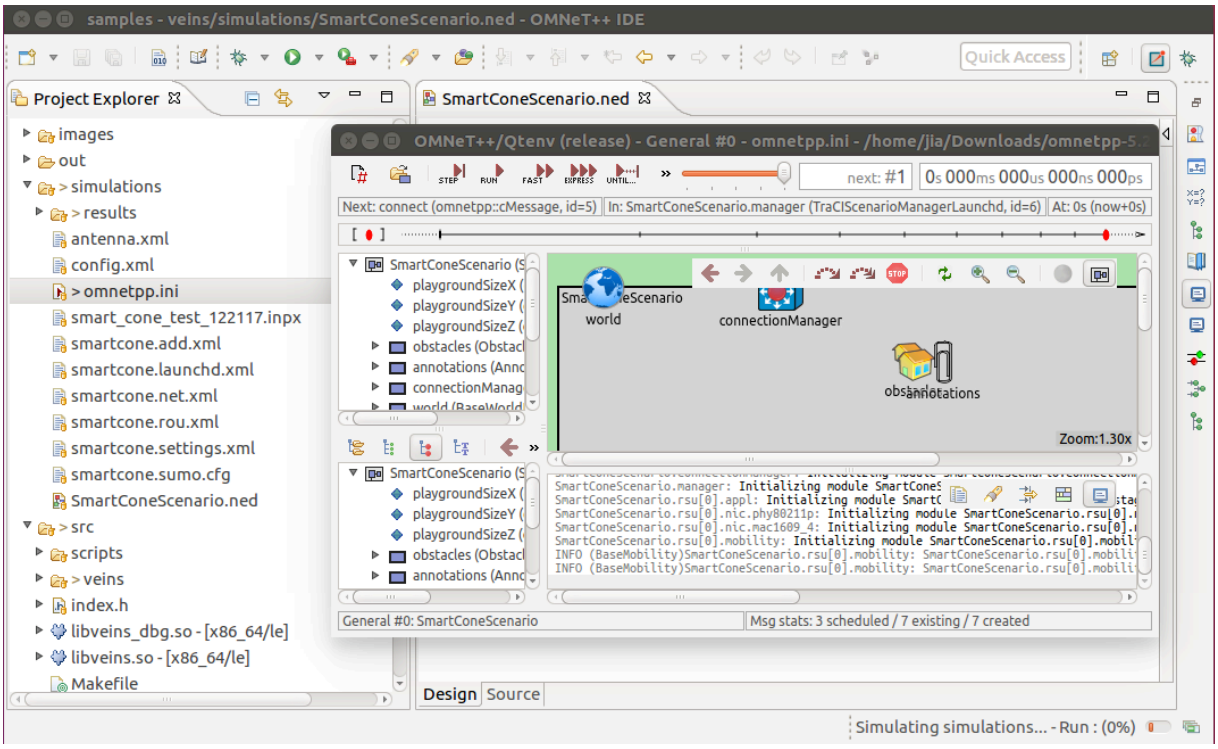


Figure 7: OMNeT++ simulator and work-flow.

2.8.3 Veins (Vehicles in Network Simulation)

Veins is an open source framework for running vehicular network simulations, which is based on OMNeT++ and SUMO (c.f. Figure 8). It enables the bidirectionally coupled network and road traffic simulation [22]. The framework provides mobility modules in OMNeT++, such as TraCICommandInterface, which can be used to retrieve simulation values or change the simulation state.

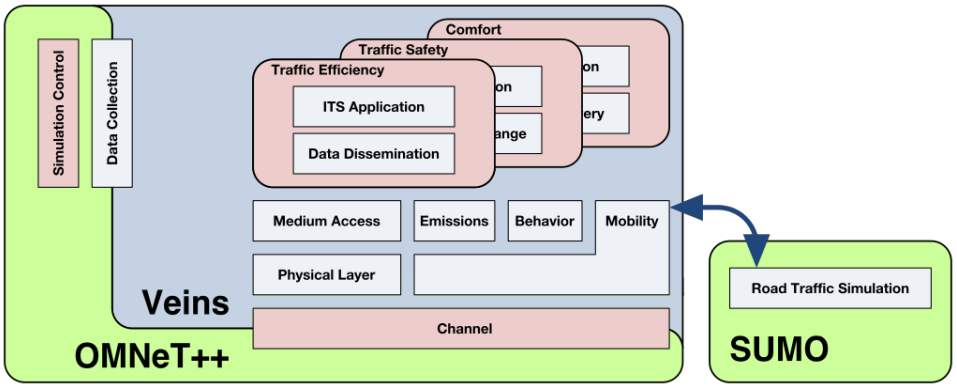


Figure 8: Architecture of Veins (from http://veins.car2x.org)

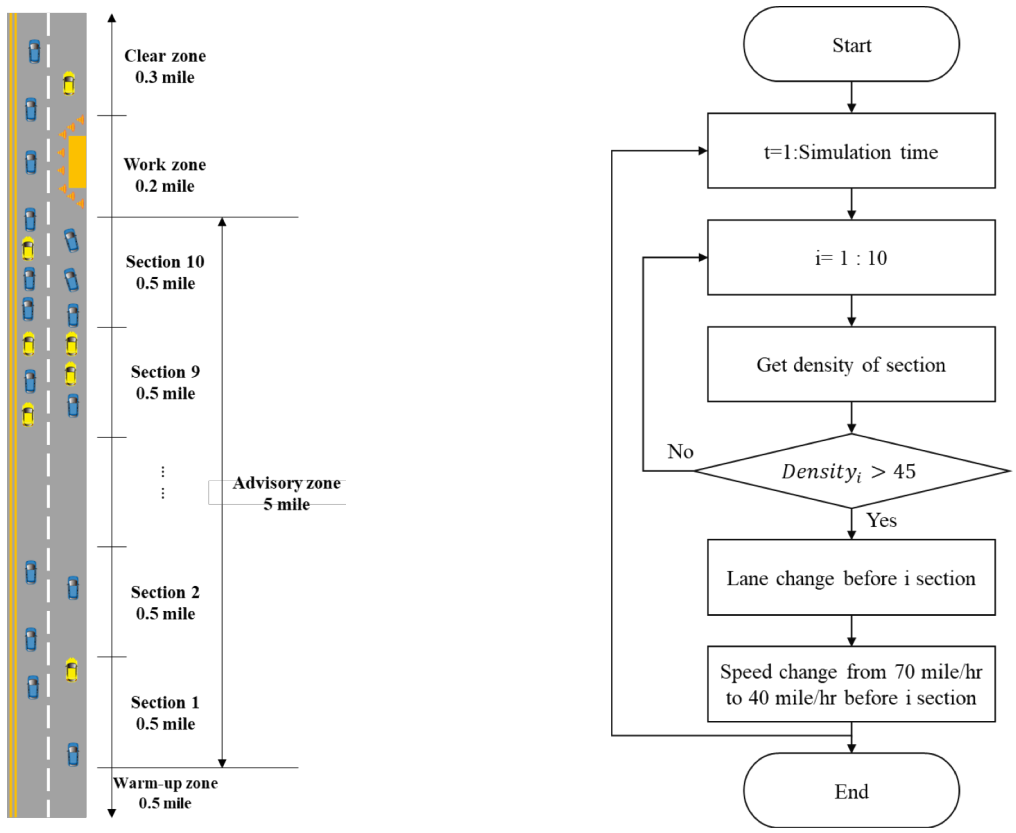
2.9 SIMULATION ENVIRONMENT

As a test site, this study modelled a 6-mile stretch of freeway in as shown in Figure 9 (a). In a 6-mile two-lane freeway, a 1000-foot work zone blocks one lane. It is assumed that the speed limits of the freeway and work zone are 70 mile/hr and 40 mile/hr, respectively. Our simulation studies are conducted under various market penetration rates of the drivers with the notifications generated by the smart cone system. The simulation results clearly demonstrate the effectiveness of the proposed system under various market penetration rate conditions.

Jeong et al. [17] found that the inter-vehicle warning information systems for moving hazards have a significant impact under LOS D traffic conditions. Therefore, this study is performed under LOS D traffic conditions. The simulation parameters utilized in our studies are presented in Table II.

