Understanding Opportunities with Connected Vehicles in the Smart Cities Context

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Yinhai Wang
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Leila Hajibabai
Mehrdad Tajalli

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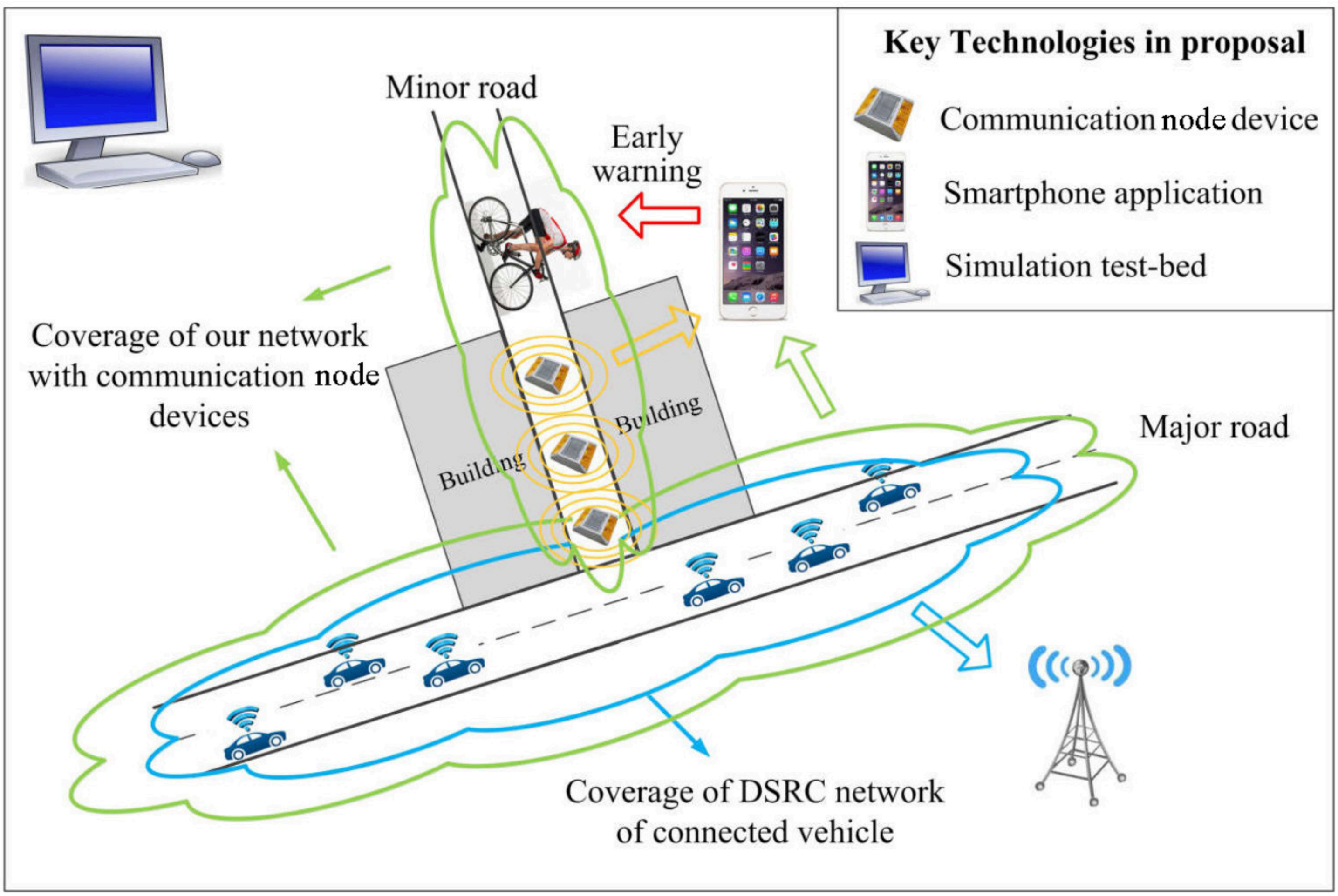

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UNDERSTANDING OPPORTUNITIES WITH CONNECTED VEHICLES IN THE SMART CITIES CONTEXT

FINAL PROJECT REPORT

By

Yinhai Wang
John Ash
Yifan Zhuang
Zhibin Li
Ziqiang Zeng
University of Washington

Ali Hajbabaie
Leila Hajibabai
Mehrdad Tajalli
Washington State University

Washington State Transportation Center (TRAC)
University of Washington, Box 354802
Seattle, Washington 98105-4631

Sponsored by

Pacific Northwest Transportation Consortium (PacTrans)
USDOT University Transportation Center for Federal Region 10
University of Washington, Box 352700
Seattle, WA 98195-2700

Washington State Department of Transportation (WSDOT)
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PO Box 47300
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16. Abstract

This research focused on using connected vehicle information to identify locations prone to conflicts between motorized and non-motorized users to improve traffic safety on multimodal roadway networks. With this information in hand, transportation system users can be alerted of potential conflicts they may be involved in, before their occurrence, allowing these users to take preventive actions by making evasive maneuvers. A comprehensive review of the literature investigated existing connected vehicle (CV) and vehicle-to-X (V2X) safety applications. The methods to allow a sensor to communicate via both dedicated short range communications (DSRC) and via Bluetooth, WiFi, or another communication protocol commonly used by mobile devices were also investigated, as well as existing surrogate safety measures and their use in conflict- and safety-prediction algorithms. The review indicated that several studies have focused on the safety and operational benefits of vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communications; however, the safety benefits of V2X communications have not been sufficiently explored.

In this project, a cost-effective, solar-energy driven, small, and lightweight communication node device, called the Smart Road Sticker (SRS), was developed to enable communications between connected vehicles and other roadway users via protocols such as LoRa and Bluetooth, and potentially DSRC. A supporting mobile application that allows pedestrians, bicyclists, and drivers of unconnected vehicles to communicate with the SRS device and vice versa was also designed. A crash risk prediction algorithm, with applications for vehicle/non-motorized user crashes, was developed to identify unsafe conditions and determine appropriate CV-based safety countermeasures for system users. Next, a connected vehicle simulation test bed was established in VISSIM to evaluate the safety benefits of the proposed methodology under various traffic and landscape conditions. The findings of this study were that the number of conflicts increased when the penetration of connected devices decreased. In addition, increasing the traffic volume had a direct relationship with increasing the number of conflicts. Finally, a real-world test bed was established for installation of sensors, data collection, and analysis, as well as to initiate further smart cities research within the state.

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TABLE OF CONTENTS

Table of Figures

Table of Tables

List of Abbreviations

CN: Communication Node
CNS: Communication Network Simulation
COM: Component Object Model
CV: Connected Vehicle
DSRC: Dedicated Short Range Communications
FARS: Fatality Analysis Reporting System
NASS GES: National Automotive Sampling System General Estimates System
NHTSA: National Highway Traffic Safety Administration
PCAM: Pedestrian Crash Avoidance/Mitigation
PCDS: Pedestrian Crash Data Study
PET: Post-Encroachment Time
SRS: Smart Road Sticker
SSAM: Surrogate Safety Assessment Model
TFS: Traffic Flow Simulation
TTC: Time to Collision
V2I: Vehicle-to-infrastructure
V2V: Vehicle-to-vehicle
V2X: Vehicle-to-device systems

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Executive Summary

Connected vehicle (CV) technology presents great potential to increase the safety of our roadway system by increasing driver situational awareness and reducing or eliminating crashes through vehicle-to-vehicle (V2V), vehicle-to-infrastructure (V2I), and vehicle-to-device systems (V2X) communications. In a connected environment, road users (drivers, pedestrians, bicyclists, etc.) will receive warnings that inform them of potential hazards through visual displays, or audible warning messages. These warnings will increase roadway users' awareness of hazards and other dangerous situations. For example, drivers can be alerted of imminent crash situations such as head-on collisions or rear-end crashes. Furthermore, when going through an intersection, roadway users can be alerted about another system user who has failed to observe the right of way so that these roadway users can take necessary actions to avoid potential crashes. Several studies have focused on the safety and operational benefits of V2V and V2I communications (as will be presented in the following); however, detailed discussion of the safety benefits of V2X communications was not found in our literature review.

This research focused on using connected vehicle information to identify locations prone to conflicts between motorized and non-motorized users to improve traffic safety on multimodal roadway networks. With this information in hand, transportation system users can be alerted of potential conflicts, before their occurrence, allowing these users to take preventive actions, perhaps by making evasive maneuvers. A comprehensive review of the literature was conducted to investigate existing V2X safety applications. The methods to allow a sensor to communicate via both dedicated short range communications (DSRC) and via Bluetooth, WiFi, or another communication protocol commonly used by mobile devices were also investigated, as well as existing surrogate safety measures and their use in conflict- and safety-prediction algorithms.

