IMPACTS OF ADVANCE IN-VEHICLE WARNING MESSAGES ON DRIVER BEHAVIOR APPROACHING MID-BLOCK CROSSWALKS

A Thesis

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Sean Laffey

Dwight David Eisenhower Transportation Research Fellow

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Approval Sheet

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Sean P. Laffey

This Thesis has been read and approved by the Examining Committee:

Dr. Brian Smith

Thesis Advisor

Dr. Gene McHale

Dr. Michael Fontaine

Dr. Byungkyu Park

Accepted for the School of Engineering and Applied Sciences:

Dean, School of Engineering and Applied Sciences

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Abstract

Mid-block crosswalks can be dangerous for both pedestrians and drivers because communication between the pedestrian and driver is non-verbal and each individual pedestrian decides when it is safe to cross. Sending an advanced warning message to a driver offers the potential to minimize the number of incidences involving vehicles and vulnerable road users, pedestrians, because a direct communication link is formed. This study designs the experimental methodology for testing driver's reactions to advance in-vehicle warning messages, develop a mobile application that both pedestrians and motorists can install on their smartphones or tablets that enables the users to communicate with each other at mid-block crossings using discrete safety messages, tests and collects data for 80 naïve test subjects' reaction to advance in-vehicle warning messages, and analyzes the safety impacts and performance metrics of the advance in-vehicle warning messages. This study finds that 73% of drivers who receive an advance warning stop for the pedestrian trying to cross while only 45% of drivers who did not receive an advanced warning stopped for the pedestrian. Drivers who received an advanced warning message approached the crosswalk with a significantly slower speed and standard deviation (19.6 mph and 3.4 mph respectively) compared to drivers who do not receive an advanced warning message (19.9 mph and 4.1 mph respectively). Drivers who received an advanced warning message began decelerating sooner for the pedestrian and more gradually for the pedestrian compared to the drivers who did not receive an advance warning message. This study finds that advanced warning messages can make crosswalks safer for drivers and pedestrians because drivers who receive an advanced warning message yielded significantly more frequently for pedestrians crossing at mid-block crosswalks, have a slower approach speed, and accelerate in a more tractable trend for a longer period of time.

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Chapter 1: Introduction

Designated mid-block crossings have been modified over time to increase the safety and functionality for pedestrians and motorists. Besides straight crossings, mid-block crosswalks can incorporate refuge gaps, staggered halves, and curb extensions; however, mid-block crosswalks are not always ideal because they can create unsafe or unpredictable situations for both pedestrians and drivers [1]. Mid-block crosswalk treatments vary by region and operational need. Often, a mid-block crosswalk is striped but receives no active infrastructure support, such as flashing warning lights, to warn pedestrians and drivers of a potential conflict. With the surge of connected vehicle (CV) technology and push for increased alternative modal usage penetration into overall travel mode choice there are ample opportunities to connect pedestrians and vehicles and provide road users with increased situational awareness, potentially reducing the number of vehicle-pedestrian incidences. The vision of this project is to leverage connected vehicle technology to incorporate vulnerable road users in the connected environment to improve mid-block crosswalk safety for both pedestrians and drivers.

1.1 Purpose and Scope

While the redesigns of mid-block crossings have made them safer for pedestrians and motorists, CV technology can be leveraged to further improve safety. The purpose of this study is to analyze drivers' reactions to advance in-vehicle warning message at mid-block crosswalks. The drivers, who are connected to the pedestrian in a virtual mid-block crossing environments (using a cellular network), will receive an advanced warning message alerting them of the presence of a pedestrian at the crosswalk. The scope of this project is to:

- Design the experimental methodology for testing driver's reactions to advance in-vehicle warning messages.

- Develop a mobile application that both pedestrians and motorists can install on their smartphones or tablets that enables the users to communicate with each other at mid-block crossings via discrete safety messages.
- Analyze the performance metrics of the cellular advance in-vehicle warning message environment.
- Test and collect data for a statistically significant number of naïve test subjects' reaction to advance in-vehicle warning messages.

1.2 Project Team

This research was conducted at the Turner Fairbank Highway Research Center (TFHRC) in partnership with the University of Virginias (UVa), the Federal Highway Administration (FHWA), and LEIDOS. To meet the requirements of the FHWA, International Review Board (IRB) and UVa, a Concept of Operations, Experimental Test Plan, and Application Acceptance Testing document were created and submitted to the appropriate party.

During the experiment, the Federal Highway Administration acted as the project coordinator, providing the research facility for the experiment, and personnel who consulted on the design of the experiment and execution of the experiment. For the application, UVa and FHWA designed the user interface for the application, system architecture, and data flow while LEIDOS coded the application required for the testing. LEIDOS provided support in recruiting test subject drivers. The University of Virginia, under the supervision of the FHWA, developed the experimental methodology, helped developed the application look, performed the experiment, collected data, and analyzed the data.

This experiment was conducted with another researcher, Austin Angulo. All researchers were required for this research to ensure the experimental operations were coordinated between the driver and the pedestrian. During the experiment, one researcher (Austin) sat in the vehicle to ensure the computer systems were properly tracking the driver and collecting data while the other researcher (myself) acted as the control pedestrian in the experiment. During the experiment, I collected and analyzed the kinematic data for the driver and vehicle (i.e. position, speed, acceleration) while Austin collected and analyzed driver data (driver eye tracking data). All documents submitted to the FHWA, IRB, and UVa were co-authored by both researchers.

1.3 Organization of Thesis

The remainder of this thesis is organized as follows:

- Chapter 2: Reviews the literature on driver behavior at mid-block crosswalks and driver reaction to advance in-vehicle warnings.
- Chapter 3: Discusses the methodology used for evaluating the divers' reactions to advance in-vehicle warning messages at mid-block crosswalks.
- Chapter 4: Presents the experimental results.
- Chapter 5: Discusses the experimental results.
- Chapter 6: Discusses the conclusions of this research and potential future works.

Chapter 2: Literature Review

2.1 Introduction

A literature review was performed to understand current driver behavior at mid-block crosswalks when a pedestrian is crossing. A literature review is first performed to understand existing mid-block crosswalk safety design features and typical pedestrian to vehicle crash characteristics. This literature review then reviews existing studies which analyze the change is drivers' behavior when an advanced warning message is received compared to no advanced warning message being received. This literature review shows the existing research results for mid-block crossing safety features, driver behavior at mid-block crosswalks, the change in driver behavior when an advanced warning message is received, and gaps in the existing research.

2.2 Mid-Block Crossing

2.2.1 Mid-Block Crossing Types

While current designs have aided cyclists and pedestrians in crossing roadways at mid-block crossings, conflicts still arise due to the confusion these designs can cause between pedestrians and motor vehicles [1]. Mid-block crosswalks can be dangerous for both pedestrians and drivers because communication between the pedestrian and driver is non-verbal and each individual pedestrian decides when it is safe to cross [2]. Figure 1 shows the Washington and Old Dominion Trail (W&OD) crossing Wiehle Ave in Reston, Va. Seen in Figure 1, this mid-block is difficult for the drivers to navigate due its position in relation to the nearby signalized intersection. Wiehle Ave services vehicles and pedestrians wishing to cross the road have trouble communicating with approaching vehicles due to the vehicle's high approach speed, limited sight distance, and wide crossing width. The minor street approaches have limited sight distance looking to the crosswalk because the mid-block crosswalk is less than 100 feet from the intersection. Providing additional protection, such as advanced driver warnings should make this a more desirable crossing for the pedestrians and motorists [2].

Figure 1- Wiehle Ave crossing in Reston, VA

A greenway mid-block crossing, far from any intersection, is seen in Figure 2. The crossing of the W&OD trail in Figure 2 has a refuge area, but the refuge is only protected by pavement markings. It has been shows that a pedestrian refuge area helps reduce pedestrian to vehicle crashes but a raised median further helps to reduce the number of crashes [3]. There are no static advanced warning signs for motorists warning of the approaching mid-block crossing; the only signage for the mid-block crossing is directly at the crossing itself. Providing additional protection, such as advanced driver warnings should make this a more desirable crossing for the pedestrians and motorists [2].

Figure 2- Sunset Hill Road crossing in Reston, VA

Multiple approach lane mid-block crossings (3 or more lanes) can increase delay because vehicles at all approaches must wait for the pedestrian to cross the crosswalk after the drivers properly interpret the pedestrian's non-verbal communicate indicating their desire to cross [2]. Communication between the pedestrian and driver becomes more complicated when a mid-block crossing crosses a road with a 3-lane (or more) cross section because one vehicle at a multi-lane approach can block an adjacent vehicle's view of a pedestrian in the mid-block crossing, seen in Figure 5. The obstructed view of the pedestrian at the mid-block crosswalk can create a dangerous crossing situation for the drivers and pedestrians. Connecting pedestrians and vehicles to provide advanced warnings that anticipate potential collisions could help reduce the time it takes for the drivers to interpret the pedestrian's intention to cross, and could help eliminate crossing confusion and ambiguities.

Besides visual communication confusion, the balance of existing laws and safety can create confusion at the mid-block crossing. Virginia law requires drivers to yield to pedestrians in the crosswalk. However, mid-block crossings can be signed to request the pedestrians to stop for traffic, along routes such as the W&OD and Mt Vernon Trails. Legally, the drivers are required to stop at the crosswalk. However, it has been studied that nearly 70% of the drivers may not yield to the pedestrians so the pedestrians are warned to stop and cross when safe [4]. An advanced warning system that connects the pedestrians and drivers should increase the driver's awareness of a pedestrian in the crosswalk, increasing the driver's compliance with the law and decreasing potential vehicle-pedestrian crashes.

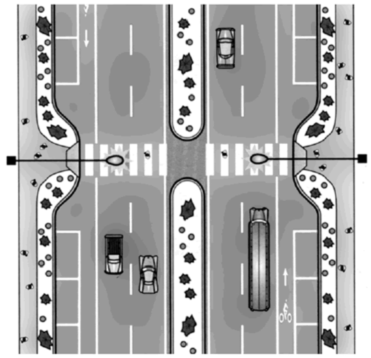

Figure 3- Example of a Common Design for a Mid-Block Crossings

2.2.2 Mid-Block Crossing Safety

Providing an advanced warning to the driver can assist the pedestrian in crossing a midblock crosswalk and potentially reduce the number of pedestrian to vehicle crashes. Seen in Table 1, of all pedestrians fatally injured in a pedestrian-vehicle collision nearly 80% of pedestrians were performing at least one action the driver could not anticipate (such as darting out, failing to yield to the right-of-way, improper crossing of the roadway). As seen in Table 2, of all pedestrians fatally injured in a pedestrian-vehicle collision nearly 70% of all pedestrian fatalities occur when it is dark, i.e. when there is poor visibility. Shown in previous studies, the average perception reaction time of a driver to an unexpected roadway obstacle (such as a pedestrian) was 1.6 seconds [5]. Providing an advanced warning to the driver could eliminate the number of actions the driver could not anticipate and improve pedestrian visibility. Sending advanced warnings to the vehicles can allow the drivers to preemptively anticipate and safely avoid vehicle- pedestrian conflicts [6].

Table 1- Pedestrian's Actions When Fatality Results from Pedestrian & Vehicle Collision

Non-Motorist Action and/or Circumstances At Time of Crash	Person Type		Total
	Pedestrian	Bicyclist	
No Improper Action	17%	26%	18%
Failure to Yield Right-Of-Way	20%	21%	21%
Not Visible (Dark clothing, No Lighting, etc.)	13%	8%	12%
Improper Crossing of Roadway or Intersection (Jaywalking)	13%	3%	11%
Dart/Dash	11%	4%	10%
In Roadway Improperly (Standing, Lying, Working, Playing, etc.)	12%	0%	10%
Failure to Obey Traffic Signs, Signals or Officer	3%	7%	4%
Inattentive (Talking, Eating, Etc.)	2%	3%	2%
Wrong-Way Riding or Walking	1%	5%	2%
Entering/Exiting Parked/Standing Vehicle	1%	0%	1%
Other (Improper Turn/Merge, operating without require equipment, Failing to have Lights on When Required, Failure to Keep in Lane, etc.)	3%	17%	5%
Not Reported	2%	1%	2%
Unknown	3%	4%	4%
TOTAL	100%	100%	100%

Table 2- Light Conditions When Fatality Results from Pedestrian & Vehicle Collision

Light Condition	Person Type		Total
	Pedestrian	Bicyclist	
Daylight	24%	49%	27%
Dark	72%	44%	68%
Dawn/Dusk	4%	6%	4%
TOTAL	100%	100%	100%

In a FHWA study conducted with data collected throughout the 1990s, it was found that the percentage of pedestrian collisions with absolutely no traffic control was 74.4%, indicating that the majority of pedestrian-motorist collisions can be mitigated with some form of advanced warning, seen in Table 3 [7]. Seen in Table 4, over 90% of pedestrian collisions occur at mid-blocks with no traffic control for both the 'dart/dash' and 'other' scenarios, indicating that an advanced warning sent to the driver can mitigate pedestrian-motorist collisions [7].

Table 3- Percentage of Pedestrian Collisions based on Control Type

Traffic Control Type	Percent of Pedestrian Collisions
No traffic control	74.4
Stop sign	7.0
Traffic signal	17.3
Other	1.4
	100

Table 4- Percentage of Pedestrian Collisions based on Crash Type and Level of Traffic Control

	TRAFFIC CONTROL*			
Pedestrian crash type	No control	Stop sign	Traffic signal	Other traffic control**
Bus-related	79.1	11.6	9.3	0.0
Other vehicle specific	90.6	4.7	4.7	0.0
Driverless vehicle	97.6	1.2	1.2	0.0
Backing vehicle	96.1	1.1	2.2	0.7
Disabled vehicle related	87.3	2.5	7.6	2.5
Working/playing in road	77.9	8.6	5.0	8.6
Walking along roadway	96.1	2.1	1.3	0.5
Not in road	94.3	3.1	0.9	1.7
Vehicle turning at intersection	15.5	20.0	63.3	1.2
Intersection dash	66.0	9.8	24.0	0.3
Driver violation at intersection	38.8	24.7	34.1	2.4
Other intersection	47.5	9.6	42.2	0.6
Midblock dart/dash	94.4	1.9	2.9	0.8
Other midblock	91.1	1.0	6.6	1.4
Miscellaneous	85.0	5.3	7.2	2.5
ALL CRASHES	74.4	7.0	17.3	1.4

*Cases with unknown traffic control excluded.
**Flashing signal, yield sign, railroad crossing, official flagger.
Source: *Pedestrian and Bicycle Crash Types of the Early 1990s*, Hunter, W., J. Stutts, W. Pein, C. Cox, UNC HSRC, FHWA-RD-95-163, 1996.

The same study conducted by the FHWA found that the majority of the pedestrian-vehicle collisions were caused by the pedestrian. Seen in Table 5, 92% of collisions classified as ‘dart/ dash’ at mid-block crosswalks were the fault of pedestrians only; 60% of pedestrian collisions classified as ‘other’ at mid-block crosswalks were the fault of pedestrians [7]. The city of Saint Louis attempted to mitigate the number of pedestrian to vehicle collisions at mid-block crosswalks by providing stop and yield control for the pedestrians and legally requiring the pedestrians to stop for vehicles [8, 9, 10]. However, it was found that the pedestrians ignored the control signs and crossed assuming the motorists would yield to the pedestrians [9, 10]. Uncontrolled mid-block crossings create unpredictable and unsafe situations because each pedestrian decides when they feel it is safe to cross, the driver only reacts to the pedestrian. An advanced warning sent to the driver can mitigate pedestrian-motorist collisions because the pedestrian's current unpredictable action could be anticipated.

Table 5- Percentage of Pedestrian Collisions based on Crash Type and Fault

	FAULT*						
Pedestrian Crash Type Subgroup	**Driver Only**	**Driver; Pedestrian Unknown**	**Pedestrian Only**	**Pedestrian; Driver Unknown**	**Both**	**Neither**	**Unknown**
Bus-related	34.1	0.0	50.0	2.3	9.1	2.3	2.3
Other vehicle specific	21.3	4.3	45.7	6.4	20.2	0.0	2.1
Backing vehicle	67.8	3.7	10.3	0.3	13.4	0.6	4.0
Disabled vehicle related	62.9	0.8	8.9	3.2	21.0	1.6	1.6
Working/playing in road	36.8	0.7	50.7	2.6	6.6	0.0	2.6
Walking along roadway	18.0	2.8	28.8	12.8	34.5	0.2	3.0
Ped. not in road	61.0	3.2	22.0	0.7	8.3	0.9	3.9
Vehicle turning at intersection	79.1	1.8	9.3	0.6	6.8	0.2	2.2
Intersection dash	0.6	0.0	90.6	2.2	6.6	0.0	0.0
Driver violation at intersection	87.6	3.9	0.4	0.4	6.6	0.0	1.2
Other intersection	12.6	3.3	59.5	5.5	11.4	0.4	7.3
Midblock dart/dash	1.0	0.2	91.8	1.8	5.0	0.2	0.0
Other midblock	11.5	2.2	60.4	5.3	16.0	0.5	4.1
Miscellaneous	39.3	2.0	21.7	3.3	18.9	7.1	7.8
ALL CRASHES	34.8	2.1	43.2	3.4	12.5	1.0	3.2

*Cases with unknown fault excluded.
Source: *Pedestrian and Bicycle Crash Types of the Early 1990s*, Hunter, W. J. Stutts, W. Pein, C. Cox, UNC HSRC, FHWA-RD-95-163, 1996.

With the increased capabilities of connected vehicle technology, it is now possible to connect pedestrians and motorists in a virtual environment, to transmit advanced warnings to drivers when pedestrians are present at greenway mid-block crossings, and to hopefully limit the number of pedestrian crashes.

It is anticipated that sending drivers an advanced warning will help reduce the number of pedestrian to vehicle crashes. Currently, rectangular rapid flashing beacons, a static sign with flashing light combination, are used in the field and have been shown to improve driver yield compliance when pedestrians are present at a mid-block crosswalk [4]. It has also been shown that the presence of a treatment at a crosswalk alone does not cause vehicles to slow down; the presence of a pedestrian causes the driver to slow down and yield and the crosswalk treatment applied enhances the driver awareness of the pedestrian [11].

2.3 Driver Behavior

2.3.1 Driver Behavior at Mid-Block Crosswalks

A pedestrian crossing at a mid-block crosswalk in the trajected path of the vehicle can create a dangerous situation for both the driver and the pedestrian. It has been shown that anything less than a traffic signal typically failed to produce over 70 percent of drivers yielding at crosswalks on multilane roads [4]. If the percentage of drivers who yield to pedestrians increases, the number of vehicle to pedestrian crashes can be reduced [6]. In an attempt to minimize the number of pedestrian-vehicle collisions, advanced warning messages can be sent to drivers warning of potential collisions.