TABLE II: SIMULATION PARAMETERS

Parameter		Value
Network	Number of lanes	2
	Speed limit	Normal: 70 mile/hr Work-zone: 40 mile/hr
	Volume	2000 pc/hr/ln
	Market Penetration Rate (MPR)	0 %, 20%, 40%, 60%, 80%, 100%
	Length of work zone	0.2 mile (1000 feet)
	Length of analysis section	6 mile
Simulation	Simulation time	4000 s (warm-up period: 400 s)
	Number of iterations	10



(a) Description of work zone section *(b) Operational process of the smart cone system*

Figure 9: Test Site and Operational Concept.

2.9.1 VISSIM

In order to evaluate the proposed system, this study developed a simulation-based performance evaluation tool employing VISSIM, a microscopic traffic simulation tool. The cloud-based smart cone system is implemented in VISSIM using its API. The tool captures individual vehicle's movements and their interactions over given traffic networks through car-following and lane-change behaviors in risk-free conditions.

2.9.2 SUMO

The SUMO simulation mainly consists of the following four files:

- smartcone.net.xml: this is the network file that describes the traffic-related attributes of the simulation, such as edges, lanes, junctions, etc. In our simulation, the SUMO network

is important from the VISSIM simulation file with some necessary adjustments using the tool named netedit. For example, the length in VISSIM is in miles, while in SUMO it is in meters.

- smartcone.rou.xml: this file contains the information of vehicles, vehicle types and routes in the simulation. In our study, we used the tool named duarouter to generate the route with randomized departure time.
- smartcone.add.xml: in this file, we specified two additional output, which are lane data and edge data for performance evaluation purpose.
- smartcone.sumo.cfg: this is the configuration file of SUMO simulation. It specifies above mentioned files as input, simulation time, and output. We set tripinfo as our output, which contains the information such as delay and arrival time.

2.9.3 Veins and OMNeT++

As discussed above, we use Veins as the framework to simulate the DSRC communication provided by OMNeT++ in our traffic simulation provided by SUMO. In OMNeT++, we define the network in the ned file, which is considered as our simulation scenario.

2.9.3.1 Network Scenario

The smart cone simulation scenario is shown in the following figure. The key modules of scenario are the connectionManager, manager, and rsu (c.f. Figure 10). The connectionManager module controls all connection related tasks. It is the central module that coordinates the connections between all nodes, and handles dynamic gate creation. It periodically communicates with the mobility module and Channel Access. The rsu module has the same network layers as that of the vehicle/car depicted above. The difference is that rsu module is only responsible for receiving and sending messages, but does not take any action based on the content of the message. The manager module connects to a running instance of the SUMO TraCI server, and automatically disconnects the server when the simulation ends. Besides, it is also responsible for creating a TraCIMobility submodule for each probe vehicle created in SUMO.

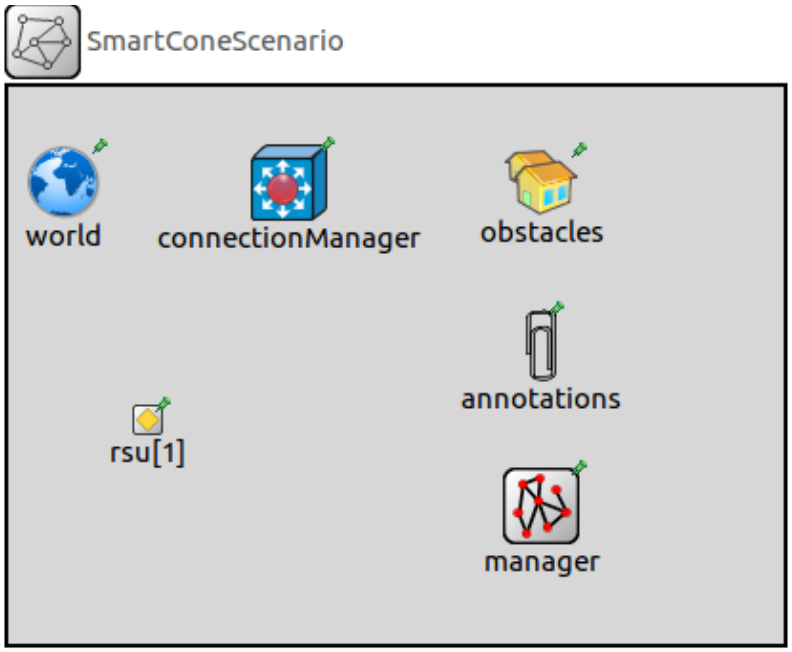


Figure 10: Entities of the smart cone scenario.

2.9.3.2 Mobility Module

For each vehicle created in SUMO, it contains a mobility submodule of type TraCIMobility. At regular intervals it will use this module to advance the simulation in SUMO and update the node's mobility information, including position, speed, direction, etc., based on the behavior of the vehicle (c.f. Figure 11). Besides, each probe vehicle also has an application layer, where we enable the smart cone system on the vehicle side functions, such as lane change and send messages. The NIC (Network Interface Card) on the vehicle is using IEEE802.11p.

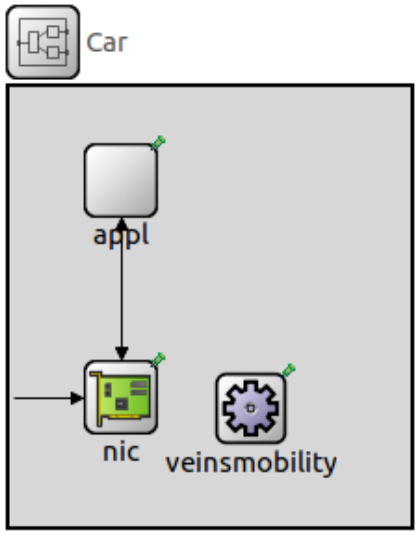


Fig 11: Vehicle model.

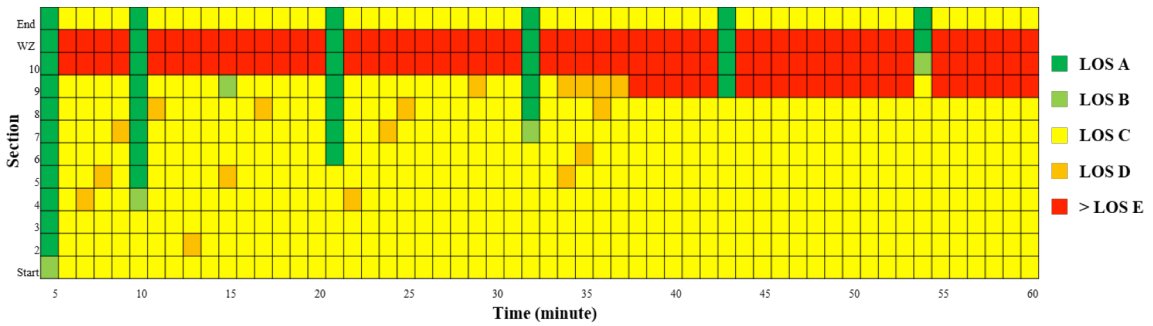
2.10 APPLICATION LOGIC

In the simulation using SUMO, Veins and OMNeT++, the application logic follows the operational process of the smart cone depicted in Fig 9 (b).

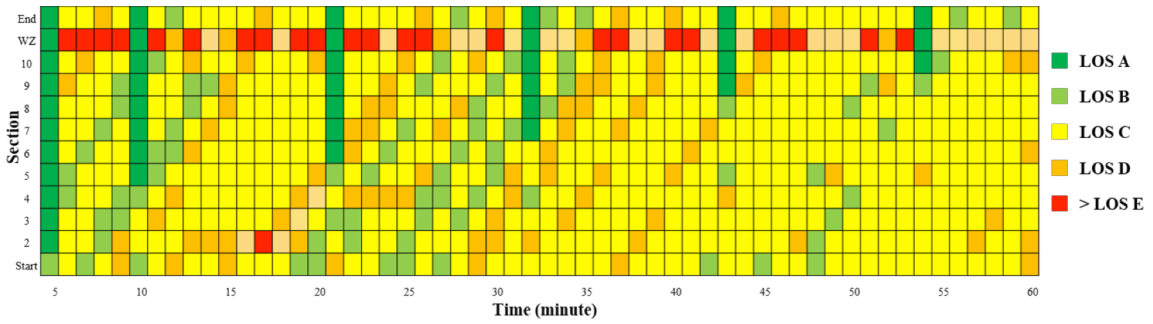
2.11 PERFORMANCE EVALUATION

This study compares three performance measures – average delay, throughput, and the number of conflicts. While the average delay and the throughput are used for evaluating the operational efficiency of the smart cone system, the number of conflicts is used as a proxy measure of traffic safety. The delay is estimated by calculating the time difference between the actual travel time and the theoretical travel time at the free-flow speed [18]. The throughput is defined by the number of vehicles successfully passed the work zone during the analysis period. These are critical performance measures for interrupted-flow facilities [18, 19]. The number of conflicts is obtained by observing situations in which two or more road users approach each other in time and space to such an extent that there is risk of a collision if their movements remain unchanged. This measure generally used for evaluating traffic safety as alternative of crash analysis [20, 21].