The review indicated that several studies have focused on the safety and operational benefits of V2V and V2I communications. However, those that discussed the safety benefits of V2X communications were limited.

In this project, a cost-effective, solar-energy driven, small, and lightweight communication node device, called the Smart Road Sticker (SRS), was developed to communicate with connected vehicles via the LoRa wireless data communication technology and DSRC, and with pedestrians, bicyclists, and unconnected vehicles through cell phones and other mobile devices via Bluetooth. A supporting mobile application that allows pedestrians, bicyclists, and drivers of unconnected vehicles to communicate with the SRS device and vice versa was also designed and tested. Next, a crash risk prediction algorithm was developed to identify unsafe conditions and determine appropriate CV-based safety countermeasures to be presented to system users. A connected vehicle simulation test bed was established within VISSIM to evaluate the safety benefits of the proposed methodology under various traffic and landscape conditions. The simulation showed that the number of conflicts increased when the penetration rate of connected devices decreased. In addition, increasing the volumes of pedestrians and vehicles had a direct relationship with increasing the number of conflicts. The simulation results also indicated that the number of conflicts between through-moving vehicles and pedestrians crossing the road was the highest. This is because of the higher volumes of vehicles that went straight (70 percent of the total volumes of vehicles). Increasing the penetration rate reduced the number of through-movement conflicts significantly. The number of conflicts for left turns and right turns also decreased. Generally, the number of conflicts decreased with higher penetration rates, when the penetration rate increased among higher volumes.

A final part of the project involved development of a real-world test bed in which sensors developed for the project could be installed, and the corresponding data could be collected and analyzed. The test bed was initially designated to be along Montlake Boulevard near the University of Washington (UW) campus; however, for a variety of reasons, the test bed site ultimately was assigned along State Route 522 (SR 522, also known as NE Bothell Way). At the test bed, two types of sensors were installed: (1) the Smart Road Sticker and (2) a Media Access Control (MAC) address sensor developed by the UW Smart Transportation Applications and Research Laboratory (STAR Lab) known as the Mobile Unit for Sensing Traffic, Version 2 (MUST-II). The initial plan for the project called for testing the surrogate safety algorithms at the test bed; however, because of time and safety constraints, the plan was changed following the discussions with the project sponsors. The team is continuing to refine the surrogate safety algorithms and mobile app and hopes to test them at the test bed in the near future.

1.0 Introduction

1.1 General Background and Motivation

In 2017, 37,133 people were killed as a result of traffic crashes in the United States (NHTSA, 2018). Of those people, 5,977 were pedestrians and 783 were bicyclists (NHTSA, 2018). Though these numbers represent decreases from the 2016 values, and while continual efforts are made to improve safety in vehicles and along roadways, there is still a long way to go. These statistics further indicate the importance of targeting pedestrians, bicyclists, and other non-motorized road users in developing new traffic safety-related technologies as these especially vulnerable road users represent more than 17 percent of all traffic-related fatalities. In addition to the tremendous amount of work required to reach a common target goal of zero traffic-related fatalities, or at least drastically decrease the numbers of deaths on roadways, traffic congestion is also a problem that affects nearly all U.S. residents, whether they themselves travel or not. For 2014, the Texas Transportation Institute's *Urban Mobility Scorecard* noted that for "very large areas," including New York-Newark, Los Angeles, Chicago, and more, 231,970,000 hours of travel delay were incurred as a result of traffic congestion (Schrank et al., 2015). This congestion was further associated with 99,490,000 gallons of additional fuel consumption and a total cost (based on delay and fuel costs) of more than 5 billion U.S. dollars (Schrank et al., 2015). In recent years, transportation authorities have been investigating a variety of alternative solutions to the aforementioned problems. As communication and vehicle technologies continue to improve over time, one such alternative that appears to be able to address such problems is the implementation of a connected vehicle (CV) environment.

At the risk of oversimplifying the concept, a connected vehicle environment is an environment in which vehicles are able to communicate with other vehicles (V2V), infrastructure

(V2I), and other entities such as pedestrians and/or bicyclists (V2X). The communication is generally enabled via 5.9 GHz Dedicated Short Range [radio] Communications (DSRC). Communications take place between and among onboard equipment (OBE, i.e., DSRC units within a vehicle) and roadside equipment (RSE, i.e., DSRC units external to a vehicle), although cellular solutions involving 4G and 5G are receiving attention today as well. The latter communication options have potential to expand the scope of CV environments by allowing all users with mobile devices to be "connected." Generally, in CV environments, connected travelers are able to communicate with each over DSRC by sending Basic Safety Messages (BSMs) that contain information on the vehicle's GPS position, speed, acceleration, size (length and width), braking status, and many other useful pieces of information that have a variety of safety applications, especially for alerting drivers of potential safety hazards (Kenney, 2011).

Over the past decade or so, a variety of connected vehicle test beds have been established around the U.S. in locations including Ann Arbor, Michigan, New York City, Tampa, Florida, and Wyoming (NHTSA, 2012; USDOT ITS JPO, 2018). The Washington State Department of Transportation (WSDOT) has also worked with Battelle to establish a small-scale CV test bed in Washington state, in which they tested queue warning and speed harmonization technologies in a freeway setting (Stephens et al., 2015). In 2019, WSDOT is also working to establish several other CV test beds across the state in a variety of settings as part of the Signal Phasing and Timing (SPaT) Challenge offered by the National Operations Center of Excellence.

Closely related to the concept of a CV environment is that of a smart city. The term is widely used, but its exact definition is often unclear. Schaffers et al. (2011) noted that instrumentation, networks of openly communicating mobile devices, and sensors used for data collection purposes will enhance prediction models to solve urban problems, while simultaneously making cities smarter. While this definition still is a bit vague, one can quickly see connections between CV environments and the smart cities concept. That is to say, establishment of a CV environment involves instrumenting a location with communications devices and sensors that will ultimately be used to collect data and help solve traffic safety- and mobility-related problems. The instrumentation component of a smart city is crucial, as it allows high-volume data collection in real time that can be used for decision making over a variety of time horizons. Ultimately, the creation of instrumented test beds, which also allows for the study of connected vehicles and real-time data collection, will serve as a great first step in shaping the vision of a smart city in the State of Washington.

1.2 Project Outline and Objectives

From the preceding background section, two things should be clear: (1) studying CV environments is an important step in helping solve traffic safety- and mobility-related problems, and (2) embracing the vision of a smart city via study of CV applications—and more generally sensor development, installation, and data collection—can help with a variety of important decision-making applications. Furthermore, it is important to note that although several studies have focused on the safety and operational benefits of V2V and V2I communications, the safety benefits of V2X communications have so far not been discussed in published materials. That is to say, applications of CV technologies have mainly been focused only on motorized road users and have neglected non-motorized users such as bicyclists and pedestrians. Therefore, the goals of this research were two-fold. The first goal was to develop a solution to improve the safety of non-motorized road users (especially pedestrians) in a CV environment on a multimodal roadway. The second goal was to plan for, instrument, and collect/analyze data at a smart city test bed. These broad goals were accomplished via the following objectives, each of which is described thoroughly in the remainder of the report:

- Review and summarize the relevant literature on CV/V2X safety applications, communications systems, surrogate safety measures, and simulation platforms for testing algorithms developed herein.
- Design and build a cost-effective, solar-energy driven, small, and lightweight communication node device (i.e., a hardware component) called the Smart Road Sticker (SRS), which can enable communications between connected vehicles and other road users via LoRa, Bluetooth, and potentially DSRC.
- Develop a supporting mobile application that allows pedestrians, bicyclists, and drivers of unconnected vehicles to communicate with the SRS device and vice versa.
- Establish a crash risk prediction algorithm, based on the theory of surrogate safety, that can identify unsafe conditions and determine appropriate CV-based safety countermeasures to be presented to system users, in this case, drivers and pedestrians.
- Create a connected vehicle simulation test bed in VISSIM to evaluate the proposed crash risk prediction algorithm methodology under various traffic and landscape conditions.
- Establish a real-world test bed for the installation of sensors, data collection, and analysis.

2.0 Literature Review

A comprehensive review of the literature focusing on connected vehicle safety applications, V2X communications and safety applications for non-motorized road users, communication systems for delivering warning messages, surrogate safety measures and algorithms, and simulation technologies for CV applications is presented in this chapter. The first three sections motivated the development of the communication node (CN) device and supporting mobile application, while the latter two sections motivated the development of the crash risk prediction algorithm and its evaluation via a simulation test bed.