The interactions of pedestrians and drivers have been analyzed in multiple studies. It has been noted that variables pertaining to the crosswalk site, the driver, and the pedestrian all affect the interaction of pedestrians and drivers [2]. The crosswalk variables include the site and the treatment the crosswalk receives; the variables affecting the vehicle include velocity, the type of vehicle, and personal characteristics of the driver; variables affecting the pedestrian include the distance from the driver at the point when the pedestrian steps into the street, the awareness of the pedestrian at the crosswalk, the number of pedestrians, and the appearance of the pedestrian [2]. It has been shown that a marked crosswalk increases the effectiveness of reducing a driver's speed compared to a non-marked crosswalk; it has been shown that the higher the driver's approach speed to the crosswalk is, the less inclined (or less able) the driver is able to slow for the pedestrian; a pedestrian's entry into the road a short distance from an oncoming vehicle was less effective in influencing the driver to slow or stop compared to a pedestrian entering the road with a longer distance from an oncoming vehicle [2]. However, it should be noted that drivers slow down for pedestrians on crosswalks and not for painted lines on the roadway, the markings on the road enhance the driver's reaction to a pedestrian on the road [11].

For this experiment, a "control" pedestrian is used to study the effects of in-vehicle warning messages on drivers. Using a control pedestrian, the same pedestrian for every driver test subject eliminates the pedestrian variables. For this experiment, a "control" site is also used to study the effects of in-vehicle warning messages on drivers. Using a control site, the same site for every driver test subject eliminates the site variables.

2.3.2 Driver Reaction to Advanced Warning Messages

Seen in previous studies, it has been found that advanced warning messages are effective at increasing the driver awareness of unsafe situations [6]. Shown in previous studies, one of the largest factors in the effectiveness of an advanced warning message is the message lead time, how far in advanced of the potential incident the driver receives the advanced warning message [6]. It was found that the safety benefits are noticeable in an optimal time range, the driver should receive the advanced in-vehicle warning message between 4 seconds to 8 seconds before the potential conflict [6]. It has been shows that the maximum effectiveness of warning messages was achieved when the control lead time was within the range of 5 seconds to 8 seconds [6]. When drivers receive advanced warning messages within this time range, it was found that driver had a shorter reaction time and decelerated more gradually [6]. If the driver receives the message with less than 4 seconds, the driver does not have adequate time to react to the situation [6]. If the driver receives the message with more than 8 seconds, the driver does not react to the message [6]. However, it should be noted that this study was conducted in a simulator and the collision warnings were for vehicle to vehicle collisions and not for pedestrians.

For this experiment, the advanced warning is targeted to be sent to the driver 6 seconds before the driver reaches the crosswalk. Assuming a driving speed of 25 miles per hour for the average driver, the advanced warning is target to be sent 216 feet before the crosswalk.

2.4 Gaps in Research

Driver reactions to the presence of a pedestrian at a mid-block crosswalk and driver reaction to advanced warning messages have been analyzed in separate studies. The study that analyzed driver's reactions to pedestrians at mid-block crosswalks did not send the driver an in-vehicle advanced warning message. The study that analyzed the driver's reaction to advance in-vehicle warnings studied the effects of message lead-time and the driver's response, did not use a pedestrian for the studied hazardous condition, and was performed in a simulator which cannot perfectly mimic real-world conditions [13].

The anticipated results from this study are expected to be positive because the results from the pedestrian crossing study, advanced warning study, and other existing studies have positive results. It is anticipated that an advanced in-vehicle warning messages should increase driver awareness of pedestrians at mid-block crosswalks, correlating to a slower approach speed to the crosswalk and an increased driver yield rate for the pedestrian trying to cross the crosswalk.

No study has specifically used naïve human test subjects in a field study to analyze the effects of advanced in-vehicle warning messages on driver behavior when approaching a mid-block crosswalk that a pedestrian is attempting to cross. This study uses 80 naïve human test subjects as drivers and a control pedestrian to analyze the effects of advanced in-vehicle warning messages on driver behavior when the driver is approaching a mid-block crosswalk that a pedestrian is attempting to cross.

Chapter 3: Methodology

3.1 Introduction

This section discusses the required resources and experimental design to conduct the experiment. The resources required include the application that connects the pedestrian and driver, the test site (given by the FHWA), and the test vehicle (given by the FHWA). The experimental design is created using existing studies and the human factors teams at the Federal Highway Administration (FHWA). The experimental design is approved by the Internal Review Board (IRB) because naïve human test subjects are used.

3.2 Application Design

For testing purposes, a virtual mid-block crossing environment is created to connect the drivers and pedestrians. Before the system was created, a Concept of Operations was written to define how the system would operate and how the users would interface with the system.

It was decided that a cellular phone will be used for the pedestrian to send an advanced warning message to the driver. The driver received the message on a cellular device (a tablet) which is mounted on top of a vehicle's on-board computer display. Cellular devices are used for the potentially immediate implementation and ability to easily tie into existing connected vehicle networks. The proposed system operates through a central server, where the messages are collected, processed, and sent to the appropriate devices. At the central server, messages can be disseminated across multiple types of devices, including cellular devices and DSRC devices. The application, designed by UVa and the Federal Highway Administration was coded using Android application development software by LEIDOS, the Federal Highway Administration on-site contractor. While LEIDOS coded the application, the user interface and data flow (how the pedestrian and driver are connected) was developed by the University of Virginia and the Federal

Highway Administration. The full Concept of Operations and Application Acceptance testing documents were submitted to the Federal Highway Administration.

3.2.1 Concept for the Proposed System

The mobile application is designed using wireless communications to create an environment consisting of stagnant virtual midblock crossings, overlapping the existing midblock crossings, which users interact with. When a pedestrian is in range of the delineated crossing the virtual environment will recognize that a user is present and enable the user to request a call for crossing. Drivers will also need to be equipped with the application that interacts with the virtual network. When the driver is within a designated range of the virtual crosswalk and a pedestrian sends out a notification of their presence at the mid-block crossing using the mobile application, a visual and audible message will be transmitted to the driver, warning them that a pedestrian is present.

Note that the application created for this experiment is a proof of concept developed specifically for this experiment. Besides the ubiquitous nature of cellular devices, a cellular network is chosen due to the limited required creating, maintenance, and operating costs. Discussed in the Future Works section, to make the system available to the public, the application can be modified to expand the proposed system to include multiple crosswalks and multiple users.

3.2.2 Operational Needs

The primary objective of this application is to increase awareness of conflicts at mid-block pedestrian crossings by notifying drivers of pedestrian presence via cellular connectivity. The goals of this application, assuming it is widely implemented, include:

- Build an environment to enhance safety at mid-block crossings where adequate safety precautions aren’t always present.

- Create a virtual environment to limit the need to install costly equipment at every mid-block crossing.
- Deliver personal messages for drivers warning them of vulnerable users requesting to cross, limiting the chance of not seeing someone around the crossing.
- Deliver advanced warnings for potentially distracted drivers of vulnerable users in the vicinity requesting to cross, minimizing the chance of the pedestrian not being seen.
- Increase ratings of drivers who yield for pedestrians at mid-block crossings.
- Minimize wait time for both pedestrians and motorists at mid-block crossings.
- Prevent conflicts at crossing where both users attempt to cross at the same time.
- Prevent conflicts at crossing where vehicles in adjacent lanes attempt to pass vehicles yielding to pedestrians unknowingly.
- Establish a simple, functional application that can be incorporated into the overall CV environment and protocol.

Assuming the application is widely implemented, there are many variables that must be addressed by the system that can influence the acceptance and usefulness of the technology:

- User technology acceptance and perception of effectiveness.
- The rate of drivers who yield for pedestrians at mid-block crossings.
- The change in driver behavior to the presence of a pedestrian present at a mid-block crosswalk.
- Cellular connection and accuracy.
- Message latency and appropriate messaging time.

The proposed system accomplishes the goals and optimizes the variables using geofences, a process of using GPS technology to virtually draw geographic boundaries which allow mobile technologies to trigger a response when within the defined space. The proposed system creates a virtual active warning system for a mid-block crosswalk by allowing only users inside of the geofences to interact with each other, as seen in Figure 4. The geofenced cellular network will delineate three geofenced areas, one pedestrian geofence and two vehicle geofences:

- Pedestrian geofence- A boundary encompassing the mid-block crosswalk and adjacent sidewalk.
- Vehicle geofence- Two boundaries adjacent to either side of the mid-block crosswalk.

Figure 4- Pedestrian and Vehicle Geofenced Areas

The pedestrian can broadcast an advanced warning message to the drivers only when a pedestrian is present in the pedestrian geofence, ensuring pedestrians are crossing the street at defined locations. Having the pedestrians cross at defined locations ensure that the drivers can predict where the pedestrians will be crossing, and will not be ‘darting/ dashing’ in front of the vehicles at non-geofenced areas. Having the pedestrians cross at defined locations allows department of transportation agencies to add additional crosswalk safety features (such as pavement striping and static signs), further enhancing the safety of the mid-block crosswalks. Only vehicles in the vehicle geofence will receive an advanced warning message, ensuring only vehicles approaching the mid-block crosswalk will receive an advanced warning message. This ensures that the majority of the pedestrian crossing messages received will be relevant; the messages should only be received when a pedestrian is present and crossing at the crosswalk.

3.2.3 System Overview

The virtual crossing network is created using localized, designated geospaces, defined by localities on GPS maps at mid-block crossings. Users in the geospaces have the ability to interact with the virtual crosswalk. The interaction between users and the environment is initiated by the user by opening the application on their phone. Users will have the option to define themselves as a Pedestrian or Motorist upon opening the application and are able to alter roles between trips, seen in Figure 5.

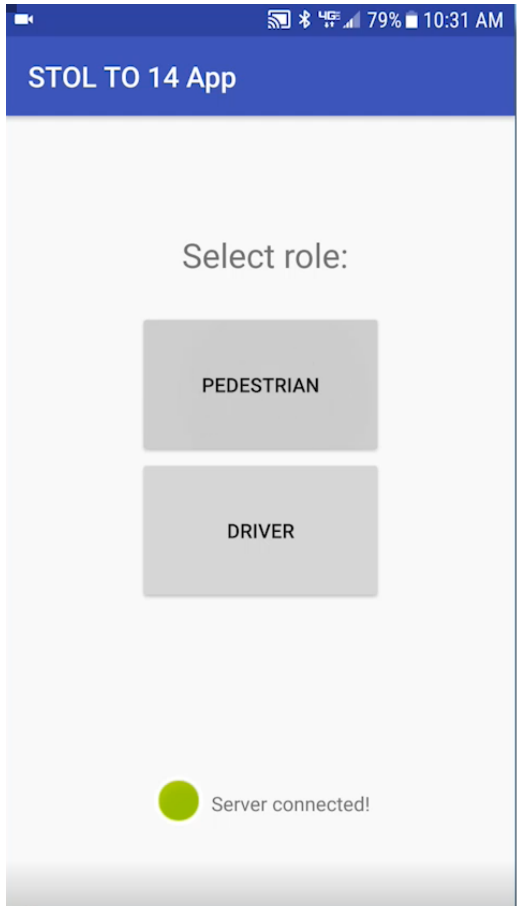

Figure 5- Pedestrian Crossing Application Home Screen

The fundamental data flow for messaging between users is displayed in Figure 6. The detailed system architecture for operations can be found in Figure 7.

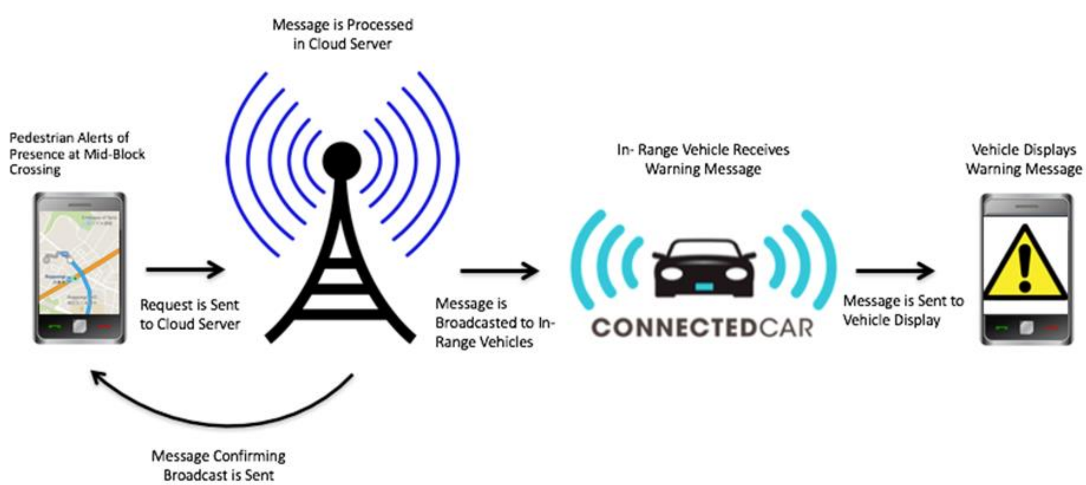

Figure 6- Message Data Flow

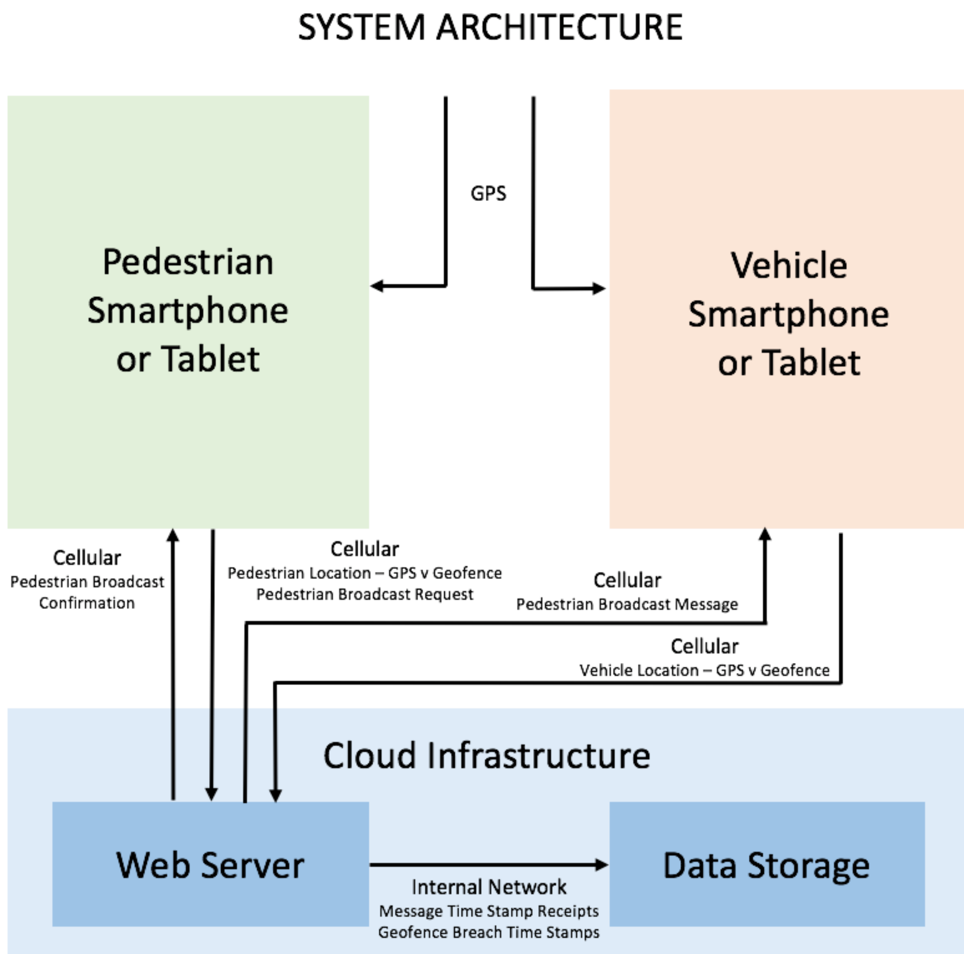

Figure 7- System Architecture

3.2.4 Pedestrian Driver Interaction

The pedestrians and drivers will be connected using a cellular phone application that operates using a cellular network, seen in Figure 6. The applications between the drivers and pedestrians will interface when both the driver and pedestrian are in the pre-defined geofenced areas. When a pedestrian is in the Pedestrian Geofence delineating the mid-block crosswalk, the pedestrian will be given the option within the application to notify any drivers within the designated Vehicle Geofence of their presence at the mid-block crosswalk. Seen in Figure 6, the pedestrian and driver are connected through a cloud server. When a pedestrian broadcasts a crossing message, the cloud server receives the pedestrian's request and broadcasts the message to all connected vehicles in the vehicle geofence areas.

3.2.5 Pedestrians Network Interaction

The pedestrians will interact directly with the network. The pedestrians with the application installed on their cellular device are responsible for physically pushing a button on their screen indicating their presence at the mid-block crossing and their desire to cross. Only when the pedestrian signals their intention to cross will the drivers receive an audio and visual warning message. Once the pedestrian has pressed the button on their screen, the pedestrian receives a message that their notification of presence is being broadcasted to motorists within the Vehicle Geofence. The pedestrians will not receive a warning message or any operational message (a message indicating that it is safe to cross) as this application is designed to only operate as a situational awareness application.

3.2.6 Drivers Network Interaction

The drivers with the application installed on their cellular device will automatically be connected to the virtual network when inside the geofenced area. It is assumed that drivers will have their phone or tablet mounted to their dashboard or windshield, being used as a GPS device. If a pedestrian signals their presence at the crossing, the vehicles in the vicinity of the mid-block crosswalk within the Vehicle Geofence will automatically receive a visual and audio warning message, notifying them of the presence of the pedestrian, seen in Figure 8.