The Figure 12 compares changes traffic densities over time at individual upstream sections before and after implementing the smart cone system. As depicted, the jam density conditions (in red) just upstream sections of the work zone are greatly improved when all drivers comply the recommendations from the smart cone system. Without the smart cone system, traffic queues started to build up at the work zone and these queues expanded upstream.



(a) Base case (no vehicles informed, 0% market penetration rate)

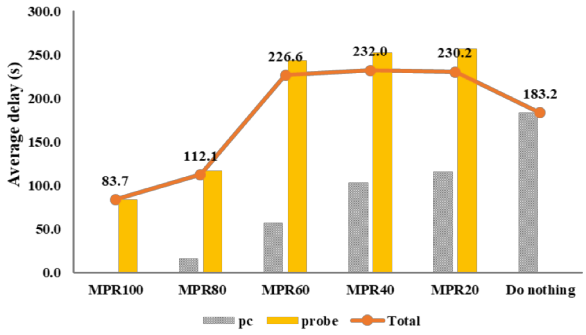


(b) All vehicles are informed (100% market penetration rate)

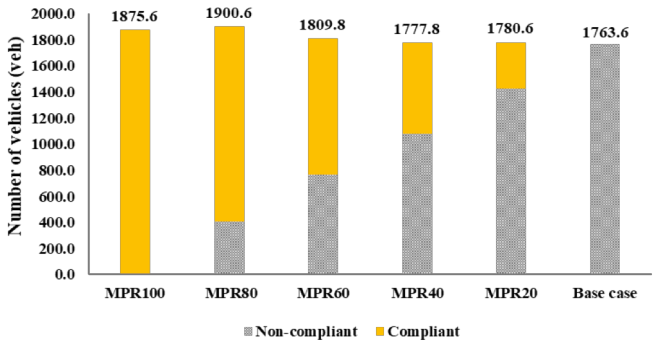
Figure 12: Time-Space diagram of density.

Three performance metrics are compared in Figure 13. The average delay is significantly decreased when more than 80% of drivers comply the system recommendations. The average delay decreases by 54.3% and 18.8% with market penetrations of 100% and 80%, respectively. However, the simulation results show that the average delay increase at low market penetrations. It may be due to the interference of non-compliant vehicles that try to take advantage in the system. As compared delays between complied and non-compliant vehicles, the average delay of the non-compliant vehicles continuously decreases as the market penetration increases while that of the compliant vehicles increases at low levels of market penetrations and decreases after reaching a certain level of market penetration. This implies that the systems should be carefully designed to achieve the objective. Further analysis is needed to understand why the system is worsened with lower market penetrations and to develop better operation algorithms. The overall throughput marginally increases during the whole simulation period as the market penetration increases.

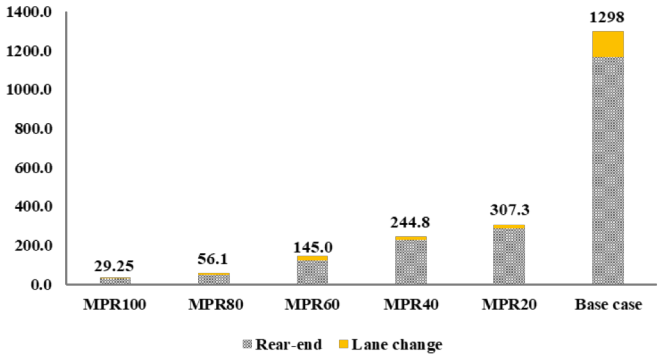
The number of conflicts, a surrogate measure of traffic safety, decreases remarkably with the use of the proposed smart cone system. This system induces lane changes in advance. In addition, this system recommends travel speed to achieve smoother lane changes. Therefore, traffic conditions become more stable over time.



(a) Average delay



(b) Throughput (Number of vehicles)



(c) Number of conflicts

Figure 13: Performance metrics.

Overall, the simulation results indicate that this system can help to resolve queues caused by work zones. In addition, this system can enhance traffic safety by inducing stable traffic conditions. However, to secure operational efficiency and traffic safety, the system may require more than a certain level of market penetration or need to developed better operational algorithms to overcome this weakness.

3 SMART CANE SYSTEM

3.1 OVERVIEW

Blind and visually impaired pedestrians have limited mobility options, and they rely heavily on walking and transit for their transportation needs. One of the major issues for these pedestrians is crossing intersections. Accessible Pedestrian Signal (APS), as a mean of helping their intersection crossings, was introduced in the United States as early as 1920. The most recent type of APS is the beaconing APS which has shown improvements in road crossing abilities for blind pedestrians although it has many drawbacks. This study developed a cane to enhance safety and crossing abilities of visually impaired pedestrians at intersections. The cane, named Smart-Cane, is composed of three subsystems: the veering adjustment system using RFID technology where device-to-infrastructure (D2I) communication is established; driver alert system where device-to-vehicle (D2V) communication is established through DSRC is established; and the green time system where connection is established through WiFi with the signal controller and device-to-infrastructure (D2I) communication is established. Three scenarios (A, B & C) were proposed to study the improvements of the Smart-Cane over APS. Findings state that the Smart-Cane proved feasibility and practicability over APS.

3.2 OBJECTIVE AND SCOPE

This work is intended to ease the process of crossing and improve safety at intersections by aiding BVI pedestrians in maintaining heading. Furthermore, complete crossing successfully and within the crosswalk, decrease crossing time, increase independence on other cues while crossing and increase self-confidence for the BVI.

According to the data from the United States Census Bureau (23), difficulty seeing is defined as experiencing blindness or having difficulty seeing words and letters in ordinary newsprint even when wearing glasses or contact lenses. Those lacking the ability to see words and letters constituted about 8.1 million people that are 3.3 percent of the 241.7 million population aged 15 years and older in the United States in 2010. The primary modes of transportation for the Blind and Visually Impaired (BVI) are walking or public transit. To improve the accessibility and level of confidence for the BVI pedestrians, it is essential to remove both physical and mental barriers that might obstruct their mobility.

Visually impaired pedestrians require information on intersection geometry, signal timing, and traffic to complete crossing safely. BVI pedestrians need to perform certain tasks, among which

are street detection, locating crosswalk, alignment, specifying an appropriate time to cross, and maintaining a straight heading while crossing intersections (24-28). Audible pedestrian signals (APS) first appeared in the United States in 1920 and were not included in the Manual on Uniform Traffic Control Devices (MUTCD) until 2000 (29). Forty two percent of all crossings in a study performed at three cities that did not involve outside assistance ended outside the crosswalk (30).

3.3 RESEARCH PROBLEM

Pedestrian veering occurs due to the minor difference in length of the human legs (31). The amount of veering depends on the personal physical characteristics of pedestrians (32). Veering might slightly be increased when crossing quiet and wide intersections. Sixty-six percent of Orientation and Mobility (O&M) trainers claimed that their students had difficulties in knowing where the destination corner was (33).

On one hand, the shape and development of APS have effectively solved some of the crossing issues faced by BVI. On the other hand, APS has certain drawbacks. Among which are repeating tone adds 5 decibels of noise within 6 to 12 feet, no standard location for the pushbutton, and requirement of additional stubs for installing pushbutton station (34). Other issues included the volume of audible messages, not knowing which street has the 'WALK' phase and that BVI pedestrians confused signal tones with traffic (33). Additional problems were associated with "keeping direction while walking in the crosswalk" even with an APS; additionally, the acoustic signals were often confusing (35). Interference might occur when two parallel crossings have audible walk signals at the same time causing blind pedestrians to be drawn towards the intersection (36).

To meet BVI pedestrians' needs at intersections, an integrated system installed on a cane and called the Smart-Cane was suggested to improve safety, crossing performance, and mobility of pedestrian crossing at intersections. The system is comprised of three subsystems which work together to increase convenience and safety of pedestrians' intersection crossing.