2.1 Connected Vehicle Safety Applications

CV technology presents great potential to increase the safety of roadway systems by increasing driver situational awareness and reducing or eliminating crashes through vehicle-to-vehicle, vehicle-to-infrastructure, and vehicle-to-device systems communication. CV technology employs dedicated short range wireless communication systems (or cellular systems) to share basic safety messages (e.g. vehicle location, speed, acceleration rate, etc.) among other equipped vehicles, road users, and infrastructure. According to a U.S. Department of Transportation study (Najm et al., 2010), combined V2V and V2I systems will potentially address about 81 percent of all vehicle target crashes, 83 percent of all light-vehicle target crashes, and 72 percent of all heavy-truck target crashes annually. CVs will also help roadway users (e.g., vehicle drivers, pedestrians, and bicyclists) to either avoid crashes or reduce their severity.

Most recent studies have considered the safety applications of CV technologies in V2V communications and their application in real-world situations (Ahmed-Zaid et al., 2011; Kandarpa et al., 2009; Dion et al., 2011; Consortium et al., 2005). These will significantly reduce the probability of collisions occurring and near-collision events. In fact, several types of warning messages, such as forward collision warnings, lane change warnings, do-not-pass warnings, and control loss warnings make drivers aware of crash prone situations. However, although V2V communication can provide effective tools to reduce the number and severity of crashes, it cannot address all possible types of crashes. Therefore, V2I communications that make use of roadside equipment such as signal controllers are considered another means to improve safety via the application of CV technologies. For example, Maile et al. (2008) developed a cooperative intersection collision avoidance system to warn drivers about violations of stop signs or traffic signals. Moreover, the information from signalized crosswalks can be sent to approaching vehicles as a warning to make drivers aware of the presence of pedestrians in the crosswalk (ITERIS, 2017).

2.2 V2X Communications and Safety Applications for Non-Motorized Road Users

Even though V2V and V2I communications may help prevent a significant number of crashes, there is still a gap in terms of connecting drivers, pedestrians, bicyclists, and motorists to each other. For this reason, V2X communication has been introduced. As part of the application of V2X communications to avoid crashes, some studies have tested detecting the presence of pedestrians in the vicinity of the vehicle with in-vehicle sensors when the vehicle moves forward and the emergency braking system is available. Yanagisawa et al. (2014) developed pedestrian crash avoidance/mitigation (PCAM) system to detect a pedestrian in front of a vehicle by using radar and a camera. This system applies the brake automatically when detection happens. Before braking activation, the system evaluates the benefit of activation on the basis of harm measure functions. When the harm-measure meets the pre-defined threshold, the system activates the brakes. To investigate the effectiveness of the brake assist system, Badea-Romero et al. (2013) considered 139 collisions between vehicles and pedestrians and extracted detailed information in terms of safety factors and injury severity. Then the collision scenarios were reconstructed in a simulator, which added the brake assist system and antilock braking features to vehicles. In most of the cases, the collision could not have been avoided, but the injury severity and collision speed could have been reduced significantly.

Although the use of on-board sensors and computer vision techniques to activate the automatic braking system is helpful in preventing possible collisions between vehicles and pedestrian and bicycles, their performance may not be satisfactory in poor visibility conditions, when the pedestrian is far from the detecting device, or when the pedestrian is not in the line-of-sight of the sensor. V2X technology provides the opportunity to fill this gap by using DSRC or cellular network technologies, especially as smart phones become more prevalent among people within all age groups.

2.3 Communication Systems for Delivering Warning Messages to Non-Motorized Road Users

Wu et al. (2014) developed a communication system between vehicles and smart phones using DSRC technology through a collaboration between Honda and Qualcomm. In addition, information about the position of the pedestrian was extracted from the pedestrian's smart phone GPS and inertial system, and the pedestrian's path was predicted by using an algorithm that applied the extracted information. The developed application provided extra information about the pedestrian's distraction condition to the driver as well. To estimate the vehicle's path, the vehicle's yaw rate, speed, and location were utilized. Knowing the predicted paths of the vehicle and pedestrian, the algorithm identified the risk of collision and warned users accordingly. The developed application was tested on different scenarios with and without obstructions between the vehicle and the pedestrian, and the results were successful.

During the communication between drivers and pedestrians, the warning message can be sent to drivers, pedestrians, or both parties. Hussein et al. (2016) indicated that sending the warning messages to both pedestrian and vehicle led to better safety performance. Anaya et al. (2014) assumed that only pedestrians received the warning and had to take the proper crash mitigation action. This study investigated the performance of the developed application, V2ProVu, which applied WiFi communications, measured the risk of the situation, and sent the proper warning message to the pedestrian's smart phone. The results of the study indicated that blockages between the vehicle and pedestrian reduced the performance of the application. In addition, the accuracy of pedestrian's position measurement affected the outcome of the procedure because the GPS information from the cell phone was not precise. Sugimoto et al. (2008) showed that errors in the GPS data from cell phones were about 10 meters for 95 percent of the observations, although errors in longitudinal positions were less than those for lateral positions.

Sending warning messages to drivers and pedestrians may be distracting and bothersome in unnecessary conditions. Therefore, it is necessary to filter warning messages before they are sent. David and Flach (2010) provided some criteria for filtering unnecessary messages. For example, the warning message should be sent to a pedestrian when his/her movement is toward the street. In addition, assuming the maximum speed for a pedestrian will indicate whether or not s/he will reach the collision point before the car's passing and whether or not the message should be sent. More sophisticated filters can be based on attributes such as movement history, personal profile, distracting activities of the pedestrian, and risk level of the location.

2.4 Surrogate Safety Measures and Algorithms

The occurrence of an incident/collision is a rare and random event that does not follow a timeline. To predict the occurrence of a crash, a safety prediction model is required. However, the current developed crash prediction models are designed to estimate the frequency or severity of crashes on the basis of factors such as roadway geometrics, traffic volume, etc. In addition, the predictions from such models may not be highly accurate, as there can be tremendous variance in crash counts at different sites, even if they are "similar" in terms of roadway geometry and traffic volume, because of considerations such as driver population. Surrogate safety measures are able to fill this gap by predicting a collision on the basis of trajectory information and without being dependent on information from previously occurring collisions; therefore, they are highly relevant in environments where vehicles and pedestrians and bicyclists are able to communicate with each other.

The traffic conflict technique is one of the most important surrogate measures in safety applications (Gettman et al., 2008). A conflict is defined as "an observable situation in which two or more road users approach each other in time and space to such an extent that there is risk of collision if their movements remain unchanged" (Amundsen and Hyden, 1977). The traffic conflict technique looks for the abnormal and evasive behavior of drivers, such as strong braking, to predict a collision-prone situation. The number of traffic conflicts usually indicates the frequency of a near-collision event. However, it does not indicate the severity of that possible collision. Therefore, other surrogate measures such as time to collision (TTC) and post-encroachment time (PET) have been introduced. TTC is defined as the "expected time for two vehicles to collide if they remain at their present speed and on the same path" (Gettman and Head, 2003). PET is also defined as the "time lapse between the end of encroachment of the turning vehicle and the time that the through-vehicle actually arrives at the potential point of collision" (Gettman and Head, 2003). The encroachment time can be defined as the "time duration during which the turning vehicle infringes upon the right-of-way of the through-vehicle" (Gettman and Head, 2003).

Several surrogate safety measures have been proposed to be considered in safety analysis. Gettman and Head (2003) developed a software application called the Surrogate Safety Assessment Model (SSAM) to detect conflicts between pairs of vehicles and analyze the outcomes of a simulation directly by using the trajectory information of vehicles. With SSAM, several surrogate safety measures are calculated automatically, and the results for the total study period are provided. The surrogate measures shown as outcomes of SSAM are presented as follows:

- Minimum time-to-collision
- Minimum post-encroachment
- Initial deceleration rate
- Maximum deceleration rate
- Maximum speed
- Maximum speed differential
- Vehicle velocity change had the event proceeded to a crash.

In studies that have analyzed the possible collision between vehicles and non-motorized road users such as pedestrians, the TTC factor has been most commonly selected as the safety surrogate measure, and the risk estimation algorithms are defined on the basis of this measure. The general framework for risk estimation in smartphones or on-board units in vehicles, in each time step, in different studies is shown in Figure 2.1 (Wu et al., 2014; Hussein et al., 2016; Anaya et al., 2014; Sugimoto et al., 2008; David and Flach, 2010). The onboard unit in vehicles and the smartphone receive the information about the position of surrounding devices and calculate the estimated conflict point. On the basis of the distance between each device and the current speed, the time to collision will be estimated for rear-end and crossing conflicts (Davis et al., 2002). The value of δ in the algorithm defines a threshold that indicates the risk of the situation. This threshold is mostly considered to be a predefined value that represents the average time that a driver takes for reacting and braking with maximum deceleration until the vehicle stops completely.