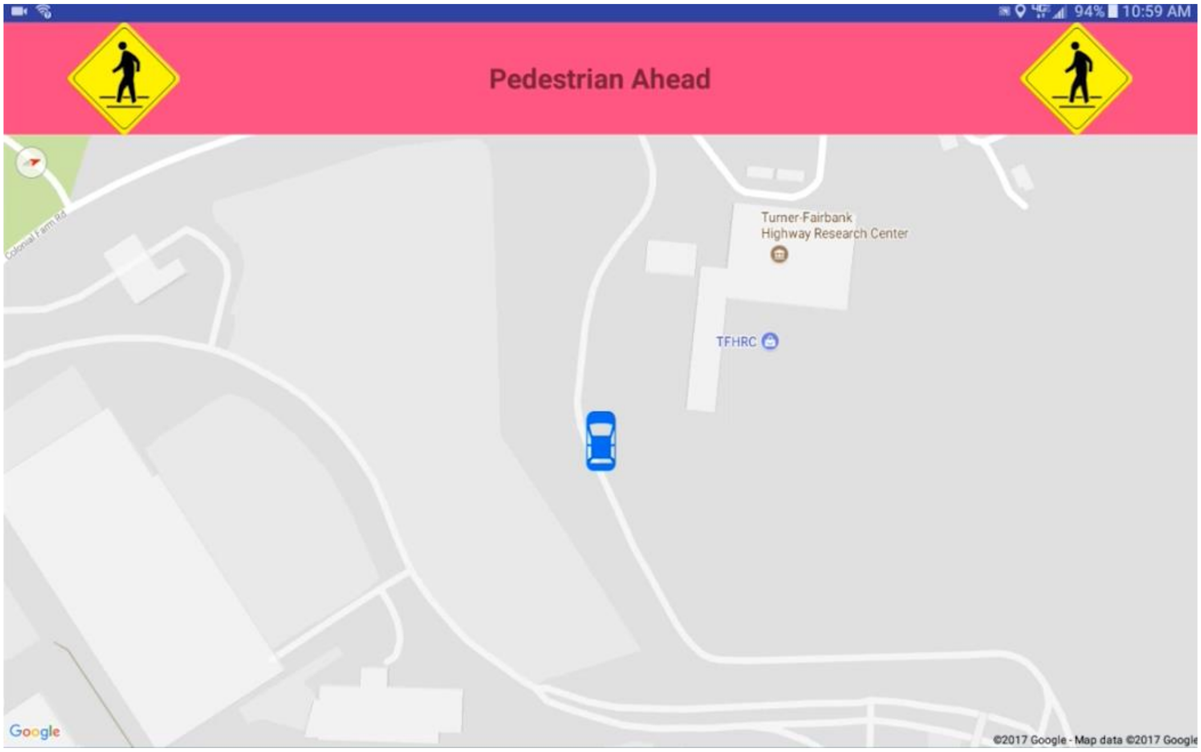

Figure 8- Pedestrian Ahead Warning Received by Driver

If widely implemented, the application requires that localities (city, town, etc.) develop a GPS map layer that the application can access and update as the user travels between localities. The map layer will consist of designated geospaces that define the area of operations for the virtual crosswalk.

3.3 Experimental Design

3.3.1 Experimental Design Overview

This study requires 80 naïve human test subjects to drive a test vehicle. The 80 human test subjects will be operating the same test vehicle equipped with the same tablet with the capability of displaying a visual and playing an auditory warning to the driver. For this experiment, the test subject will individually drive one lap four (or more) times for approximately 10 minutes total, including one warm-up lap, two test laps, and one lap between the test laps. The laps will pass over a mid-block crosswalk, seen in Figure 4. The warm up lap is used so the driver becomes comfortable with the vehicle. This warm up lap also gives the pedestrian a queue that the experiment is beginning and ample time to prepare for second lap, the first test lap. After the warm-up lap is complete, the driver will complete at least 3 more laps where the driver will be exposed to the pedestrian at least twice, during the two test laps, seen in Figure 4. During one test lap, the pedestrian will send an advanced warning message to the driver indicating that the pedestrian wants to cross the mid-block crosswalk. During one test lap, the pedestrian will be at the mid-block crosswalk and attempt to cross without sending an advanced warning message; the pedestrian will attempt to non-verbally communicate with driver that they want to cross and no advanced warning message will be sent to the driver. Between the two laps the pedestrian is attempting to cross the street, the pedestrian will not be present. This lap is used in an attempt to make the driver feel like the pedestrian the first time was not a part of the test. The 80 test subjects are broken into two groups, Group A received no advanced warning on their first exposure to the pedestrian and an advanced warning on their second exposure to the pedestrian (lap 4) and Group B received an advanced warning on their first exposure to the pedestrian and no advanced warning on their seconds exposure to the pedestrian. A typical testing schedule for the driver is listed below in Table 6.

Table 6- Typical Driver Testing Schedule

Typical Test Schedule		
Track Lap	Group A (40)	Group B (40)
Lap 1	No Test	No Test
Lap 2	No Warning	Warning
Lap 3	No Test	No Test
Lap 4	Warning	No Warning

While most subjects only required 4 test laps, listed in Table 6, some test subjects required more than 4 laps because the test is conducted on an open local road. If other vehicles or pedestrians were present during one of the test laps (lap 2 or lap 4) the pedestrian would disappear from the test track before the driver could see the pedestrian and the test lap would be moved to the subsequent lap.

3.3.2 Test Location

The test course for this experiment will be a lap at the Federal Highway Administration's Turner Fairbank Highway Research Center located in McLean, Virginia. The test lap will be on a two-lane cross section, bi-directional road that encircles the research center. There is one mid-block crosswalk present that the lap passes over, outlined in red in Figure 9. There are sidewalks leading up to the mid-block crosswalk that the pedestrian will be walking on and signalized intersections along both approaches of the midblock crosswalk. The direction that the test subjects will be driving is indicated by the red arrow in Figure 9. The mid-block crossing to be tested at is shown in Figure 10 from the driver's perspective. The required time to navigate a full test laps is approximately 2 minutes. During all phases of testing, the signal immediately west of the mid-block crossing, is set to an always green phase for Innovation Drive so as to not impact driver performance when testing; the driver will be told this during the experiment. The perpendicular approaches at this intersection are to be set to always red.

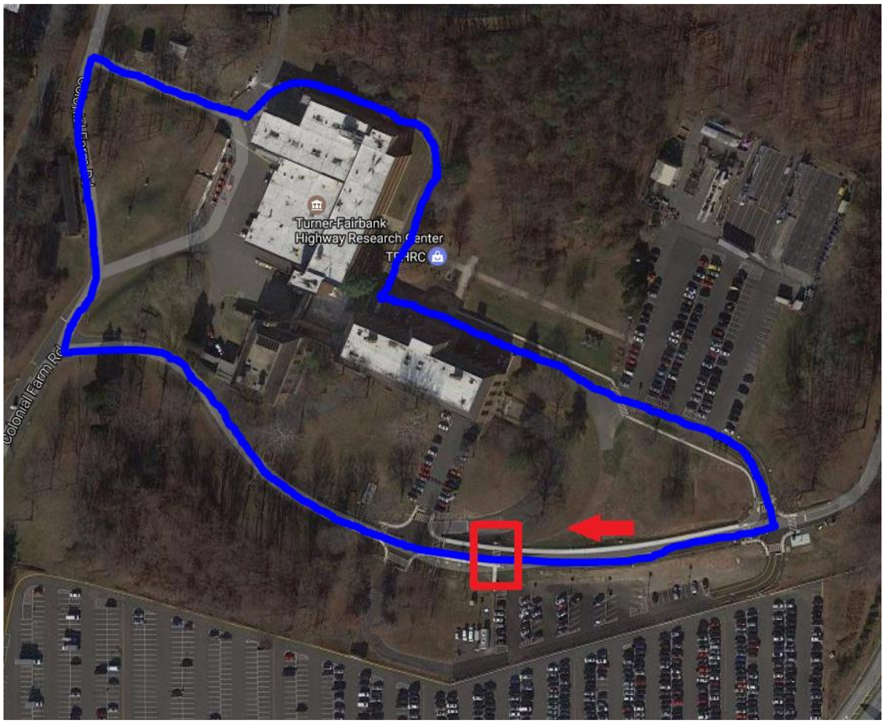

Figure 9- Designated Test Lap Around the Turner Fairbank Highway Research

Figure 10- Test Designated Mid-Block Crossing (with Pedestrian) at Approach

While the test lap encircles the entire Turner Fairbank Highway Research Center, the portion of the experiment that is analyzed is the approach to the mid-block crosswalk, seen in Figure 11.

Figure 11- Mid-Block Crosswalk Approach

3.3.3 Pedestrian Actions

Shown in the literature review, to eliminate the pedestrian variable from the experiment, a control pedestrian is used; the same pedestrian was used for every test lap for every test subject. The pedestrian wore identical clothing for all, which included brown loafers, khaki pants, a light blue button up shirt, a black watch, and eye glasses. The pedestrian crossed the street at the mid-block crosswalk if the driver stopped or slowed down and signaled for the pedestrian to cross. Seen in Table 6, the pedestrian always attempted to cross the road on the test laps, typically Lap 2 and Lap 4. The pedestrian attempted to cross the street in the same manner for both test laps, whether an advanced warning message was sent or not:

- The pedestrian would approach the crosswalk, walking at approximately 3 feet per second, arriving at the mid-block crosswalk detection pad approximately 6 seconds before the driver would reach the crosswalk.
- The pedestrian was holding the phone in their left hand and the pedestrian’s right had was in their pocket.

- The pedestrian would stop at the yellow detection pad with their right foot on the middle of the pad and the left foot behind, on the concrete.
- Once standing on the detection pad, the pedestrian would raise the phone while making eye contact with the driver.
- If the pedestrian was sending an advanced warning message, the pedestrian would send the advanced warning message at this moment, nod their head up (indicating their intention to cross) and would not make any other gestures.
- If the pedestrian was not sending an advanced warning message, the pedestrian would make eye contact with the driver nod their head up (indicating their intention to cross) and would not make any other gestures.

In an attempt to control the uncontrolled site variables in the experiment (the presence of other pedestrians and other vehicles), the pedestrian attempted to cross only when the test area was clear of other vehicles and pedestrians. Other potential issues accounted for in experimental variations included the phone GPS failing (causing the advanced warning message system to fail) and other vehicles being present when the pedestrian was attempting to cross (taking the driver's attention away from the pedestrian and allocating it to other vehicles).

- If the GPS failed, the contingency plan was for the pedestrian to approach the mid-block crosswalk (as they would for a fully functioning experiment) but to walk past the mid-block crosswalk without attempting to cross. This method was chosen because the cellular phone GPS failure could not be predicted until the pedestrian began approaching the mid-block crosswalk and would have already been seen by the driver. The pedestrian would attempt to cross the mid-block crosswalk on the next lap the driver approached the mid-block crosswalk.

- If there was another vehicle present, the contingency plan was for the pedestrian to quickly run back to the pedestrian hiding place before the driver appeared. Because the driver could be seen by the pedestrian before the driver could see the pedestrian, the pedestrian had adequate time to judge if a vehicle would be present in the test track at the same time at the same time as the driver test subject. The pedestrian would attempt to cross the mid-block crosswalk on the next lap the driver approached the mid-block crosswalk.

The 80 test subjects are recruited using an existing database of participants who are willing to participate in tests the Federal Highway Administration is running. The test subjects were a demographically diverse group across race, gender, and age. The full test design is submitted and approved by the Federal Highway Administration and IRB.

3.3.4 Human Test Subject Reactivity

Test subject reactivity is the phenomenon that occurs when individuals alter their performance or behavior due to the awareness that they are being observed [14]. To minimize the test subject's reactivity, specific steps were taken to ensure the subjects bias was minimized. Specifically, the three biases that were accounted for include:

- Hawthorne effect- subjects behave differently if they know they are being watched vs if they are not being watched.
- Pygmalion effect- subjects will perform better if the subject believes they are expected to perform better.
- Placebo effect- subjects will behave/ react differently if they believe they are put into a specific group of a study.

The Hawthorne effect was minimized by telling the subjects that the test involved driving about 4 preliminary laps around the test track and then would drive off of the TFHRC facility for the experimental testing. The actual test was occurring during these 4 preliminary laps. Because the drivers were told that the 4 laps around the TFHRC were for the drivers to learn how the vehicle drivers and it was assumed that the drivers would not feel like they are being watched so would be driving naturally.

The Pygmalion effect was minimized by telling the subjects that the test involved driving about 4 laps around the test track and then would drive off of the TFHRC facility for the experimental testing. Because the subjects are told these first four laps are to learn how to drive the vehicle, it was assumed that the drivers would not feel like they are expected to perform in any specific manner; the drivers would expect to perform in a specific manner when they are supposed to leave the facility.

The Placebo effect was minimized by telling the subjects that the vehicle was capable of receiving four types of messages, Construction Ahead Warning, Pedestrian Ahead Warning, Curve Speed Warning, and Pothole Ahead Warning. The drivers only received the Pedestrian Ahead Warning. This methodology was chosen because it was assumed that any driver in a connected vehicle would be aware that the vehicle can receive an advanced warning message, but the exact type of message is unknown.

Chapter 4: Experimental Results

4.1 Introduction

This section describes the data and results of the analysis. The data for this experiment comes from multiple sources. The results for this experiment analyzed the application functionality, the drivers' yielding reaction, the drivers' response to a questionnaire, and the drivers' kinematic results.

4.2 Data Collection

The data was collected for each individual driver. The data collected was broken into five types:

- Driver Reaction- A binary value was collected during the experiment, stating if the driver stopped or did not stop when the pedestrian attempted to cross the street at the mid-block crosswalk.
- Driver Questionnaire- A questionnaire was administered to the drivers after the experiment to evaluate if the driver found the advanced warning message useful, if the driver would like to see the technology installed on their cellular devices, and if the driver found the advanced warning message distracting or not.
- Cellular Phone Tracking Data- tracked the tablet and phone used in the experiment; the data collected includes a timestamp (ms), the user role (pedestrian or motorist), latitude (deg), longitude (deg), heading (deg), speed (m/s), location accuracy (m), and avg latency (ms)
- Cell Phone Event Data- tracked key events happening to the application including timestamp (ms), user role (pedestrian or motorist), and event type (which include Pedestrian Registration, Geofence Entered, Geofence Exited, Motorist Registration,

Pedestrian Warning Broadcast Start, Crossing Request Approved, Pedestrian Warning Broadcast Delivered, and Pedestrian Warning Broadcast End).

- Vehicle data- tracked the vehicle used in the experiment; the data collected include a timestamp, latitude (deg), longitude (deg), elevation, speed, steering wheel angle, engine revolutions per minute (RPM), acceleration, and brake position.

Note that during the experiment, 92 subjects were tested. Driver reaction was recorded for all 92 subjects. Cell phone data (tracking data and event data) was collected for 80 subjects; cell phone data was lost for 12 subjects. Vehicle data was collected for 62 subjects; of the 80 subjects who have cell phone event data, vehicle data was lost for 18 subjects.

4.3 Application Test Results

The Application Acceptance Testing was performed using the Cell Phone Event Data, which listed when the application was sent by the pedestrian, when the message was received by the central server, and when the message was delivered to the driver. It was found that the application on both the phone and tablet operated as expected. The major tests met include:

- Message sent from the phone to the central server
- Message broadcasted from the server to the vehicle
- Low latency between the message being broadcasted by the pedestrian and being received by the vehicle
- Message received in all areas of the geofence

During the Application testing, it was found that a message was successfully sent from the user to the central server, from the central server to only the vehicle in the geofence. The latency between the message being sent from the cellular device to the central server and from the central server to the driver’s tablet was tested and found to be nominal. On average the driver received the advanced warning message approximately 0.094 seconds after the pedestrian broadcasted the warning message; on average, the message took approximately 2 milliseconds to travel from the pedestrian to the server and approximately 92 milliseconds to travel from the server to the vehicle.

4.4 Driver Yielding Reaction

The initial data collected for each subject was the driver yielding reaction, whether the driver stopped for the pedestrian or did not stop for the pedestrian. The driver reaction was collected at the end of each test subject's test. Throughout the experiment, 92 participants were tested (an additional 12 subjects beyond the planned 80 were tested because12 subjects' cellular data was lost). Seen in Figure 12, on the first lap of the experiment, of the drivers who did not receive an advanced warning message (40 subjects total), 45% of the drivers stopped for the pedestrian at the crosswalk and 55% of the drivers did not stop. Seen in Figure 12, on the first lap of the experiment, of the drivers who did receive an advanced warning message (52 subjects total), 73% of the drivers stopped for the pedestrian at the crosswalk and 27% of the drivers did not stop. The first lap for the two test groups (Group A and Group B) are compared to determine if there is a statistical significant difference in the driver reaction to the presence of a pedestrian at a mid-block crosswalk. Note that second test lap is not analyzed because the driver's second exposure to the pedestrian creates uncontrolled variables that cannot be meaningfully analyzed.

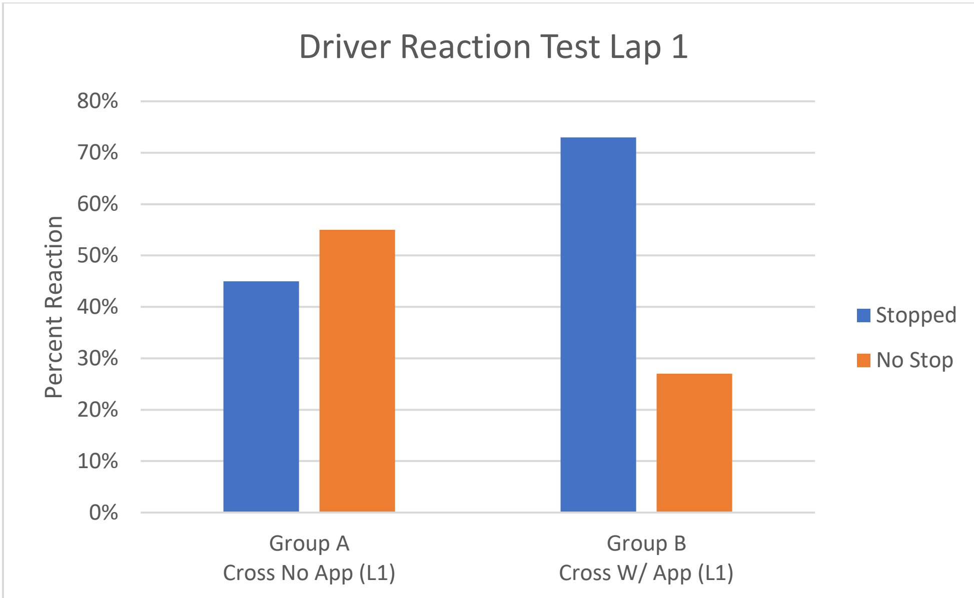

Figure 12- Test Lap 1 Driver Reaction to Pedestrian Crossing

Seen in Figure 12, the number of drivers who stopped increased when an advanced warning message was received verses when an advanced warning message was not received. When a Two Sample Proportion test for all 92 subjects was performed at a 95% confidence interval, it is seen that there is a statistically significant change in driver's stopping when an advanced warning message is received by the drivers. In Figure 13, it is assumed that the null hypothesis was that SampleP1 = SampleP2. The alternative hypothesis is assumed to be that SampleP1 < SampleP2. Seen in Figure 13, when the Proportion Z Hypothesis Test is performed at the 95% confidence interval (using MiniTab), a p-value of 0.003 was calculated indicating that there is a statistically significant difference in the driver's behavior when an advanced warning message is received compared to not receiving an advanced warning message (note that a p-value less than 0.05 suggests that the null hypothesis should be rejected).