The first subsystem is the blind pedestrian veering adjustment system which can be used by BVI to help prevent veering outside the crosswalk, minimize crossing time, and increase self-confidence and independence. The adequate perception needed to identify a location relative to the crosswalk is given through the Smart-Cane. In addition, the Smart-Cane provides helpful information about the intersection before crossing. Radio Frequency Identification (RFID) is

used for this subsystem. Communication to the BVI pedestrian is accomplished through text-to-speech. The second subsystem is the driver alert system. This system alerts drivers approaching, yielding, and idling at intersections to the presence of pedestrians within crosswalks. It also helps increase safety of pedestrians and minimize conflicts between vehicles and pedestrians through Dedicated Short Range Communication (DSRC). The third subsystem is the green time system designed to extend pedestrians' signal green time through WiFi communication.

This research is intended to make communities more livable by utilizing Device-to-Infrastructure (D2I) and Vehicle-to-Device (V2D) communication technologies to assist non-motorized road users, especially those with disabilities in crossing intersections safely.

The current research is intended to address whether the Smart-Cane at intersections where audible beaconing might fail to provide guidance and assistance in crossing is able to:

1. Help improve the crossing abilities of BVI pedestrians.
2. Maintain BVI pedestrians heading.
3. Minimize veering of BVI pedestrians.
4. Decrease crossing time.
5. Increase independence and self-confidence.

3.4 RELATED WORK

Accessible Pedestrian Signal (APS) is defined as a device that communicates information about pedestrian timing in nonvisual formats such as audible tones, verbal messages, and/or vibrating surfaces *(7)*. Various studies, which examined the benefits of APS, found that APS improves the crossing actions of blind pedestrians. Moreover, research proved that APS devices allow more accurate judgments of the onset of the walk interval, reduce the number of crossings beginning during "Don't Walk" phase, reduce delay, and result in more crossings completed before signal phase changes *(37)*.

Studies on complex intersection crossing by blind pedestrian before and after installation of APS and again after installation of innovative device features in two cities were conducted *(38)*. The findings proved that numerous improvements in pedestrian performance were observed. The most significant improvements occurred with timing measures and some improvements in orientation and wayfinding. The researchers' observations of participants indicated that when

the audible beacon was called in one city, it was difficult to hear the "Walk" indication at the waiting location due to the incorrect direction that the speakers aimed at. In addition, the audible beacon did not seem to improve the "ending within the crosswalk" behavior of participants as expected. In the event that participants did not align accurately, they often veered outside the crosswalk. Another study targeted blind pedestrians' complex intersection crossing behaviors before and after installation of APS *(39)*. The results showed that less than 50% of crossings were completed within the crosswalk, and no improvements in starting within the crosswalk were noticed. Furthermore, while APS provided information about the status of the pedestrian signal, APS generally did not provide good wayfinding information, especially, in case where the sound was emitted from both ends of the crosswalk.

Standard APS (no beaconing), prototype beaconing APS, and raised guide strip were three treatments that were compared *(40)* according to their ability to assist in establishing and maintaining a correct heading for blind pedestrians. Sixty percent of participants' crossings were performed outside the crosswalk in the standard APS condition and were more than half of the time outside by 6 feet or more, exposing them to danger by being in the path of through or idling traffic at the intersection. With the beaconing APS, participants were outside the crosswalk by 6 feet or more at 16.5% of the time.

A study evaluated which push-button-integrated APS features and how much information was required to use those features correctly were useful to blind pedestrians *(41)*. Results suggested that none of the APS reliably provided useful information on wayfinding compared to any other devices.

Surveys investigating problems experienced by blind pedestrians while crossing streets with audible signals were conducted by the American Council of the Blind (ACB) and the Association for Education and Rehabilitation of the Blind and Visually Impaired (AER). In the AER survey, 66% of participants indicated that they had difficulty knowing where the destination corner was because traffic was intermittent, while in the ACB survey, 79% of respondents indicated that they sometimes had difficulty determining the location of the destination corner. In the case that sounds were broadcasted from speakers mounted on the pedestrian signal head, ACB (6%) and

AER (39%) survey respondents claimed that blind pedestrians had not had the ability to localize APS sounds for guidance in crossing streets. Furthermore, 85% of ACB survey respondents indicated that they were sometimes confused by unexpected features as median islands. As for intersections equipped with APS that had "bird call", bells, and buzzers sounds, 45% of the ACB survey respondents considered signals to be too loud, while 71% considered them as too quiet. However, in the AER survey, 24% considered the signals too loud and 52% reported that they were too quiet. Eight percent of the ACB respondents claimed that they had been struck by a vehicle at an intersection and 28% had had their long canes run over *(42) (43)*.

3.5 SMART-CANE DEVELOPMENT

Developing a system that can enhance safety and mobility of non-motorized road users through technology is essential especially when Connected Vehicles (CV) technologies are being developed with lack of attention given to disabled pedestrians.

Radio Frequency Identification (RFID) has been identified as the most appropriate technology among different sets of alternatives due to high convenience, small size and rigidity of RFID tags, and portability. The Smart-Cane consists of the RFID reader, 360° antenna, a microcontroller, and a small portable power bank (c.f. Figure 14). A mobile phone is used to disseminate the information to the pedestrian through audible messages. The final component is the passive RFID tags which are deployed on the crosswalk at four levels, starting line tags, right boundary tags, centerline tags, left boundary tags, and finish line tags.

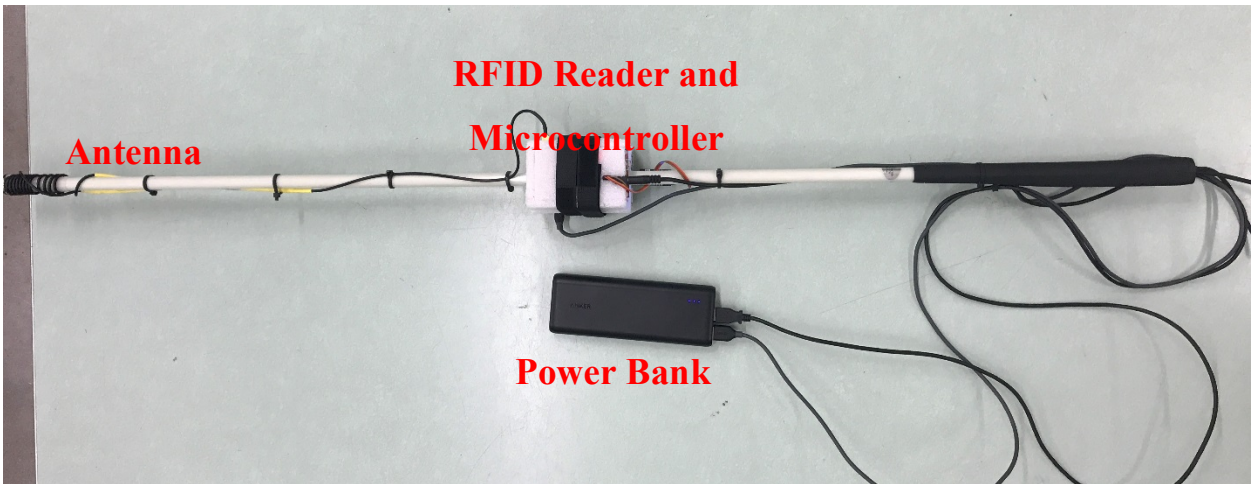


Figure 14: Smart Cane Components.

3.5.1 Method

The data were collected using pre and post surveys and field experimentation. The pre-survey was conducted to study the participants' navigational and mobility skills and required crossing information by participants and to examine the usefulness of Accessible Pedestrian Signals (APS) in providing guidance while crossing. The post-survey was conducted to study the BVI participants' opinion and feedback on the Smart-Cane. The field experimentation consisted of 3 scenarios to mainly measure the veering tendency of participants.

3.5.2 Participants

Thirty two sighted participants, who were blindfolded throughout experimentation to ensure consistency, participated in the first stage of experimentation. Twenty two were males and ten were females. Twenty three aged 18-34 and nine aged 35-64.

The second stage of experimentation included 10 BVI participants that were recruited through MidWest Enterprises for the Blind (MWEB). All participants were blindfolded to ensure consistency across experimentation. The sample size included 3 females and 7 males, 5 aged 35-44 and 5 aged 45-64. Five of them reported using a long cane as their main mobility instrument, and 5 reported using other means but also had experience using the cane. All participants noted having normal hearing and no disabilities.

All participants provided their informed consent. The described experimentation procedure, methods, and surveys were approved by Western Michigan University's Human Subjects Institutional Review Board (HSIRB).