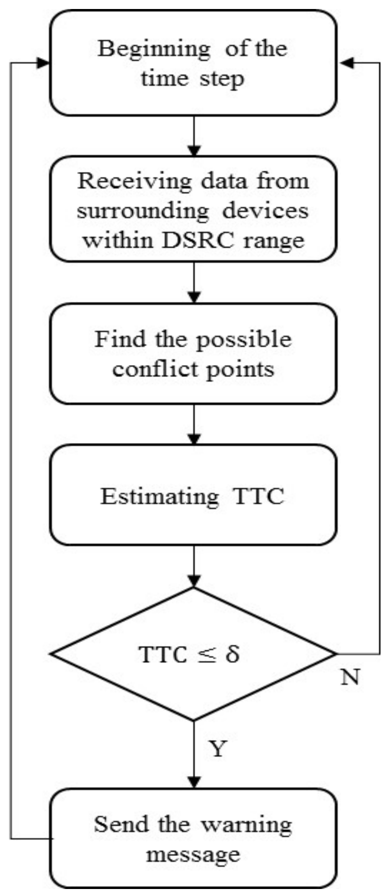

Figure 2.1: Risk estimation framework

2.5 Simulation Technologies and Methods for Modeling a CV Environment

Many types of traffic flow simulation (TFS) tools exist (e.g., VISSIM, Paramics, Aimsun, SUMO, etc.), but none of them are able to simulate the entire communication process among road users in a CV environment. Certain communication network simulation (CNS) tools exist as well (e.g., NS2, Qualnet, Jist/SWANS, GloMosim, etc.), but none of them are able to reflect the relationships between network communication and corresponding driver behavior interactions. A CV simulation contains three key elements, namely, the TFS, CNS, and specified CV applications. According to the implementation and interaction modes of the simulation elements, the CV simulation can be classified into two types, one based on a simplified communication model (Tanikella et al., 2007), and the other based on a loosely coupled simulation method (Marfia et al. 2007).

Some technologies and methods have been developed and used to simulate CV environments. Wu et al. (2015) used Visual Basic and the VISSIM COM (Component Object Model) interface to develop a simulation model in a CV environment. Sun et al. (2016) proposed a CV simulation prototype system based on integration of three components in one coupling. In the simulation implementation procedure, a commercial off-the-shelf, time-stepped VISSIM simulator and an open-source, event-driven NS2 simulator were selected as the basic simulation tools to develop the system.

3.0 Development of Communication Node Device and Mobile Application

An initial literature search showed that researchers have investigated V2X communications and developed devices and methodologies to communicate information about possible safety issues with pedestrians and other non-motorized road users to drivers of motor vehicles (Sugimoto et al., 2008; Hisaka and Kamijo, 2011). However, although these studies made initial strides in the V2X arena, they focused on the safety issue from one perspective only, namely, that of the motorist. To date, little work has been done to address safety issues, particularly conflicts between motorized and non-motorized users, in a connected vehicle environment from the perspective of the non-motorized user. The authors think that providing safety information to non-motorized users is just as important as providing similar information to drivers, as both parties may ultimately be able to take preventive actions to avoid conflicts. Therefore, the development of a device to enable V2X communications, as well as non-motorized user detection, from the perspectives of both the hardware and software is discussed in this chapter. Preliminary testing of the sensor, as well development of additional sensors with smart city applications, and a plan to instrument a real-world test bed with those sensors are also presented in this chapter.

3.1 Smart Road Sticker Design for Bluetooth Detection

The goal was to develop a solar-energy driven, small, and lightweight CN device, as shown in Figure 3.1, that could be installed along the roadside. This sensor would receive messages from connected vehicles and infrastructure (such as signal controller cabinets) and transmit pertinent safety information/warning messages to users' cellular devices via Bluetooth or suitable communication protocols. This would allow system users, especially non-motorized users who do not have access to DSRC devices, to send/receive critical safety information and would greatly increase the potential number of “connected” users across all modes on a given facility. Besides allowing for communication among vehicles, infrastructure, and non-motorized users, the sensors would be able to transmit information from one sensor to another. By developing a small and relatively inexpensive sensor, multiple sensors could be easily installed in critical areas to overcome issues of transmission range, and they would allow users (regardless of mode) to be informed of safety issues/potential conflicts well in advance of their arrival to the site of the potential conflict.

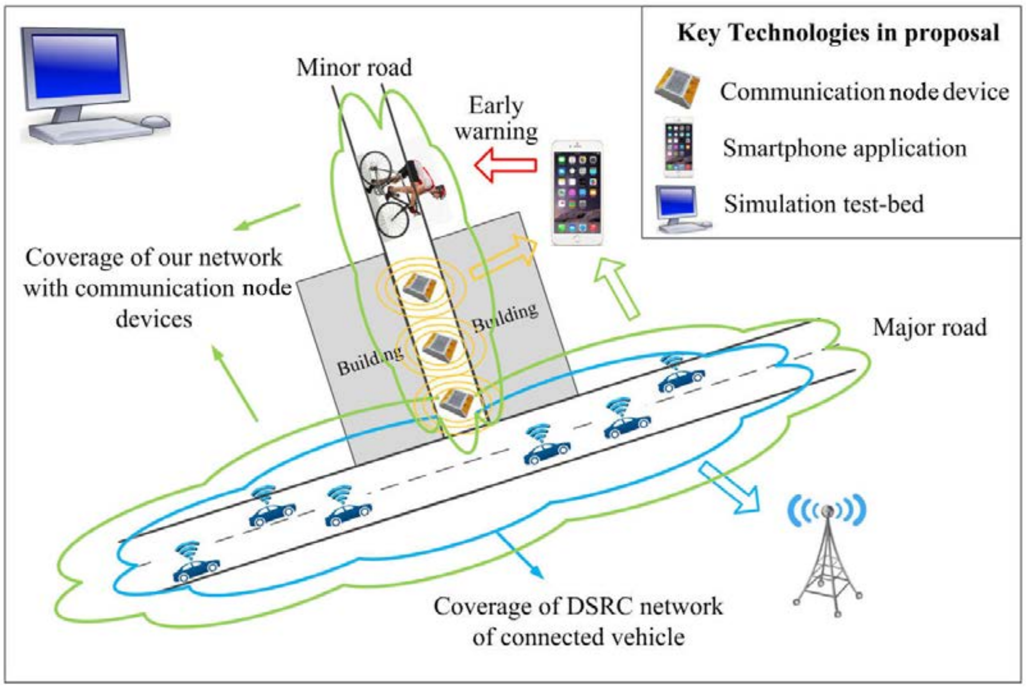

Figure 3.1: Illustration of the CN device application in a vision-restricted street scenario

The CN device developed was named the Smart Road Sticker (SRS). There are four components in the SRS: the central processing module, long range communication module, Bluetooth detection module, and the power module. The central processing module uses the ATmega 328P chip for processing the Bluetooth device information, and the long-range communication module uses LoRa wireless data communication technology to achieve both long distance communication and low power consumption. The Bluetooth detection module uses the HC-05 Bluetooth module at the master mode to search surrounding Bluetooth devices positively. The power module is a high-capacity, Lithium-ion battery designed to support continuous work. The structure of the SRS is shown in Figure 3.2. The detection time for one interval is five seconds and the maximum number of devices able to be detected at once is ten. During the detection interval, the sticker will send detection results when the number of devices detected reaches the maximum number. Otherwise, the sticker will still send data at the end of the detection interval.

Figure 3.2: Smart Road Sticker exterior

3.2 Software Development

Once the sensor was designed to receive information from CVs and the CV infrastructure was designed, the next step was to develop a mobile device application for receiving information from the sensors and presenting pertinent safety information to users who had the application installed on their phones or other mobile devices. Such information would comprise warnings about potential conflicts that might allow users to take corrective or evasive actions to prevent the conflicts from ever happening. Again, the goal of developing the mobile application and the CN device was to allow transmission of safety information to a larger percentage of the traveling population, regardless of their mode, because at least at the present time non-motorized users do not have DSRC-capable devices. Previous studies, such as Roodell (2009), addressed the communication of safety information in a connected vehicle environment between DSRC and cellular phones, but primarily from the perspective of the driver and not in terms of presenting warnings/information to pedestrians and bicyclists. As previously mentioned, cyber security and privacy are important issues to address in designing a mobile application.

The software can be categorized into two types: mobile phone application and a personal computer (PC) application. The mobile phone application (STAR Detection App) is based on the Android platform and can send beacons at a specific rate. The PC application will listen to the LoRa receiver port and filter the data received. Only Bluetooth MAC addresses registered in the system will be displayed. The interfaces for the Android and PC applications are shown in Figure 3.3. To guarantee cyber security and privacy, Bluetooth MAC addresses are encrypted in the mobile and PC applications, as they are technically personally identifying information.