Test and CI for Two Proportions

```
Sample   X   N  Sample p
1       18  40  0.450000
2       38  52  0.730769


Difference = p (1) - p (2)
Estimate for difference:  -0.280769
95% upper bound for difference:  -0.116522
Test for difference = 0 (vs < 0):  Z = -2.74  P-Value = 0.003

Fisher's exact test: P-Value = 0.006
```

Figure 13- Two Proportions Z Hypothesis Test for 92 Drivers' First Test Lap

Note that when the 12 subjects who cellular data was lost are removed from the data set for the Proportion Z Hypothesis Test, a p-value of 0.021 is calculated, suggesting there is a statistically significant difference in the driver's behavior when an advanced warning message is received compared to not receiving an advanced warning message, seen in Figure 14.

Test and CI for Two Proportions

```
Sample   X   N  Sample p
1       18  40  0.450000
2       27  40  0.675000


Difference = p (1) - p (2)
Estimate for difference:  -0.225
95% upper bound for difference:  -0.0472958
Test for difference = 0 (vs < 0):  Z = -2.03  P-Value = 0.021

Fisher's exact test: P-Value = 0.035
```

Figure 14- Two Proportions Z Hypothesis Test for 80 Drivers' First Test Lap

Similar results were observed for the second lap, seen in Figure 15. Seen in Figure 15, 80% of the test subjects stopped when they received an advanced warning message on their second lap and 63% of the test subjects stopped when they did not receive an advanced warning message. For the entire study, a statistical analysis is not performed for the second test lap because the driver is exposed to the pedestrian for the second time. On the driver's second exposure there are more uncontrolled variables that cannot be accounted for (discussed in the

Human Test Subject Reactivity Section) which can affect the results of the experiment, such as the driver beginning to realize they are in a test, and the driver seeing the pedestrian for their second time in a very short period of time.

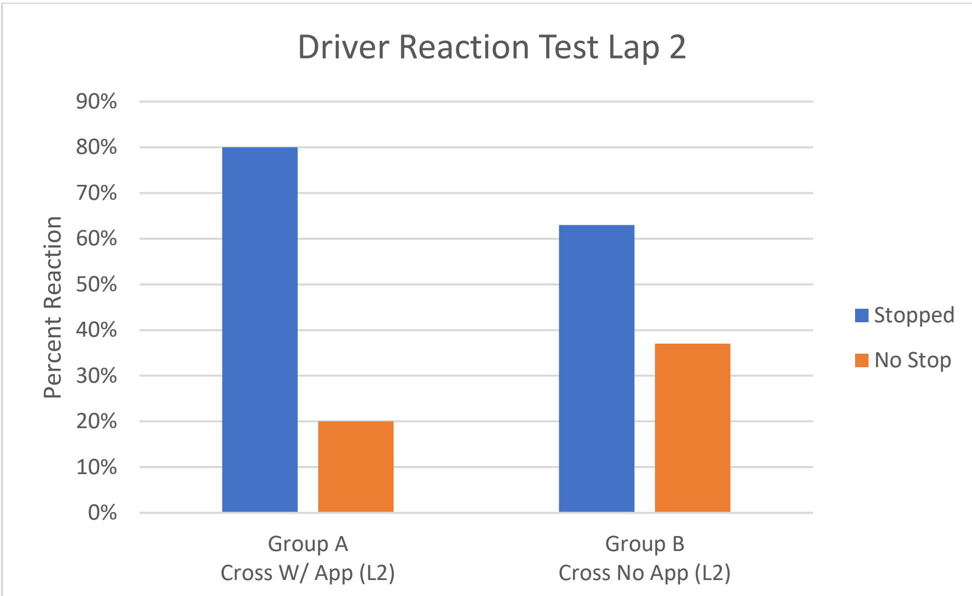

Figure 15- Test Lap 2 Driver Reaction to Pedestrian Crossing

Comparing Figure 12 and Figure 15, both test groups saw an increase in drivers stopping for the pedestrian when an advanced warning message was received compared to no advanced warning message being received (in Group A 80% of the drivers stopped when they received an advanced warning message while 45% of the drivers stopped when they did not receive an advanced warning message, in Group B 73% of the drivers stopped when they received an advanced warning message while 63% of the drivers stopped when they did not receive an advanced warning message). Analyzing the percent of drivers who stopped for the pedestrian in Group B shows that the advanced warning message increases the percentage of drivers who stop, and it is not the second lap alone increasing the percentage of drivers who stop. Note that while the drivers did stop more frequently for the pedestrian in the crosswalk when an advanced warning message was received by the driver compared to the driver not receiving an advanced warning message, the drivers are not legally required to stop for a pedestrian unless the pedestrian is in the crosswalk.

4.5 Driver Questionnaire

Each test subject was asked to fill out a questionnaire at the end of their test. The three questions asked the driver to rate if they agree or disagree with a given statements; a 5-tier rage was given for the drivers from Strongly Agree with the statement to Strongly Disagree with the statement, available in Figure 16 and Figure 17. The drivers were asked three questions:

- **Question 1**: The pedestrian warning application increased my awareness of present pedestrians at the mid-block crosswalk.
- **Question 2**: The pedestrian warning application is a feature I would like to see incorporated into GPS technologies.
- **Question 3**: I found the pedestrian warning application to be more distracting than helpful.

Note that the drivers were also asked to provide their personal feedback for the application and the experiment but the suggestions are not discussed in this paper.

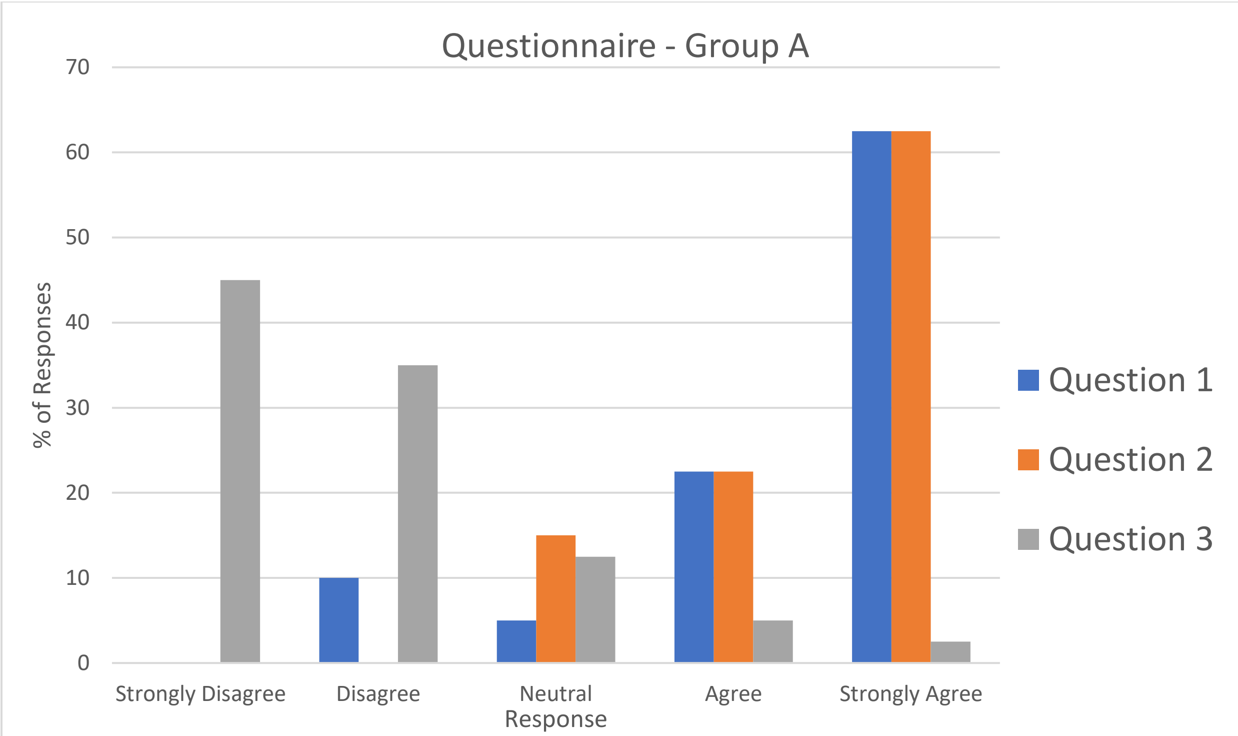

Figure 16- Questionnaire Responses Group A- First Test Lap No Warning

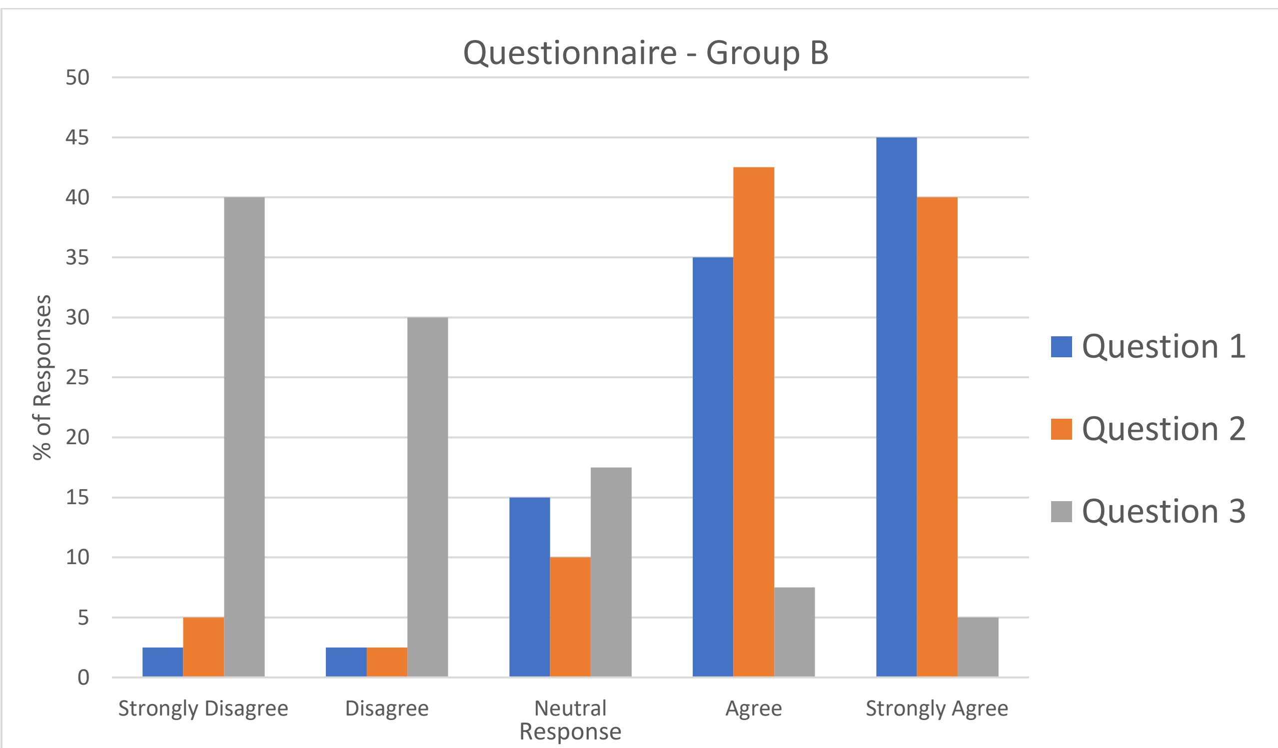

Figure 17- Questionnaire Responses Group B- First Test Lap with Warning

Seen in the Figure 16 and Figure 17 above, overall, the drivers found the advanced warning message increased their awareness of the pedestrian at the mid-block crosswalk, found that the pedestrian warning application was more helpful than distracting, and the drivers would like to see the pedestrian warning application incorporated into GPS technologies.

Seen in Figure 16, for Group A, who did not receive an advanced warning message on their first lap, 85% of the test subjects felt that the application increased their awareness of the presence of the pedestrian at the crosswalk, 5% felt that the application had a neutral effect, and 10% felt that the application did not increase their awareness of the pedestrian at the mid-block crosswalk. Seen in Figure 16, for Group A, 85% of the test subjects would like to see the technology incorporated into future GPS technologies while the remaining 15% had a neutral feeling. Seen in Figure 16, for Group A, 80% of the test subjects felt that the application was more helpful than distracting, 12.5% felt that the application had a neutral effect, and 7.5% felt that the application was more distracting than helpful.

Seen in Figure 17, for Group B, who did not receive an advanced warning message on their first lap, 80% of the test subjects felt that the application increased their awareness of the presence of the pedestrian at the crosswalk, 15% felt that the application had a neutral effect, and 5% felt that the application did not increase their awareness of the pedestrian at the mid-block crosswalk. Seen in Figure 17, for Group B, 82.5% of the test subjects would like to see the technology incorporated into future GPS technologies, 10% felt neutral about installing the technology on GPS devices, and 7.5% would not like to see the technology installed on GPS devices. Seen in Figure 17, for Group B, 70% of the test subjects felt that the application was more helpful than distracting, 17.5% felt that the application had a neutral effect, and 12.5% felt that the application was more distracting than helpful.

4.6 Kinematic Data

The kinematic data was collected using the cellular devices (cellular data) and the vehicular Controller Area Network (CAN) data. The kinematic data analyzed included the drivers' speed, acceleration, and deceleration over time and GPS location. While kinematic data was collected for all laps the naïve test subject performed, only the data collected in the test area, seen in Figure 6, was analyzed. It was decided that the test lap for each driver would begin when the vehicle enters the test area but ended when:

- If the vehicle did not stop for the pedestrian, the test ends when the vehicle passed through the entire test area.
- If the vehicle did stop for the pedestrian, the test ends when the pedestrian first steps off of the crosswalk and into the street.

The kinematic data analysis is performed only for the first test lap, the driver's first exposure to the pedestrian. A statistical analysis is not performed for the second test lap because the driver is exposed to the pedestrian for the second time. On the driver's second exposure there are more uncontrolled variables that cannot be accounted for (discussed in the Human Test Subject Reactivity Section) which can affect the results of the experiment, such as the driver beginning to realize they are in a test, and the driver seeing the pedestrian for their second time in a very short period of time.

4.6.1 Data Cleaning and Validation

Two datasets for the kinematic data are available, cellular data and CAN data. The two data sets were compared against each other to determine which dataset should be used for the analysis. Both of the datasets had to be cleaned so the start points and end points were the same so a meaningful comparative analysis could be performed. Both datasets have advantages and disadvantages, the cellular data was collected for all 80 test subjects while the CAN data was collected for only 62 subjects, but the CAN data is more accurate due to the frequency of the speed data being collected; the CAN data is collected once every 0.1 seconds (10 hertz) while the cellular data was collected once every 1 second (1 hertz). Seen in the Appendix A Speed Curve Correlation graphs, the cellular data appears to be a step function while the car data appears to be a smooth curve.

The start and end points for each test run for the cellular data and vehicle data were validated by comparing the two data sets, seen in Appendix A Speed Curve Correlation Graphs. The start and end points for the CAN data were accurately obtained because the start and end points could be seen on video. The start point for the cellular data was initially assumed to be at the middle of the up-stream intersection, pulled from the data as a certain GPS coordinate. Then, to create the Speed Curve Correlation graphs (in Appendix A), the start point (in seconds) was adjusted (left and right) to align with the CAN data. The time in the run was used for data validation since the speeds were updated at different frequencies for the cellular data and the CAN data. To determine the proper cellular phone data end point:

- For vehicles that stopped for the pedestrian:
  - Begin the experimental run when the vehicle enters the defined test area (approximately 380 feet from the crosswalk)
  - End the experimental run when:
    - If there is vehicle data, end at the time (in seconds) when the vehicle data test run ends
    - If there is no vehicle data, end when the vehicle begins accelerating
- For vehicles that did not stop for the pedestrian:

- Begin the experimental run when the vehicle enters the defined test area (approximately 370 feet from the crosswalk)
- End the experimental run when the driver leaves the defined test area

Seen in Appendix A Speed Curve Correlation graphs, the average speed curve shows that the beginning and end points of the cellular data align well with the vehicle data; the correlation between the two data sets has an R^2 value of 0.90 with a standard deviation of 0.05. The cellular data and CAN speed data points are graphed on the y-axis and the time in test lap is graphed on the x-axis. Seen in Appendix A, the average R^2 value of 0.90 shows hat the beginning and end points of the cellular data align well with the vehicle data.

4.6.2 Kinematic Data Set Chosen

After the cellular data and CAN data was aligned, the datasets are compared to determine which dataset to use in the analysis. While the speed curves are closely correlated, the speed data between the two datasets has a week correlation, seen in Appendix A Speed Data Correlation graphs. On the x-axis the speed from the CAN data is graphed and on the y-axis, the speed from the cellular data is graphed. If the two speed data sets are closely correlated, the speed trend lines would appear linear, with a high R^2 value, close to 1.0. Seen in the Speed Data Correlation Graphs in Appendix A, the average R^2 value of 0.32 with a standard deviation of 0.25. Because there is not a strong relationship between the cellular data and the vehicle data, the vehicle data is used because it is more accurate and reliable.

4.6.3 Kinematic Data Results

Seen in the Event Data results, the average message was received by the driver approximately 216 feet before the crosswalk, with a standard deviation of 26 feet. Assuming an average driving speed of 24 mph (the approximate 95th percentile speed for the drivers without receiving any advanced warning message when 216 feet away from the crosswalk), the warning was sent 6.1 seconds before the driver approached the crosswalk with a standard deviation of 0.7 seconds.

All drivers in the experiment drove through the test course with similar driving behavior when the pedestrian is not present, seen in Figure 18. Because all drivers traveled in a similar manner without an advance warning (no pedestrian present), and the scope of the experiment is to compare the drivers' reaction to an advanced warning message and drivers' reaction without seeing an advanced warning message, only the speed and acceleration after the message was sent is analyzed.