3.5.3 Experimental Design

An isolated parking lot near the College of Engineering and Applied Sciences at Western Michigan University (WMU) was chosen for experimentation. The parking lot was not frequently used, and during experimentation, the entrance was closed to avoid unanticipated vehicle noises. The first stage of experimentation took place on 3 consecutive weekdays during

July 2017, and the second stage took place on two consecutive weekends (Saturdays and Sundays) in August 2017.

A typical simulated crosswalk was constructed in the parking lot which consists of 7 lanes (12 feet wide lanes), a total length of 84 feet and width of 10 feet *(29)*. RFID tags were placed at 1 foot spacing along the length of the crosswalk, and at 2.5 feet spacing along the width of the crosswalk. Tags were also placed at the start and finish lines of the crossing walk (c.f. Figure 15). The dashed white lines represent the RFID tags and the orange dots represent the data measurement points.

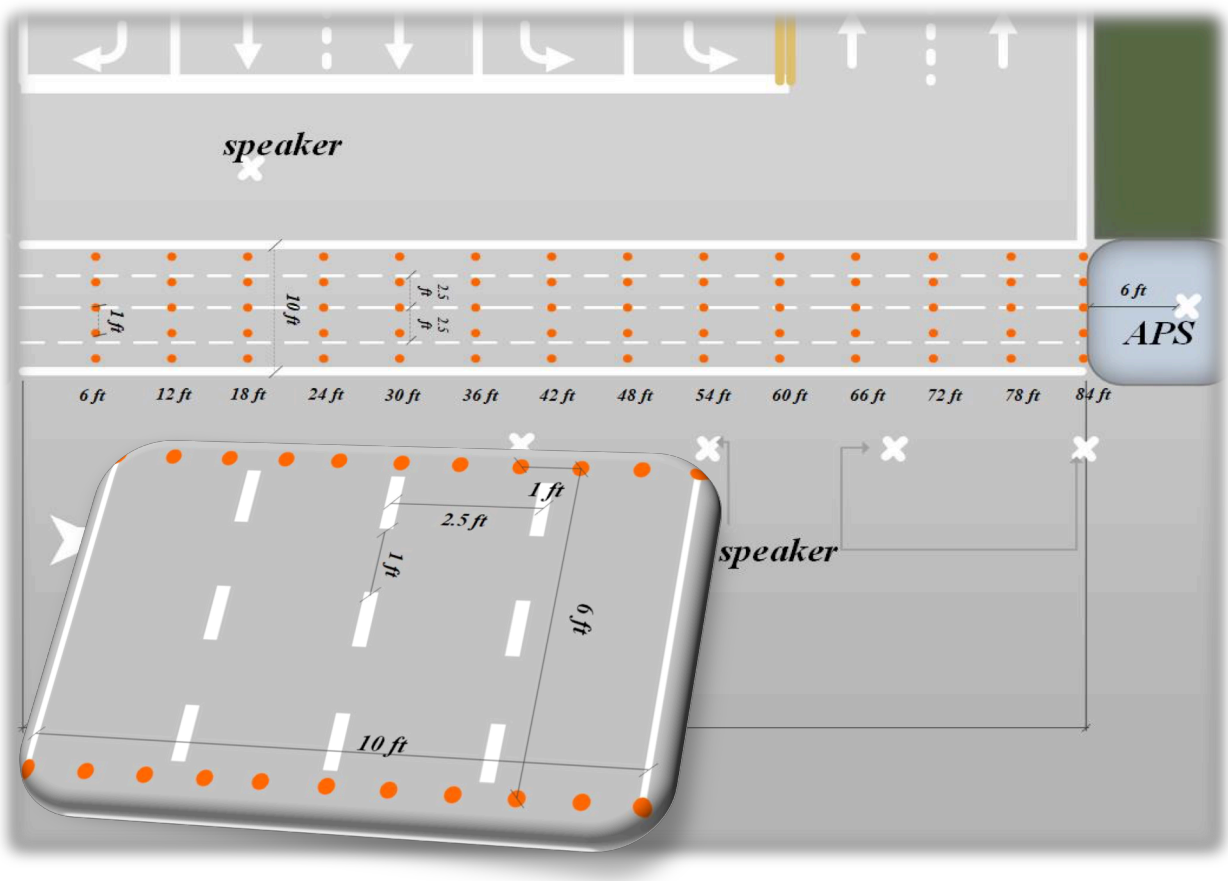


Figure 15: Simulated Crosswalk Layout.

To mimic real life crossing scenarios, 5 loudspeakers were used to emit traffic noise. The speakers were spread evenly on the crosswalk and placed on 2 feet high chairs (almost the height of vehicle engines). YouTube was used to obtain the traffic noise audio recording and was

chosen amongst several other recordings to represent the most realistic traffic noise. The traffic noise level was measured using RadioShack digital sound level meter. To calibrate the noise level, a higher quality sound level meter (Larson-Davis) calibration curve was used to provide more accurate values, and after calibration, it was between 65 and 70 dBA throughout the entire recording. The noise level was chosen based on a study conducted on different sites in Kalamazoo, Michigan *(44)*.

The APS beacon speaker used was of a beeping type and was mounted on a tripod at a typical height of 8 feet above the ground level and was positioned 2.5 feet from the center and 6 feet from the end of the crosswalk (c.f. Figure 16). The audible beaconing was compliant with the MUTCD requirements for APS and sounded at 1 Hz and a frequency of 880 Hz. The sound level of the beacon was at a theoretical value of 82 dBA at around 3.3 feet distance.

Figure 16: Actual Simulated Crosswalk.

The collected data included calculated distance from the center line at a 6 feet increment from the starting line. The measurements taken right of the centerline were given a positive (+ve) sign and those to the left were assigned a negative (-ve) sign *(45)*. The second set of data examined whether the pedestrian veers outside the crosswalk boundaries. The third set examined whether pedestrian completes crossing inside or outside the crosswalk and time taken to complete each trial.

The sighted participants in the first stage of experimentation were given a training session on the techniques taught by Orientation & Mobility (O&M) instructors to the BVI pedestrians on the methods of using the cane (i.e. double tap technique). They were blindfolded and underwent 3 practice crossings after the training session to get familiar and be comfortable with applying the double tap technique. The sighted were diverted away from the starting point and guided to the starting line blindfolded and aligned.

The participants in this stage went through 3 scenarios that included one trial per scenario. As for scenario A, participants attempted to cross the crosswalk blindfolded with nothing provided except a cane as a cue. Scenario B, they were asked to cross with the presence of simulated traffic noise as well as a beeping sound from APS. In scenario C, they attempted to cross with Smart-Cane and the presence of traffic noise.

Unlike the first stage, the second one participants completed 3 practice crossings prior to experimentation. After that, 3 scenarios were performed, 3 trial crossings in each. All in all, each participant went through a total of 12 crossings to minimize chance occurrence and error of human behavior. Also, scenario A included traffic noise to provide consistency throughout the scenarios. A table was positioned 3 feet before the simulated crosswalks' starting line. BVI participants' first task was to use the long edge of the table to align correctly and use the grove in the table to center themselves on the crosswalk. When the participants felt comfortable and were ready to start crossing, they were given permission to do so, and they attempted to maintain a straight heading throughout the 84 feet.

The participants were stopped if they veered more than 5 feet from the centerline to avoid collision with loud speakers. The scenarios were counterbalanced to minimize bias as well. The crossing direction was the same for all trials. Participants were asked to walk normally without providing any timing constraints.

3.5.4 Data Analysis

Readings at 24, 48, 72 and 84 feet, which represent typical lane widths of 2, 4, 6 and 7 traffic lanes, were analyzed. Some participants were stopped by the researcher because they veered outside the crosswalk boundaries, and could not finish crossing the crosswalk completely; consequently, some readings were missing, and this was most common in scenario A. The missing readings, were either filled with +5 or -5, depending on the participants' last position relative to the centerline. All statistical analysis was conducted using SAS version 9.4.

While in the first stage of experimentation, descriptive statistics, maximum and absolute deviations as well as percent completion of the crosswalk, were used, absolute, constant, and variable error were the main descriptive statistics used in the second stage.

In the second stage, the single-factor ANOVA (one-way ANOVA) statistical analysis of variance test was conducted to test the statistical significance of the improvements caused by the Smart-Cane. Furthermore, Tukey multiple comparison (Tukey test) procedure was used where ANOVA was significant. The significant level used was 0.1 with a confidence level of 90%. To check the presence of overall directional bias (constant error) in each scenario, a one-sample t-test was conducted.