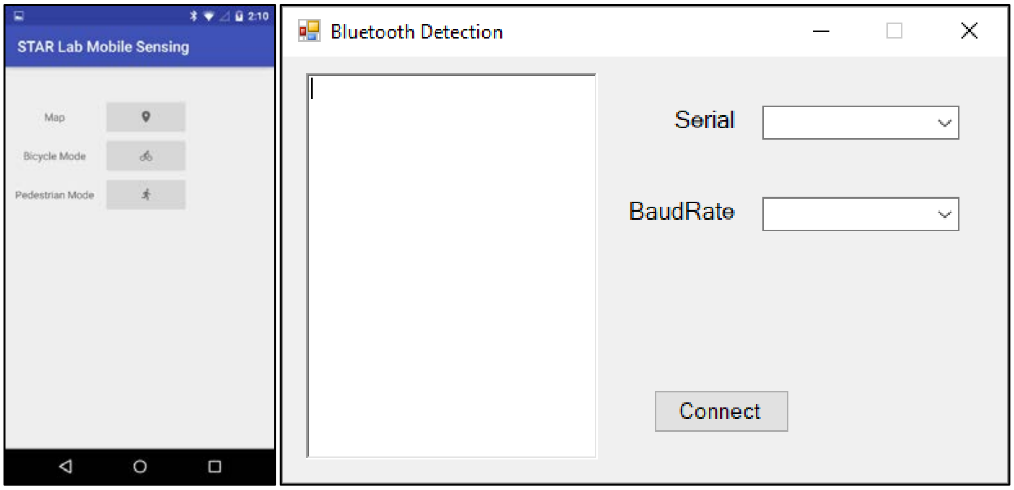

Figure 3.3: Interface of Android and PC applications

3.3 Experiment Results

Experiments were done from several perspectives, including that of basic function verification and detection distance measurement. The basic function of the sticker is to detect mobile devices with the STAR Detection App installed. Once a device has been detected, the SRS sends data to the receiver and PC via LoRa. The coded MAC address of the detected device is then displayed on the screen.

Ultimately, an experiment was conducted near the Burke Gilman Trail (a multi-use path for bicyclists and pedestrians) on the University of Washington campus in Seattle. The detection results and experimental scenario (in which a pedestrian walks past the SRS) are shown in Figure 3.4.

The testers opened and ran the mobile application at different distances from the SRS. The detection results are shown in Table 3.1. The results indicated that the detection error ratio increased dramatically when the distance from the SRS exceeded 8 m. As a result, the maximum effective distance of detection was set to be 8 m, as shown in Figure 3.5.

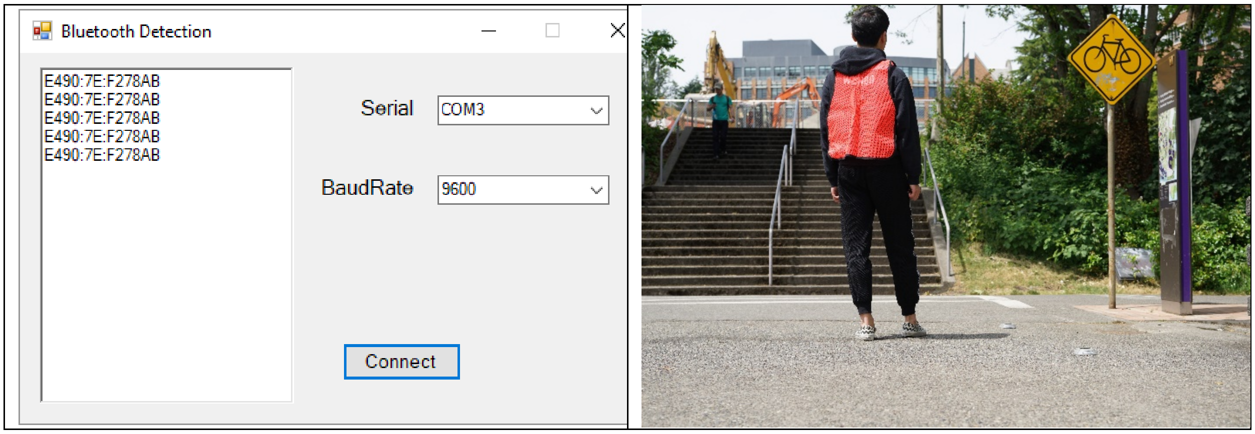

Figure 3.4: Detection result and experiment scene

Table 3.1: Detection results at different distances from the SRS

Distance	Total Number	Detection Number	Error Ratio
2m	20	19	0.05
4m	20	18	0.10
6m	20	18	0.10
8m	20	15	0.25
10m	20	8	0.60

Figure 3.5: Maximum effective detection distance (8 m from the SRS)

3.4 Additional Sensor Installation

In addition to the Smart Road Stickers, the research team wanted to install other sensors at a real-world test bed site both to collect more information on travel patterns in the area and to begin a partnership with WSDOT to test sensors developed in-house in a real-world setting; the establishment of this test bed is presented later in this chapter. The UW STAR Lab had worked to develop a low-cost Bluetooth and WiFi MAC address sensor known as the Mobile Unit for Sensing Traffic Version II (MUST-II). The MUST-II is a mobile sensing device that can detect MAC addresses for Bluetooth and WiFi devices (e.g., smart phones, iPads, etc.). By deploying MUST-II sensors, one can collect volume, travel time, and small-scale origin-destination (OD) information for sampled devices. The MUST-II sensor is small (approximately 85 mm by 58.5 mm by 18 mm) and is built around the Raspberry Pi computer, with additional peripherals added for mobile sensing, data transfer, and global positioning systems (GPS) locationing (Figure 3.6). To protect the computer and peripherals from the elements, the components are placed in a waterproof case before installation. The case can either be placed inside the signal cabinet, adhered to the outside of the cabinet, or pole-mounted. If placed inside the cabinet, an antenna must be installed. Installation of the MUST-II sensors was also important for this project because they could serve as a base station to communicate with the Smart Road Stickers and transmit data collected from the stickers back to the research team’s servers.

Figure 3.6: MUST-II sensor

An important component of any project collecting personally identifying information (in this case the MAC addresses of mobile devices) is ensuring proper cyber security. To ensure user anonymity in this project, a hashing algorithm was used to anonymize all collected MAC addresses so that they could not be traced back to an original user's device upon collection.

3.4 Development of a Plan to Instrument the Test Bed Site

The initial plan for this project called for the development of a test bed along Montlake Boulevard near the UW campus. The idea for establishing the test bed was to create a real-world site where the sensors and algorithms developed for this project could be studied. Small-scale and laboratory tests certainly are important and have their place, but testing in the real world would provide an opportunity to see how the devices would perform in a more complex environment where traffic, weather, and other conditions are typically more intense and random than can be observed in small-scale tests. Montlake Boulevard seemed to be an ideal site, as it is close to the UW campus, runs parallel to and has crossings with the Burke Gilman multi-use trail, and supports a variety of multimodal operations. Ultimately, however, the location of the test bed was changed to State Route 522 (SR 522, also known as NE Bothell Way). This change was made for a variety of reasons, including but not limited to the fact that several intersections along this corridor will be instrumented as part of a future WSDOT/UW project. This future project will be closely related to the aforementioned SPaT Challenge. Furthermore, the Burke Gilman Trail and its multi-modal operations run parallel to SR 522, making SR 522 an ideal choice for a test bed.

Five intersections along SR 522 were selected for sensor installation as part of the test bed. The chosen intersections were as follows and can be seen in Figure 3.7:

- NE 153rd St.
- State Route 104 (SR-104)
- 61st Ave. NE
- 68th Ave. NE
- 83rd Pl. NE.