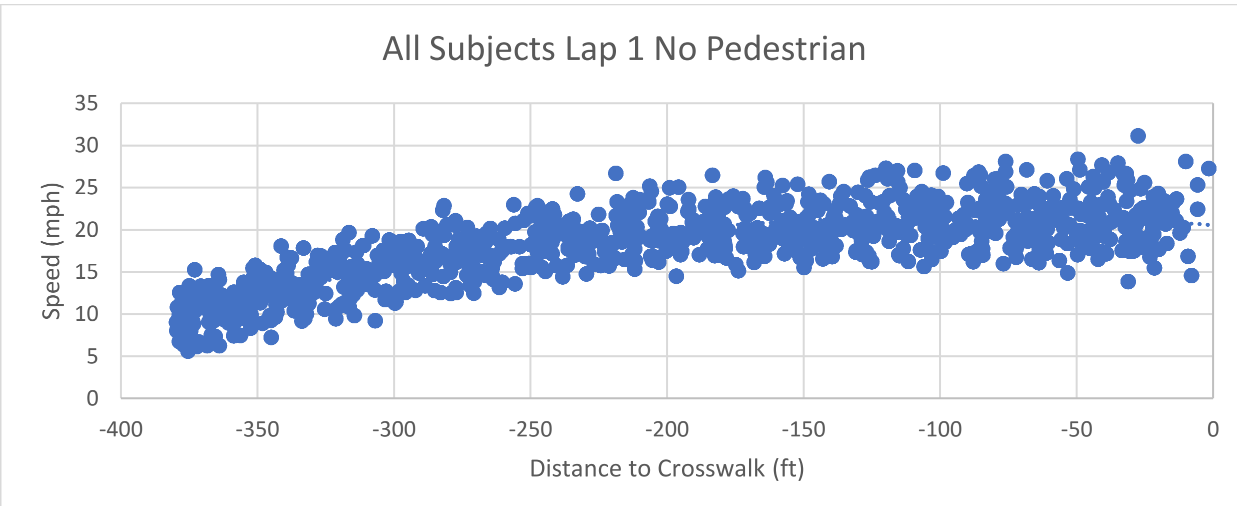

Figure 18- Test Lap 1 No Pedestrian Present

The drivers who receive an advanced warning message approached the crosswalk at a slower speed than the drivers who did not receive an advanced warning message. Noted above, the average message was sent approximately 216 feet (6.1 seconds) before the end of the experimental run. Seen in Figure 19, before a message is sent, between 380 feet and 216 feet before the crosswalk, the drivers who receive an advanced warning and who do not receive an advanced warning display similar driving behavior. However, seen in Figure 19, when the drivers are approximately 216 feet away from the crosswalk, the drivers who receive an advanced warning and who do not receive an advanced warning begin to display differing driving behaviors. Seen in Figure 19 (and verified in the results section), approximately 120 feet away from the crosswalk the biggest difference of driving behavior is apparent. More driver who received the advanced warning are moving at a slower speed and stopping than the drivers who did not receive and advanced warning.

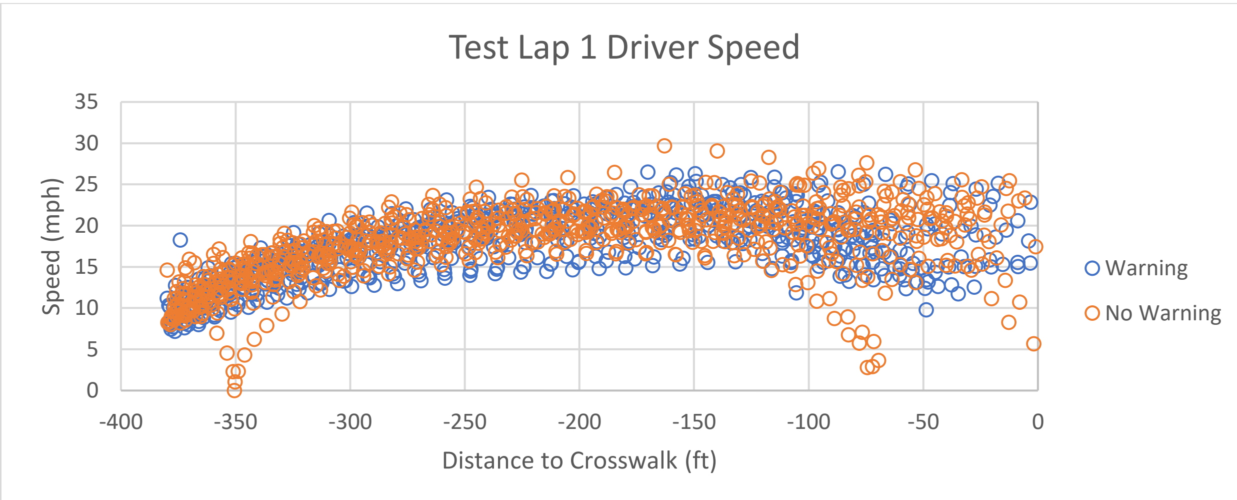

Figure 19- Test Lap 1 All Drivers Speed

After the message was received by the drivers, approximately 216 feet from the end of the crosswalk, with the drivers traveling with a 95th percentile speed of 24 miles per hour, the drivers have 6.1 seconds to react to the advanced warning message before they reach the mid-block crosswalk. The drivers who did not receive an advanced warning message traveled at an average speed of 19.90 mph with a standard deviation of 4.06 mph and stopped approximately 29 feet away from the crosswalk. The drivers who received the advanced warning message traveled at a lower average speed of 19.56 mph with a standard deviation of 3.40 mph and stopped approximately 39 feet from the crosswalk. Seen in Appendix B, this difference in speed and standard deviation represents a statistically significant difference in driving speed (because the p-value is less than 0.05) when approaching the mid-block crosswalk.

To determine where the statistical significance in speed appears, the speed compared to the distance from the crosswalk was grouped into bins of average speed every 20 feet, seen in Figure 20. The standard error bars are shown for each bin, around each point, to represent the average variance in speed every 20 feet. For each of the 20 bins, a Two-Sample T test was run to determine if there was a statistically significant difference in the driver's speed for each of the 20 foot bins, shown in Table 7, with calculations in Appendix B.

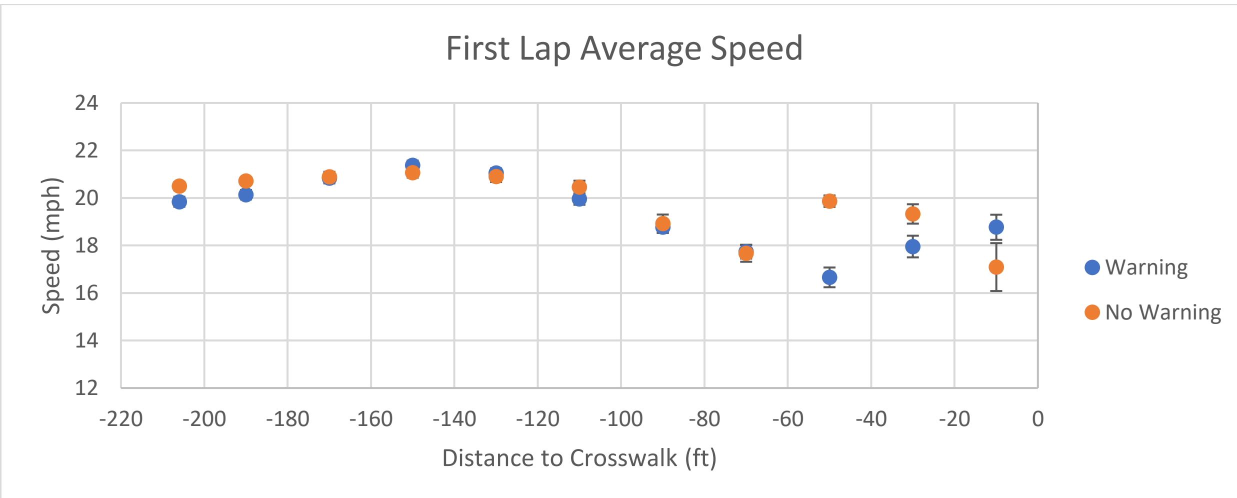

Figure 20- Driver Speed When First Exposed to Pedestrian

Seen in Table 7 and Appendix B, there is a statistically significant difference for the drivers who receive and advanced warning message and the drivers who do not receive an advanced warning message when the message is first received (when between 216 feet and 180 feet away from the crosswalk) and then when approaching the crosswalk, 100 feet to 80 feet away from the crosswalk, and 60 to 20 feet away from the crosswalk. Seen in Figure 20, both groups of drivers slowly increased their speed between 216 and 160 feet away from the crosswalk. Between 160 feet and 40 feet away from the crosswalk, the drivers who received the advance warning consistently lowered their speed at approximately 1 mph per 20 feet and then consistently increased their speed at a rate of 0.8 mph per 20 feet until the driver was 0 feet away from the crosswalk. The drivers who did not receive the advance warning decreased their speed when 160 feet away from the crosswalk until the drivers were 806feet away from the crosswalk at a rate of approximately 0.8 mph. Between 60 feet away from the crosswalk the drivers increase their speed and then decrease their speed when 40 feet away from the crosswalk until the driver is 0 feet away from the crosswalk.

Table 7- Group A (No Warning) and Group B (With Warning) Average Speed (mph)

Bin	No Warning Speed (StDev)	Warning Speed (StDev)	P-value	Statistical Difference
From -216 to -200	20.5 (2.05)	19.84 (2.55)	0.019	Yes
From -200 to -180	20.71 (2.12)	20.14 (2.56)	0.025	Yes
From -180 to -160	20.89 (2.48)	20.83 (2.84)	0.838	No
From -160 to -140	21.06 (2.53)	21.38 (2.61)	0.257	No
From -140 to -120	20.9 (2.76)	21.05 (2.5)	0.625	No
From -120 to -100	20.45 (3.43)	19.95 (3.11)	0.151	No
From -100 to -80	18.92 (4.87)	18.78 (3.09)	0.007	Yes
From -80 to -60	17.67 (6.56)	17.74 (3.38)	0.901	No
From -60 to -40	19.87 (3.29)	16.66 (4.24)	0.000	Yes
From -40 to -20	19.33 (3.76)	17.96 (4.34)	0.025	Yes
From -20 to 0	17.09 (6.51)	18.77 (3.56)	0.076	No

To determine where the statistical significance in acceleration appears, the acceleration is compared to the distance from the crosswalk was grouped into bins of average acceleration every 20 feet, seen in Figure 21. The standard error bars are shown for each bin, around each point, to represent the average variance in speed every 20 feet. For each of the 21 bins, a Two-Sample T test was run to determine if there was a statistically significant difference in the driver's acceleration for each of the 20-foot bins, shown in Table 8, with calculations in Appendix C.

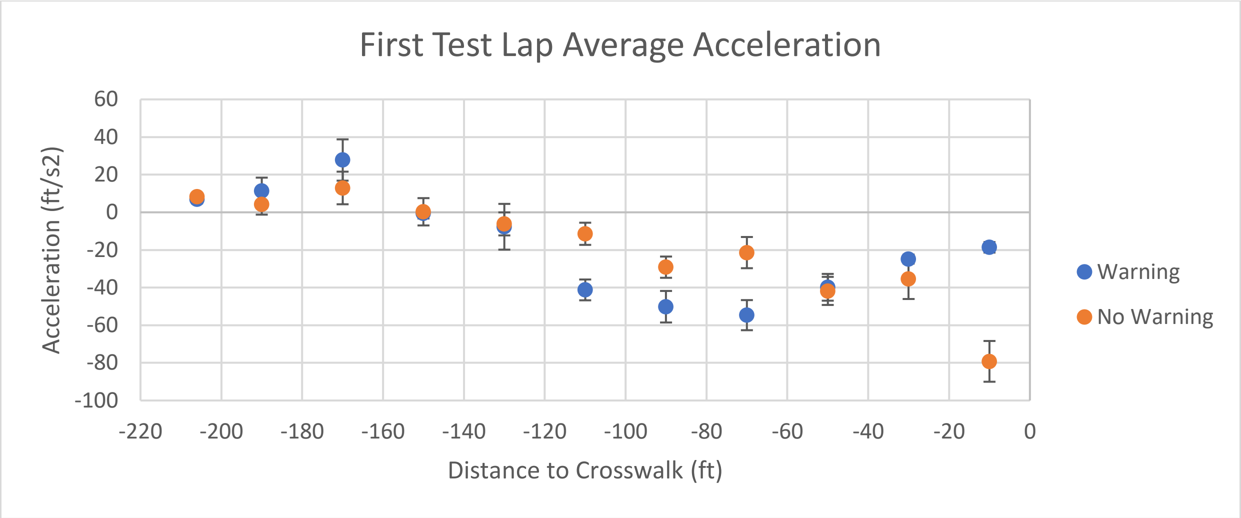

Figure 21- Driver Acceleration When First Exposed to Pedestrian

When the acceleration of the drivers is analyzed, it can be seen that when the drivers who receive an advanced warning begin decelerating further away from the pedestrian compared to the drivers who do not receive an advance warning, seen in Figure 21. When the drivers in both groups are between 216 feet from the crosswalk and 160 feet from the crosswalk, the drivers are accelerating. Between 160 feet and 140 feet from the crosswalk, both groups are accelerating at a rate close to zero, the drivers who receive an advance warning are decelerating at a rate of 0.53 ft/s^2 and the drivers who do not receive an advance warning are accelerating at a rate of 0.28 ft/s^2. Between 140 feet and 120 feet from the crosswalk, both groups are decelerating at similar rates, -7.68 ft/s^2 for the drivers who receive an advance warning message and -6.61 ft/s^2 for the drivers who did not receive an advance warning message. When the drivers are between 120 and 60 feet away from the crosswalk, the drivers who receive an advanced warning message, are decelerating at a statistically significant lower value compared to the divers who did not receive an advance warning, seen in Figure 21. Between 60 and 20 feet from the crosswalk there is no statistical difference in acceleration rates as the drivers who did not receive an advance warning begin decelerating more urgently, matching the drivers who received an advance warning. Seen in Figure 21, the deceleration of the drivers who receive no warning is rapid, -79.21 ft/s^2 when 20 to 0 feet away from the crosswalk, creating a statistically different deceleration rate compared to the drivers who receive an advance warning (-18.6 ft/s^2).

Table 8- Group A (No Warning) and Group B (With Warning) Average Acceleration (ft/s^2)

Bin	No Warning Acceleration (StDev)	Warning Acceleration (StDev)	P-value	Statistical Difference
From -216 to -200	8.32 (54.64)	6.91 (22.43)	0.778	No
From -200 to -180	4.17 (53.68)	11.3 (67.26)	0.279	No
From -180 to -160	12.94 (99.63)	27.8 (127.53)	0.239	No
From -160 to -140	0.28 (105.59)	-0.53 (110.07)	0.946	No
From -140 to -120	-6.16 (85.77)	-7.68 (147.45)	0.908	No
From -120 to -100	-11.41 (88.17)	-41.23 (90.2)	0.002	Yes
From -100 to -80	-29.16 (61.47)	-50.17 (85.99)	0.008	Yes
From -80 to -60	-21.41 (99.26)	-54.65 (89.11)	0.001	Yes
From -60 to -40	-41.77 (98.85)	-39.84 (86.59)	0.867	No
From -40 to -20	-35.39 (113.63)	-24.86 (69.06)	0.426	No
From -20 to 0	-79.21 (77.54)	-18.6 (90.4)	0.000	Yes

Note that as both groups progress through the test lap, the sample size decreases because of the way the experimental test area is defined. Stated above, the experiment ends when the drivers either pass the mid-block crosswalk if the driver did not yield for the pedestrian, or when the driver stops for the pedestrian, which varies each subject. When the analysis was performed for the entire 216 feet for each subject, it was observed that the drivers accelerating after the pedestrian crossed significantly changed the results of the analysis. Seen in Table 9, the decision to end the test when the pedestrian completely crosses was made because, after the drivers watch the pedestrian cross, the driver’s reaction to an advanced warning message in the presence of a pedestrian are no longer being analyzed since the pedestrian is gone. Breaking the analysis into bins of 20 feet accounts for the difference in sample size as the experiment progresses because the statistical analysis is a function of sample size.

Table 9- Percent of Drivers in Test Run

Bin	Percent of Drivers in Experiment	
	No Warning	Warning
140 to 120	100.00%	100.00%
120 to 100	100.00%	96.30%
100 to 80	93.55%	92.59%
80 to 60	80.65%	66.67%
60 to 40	67.74%	51.85%
40 to 20	48.39%	37.04%
20 to 0	0.00%	0.00%

Chapter 5: Results Discussion

5.1 Introduction

Combining all of the results of this study, it can be seen that there is a statistically significant difference in the percentage of drivers yielding to pedestrians at mid-block crosswalks, the driver's approach speed to a mid-block crosswalk, and driver's acceleration when approaching the mid-block crosswalk. Looking at the speed analysis and the acceleration analysis together shows the influence the advanced warning message has on driving behavior.

Only the first test lap is analyzed for each of the test subjects. During the second test lap, there are uncontrolled variables that cannot be accounted for in the experiment and affect the results of the research. This suspicion is confirmed when comparing the driver's first and second lap yield reaction. Seen in these two figures, the percentage of drivers who yielded for the pedestrian increased for both the drivers who did not receive an advanced warning and the drivers who did receive and advanced warning.

5.2 Application Test Results

The application operated nearly perfectly with minimal GPS inaccuracies and low message latency. The message latency from the time the message was sent from the pedestrian to the time the message was received by the driver was nominal, less than 0.1 seconds.

5.3 Driver Yielding Reaction Results.

Seen in the results, the drivers who receive an advance warning yield for the pedestrian trying to cross the mid-block crosswalk significantly more than the drivers who did not receive an advance warning. 73% of the drivers who receive an advance warning message yield for the pedestrian while 45% of the drivers who did not receive an advance warning message yield for the pedestrian. The driver yielding reaction aligns well with the number of participants left in the experiment, seen in Table 9 in the kinematic results section. The average stopping distance for drivers who did not receive an advance warning is 29 feet from the crosswalk while the stopping distance for drivers who did receive an advance warning is 39 feet from the crosswalk, both distances wall in the 40 foot to 20 foot bin. Seen in Table 9, nearly all of the drivers who did not receive an advance warning message who yielded for the pedestrian occurred before the 20 foot to 0 foot bin, and approximately 10% of the drivers who did receive an advance warning message who yielded for the pedestrian occurred in the 20 foot to 0 foot bin.

5.4 Questionnaire Results

The questionnaire shows that application is considered to be successful because the driver finds the application helpful without being distracting. Because the drivers would like to see the technology installed on existing GPS technologies, it can be inferred that the drivers would pay attention to the advanced warning message.

While the questionnaire responses followed a similar overall trend, it can be inferred that the differences in the questionnaire responses come from the order each group received the advanced warning message. Because Group A did not receive the advanced warning message on the first lap and did on the second, it can be assumed the drivers felt more aware of the pedestrian's desire to cross because of the application, seen in the Driver Reaction results, only 45% of the drivers stopped on the first test lap compared to 80% on the second test lap. Because the drivers in Group B received the advance warning message on the first lap, it can be inferred that the drivers felt that the driver would have noticed and yielded for the pedestrian without the warning [15].