3.6 RESULTS AND DISCUSSIONS

3.6.1 1st Stage Results

In the first stage, when using the Smart-Cane (scenario C), the overall average pedestrian performance in terms of trajectory was the best, and the worst was when the APS beaconing was introduced (scenario B).

Scenario A proved to have the worst performance in terms of absolute deviation, with a value of 171 feet and 120 feet for the standard deviation. The absolute deviation value improved for scenario B (99 feet) with a standard deviation of 75 feet. The mean absolute deviation over the entire length of the crosswalk was 13.3 feet for scenario C with a standard deviation of 5.8 feet. It is evident that scenario C was the best in terms of minimizing the absolute deviation; furthermore, there was a large decrease in absolute deviation between scenario B and C. Maximum deviation for scenario C was 2.5 feet, whereas the maximum deviation was 5 feet for both scenarios A and B.

The participants completed 45.5% of the crosswalk on average in scenario A, whereas, in scenario B, participants finished 67.4% of the crosswalk. In scenario C, they completed crossing the entire crosswalk successfully (100%).

3.6.2 2nd Stage Results

A walking trajectory sample of a BVI pedestrian averaged over the 3 scenarios is demonstrated below (c.f. Figure 17). The straight solid gray lines are the tag deployment boundaries, and the straight solid red lines are the crosswalk boundaries. Each trajectory is averaged out for the 3 trials. Participants performed best in scenario C and scenario B ranked second. To illustrate the variation in crossing performance across participants, a walking trajectory of all participants throughout the three scenarios is shown in (c.f. Figure 18).

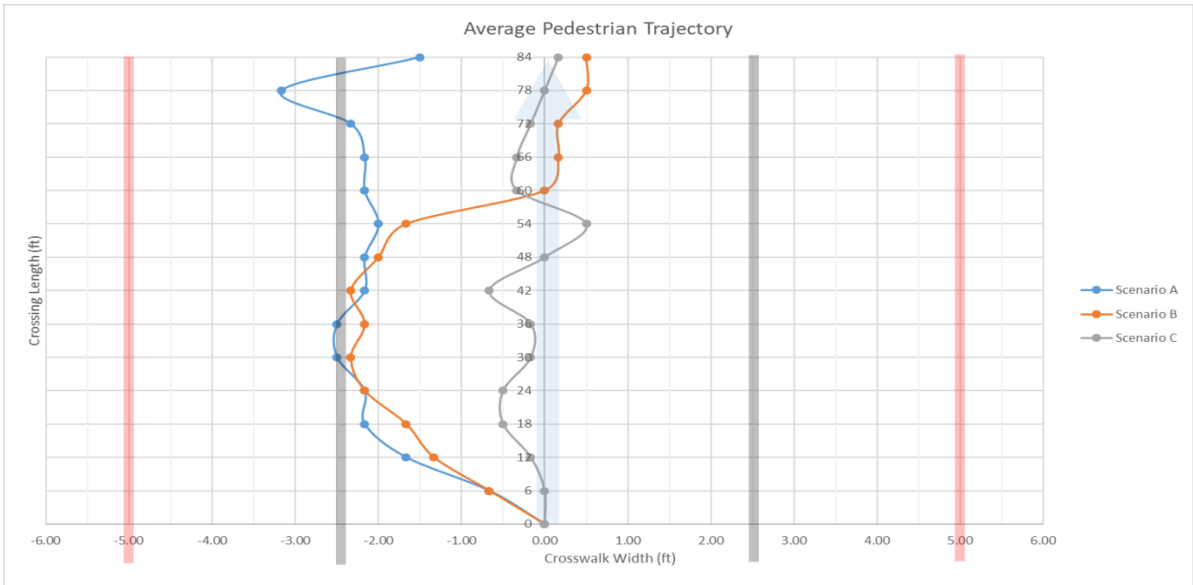


Figure 17: Average Pedestrian Trajectory.

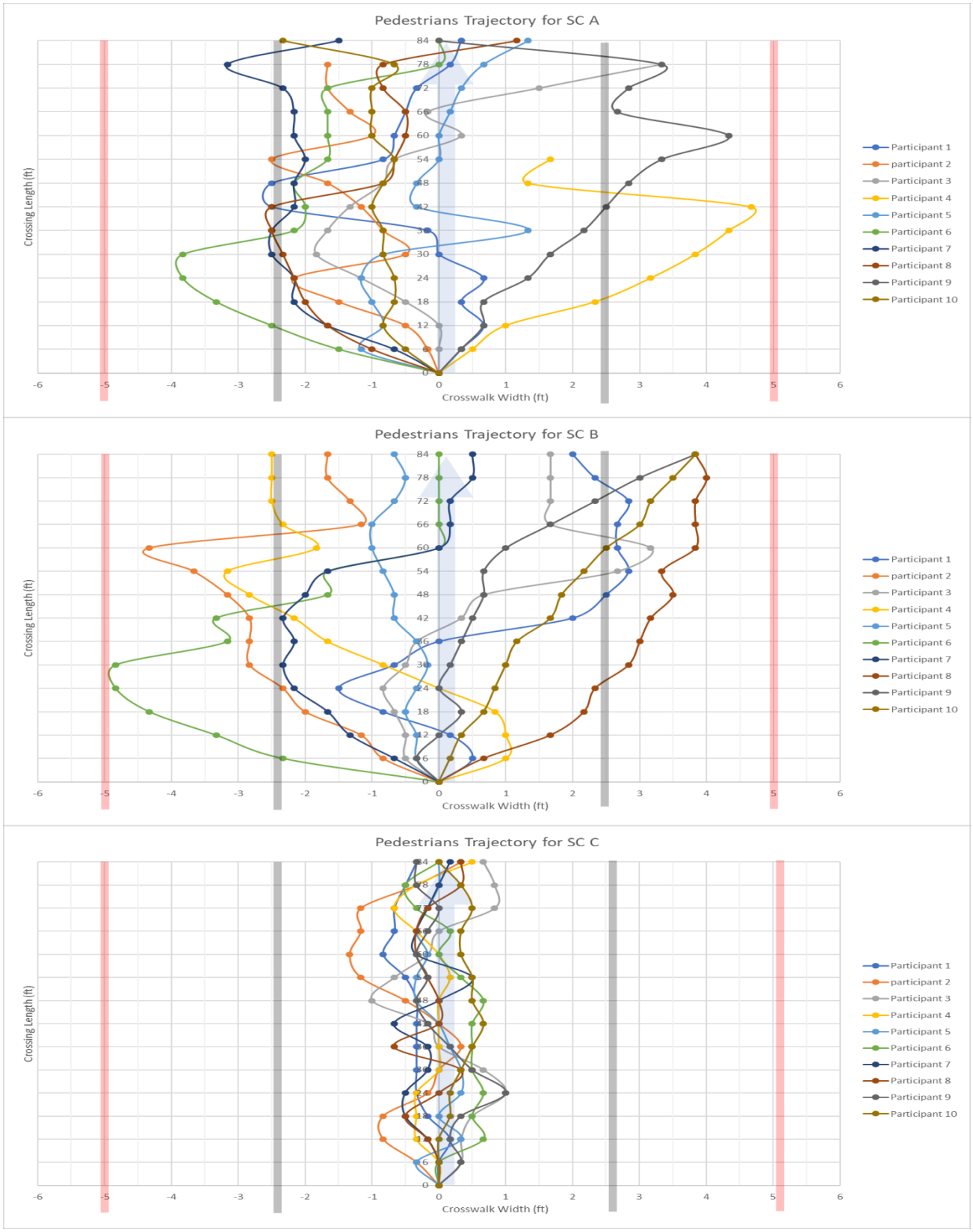


Figure 18: Pedestrian Trajectories for Scenario A, Scenario B and Scenario C.

The pre-survey was conducted to compare participants' crossing experience in intersections equipped with APS to those without APS, and to point out difficulties faced while crossing. About 44% of participants "rarely" indicated having difficulties while crossing intersections unequipped with APS, while 56% claimed having difficulties either all or some of the time. A five-point scale was used, and the average score was 2.64, where 5 indicated "always" having difficulties and 1 indicating "never" having difficulties. When crossing an intersection equipped with an APS, 53.4% of participants indicated facing difficulties, and 46.6% indicated rarely or never facing difficulties with an average score of 2.42. Most participants indicated that the various intersection information required for the crossing was important. 90% of participants felt that it is important for drivers approaching or idling at the intersection to be informed of their presence.