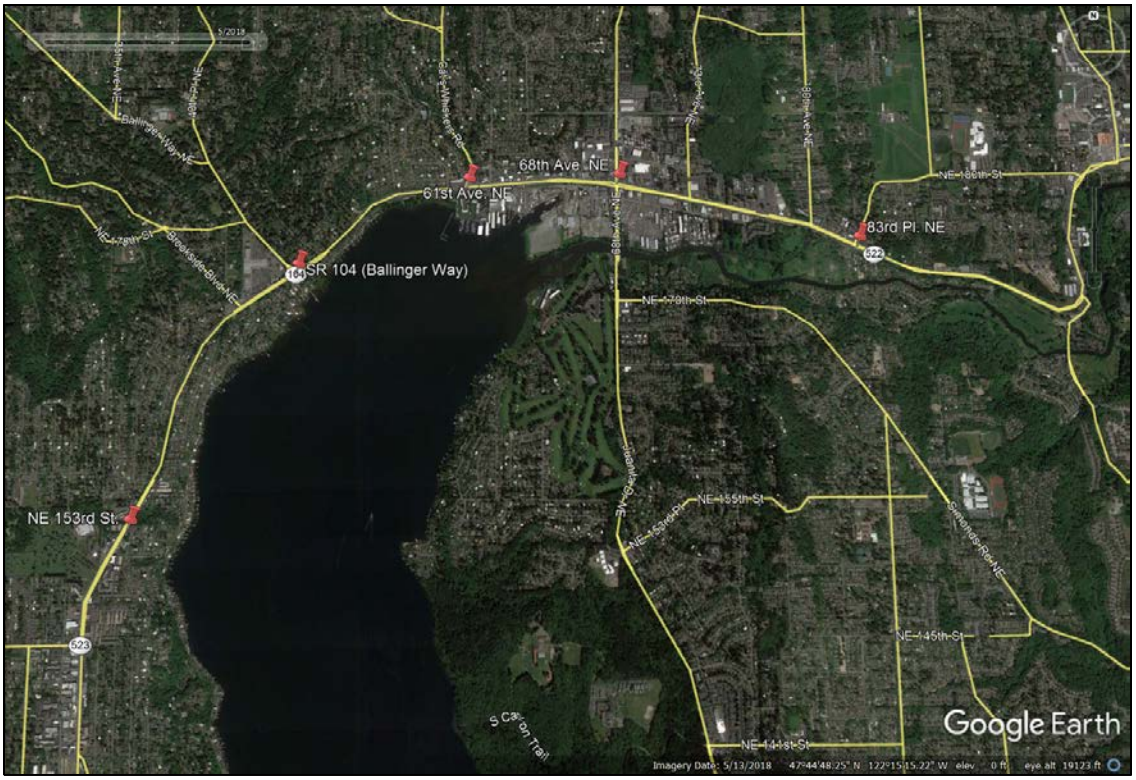

Figure 3.7: Intersections chosen for sensor installation along SR 522

Google earth V 7.3.2.5491. (May 13, 2018). Bothell, Washington, USA.
47º 44' 48.25"N, 122º 15' 15.22"W, Eye alt 19123 feet
Google 2018. http://www.google.com/earth [November 15th, 2018].

In addition to installing sensors at five signalized intersections along SR 522, the project team also decided to install sensors along the Burke Gilman Trail near the trail crossing at SR 104. At this intersection, the plan was to install two sensors trailside, one on the northeast side of the trail crossing and the other on the southwest side of the trail crossing. The locations of the trailside sensor installations can be seen in Figure 3.8. More information on the specific types of sensors installed, as well as analysis of data obtained from the installations, can be found in Chapter 5.

Figure 3.8: Trailside sensor installation locations near SR 104

Google earth V 7.3.2.5491. (May 13, 2018). Bothell, Washington, USA.
47º 45’ 13.25”N, 122º 16’ 33.87”W, Eye alt 19123 feet
Google 2018. http://www.google.com/earth [November 15, 2018].

4.0 Development and Evaluation of Prediction Algorithm for Crash Risk

This chapter summarizes the work related to the development of a prediction algorithm, rooted in the theory of surrogate safety, for estimating collision risk between non-motorized road users and vehicles. While the algorithm is applicable to different kinds of non-motorized road users, a choice was made to specifically focus on crashes involving vehicles and pedestrians. If desired, the theory can be extended to bicyclists and other non-motorized road users, as it is based on general information about the road user's trajectory, not travel mode. Additionally, it assumes that pedestrians carry a smartphone/mobile device capable of V2X communications, which enables them to be (1) detected and (2) alerted of safety issues. Later sections of this chapter describe the development of a simulation test bed in which the algorithm could be evaluated, as well as the results of the simulation tests.

4.1 Development of a Prediction Algorithm for Crash Risk between Vehicles and Pedestrians

To estimate the risk of collision between pedestrians and vehicles, a framework is needed that makes the proper connection between devices. This framework should use information such as current position and speed from the smartphones and vehicle onboard units to estimate the collision risk and warn both pedestrians and drivers to take the appropriate action within a reasonable time. In this research, we considered the time to collision as the surrogate measure for risky situations of potential crossing and rear-end conflicts. In this chapter, we propose a general framework based on the assumption that smartphone devices and onboard units provide accurate data about the positions and speeds of pedestrians and vehicles, respectively. First, the means of conflict point estimation and the approach to find are discussed. Then, the time to collision is estimated, and finally the proposed algorithm is presented.

4.1.1 Computations to Find the Conflict Point

To find the conflict point between two vehicles or a vehicle and a pedestrian, we use the information collected from the vehicle's onboard unit and the pedestrian's smartphone/mobile device. The longitude and latitude positions and the directions of movement are used to estimate the conflict point. Figure 4.1 shows the position and the direction of the movements of a pedestrian and a vehicle. The position of the conflict point can be defined on the basis of Equations 1 and 2.

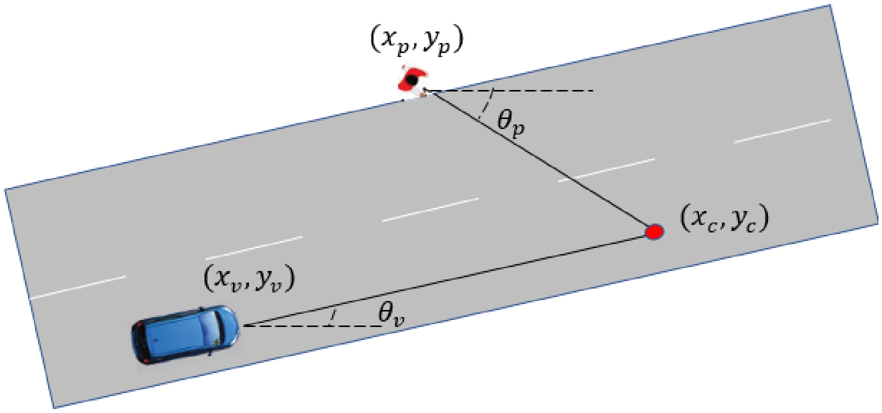

Figure 4.1: Finding the collision point

$$x_c = \frac{(y_v - y_p) - (x_v \tan(\theta_v) - x_p \tan(\theta_p))}{\tan(\theta_p) - \tan(\theta_v)} \tag{1}$$

$$y_c = \frac{(x_v - x_p) - (y_v \cot(\theta_v) - y_p \cot(\theta_p))}{\cot(\theta_p) - \cot(\theta_v)} \tag{2}$$

4.1.2 Computations for Time to Collision

Finding conflict points may be helpful for finding the frequency of conflict situations, but it does not indicate the severity of the potential conflict. Time to collision (TTC) is introduced to measure the severity of the conflict situation. TTC indicates the time at which two vehicles or a vehicle and a pedestrian will collide if they continue their movement with their current speed and path. Lower values of TTC indicate more severe possible conflicts. If TTC drops below a given threshold value, then the safety risk approaches a critical condition, and users should take action to prevent the crash. The value of TTC can be calculated on the basis of the speed and the distance to conflict point for each of the users. Equation 3 shows the measurement of TTC for crossing conflicts. However, this formulation is not appropriate for rear-end collisions. Equation 4 is appropriate for rear-end cases. Two rear-end and crossing conflicts are shown in Figure 4.2 (a) and (b), respectively.

$$\text{Crossing TTC}=\begin{cases}\frac{d_2}{v_2} & if \quad \frac{d_1}{v_1} < \frac{d_2}{v_2} < \frac{d_1+l_1+w_2}{v_1} \\ \frac{d_1}{v_1} & if \quad \frac{d_2}{2} < \frac{d_1}{v_1} < \frac{d_2+l_2+w_1}{v_2}\end{cases} \tag{3}$$

$$\text{Rear-End TTC} = \frac{x_1-x_2-l_1}{v_2-v_1} \; if \; v2 > v1 \tag{4}$$

where

x_1 = Location of the vehicle 1

x_2 = Location of the vehicle 2

v_1 = Speed of vehicle 1

v_2 = Speed of vehicle 2

d_1 = Distance to the conflict point from the front of vehicle 1

d_2 = Distance to the conflict point from the front of vehicle 2.