Seen in the questionnaire, the overall, drivers felt:

- The pedestrian warning application increased their awareness of present pedestrians at the mid-block crosswalk.
- The pedestrian warning application is a feature they would like to see incorporated into GPS technologies.

- The subject found the pedestrian warning application to be more helpful than distracting.

5.5 Kinematic Results

The kinematic results, show that the drivers who received an advanced warning message, compared to the drivers who did not receive an advanced warning message, approached the crosswalk in a more predictable pattern, potentially making mid-block crossings safer for the drivers and pedestrians.

Analyzing the speed shows that the advance warning messages have potential to make mid-block crossings safer. Analyzing the speed of the drivers who do not receive an advanced warning, it can be seen that the drivers speed and acceleration fluctuates, showing the difficulties of the vehicle to pedestrian communication. Comparatively, the group that did receive the advanced warning decelerated for a longer period of time in a more tractable rate, and approached the crosswalk with a slower speed with smaller standard deviation. Seen in the results, the drivers who do not receive an advanced warning message slow down when 160 to 60 feet away from the crosswalk; when these drivers are 60 to 40 feet away from the crosswalk, then decrease their speed 40 to 0 feet away from the crosswalk, with a rapid deceleration in the final 20 feet. The fluctuation in speed shows the uncertainty of the drivers trying to decide if the pedestrian intends to cross because the drivers are decelerating, then accelerating, then decelerating, and finally stopping rapidly between 20 and 0 feet away from the mid-block crosswalk. Analyzing the speed of the drivers who receive an advanced warning show that when the drivers are 160 to 40 feet away from the crosswalk, the drivers are slowing down their speed and slowly increasing their speed when 40 feet to 0 feet away from the crosswalk. The advance warning message has potential to make driving behavior becomes more tractable, which makes the approach to the crosswalk more predictable for the pedestrian, potential making mid-block crossings safer for the drivers and pedestrians.

Analyzing the acceleration, shows that the advance warning messages have potential to make mid-block crossings safer.

Seen in the results, there is a statistically significant difference for the drivers who receive an advanced warning message and the drivers who do not receive an advanced warning message when the driver begins approaching the crosswalk, when the drivers are 120 feet to 60 feet away from the crosswalk, and 20 to 0 feet away from the crosswalk. When the drivers are 120 feet to 60 feet away from the crosswalk, the drivers who receive an advance warning are decelerating at a faster rate (-48 ft/s^2) compared to the drivers who did not receive an advance warning (-26 ft/s^2). This statistically different deceleration shows that drivers who receive an advance warning message are aware of the pedestrian's intention to cross and are slowing down for the pedestrian at a rate which will allow the driver to stop for the pedestrian. When the drivers are between 20 feet and 0 feet from the crosswalk, the drivers who did not receive the advance warning are decelerating at a faster rate (-79 ft/s^2) compared to the drivers who did receive an advance warning message (-19 ft/s^2). The high deceleration rate difference shows that the drivers who did not receive an advance warning are quickly decelerating for the pedestrian, near at the crosswalk. This rapid deceleration shows the difficulties the pedestrian and driver have communicating because the drivers were not able to interpret the pedestrian's intention to cross the mid-block crosswalk until after the drivers who received the advance warning message did.

Note that the first time the acceleration becomes negative for the group that received the advance warning if at 160 feet (approximately 1.6 seconds after the advance warning message was sent, the average driver perception-reaction time) and the first time the group that did not receive an advance warning is at 140 feet. Because this was the first instance of deceleration for both groups, the values are relatively small so there is no statistical difference. It is anticipated that there is no statistical significant difference in speed and acceleration until 120 feet before the crosswalk because the drivers who receive the advance warning message are looking for the pedestrian and ensuring the pedestrian's non-verbal communication alight with the advance warning message, and the drivers who did not receive an advance message are trying and non-verbally communicate with the pedestrian.

Seen in the results, the drivers who receive an advanced warning approach the mid-block crosswalk at a slower speed, with smoother and longer deceleration behaviors, compared to the drivers who did not receive an advanced warning message. The driving behavior of the drivers who receive an advance warning can make the crosswalks safer for pedestrians and drivers because the drivers are aware of the pedestrian's presence and desire to cross and the pedestrians are able to more accurately predict the driver's actions.

5.6 Data Trends

Overall, the driver yield reaction when receiving the advanced warning compared to the driver yield reaction when not receiving the advanced warning shows the overall potential safety benefits. As more drivers stop, the average approach speed in the test track is decreasing, confirmed in the kinematic data. The kinematic data also shows that the drivers begin slowing down sooner when an advanced warning message is received compared to drivers who do not receive an advanced warning message. Noted in the questionnaire, the safety benefits can be seen because the majority of the drivers found the application useful for increasing their awareness of the pedestrian and the majority of the drivers did not find the warning message distracting. The slower approach speed and smoother acceleration patterns can make the communication between the driver and pedestrian easier by creating a more predictable crossing scenario for both the driver and the pedestrian because the drivers are aware of the pedestrian's presence and desire to cross and the pedestrians are able to more accurately predict the driver's actions.

Chapter 6: Conclusion

26.1 Conclusion and Discussion

The drivers who received an advanced warning message stopped more frequently for the pedestrian, approached the crosswalk at a slower speed, and with a smoother deceleration pattern compared to drivers who did not receive an advanced warning message. Through the questionnaire, it was also shown that overall, the drivers found the advanced warning message helpful because it increased their awareness of the pedestrian and was not distracting. Through the questionnaire, it was also shown that, in general, the drivers do not find the advanced warning message distracting.

When analyzing the driver's yield reaction alone, it can be seen that the advanced warning message significantly increases diver yielding percentage (from 45% yielding without an advance warning to 73% with an advance warning). Adding in the analysis of the driver's speed (which decreases after advance warning message is received to 19.3 mph with the advance warning message from 19.7 mph without the advance warning message) and acceleration (the drivers who receive the advance warning message begin decelerating when 160 feet away from the crosswalk and the drivers who do not receive the advance warning begin decelerating then 140 feet away from the crosswalk), it can be seen that the advanced warning messages create a safer crossing environment for the driver and pedestrian by making the crossing more predictable for the driver and pedestrian. The drivers who receive the advanced warning message are aware of the pedestrian's presence and intention to cross while the drivers who did not receive the advanced warning message have to find the pedestrian and interpret the pedestrian's intention to cross from the pedestrian's body language. With a more tractable driving behavior, the pedestrians can predict the driver's actions and cross the street when they feel it is safe (the drivers who receive the advance warning continuously reduce their speed from 160 feet away from the crosswalk until 40 feet away from the crosswalk then increase their average speed until they reach the crosswalk while the group that did not receive the advance warning decrease their speed when they are 160 feet away from the crosswalk until they are 60 feet away from the crosswalk then the average speed increases until they are 40 feet away from the crosswalk then the average speed decreases until they reach the crosswalk). Because the drivers who received an advanced warning message were approaching the crosswalk at a slower speed with a more predictable driving behavior, the advanced warning message can make mid-block crosswalks safer for drivers and pedestrians.

6.2 Future Research

Positive initial findings of the effectiveness of advanced warning message at mid-block crossings warrants future research be performed with this concept. This research was performed on a relatively very small scale in a very controlled environment. Before the application can be deployed in a real-world setting, more testing needs to be performed:

Noted in the literature review, the greatest potential danger for pedestrians is in the evening. While this study was conducted during the day for experimental control, the experiment should be run in the evening.

Another decision made for this study was to have the pedestrian be a control; the effects of the pedestrian using the application were not analyzed. The pedestrian should be studied to understand the effects of the advanced warning broadcasting on a pedestrian.

This experiment was performed having one pedestrian send a warning to one driver. Before the system can be deployed, system performance needs to be studied with multiple pedestrians broadcasting messages and multiple drivers receiving messages.

The system was tested in a relatively open area. The system should be tested in an urban area where multiple mid-block crosswalks exist. The performance of the system (including cellular GPS accuracy in the urban canyon and performance of the system with multiple mid-block crosswalks) and the effects of potentially multiple warning being broadcasted to a driver should be studied.

The system should also be tested in inclement weather to understand the potential impacts the advanced warning messages have on the drivers and pedestrians who may have limited visibility.

The application can also be expanded to incorporate cyclists, another vulnerable road user segment.

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Appendix A: Data Validation and Comparison

Subject 52

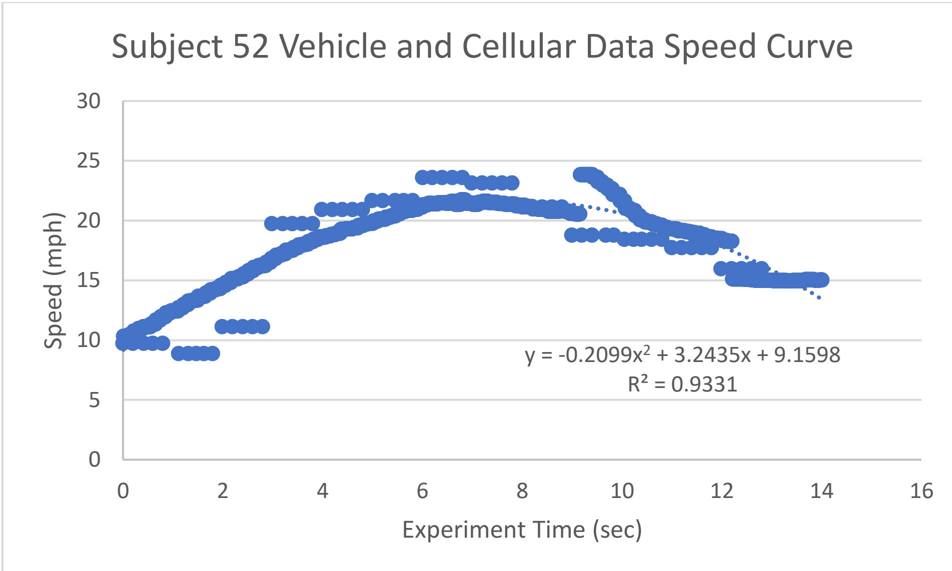


Figure 22- Speed Curve Correlation Subject 52

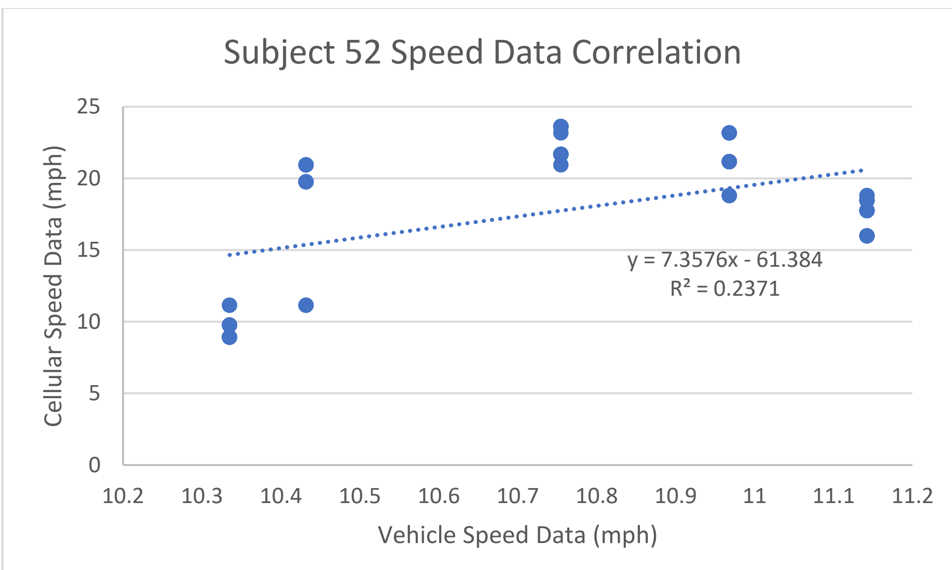
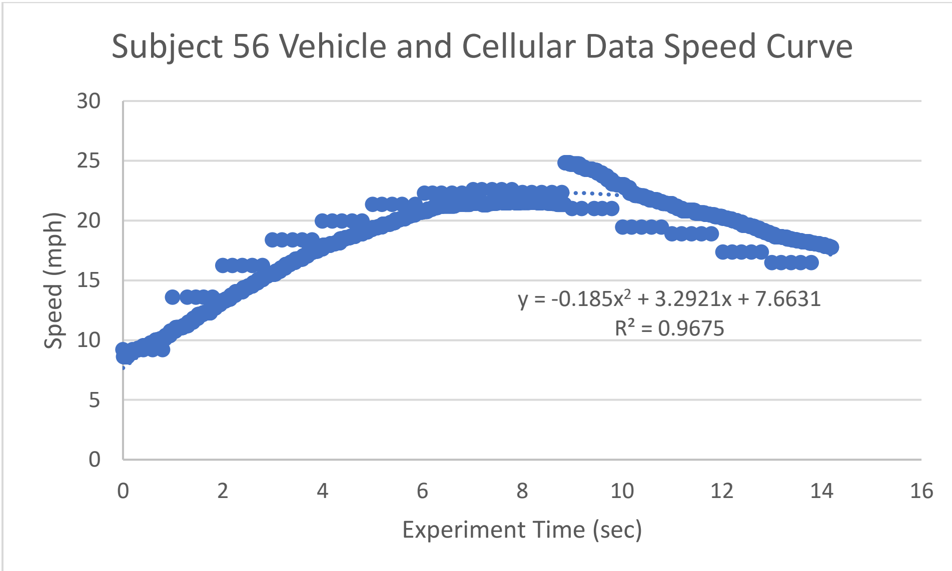


Figure 23- Speed Data Correlation Subject 52

Subject 56



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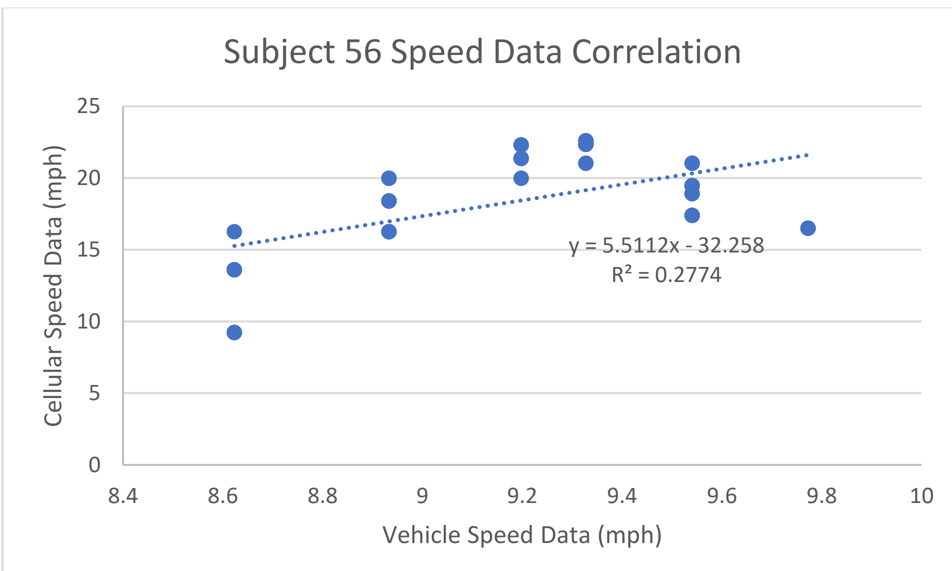
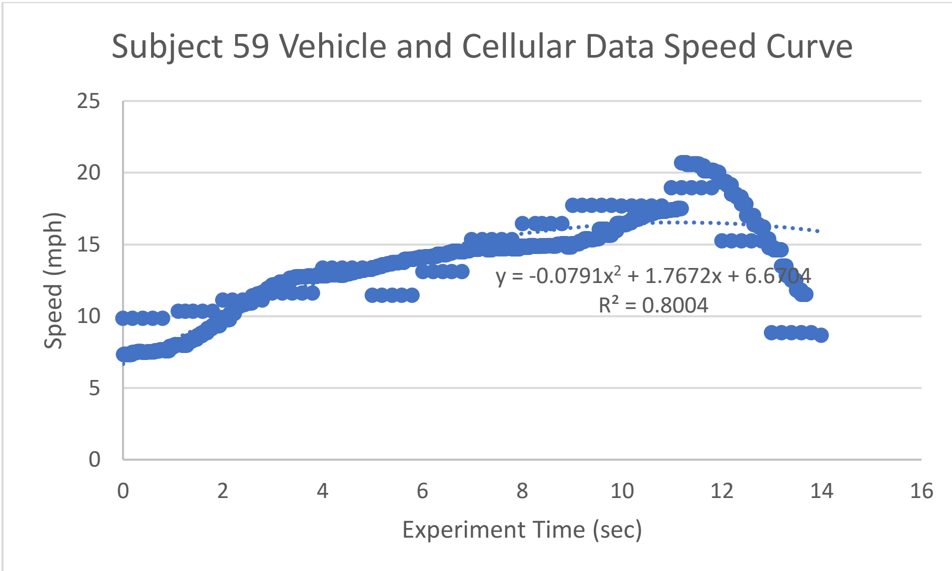