As for the experimentation stage, the average absolute deviation in scenario A and scenario B was 36 feet, with a maximum deviation of 5 feet. The average absolute deviation in scenario C was 7.5 feet with a maximum deviation of 2.5 feet.

The mean absolute error for scenario A increased as the pedestrians distance from starting line increased (SD 0.5 to 1 foot). Absolute error means increased over the entire distance in scenario B, proposing that the APS provided little guidance for the participants (SD of 1 foot). Scenario C had the lowest mean absolute error values and standard deviations (less than 0.5 foot). It is evident that scenario C was the best of all scenarios in terms of absolute errors in that it decreased veering. ANOVA was performed and was statistically significant at all distances (24, 48, 72 and 84 feet). The Tukey test conducted proved that scenario C performed the best.

The mean variable error of scenario A was 2.3 feet (SD 2 feet). The mean variable error decreased for scenario B (2 feet) and had (SD 1.5 feet). Scenario C had a mean variable error value between 0.5 and 1 foot and had (SD 0.45 foot). It is clear that scenario C had the best participants' performances. The statistical analysis was significant at each level.

The mean constant error for scenario A increased as distance of pedestrians from starting line increased (SD 3 feet), while for scenario B, the means of the constant errors decreased (SD 3

feet). Scenario C had the lowest constant error means signifying the least directional bias of all scenarios.

To check the presence of overall directional bias (constant error) in each scenario, a one-sample t-test was conducted for each scenario at each distance mark. Analysis showed that no significant constant error was found over all scenarios and distance marks. For scenario A, at 24 feet ($t = -1.33$, $p = 0.216$), at 48 feet ($t = -0.82$, $p = 0.432$), at 72 feet ($t = -0.14$, $p = 0.892$) and at 84 feet ($t = 0.2$, $p = 0.849$). For scenario B, at 24 feet ($t = -1.42$, $p = 0.189$), at 48 feet ($t = -0.75$, $p = 0.473$), at 72 feet ($t = -0.36$, $p = 0.724$) and at 84 feet ($t = -0.22$, $p = 0.830$). For scenario C, at 24 feet ($t = 1.05$, $p = 0.321$), at 48 feet ($t = -0.87$, $p = 0.405$), at 72 feet ($t = -1.1$, $p = 0.301$) and at 84 feet ($t = 1.27$, $p = 0.235$). No significant constant error was present which can be attributed to pure human behavior.

The participants completed 75% of the crosswalk on average in scenario A. They completed 85% of the crosswalk in scenario B. In scenario C, they completed crossing the entire crosswalk successfully (100%).

In the post-survey, all the participants showed their satisfaction of the Smart-Cane. 90% of participants would consider using the Smart-Cane if it was commercialized and 90% stated that they would prefer to use it over APS. Finally, 90% reported that the Smart-Cane increased their independence and self-confidence.

4 CONCLUSIONS AND FUTURE WORK

4.1 SMART CONE SYSTEM

Highway work zones reduce highway capacities and often lead to severe traffic congestions and crashes. Therefore, there is a need for traffic management systems that strive to adjust the traffic condition at work zones. This study introduces the smart cone system which actively delivers traffic information and recommendations for driving maneuvers to drivers at work zones. This system is based on the collection of real-time traffic data about nearby road segments. Based on the traffic condition inferred from the collected data, the system intelligently produces recommendations on driving maneuvers to mitigate the long-term negative impacts of the work

zone. The proposed smart cone system can help in enhancing the traffic conditions in terms of operational efficiency and traffic safety at work zones.
In addition, the performance of the proposed smart cone system is evaluated through systematic simulation studies. A microscopic simulation model is designed and is used to assess the impact of the smart cone system under various traffic flows. The VISSIM-COM interface is utilized for realizing this system. Results show that the smart cone system can significantly enhance the traffic conditions at work zones. The proposed system artificially induces speed reductions and lane changes before queues build up significantly at work zones. Furthermore, higher adoption rates lead to enhanced operational efficiencies. Therefore, the system should be promoted to the public to enhance its operational efficiency when it is deployed.

Although this study derived simulation based performance results of the proposed smart cone system, further research needs to be conducted to expand these results analytically and empirically. Firstly, the operational parameters of the smart cone system need to be adjusted towards optimized traffic conditions considering traffic safety, environmental impacts as well as operational efficiency. In addition, this study considered driver recommendations that include speed and lane changes as operational strategies. Further research should be conducted to potentially develop better operational strategies.

The simulation results in our study may dependent on a few parameters in the configuration, which include but not limited to simulation update interval, initial vehicle distribution, total number of vehicles in the simulation, car following model, number of lanes, etc. For example, in our study, we initialize two flow of cars, each of which loads vehicles at the rate of 2000 pc/hr. Changing this rate may affect the simulation result. For this reason, future study may evaluate the effect of different value of these parameters on the smart cone system.

Besides, the simulation is under 821.11p (DSRC/WAVE). In the future work, the simulation under cellular network, especially the 5G LTE can be performed.

4.2 SMART-CANE SYSTEM

The purpose of this study is to ease the process of crossing and improve safety at intersections by aiding BVI pedestrians in maintaining heading. Furthermore, complete crossing successfully and within the crosswalk, decrease crossing time, increase independence on other cues while crossing and increase self-confidence for the BVI.

The Smart-Cane is comprised of the veering adjustment system; the basic function of this system is to minimize veering behaviors of BVI pedestrians as much as possible.

The experimentation phase of this research was divided into two stages; the first stage included experimentation with 32 sighted participants, and the second stage was conducted with 10 BVI participants.

The Smart-Cane proved more preference over APS. The error calculations proved that the veering tendency of participants decreased significantly while using the Smart-Cane. The participants also maintained their heading and did not veer outside of the crosswalk all the time when using the Smart-Cane. The results of the pre-survey showed that the intersection information, which is sometimes unavailable, is very important to BVI pedestrians while crossing. The Smart-Cane provided missing information that BVI pedestrians might need to complete crossing safely, giving them more perception of the intersection they are about to cross. Taking a look at the post-survey, BVI overall satisfaction of the Smart-Cane was great and expressed willingness to adopt such technology. The Smart-Cane also proved that it decreased BVI pedestrian dependence on other cues and increased their self-confidence while crossing.

The Smart-Cane is in line with Connected Vehicles technology and Smart-Cities. The Smart-Cane with D2I, I2V and D2V communications improve BVI pedestrians' safety by providing them with intersection information (location, type, name, geometry, etc.), through alerting drivers of the BVI pedestrians presence and providing and increasing the green time allocated to the crossing.

The advancement of the Smart-Cane to include two additional systems, the driver alert and green time systems. Driver alert system informs approaching and idling drivers at intersections of the presence of BVI pedestrians to increases alertness of drivers and safety of BVI pedestrians. Green time system communicates with the signal controller and asks permission for allocating and extending pedestrians' green time.

Further experimentation with the Smart-Cane should be conducted with increasing the number of trials per scenario. Conduct experimentation at actual intersections to prove the efficiency of the Smart-Cane.

DSRC should be integrated into the Smart-Cane and test interactions with nearby vehicles at intersections, and study the rate at which drivers will collaborate with this technology and the alert which they are receiving through DSRC built in their vehicles. Smart-Cane should be further developed to include roundabouts and un-signalized intersections.

5 REFERENCES

1. Kim, T., Lovell, D. J., Paracha, J., 'A New Methodology to Estimate Capacity for Freeway Work Zones', Proceedings of the 79th TRB Annual Meeting, Transportation Research Board, Washington D.C., 2001.
2. Sarasua, W. A., Davis, W. J., Clarke, D. B., Kottapally, J., Mulukutla, P., 'Evaluation of Interstate Highway Capacity for Short-Term Work Zone Lane Closures', Transportation Research Record: Journal of the Transportation Research Board, 2004, 1877, pp.85-94
3. Yeom, C., Hajbabaie, A., Schroeder, B., Vaughan, C., Xuan, X., Rouphail, N., 'Innovative Work Zone Capacity Models from Nationwide Field and Archival Sources', Proceedings of the 94th TRB Annual Meeting, Transportation Research Board, Washington D.C., 2015.
4. Heiden, N., Geistefeldt, J., 'Capacity of Freeway Work Zones in Germany', Transportation Research Procedia, 2016, 15, pp.233–244
5. Heaslip, K., Kondyli, A., Arguea, D., Elefteriadou, L., Sullivan, F., 'Estimation of Freeway Work Zone Capacity through Simulation and Field Data', Transportation Research Record: Journal of the Transportation Research Board, 2009, 2130, pp.16-24.
6. Osman, M., Paleti, R., Mishra, S., 'Analysis of passenger-car crash injury severity in different work zone configurations', Accident Analysis and Prevention, 2018, 111, pp.161–172
7. Mohan, S., Zech, W. C. 'Characteristics of Worker Accidents on NYSDOT Construction Projects', Journal of Safety Research, 2005, 36(4), pp.353-360.
8. Hargroves, B. T., 'Vehicle Accidents in Highway Work Zones', Transportation engineering journal of the American Society of Civil Engineers, 1981, 107(5), pp.525-539.
9. Nemeth, Z. A., Migletz, D. J., 'Accident Characteristics before, during, and after Safety Upgrading Projects on Ohio's Rural Interstate System', Transportation Research Record: Journal of the Transportation Research Board, 1978, 672, pp.19-23
10. Zhu, J., Saccomanno, F., 'Safety Implications of Freeway Work Zone Lane Closures', Transportation Research Record: Journal of the Transportation Research Board, 2004, 1877, pp.53-61.
11. Finley, M. D., Theiss, L., Trout, N.D., and Ullman, G.L., 'Studies to improve the management of regulatory speed limits in Texas work zones', Federal Highway Administration, 2008.