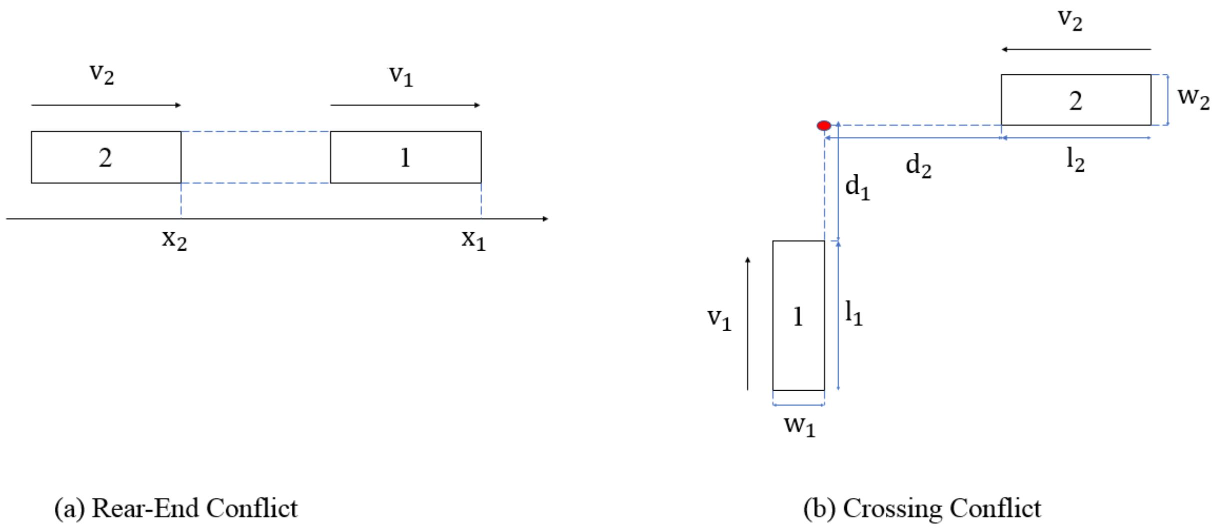

Figure 4.2 Rear-end crossing conflicts

We can also calculate the threshold for critical situations. The critical time for a vehicle is the time that a driver needs to perceive the warning message (t_p) and react to it by activating the brakes (t_{br}). In addition, we can consider a safe distance threshold between vehicles and pedestrians that should not be violated (t_{safe}). Equation 5 indicates the minimum time (δ) that a driver or a pedestrian needs to react to avoid a collision.

$$\delta = t_p + t_{br} + t_{safe} \tag{5}$$

We assume that at a critical time, the user's braking reaction is at the maximum deceleration rate, as this is an emergency situation. To be more realistic, the maximum deceleration is considered to be less when the vehicle is moving with higher speed because decelerating harshly is not safe for the passengers inside the vehicle. Therefore, a linear relationship between the current speed and maximum deceleration is assumed. Equation 6 shows this relationship. In this equation, a_0 (which takes a negative value) indicates the maximum deceleration rate that a vehicle can reach when its speed is near zero. The value for b is positive, as the rate of maximum deceleration increases when speed increases. However, for pedestrians, it is assumed that the maximum deceleration rate is a constant value equal to a_p. Therefore, the braking time for vehicles and pedestrians can be calculated with Equations 7 and 8, respectively. However, because pedestrians travel at lower speeds, we can assume that they stop instantaneously. To consider the worst case, pedestrian speed is assumed to be the maximum. The units of the time, speed, and deceleration rates in all proposed equations are s , $\frac{m}{s}$, and $\frac{m}{s^2}$, respectively.

$$MaxD = a_0 + bv \quad (6)$$

$$t_{br}^{v} = \left|\frac{1}{b}\ln(1 + \frac{b}{a_0}v)\right| \quad (7)$$

$$t_{br}^{p} = \left|\frac{v_{max}^{p}}{a_p}\right| \quad (8)$$

The safe time (t_{safe}) for vehicles and pedestrians can be calculated on the basis of Equations 9 and 10. We also define a variable, $TTCP$, to measure the remaining time for a vehicle or a pedestrian to get to the conflict point if it retains its current speed and path. Equation 11 shows this value, where d is the remaining distance. Assuming δ_v and δ_p are the critical times for the vehicle and pedestrian respectively, the critical time that considers both can be introduced as $\delta_{crit} = max\{\delta_v , \delta_p\}$. When TTC is equal to δ_{crit}, either the vehicle, the pedestrian, or both of them should reduce their speed to prevent a collision.

$$t_{safe}^{v} = \frac{d_{safe}}{v} \quad (9)$$

$$t_{safe}^{p} = \frac{d_{safe}}{v_{max}^{p}} \quad (10)$$

$$TTCP = \frac{d}{v} \quad (11)$$

4.1.3 Proposed Prediction Algorithm for Crash Risk

This section discusses the development of an algorithm to predict crash risk as a means to improve safety. This framework considers V2V and V2X communications, as the vehicles are connected to each other and are connected to pedestrians and other road users as well. The objective of the algorithm is to warn users and give them sufficient time to avoid a collision. Figure 4.3 shows the algorithm's process for identifying risky conditions and sending warning messages to users.

The proposed algorithm assumes that at each time step the vehicle's onboard unit (device i) collects information (position and speed) from surrounding devices, including other vehicles' onboard units and mobile devices within the prescribed communication range. Device j among all surrounding devices will be selected to analyze the risk condition between device i and device j. The analysis for the current time step is finished when all the surrounding devices in the covered area have been selected and analyzed. As the interaction between vehicles and pedestrians is different than the interaction between vehicles and other vehicles, user j must be defined as a pedestrian or a driver.

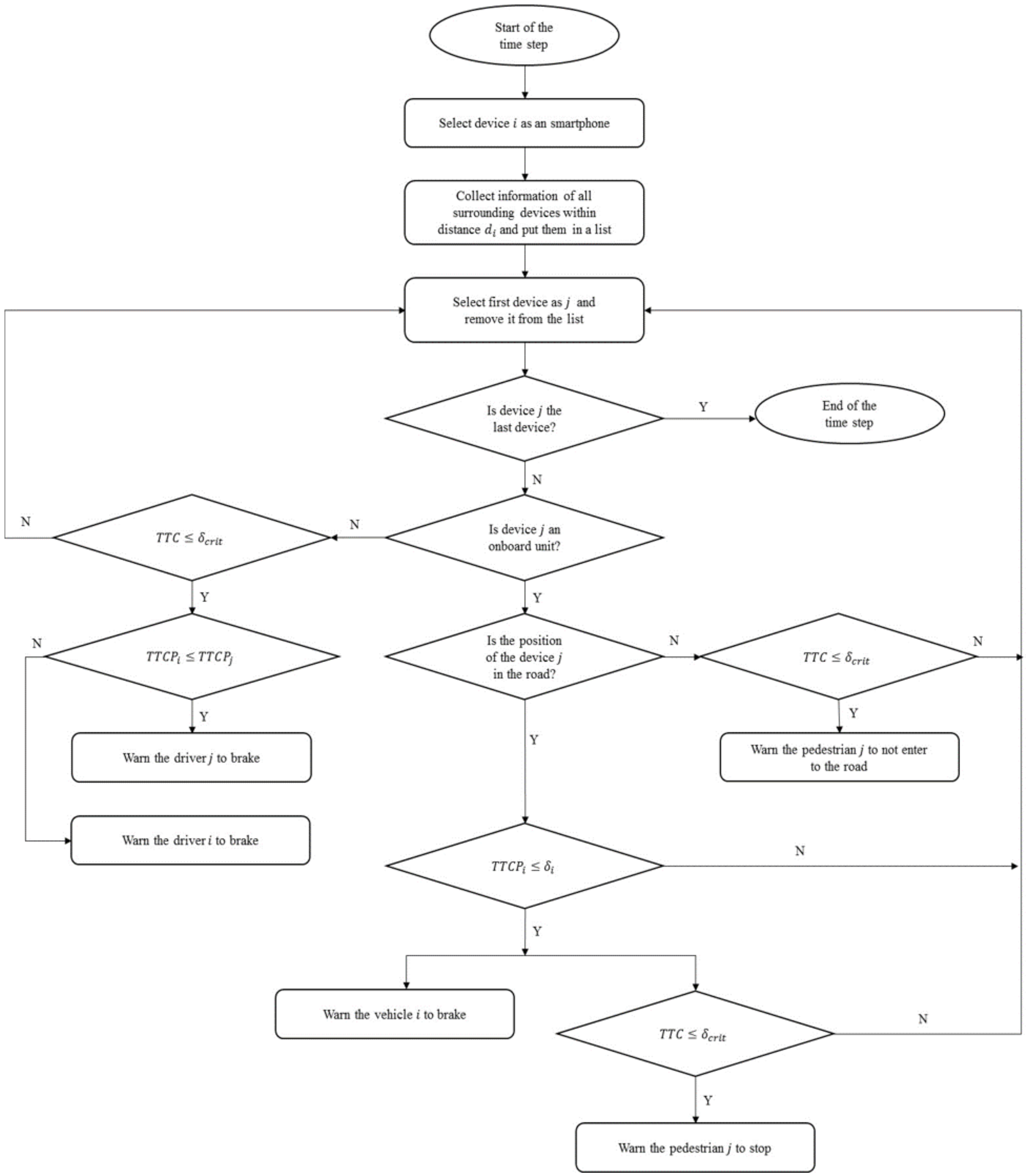

Figure 4.3: Algorithm for predicting crash risk between vehicles and pedestrians

If device j is a pedestrian's mobile device, then two conditions are possible: either the pedestrian is in the road or on the sidewalk (potentially walking along or standing still on the sidewalk). When the pedestrian is in the road and driver i reaches the critical distance ($TTCP_i \leq \delta_i$), a warning message will be sent to the corresponding driver to brake and yield to the pedestrian. However, in some cases the driver may not perform well or may not pay attention to the warnings. These cases are considered in this algorithm. In such situations, a warning message will continue to be sent to the driver, while warning messages will also be sent to pedestrian to stop or take the proper action. When the risky condition has been resolved, the warning messages will stop. Alternatively, if the pedestrian is on the sidewalk and there is a risky condition when $TTC \leq \delta_{crit}$, then a warning message will be sent to the pedestrian to stop moving forward and stay on the sidewalk until the risky condition has been resolved.