Figure 25- Speed Data Correlation Subject 56

Subject 59



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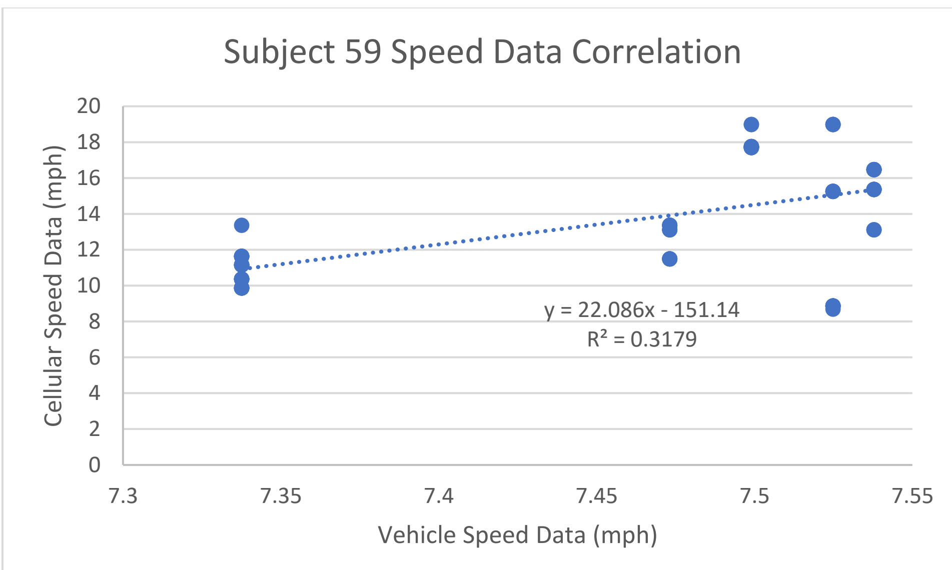
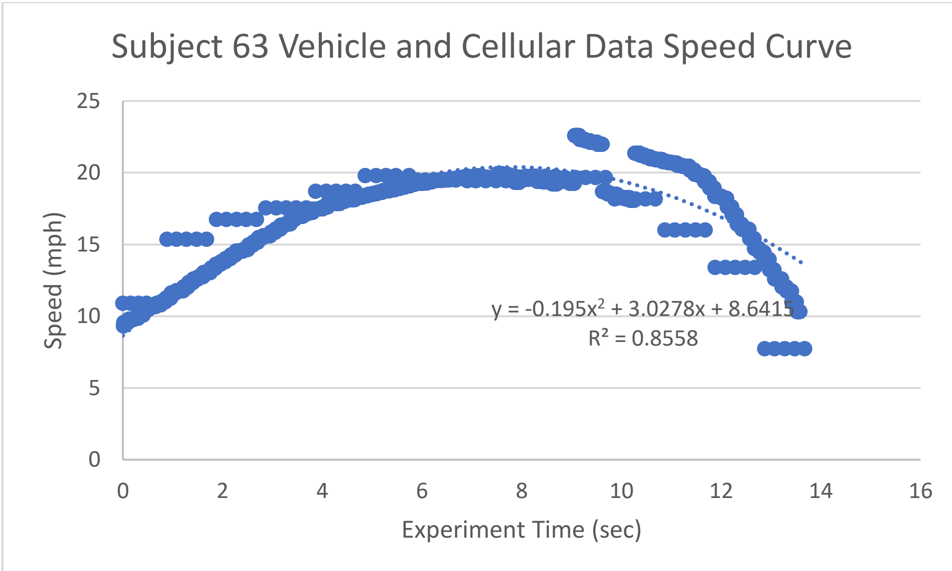


Figure 27- Speed Data Correlation Subject 59

Subject 63



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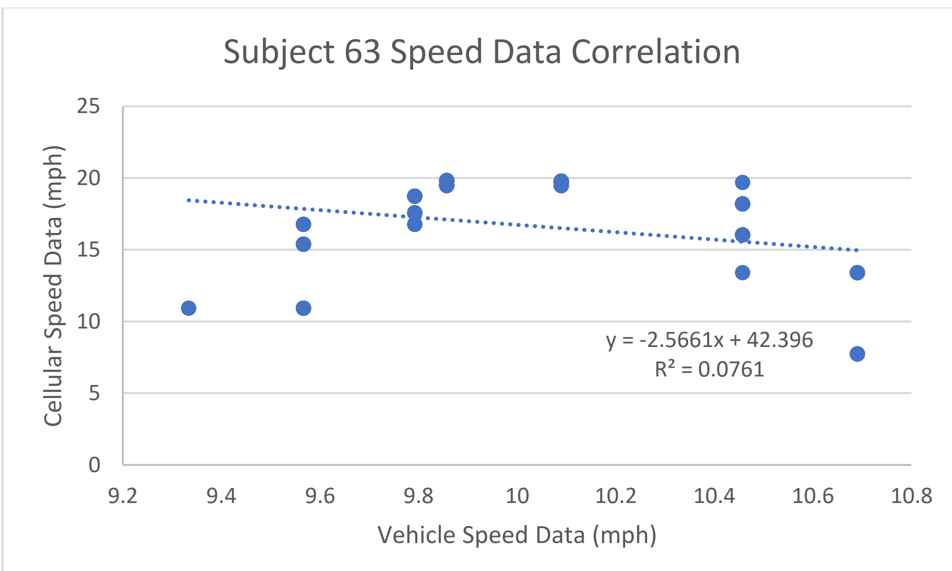