12. Iowa DOT, 'Evaluation of work zone speed reduction measures', CTRE Management Project 99-44, Iowa Department of Transportation, April 2000.
13. Lin, P. W., Kang, K. P., Chang, G. L., 'Exploring the Effectiveness of Variable Speed Limit Controls on Highway Work-Zone Operations', In Intelligent Transportation Systems, 2004, 8(3), 155-168
14. Minnesota Department of Transportation, 'Minnesota Intelligent Work Zone System Toolbox', 2008.
15. Transportation Research Board, 'Development of a Sensing Methodology for Intelligent and Reliable Work-Zone Hazard Awareness', 2011.
16. Li, Y., Bai, Y., 'Determining Optimal Deployment Location of Portable Changeable Message Sign Upstream of Work Zones', Proceedings of the 91st Annual Meeting, Transportation Research Board, Washington D.C., 2002.
17. Jeong, E., Oh, C., Lee, G., Cho, H., 'Safety Impacts of Intervehicle Warning Information Systems for Moving Hazards in Connected Vehicle Environments', Transportation Research Record: Journal of the Transportation Research Board, 2014, 2424, pp. 11-19
18. FHWA, Traffic Analysis Toolbox Volume VI: Definition, Interpretation, and Calculation of Traffic Analysis Tools Measures of Effectiveness, 2007.
19. Transportation Research Board, Highway Capacity Manual, Transportation Research Board National Research Council Washington, D.C., 2000.
20. Federal Highway Administration. Surrogate Safety Measures From Traffic Simulation Models Final Report, U.S. Department of Transportation, 2003.
21. Al-Grandour M.N., Schroeder B.J., Williams B.M., Rasdorf W.J. Conflict models for signle-lane roundabout slip lanes from microsimulation (development and validation). Transportation Research Record: Journal of the Transportation Research Board 2011, 2236, pp.92-101.
22. Christoph Sommer, Reinhard German and Falko Dressler, "Bidirectionally Coupled Network and Road Traffic Simulation for Improved IVC Analysis," IEEE Transactions on Mobile Computing, vol. 10 (1), pp. 3-15, January 2011.
23. Brault, M. W. (2012). Americans With Disabilities: 2010. United States Census Bureau. Retrieved from https://www.census.gov/content/dam/Census/library/publications/2012/demo/p70-131.pdf

24. Guth, D., & Rieser, J. J. (1997). Perception and the Control of Locomotion by blind and Visually Impaired Pedestrians. In B. B. Blasch, W. R. Wiener, & R. L. Welsh, Foundation of Orientation and Mobility (Vol. 2, pp. 9-39). New York: American Foundation for the Blind Press.
25. Hill, E., & Ponder, P. (1976). Orientation and Mobility Techniques: A Guide for the Practitioner. New York: American Foundation for the Blind.
26. Jacobson. (1993). The Art and Science of Teaching Orientation and Mobility. New York: American Foundation for the Blind.
27. LaGrow, S., & Weessies, M. (1994). Orientation and Mobility: Techniques for Independence. Palmerston North, New Zealand: Dunmore Press.
28. Willoughby, D., & Monthei, S. (1998). Modular Instruction for Independent Travel. Baltimore, MD: National Federation of the Blind.
29. U.S. DOT. (2003). Manual on Uniform Traffic Control Devices (MUTCD). Washington, D.C.: United States Department of Transportation, Federal Highway Administration. Retrieved March 2017, from mutcd.fhwa.dot.gov
30. Barlow, J. M., Bentzen, B. L., & Bond, T. (2005). Blind Pedestrians and the Changing Technology and Geometry of Signalized Intersections: Safety, Orientation, and Independence. Journal of Visual Impairment & Blindness, 99(10), 587-598.
31. Guth. (1990). Space Saving Statistics: An Introduction to Constant Error, Variable Error, and Absolute Error. Peabody Journal of Education, 67, 110-120.
32. Guth, D., & LaDuke, R. (1994). The Veering Tendency of Blind Pedestrians: An Analysis of the Problem and Literature Review. Journal of Visual Impairment & Blindness, 391-400.
33. Bentzen, B. L., Barlow, J. M., & Franck, L. (2000). Addressing Barriers to Blind Pedestrians at Signalized Intersections. Journal of Institute of Transportation Engineers (ITE), 70(9), 32-35.
34. Liao, C.-F., Rakauskas, M., & Rayankula, A. (2011). Development of Mobile Accessible Pedestrian Signals (MAPS) for Blind Pedestrians at Signalized Intersections.
35. Tauchi, M., Sawai, H., Takato, J., Yoshiura, T., & Takeuchi, K. (1998). Development and Evaluation of a Novel Type of Audible Traffic Signal for the Blind Pedestrians. The 9th International Mobility Conference Proceedings. 9, pp. 108-111. Decatur, GA: Rehabilitation Research and Development Center, Veterans Administration Medical Center.

36. Wall, R. S., Ashmead, D. H., Bentzen, B. L., & Barlow, J. (2004). Directional Guidance from Audible Pedestrian Signals for Street Crossing. Ergonomics, 47(12), 1318-1338. Retrieved from http://www.tandfonline.com/doi/pdf/10.1080/00140130410001712609?needAccess=true
37. Harkey, D. L., Carter, D. L., Barlow, J. M., & Bentzen, B. L. (2007). Accessible Pedestrian Signals: A Guide to Best Practices. Washington : National Cooperative Highway Research Program.
38. Scott, A. C., Barlow, J. M., Bentzen, B. L., Bond, T. L., & Gubbe, D. (2008). Accessible Pedestrian Signals at Complex Intersections: Effects on Blind Pedestrians. Transportation Research Record: Journal of the Transportation Research Board(2073), 94-103.
39. Barlow, J. M., Scott, A. C., & Bentzen, B. L. (2009). Audible Beaconing with Accessible Pedestrian Signals. AER journal: Research and Practice in Visual Impairment and Blindness, 2(4), 149-158.
40. Barlow, J. M., Scott, A. C., Bentzen, B. L., Guth, D., & Graham, J. (2013). Effectiveness of Audible and Tactile heading Cues at Complex Intersections for Pedestrians Who are Blind. Transportation Research Record: Journal of the Transportation Research Board(2393), 147-154.
41. Bentzen, B. L., Scott, A. C., & Barlow, J. M. (2006). Accessible Pedestrian Signals: Effect of Device Features. Transportation Research Record: Journal of the Transportation Research Board(1982), 30-37.
42. Carroll, J., & Bentzen, B. L. (1999). American Council of the Blind Survey of Intersection Accessibility. The Braille Forum, 38(7), 11-15.
43. Bentzen, B. L., Barlow, J. M., & Franck, L. (2000). Addressing Barriers to Blind Pedestrians at Signalized Intersections. Journal of Institute of Transportation Engineers (ITE), 70(9), 32-35.
44. Kim, D., Emerson, R., Naghshineh, K., & Myers, K. (2014). Influence of ambient sound fluctuations on the crossing decisions of pedestrians who are visually impaired: Implications for setting a minimum sound level for quiet vehicles. Journal of Visual Impairment & Blindness (Online), 108(5), 368.
45. Guth, D., & LaDuke, R. (1995). Veering by Blind Pedestrians: Individual Differences and Their Implications for Instruction. Journal of Visual Impairment & Blindness, 89, 28-37.