Figure 29- Speed Data Correlation Subject 63

Subject 69

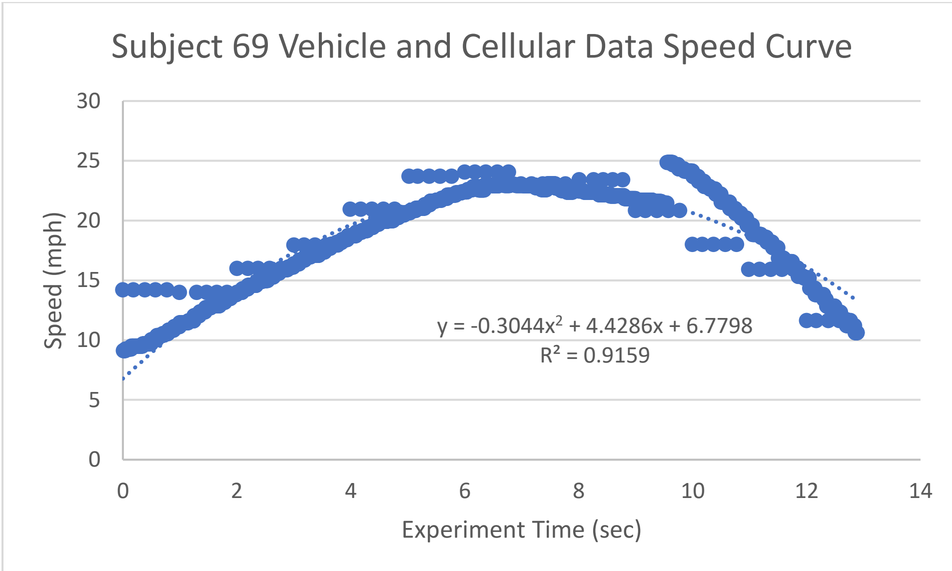

Figure 30- Speed Curve Correlation Subject 69

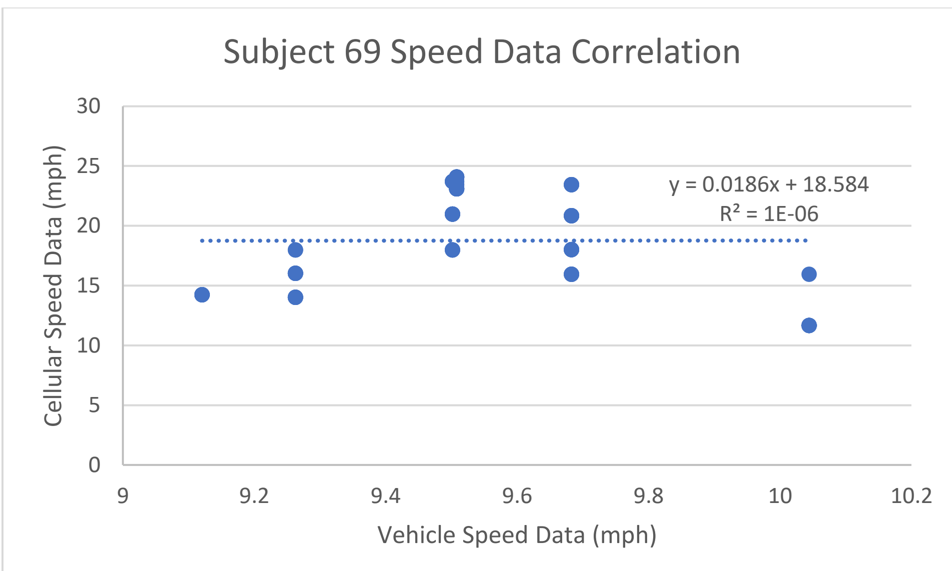

Figure 31- Speed Data Correlation Subject 69

Subject 72

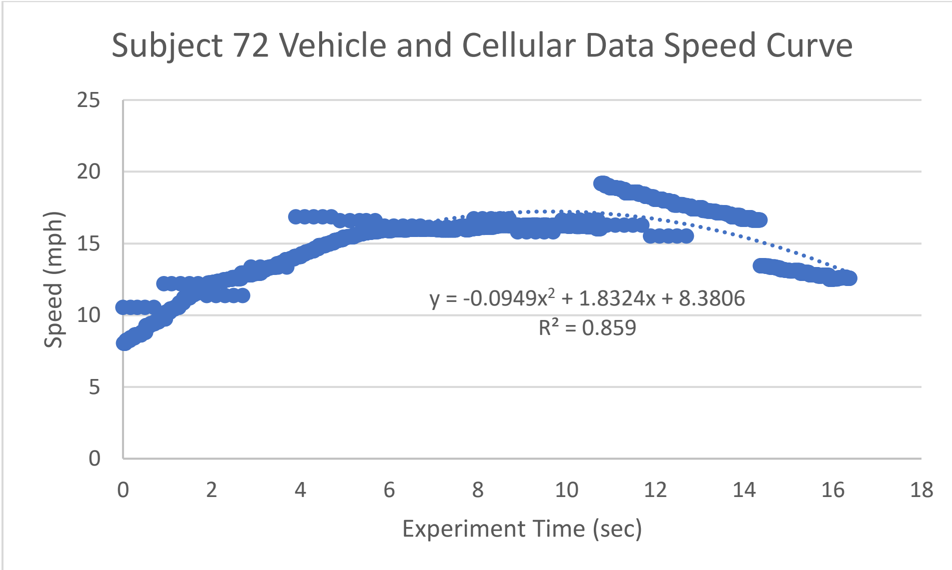

Figure 32- Speed Curve Correlation Subject 72

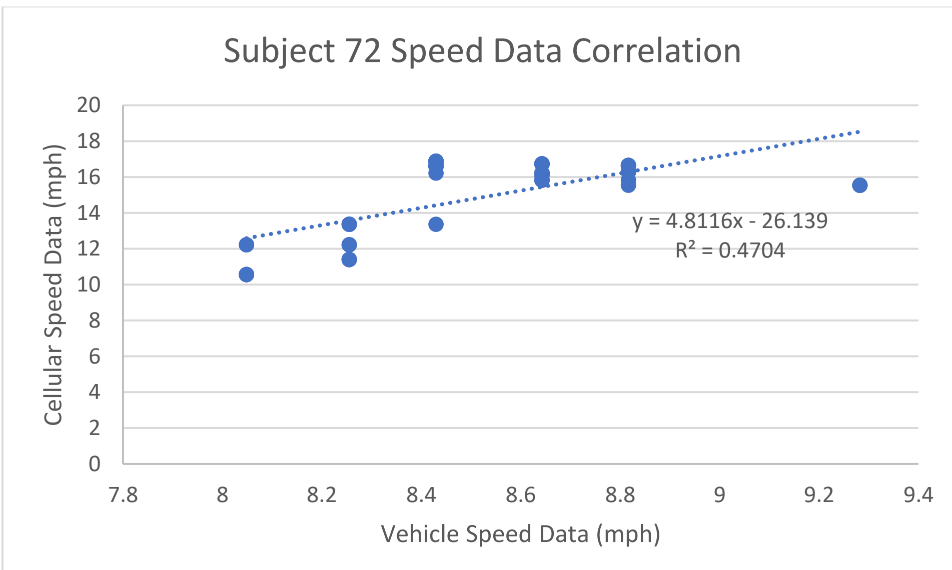

Figure 33- Speed Data Correlation Subject 72

Subject 82

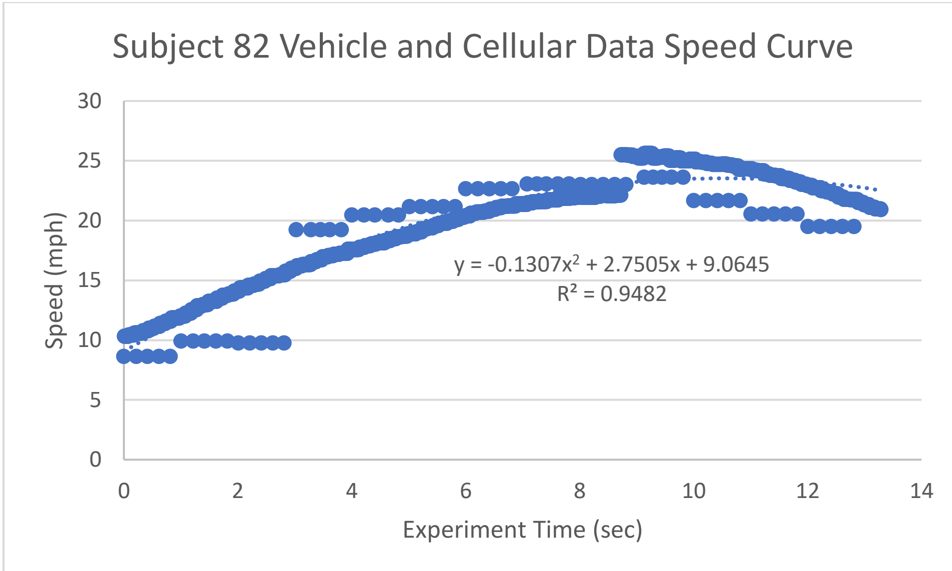

Figure 34- Speed Curve Correlation Subject 82

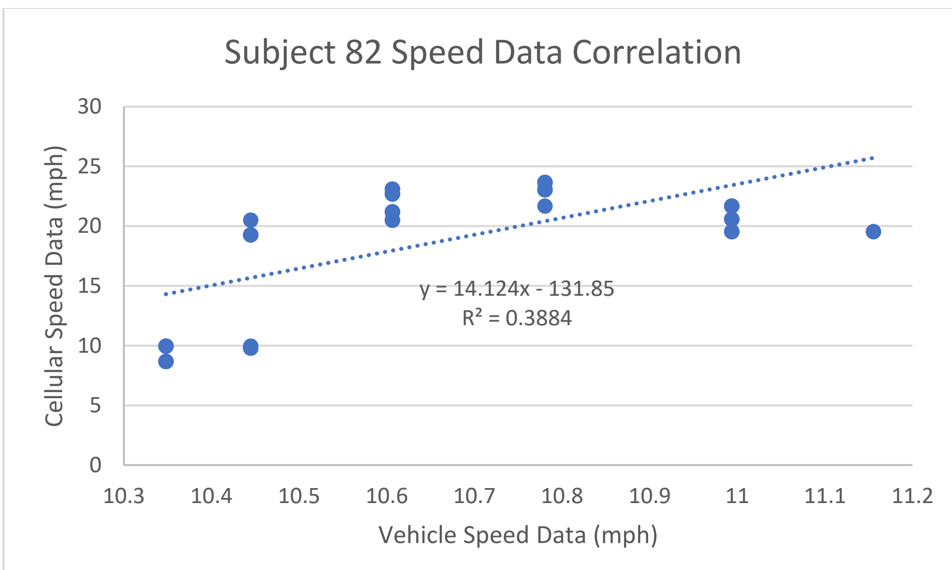

Figure 35- Speed Data Correlation Subject 82

Subject 84

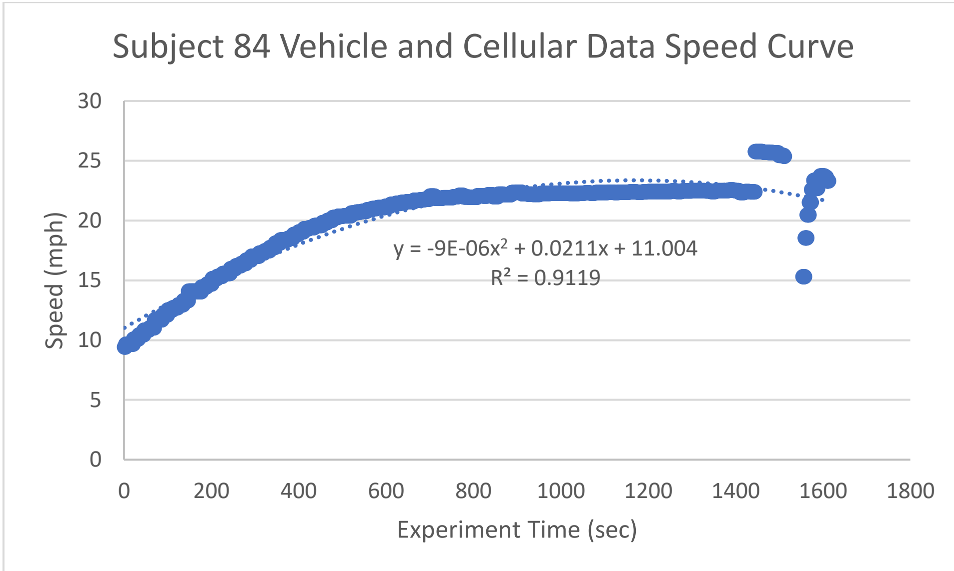

Figure 36- Speed Curve Correlation Subject 84

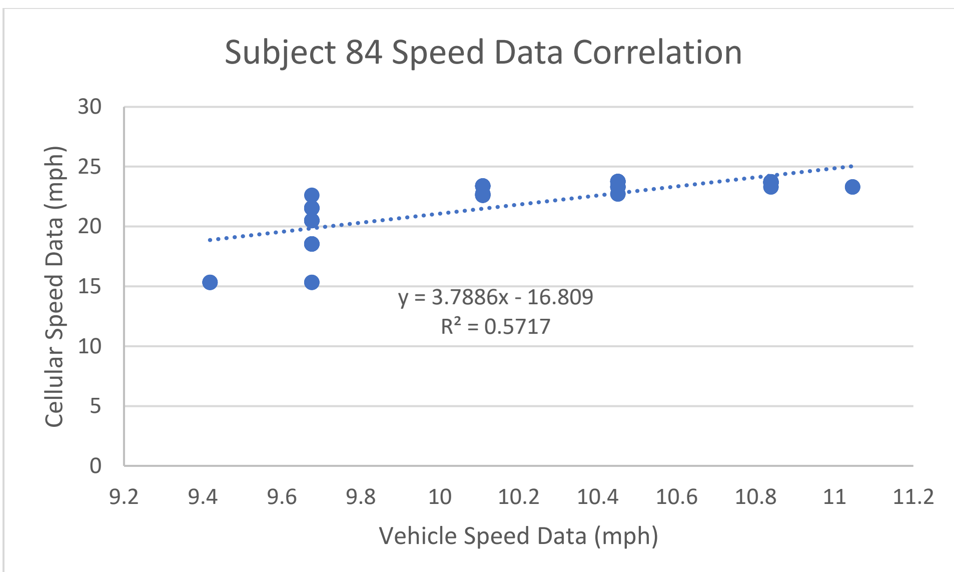

Figure 37- Speed Data Correlation Subject 84

Subject 87

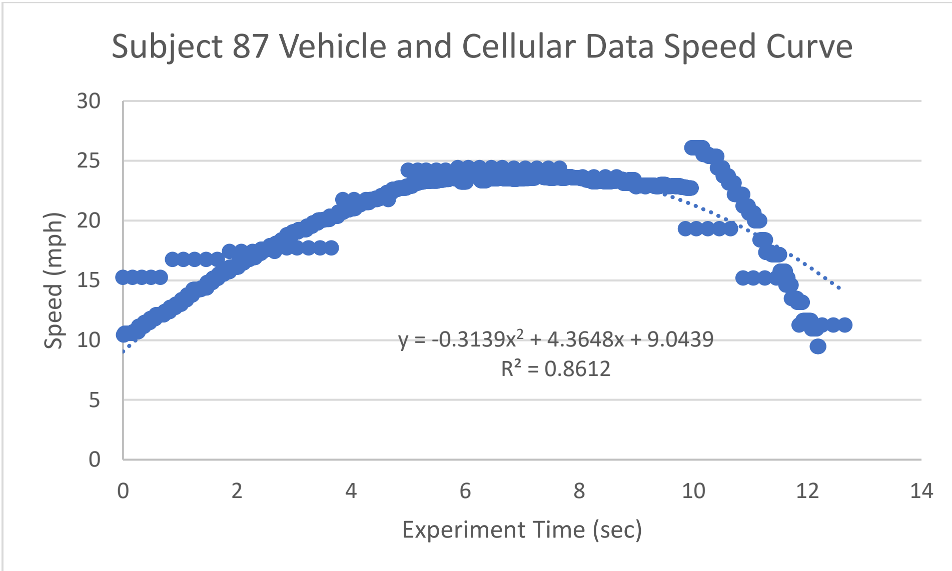

Figure 38- Speed Curve Correlation Subject 87

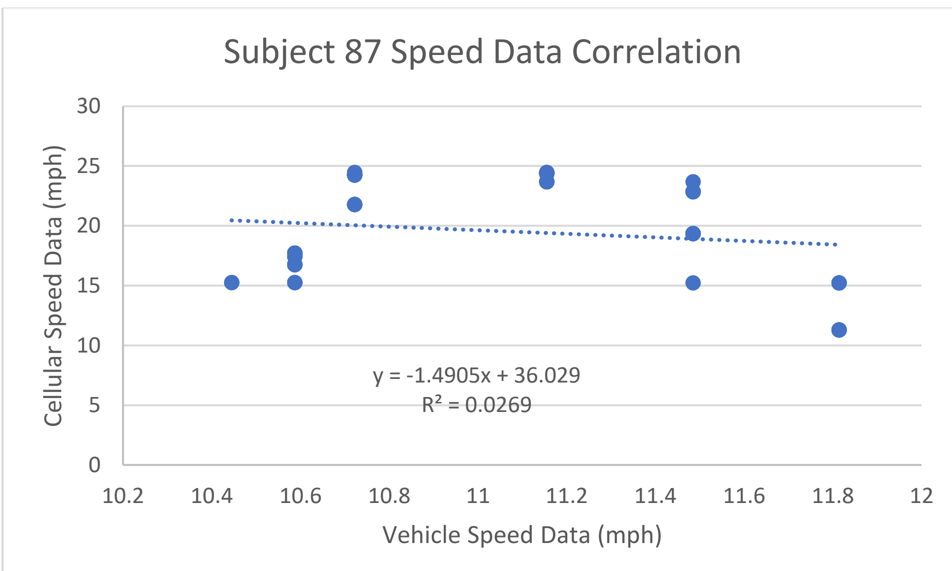

Figure 39- Speed Data Correlation Subject 87

Subject 91

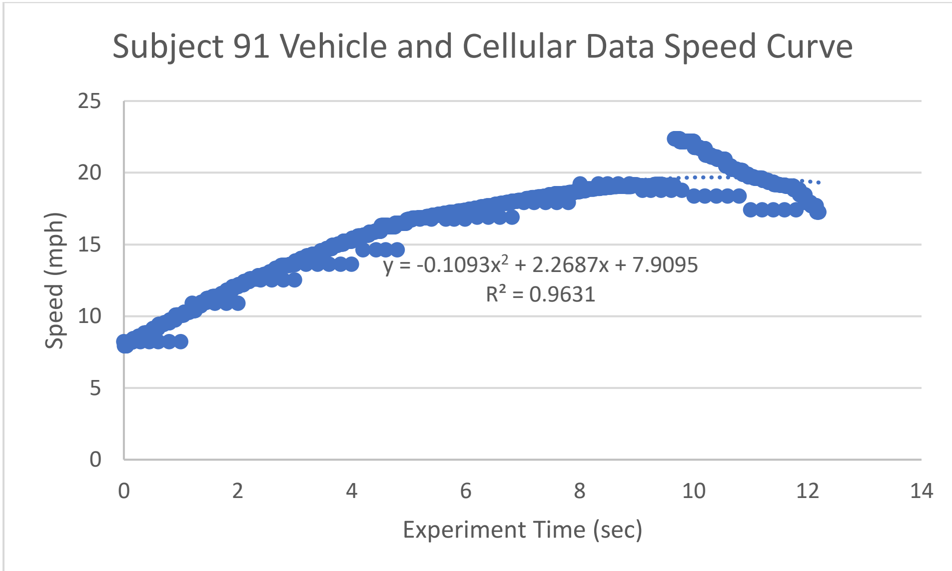

Figure 40- Speed Curve Correlation Subject 91

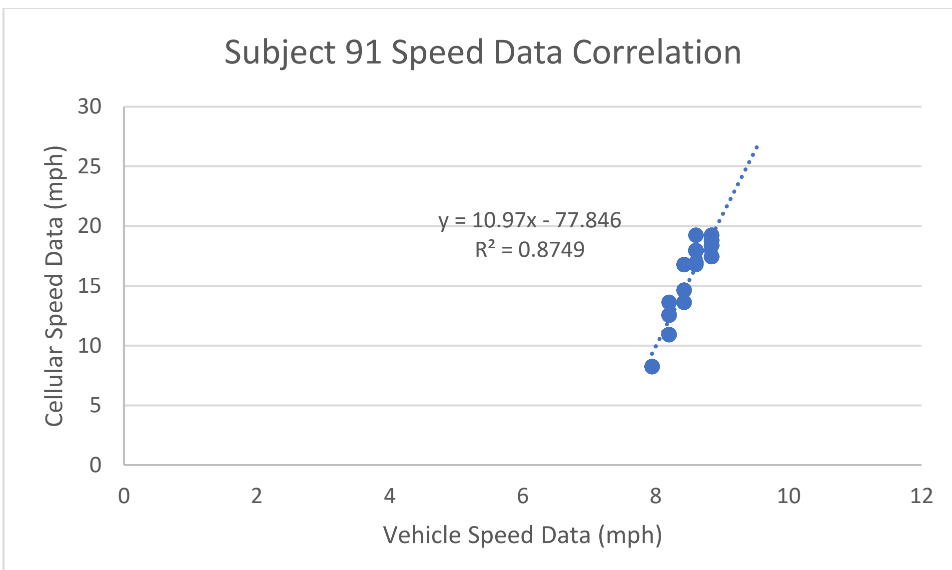

Figure 41- Speed Data Correlation Subject 91

Appendix B: Speed Statistical Analysis After Message Received

216 Feet to 0 Feet

Two-Sample T-Test and CI

```
Sample      N   Mean  StDev  SE Mean
1        1711  19.90   4.07    0.098
2        1544  19.56   3.40    0.087


Difference = μ (1) - μ (2)
Estimate for difference:  0.340
95% CI for difference:  (0.083, 0.597)
T-Test of difference = 0 (vs ≠): T-Value = 2.59  P-Value = 0.010  DF = 3234
```

Figure 42- 216 Feet to 0 Feet

216 Feet to 200 Feet

```
Sample     N   Mean  StDev  SE Mean
1        140  20.50   2.05     0.17
2        138  19.84   2.55     0.22


Difference = μ (1) - μ (2)
Estimate for difference:  0.656
95% CI for difference:  (0.108, 1.204)
T-Test of difference = 0 (vs ≠): T-Value = 2.36  P-Value = 0.019  DF = 262
```

Figure 43- 216 Feet to 200 Feet

199 Feet to 180 Feet

Two-Sample T-Test and CI

```
Sample     N   Mean  StDev  SE Mean
1        181  20.71   2.12     0.16
2        166  20.14   2.56     0.20


Difference = μ (1) - μ (2)
Estimate for difference:  0.570
95% CI for difference:  (0.071, 1.069)
T-Test of difference = 0 (vs ≠): T-Value = 2.25  P-Value = 0.025  DF = 321
```

Figure 44- 199 Feet to 180 Feet

179 Feet to 160 Feet

Two-Sample T-Test and CI

```
Sample     N   Mean  StDev  SE Mean
1        169  20.89   2.48     0.19
2        163  20.83   2.84     0.22


Difference = μ (1) - μ (2)
Estimate for difference:  0.060
95% CI for difference:  (-0.517, 0.637)
T-Test of difference = 0 (vs ≠): T-Value = 0.20  P-Value = 0.838  DF = 320
```

Figure 45- 179 Feet to 160 Feet

159 Feet to 140 Feet

Two-Sample T-Test and CI

```
Sample     N   Mean  StDev  SE Mean
1        177  21.06   2.53     0.19
2        158  21.38   2.61     0.21


Difference = μ (1) - μ (2)
Estimate for difference:  -0.320
95% CI for difference:  (-0.874, 0.234)
T-Test of difference = 0 (vs ≠): T-Value = -1.14  P-Value = 0.257  DF = 326
```

Figure 46- 159 Feet to 140 Feet

139 Feet to 120 Feet

Two-Sample T-Test and CI

```
Sample     N   Mean  StDev  SE Mean
1        174  20.90   2.76     0.21
2        164  21.04   2.50     0.20


Difference = μ (1) - μ (2)
Estimate for difference:  -0.140
95% CI for difference:  (-0.703, 0.423)
T-Test of difference = 0 (vs ≠): T-Value = -0.49  P-Value = 0.625  DF = 335
```

Figure 47- 139 Feet to 120 Feet

119 Feet to 100 Feet

Two-Sample T-Test and CI

```
Sample     N   Mean  StDev  SE Mean
1        180  20.45   3.43     0.26
2        174  19.95   3.11     0.24


Difference = μ (1) - μ (2)
Estimate for difference:  0.500
95% CI for difference:  (-0.184, 1.184)
T-Test of difference = 0 (vs ≠): T-Value = 1.44  P-Value = 0.151  DF = 350
```

Figure 48- 119 Feet to 100 Feet

99 Feet to 80 Feet

Two-Sample T-Test and CI

```
Sample     N   Mean  StDev  SE Mean
1        190  18.92   4.87     0.35
2        175  17.74   3.38     0.26


Difference = μ (1) - μ (2)
Estimate for difference:  1.180
95% CI for difference:  (0.322, 2.038)
T-Test of difference = 0 (vs ≠): T-Value = 2.71  P-Value = 0.007  DF = 337
```

Figure 49- 99 Feet to 80 Feet

79 Feet to 60 Feet

Two-Sample T-Test and CI

```
Sample     N   Mean  StDev  SE Mean
1        178  17.67   6.56     0.49
2        155  17.74   3.38     0.27


Difference = μ (1) - μ (2)
Estimate for difference:  -0.070
95% CI for difference:  (-1.176, 1.036)
T-Test of difference = 0 (vs ≠): T-Value = -0.12  P-Value = 0.901  DF = 272
```

Figure 50- 79 Feet to 60 Feet

59 Feet to 40 Feet

Two-Sample T-Test and CI

```
Sample     N   Mean  StDev  SE Mean
1        138  19.87   3.29     0.28
2        121  16.66   4.24     0.39


Difference = μ (1) - μ (2)
Estimate for difference:  3.210
95% CI for difference:  (2.271, 4.149)
T-Test of difference = 0 (vs ≠): T-Value = 6.74  P-Value = 0.000  DF = 225
```

Figure 51- 59 Feet to 40 Feet

39 Feet to 20 Feet

Two-Sample T-Test and CI

```
Sample     N   Mean  StDev  SE Mean
1        114  19.33   3.76     0.35
2         78  17.96   4.34     0.49


Difference = μ (1) - μ (2)
Estimate for difference:  1.370
95% CI for difference:  (0.175, 2.565)
T-Test of difference = 0 (vs ≠): T-Value = 2.27  P-Value = 0.025  DF = 149
```

Figure 52- 39 Feet to 20 Feet

20 Feet to 0 Feet

Two-Sample T-Test and CI

```
Sample    N   Mean  StDev  SE Mean
1        59  17.01   6.51     0.85
2        52  18.77   3.56     0.49


Difference = μ (1) - μ (2)
Estimate for difference:  -1.760
95% CI for difference:  (-3.708, 0.188)
T-Test of difference = 0 (vs ≠): T-Value = -1.79  P-Value = 0.076  DF = 91
```

Figure 53- 20 Feet to 0 Feet

Appendix C: Acceleration Statistical Analysis After Message Received

216 Feet to 0 Feet

Two-Sample T-Test and CI

```
Sample     N   Mean  StDev  SE Mean
1       1711  -13.6   89.2      2.2
2       1544    -17    101      2.6


Difference = μ (1) - μ (2)
Estimate for difference:  3.36
95% CI for difference:  (-3.21, 9.93)
T-Test of difference = 0 (vs ≠): T-Value = 1.00  P-Value = 0.316  DF = 3098
```

Figure 54- 216 Feet to 0 Feet

216 Feet to 200 Feet

Two-Sample T-Test and CI

```
Sample    N  Mean  StDev  SE Mean
1       140   8.3   54.6      4.6
2       138   6.9   22.4      1.9


Difference = μ (1) - μ (2)
Estimate for difference:  1.41
95% CI for difference:  (-8.45, 11.27)
T-Test of difference = 0 (vs ≠): T-Value = 0.28  P-Value = 0.778  DF = 185
```

Figure 55- 216 Feet to 200 Feet

199 Feet to 180 Feet

Two-Sample T-Test and CI

```
Sample    N  Mean  StDev  SE Mean
1       181   4.2   53.7      4.0
2       166  11.3   67.3      5.2


Difference = μ (1) - μ (2)
Estimate for difference:  -7.13
95% CI for difference:  (-20.06, 5.80)
T-Test of difference = 0 (vs ≠): T-Value = -1.09  P-Value = 0.279  DF = 315
```

Figure 56- 199 Feet to 180 Feet

179 Feet to 160 Feet

Two-Sample T-Test and CI

```
Sample    N  Mean  StDev  SE Mean
1       169  12.9   99.6      7.7
2       163    28    128       10


Difference = μ (1) - μ (2)
Estimate for difference:  -14.9
95% CI for difference:  (-39.6, 9.9)
T-Test of difference = 0 (vs ≠): T-Value = -1.18  P-Value = 0.239  DF = 306
```

Figure 57- 179 Feet to 160 Feet

159 Feet to 140 Feet

Two-Sample T-Test and CI

```
Sample     N  Mean  StDev  SE Mean
1        177     0    106      7.9
2        158    -1    110      8.8


Difference = μ (1) - μ (2)
Estimate for difference:  0.8
95% CI for difference:  (-22.4, 24.1)
T-Test of difference = 0 (vs ≠): T-Value = 0.07  P-Value = 0.946  DF = 325
```

Figure 58- 159 Feet to 140 Feet

139 Feet to 120 Feet

Two-Sample T-Test and CI

```
Sample     N  Mean  StDev  SE Mean
1        174  -6.2   85.8      6.5
2        164    -8    147       12


Difference = μ (1) - μ (2)
Estimate for difference:  1.5
95% CI for difference:  (-24.5, 27.6)
T-Test of difference = 0 (vs ≠): T-Value = 0.12  P-Value = 0.908  DF = 258
```

Figure 59- 139 Feet to 120 Feet

119 Feet to 100 Feet

Two-Sample T-Test and CI

```
Sample     N   Mean  StDev  SE Mean
1        180  -11.4   88.2      6.6
2        174  -41.2   90.2      6.8


Difference = μ (1) - μ (2)
Estimate for difference:  29.82
95% CI for difference:  (11.17, 48.47)
T-Test of difference = 0 (vs ≠): T-Value = 3.14  P-Value = 0.002  DF = 350
```

Figure 60- 119 Feet to 100 Feet

99 Feet to 80 Feet

Two-Sample T-Test and CI

```
Sample     N   Mean  StDev  SE Mean
1        190  -29.2   61.5      4.5
2        175  -50.2   86.0      6.5


Difference = μ (1) - μ (2)
Estimate for difference:  21.01
95% CI for difference:  (5.50, 36.52)
T-Test of difference = 0 (vs ≠): T-Value = 2.67  P-Value = 0.008  DF = 312
```

Figure 61- 99 Feet to 80 Feet

79 Feet to 60 Feet

Two-Sample T-Test and CI

```
Sample     N   Mean  StDev  SE Mean
1        178  -21.4   99.3      7.4
2        155  -54.6   89.1      7.2


Difference = μ (1) - μ (2)
Estimate for difference:  33.2
95% CI for difference:  (12.9, 53.5)
T-Test of difference = 0 (vs ≠): T-Value = 3.22  P-Value = 0.001  DF = 330
```

Figure 62- 79 Feet to 60 Feet

59 Feet to 40 Feet

Two-Sample T-Test and CI

```
Sample     N   Mean  StDev  SE Mean
1        138  -41.8   98.8      8.4
2        121  -39.8   86.6      7.9


Difference = μ (1) - μ (2)
Estimate for difference:  -1.9
95% CI for difference:  (-24.6, 20.8)
T-Test of difference = 0 (vs ≠): T-Value = -0.17  P-Value = 0.867  DF = 256
```

Figure 63- 59 Feet to 40 Feet

39 Feet to 20 Feet

Two-Sample T-Test and CI

```
Sample     N   Mean  StDev  SE Mean
1        114    -35    114       11
2         78  -24.9   69.1      7.8


Difference = μ (1) - μ (2)
Estimate for difference:  -10.5
95% CI for difference:  (-36.6, 15.5)
T-Test of difference = 0 (vs ≠): T-Value = -0.80  P-Value = 0.426  DF = 187
```

Figure 64- 39 Feet to 20 Feet

20 Feet to 0 Feet

Two-Sample T-Test and CI

```
Sample    N   Mean  StDev  SE Mean
1        59  -79.2   77.5    10
2        52  -18.6   90.4    13


Difference = μ (1) - μ (2)
Estimate for difference:  -60.6
95% CI for difference:  (-92.5, -28.7)
T-Test of difference = 0 (vs ≠): T-Value = -3.77  P-Value = 0.000  DF = 101
```

Figure 65- 20 Feet to 0 Feet

Appendix D: Presentations

“User recognition at mid-block crossings via connected vehicle technology” (presentation), ITSVA/VASITE Joint Conference, Richmond, VA, 2017.

“User recognition at mid-block crossings using connected vehicle technology” (presentation and demonstration), Connected Vehicle Pooled Fund annual meeting, McLean, VA, 2017.