When device j is a vehicle onboard unit, the interaction can be different. In this case, when a risk of a collision is detected as $TTC \leq \delta_{crit}$, the warning message will be sent to the vehicle that has the higher value for time to reach the collision point. In other words, the closer vehicle will pass the conflict point while the farthest one will yield to it. It is assumed that the vehicles will start to reduce their speed with the maximum deceleration rate, as described in the previous section, when the warning message is sent to them. The value of the new speed can be estimated with Equation 12. In this equation, v_t is the current speed of the vehicle and v_{t+1} is the estimated speed for the next time step, where the length of the time step is Δt.

$$v_{t+1} = v_t + MaxD.\Delta t \qquad (12)$$

4.2 Simulation Evaluation Approach

To investigate the effectiveness of the proposed crash risk prediction algorithm, a simulation approach that allowed testing a variety of conditions was needed. In this study, the VISSIM microscopic simulator was used because it provided the tools required to simulate the CV condition and corresponding interactions between vehicles and pedestrians. A simulation test bed was created in VISSIM, and different scenarios were tested within it. This section describes the procedures for creating the test bed and the tested scenarios.

4.2.1 VISSIM

VISSIM is a popular traffic microsimulation software package that simulates driver behavior by using the Wiedemann car following model. In addition, it is able to simulate pedestrians' behavior and their interactions with vehicles. VISSIM provides the ability to export the results of a simulation as inputs to the SSAM. VISSIM also provides the opportunity to take control of vehicles and pedestrians with external logic through the COM interface. The latter feature of this software was desirable for this study because V2X communication provides more information to drivers that could be used to enhance the reactions of drivers and pedestrians in unsafe situations. The research team has used VISSIM extensively in the previous studies to model CVs in transportation networks (Islam and Hajbabaie, 2017; Mohebifard et al., 2019; Mohebifard and Hajbabaie, 2018a; Mohebifard and Hajbabaie, 2018b; Tajalli and Hajbabaie, 2018; Mirheli et al., 2018; Mirheli et al., 2019).

The earlier versions of VISSIM (e.g., VISSIM 5.00 and before) used to introduce a ready-to-use Car2X module for driving behavior that automatically made the equipped vehicles aware of unsafe situations and had them react accordingly. However, later versions of VISSIM (e.g., VISSIM 6.00 and after) do not offer this module. Moreover, using the predefined modules could be limiting. The VISSIM COM interface provides the opportunity to identify traffic conditions and control the behaviors of drivers and pedestrians in an online environment. For example, when a vehicle receives a warning message about the possibility of a collision, it will reduce its speed to maintain a safe distance. The structure for implementing the proposed safety performance algorithm in VISSIM is shown in Figure 4.4.

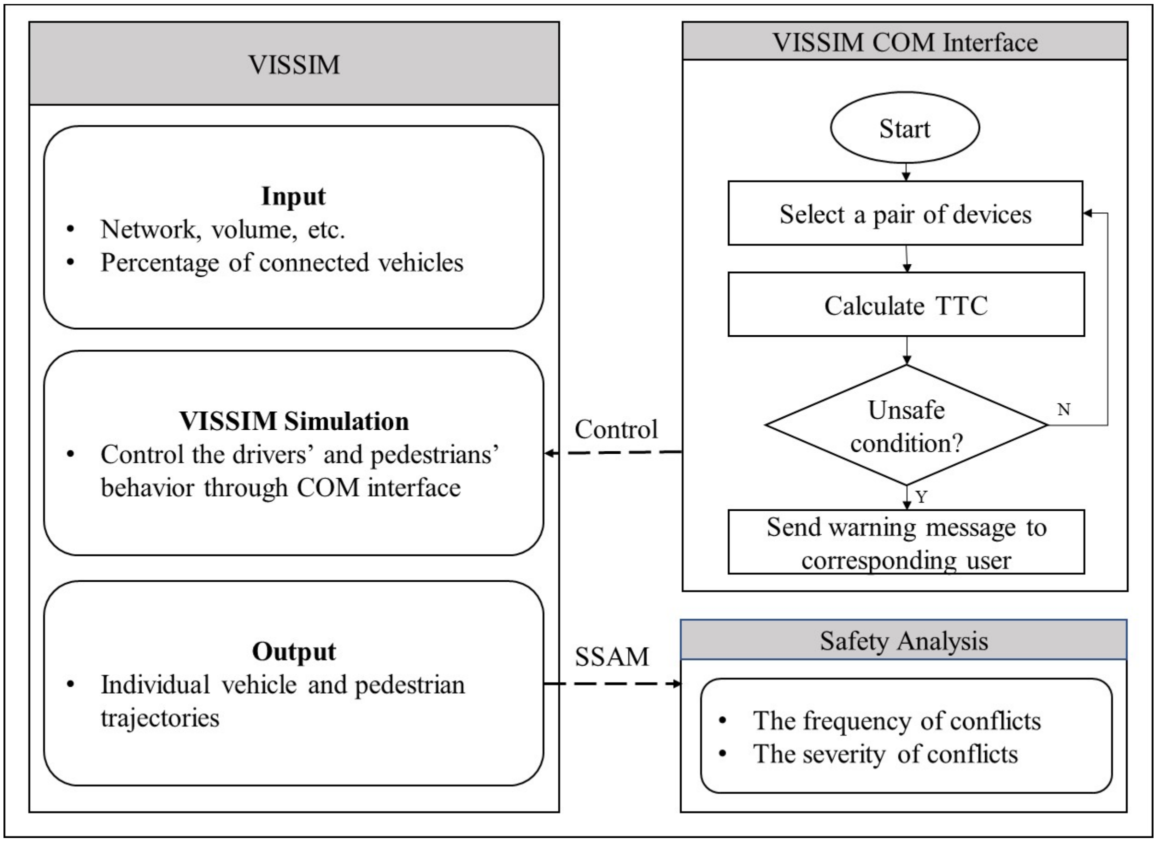

Figure 4.4: Structure of simulation within VISSIM

As shown in Figure 4.4, the network and the required inputs, such as the percentages of vehicles equipped with onboard units and the percentages of pedestrians equipped with smartphones, are predefined. Through the COM interface, the proposed crash risk prediction algorithm is implemented to detect risky situations by using information from vehicles and pedestrians that are connected to each other. Then, the time to collision can be estimated and used as a basis on which to change the behavior of users by changing their speeds. After each simulation run is complete, the trajectory file output of VISSIM is inserted into the SSAM, and the number of conflicts between vehicles and pedestrians, as well as their estimated severities, are found.

4.2.2 Simulation Test Bed

As previously mentioned, for this project, a simulation test bed was created in VISSIM. In order to best mimic real-world and safety-critical applications, it is important to have a bit of context regarding pedestrian crashes. According to NHTSA (2019), the majority of collisions resulting in pedestrian fatality occur in urban areas (80%). Further, NHTSA notes that regardless of vehicle type, the majority of fatal pedestrian crashes occur when the impact point is on the front of the vehicle (NHTSA, 2019). This scenario could occur in situations in which a vehicle is traveling straight, as well as making a turn, depending on how and where a pedestrian is crossing the road. Simulating the behavior of drivers and pedestrians in an urban intersection covers most of these cases. Therefore, a test network with a four-leg intersection with both vehicle and pedestrian movements was created to investigate the V2V and V2X communications and their corresponding impact on conflicts and crash risk. Figure 4.5 shows the studied network containing an intersection. Each approach of the intersection contained one exclusive left turn pocket and one lane for through and right turn movements.

This intersection had a symmetric shape with four legs. Each direction had one lane with a left-turn pocket. The studied intersection could be signalized or un-signalized. In addition, pedestrians could move through the intersection in all directions. When a vehicle is going straight, turning left, or turning right, there was potential for a conflict between the vehicle and pedestrians who were crossing the road. For this network, it was assumed that the vehicle speed limit was 50 km/hr and that pedestrians moved at a maximum speed of 5 km/hr. In this study, we worked with an un-controlled intersection without any signal or stop/yield sign to consider the worst-case scenario. Therefore, vehicles move freely on all incoming approaches until they receive a warning message to be aware of the unsafe situation. As a result, the effect of communications between connected vehicles and pedestrians could be evaluated by taking remedial action to prevent conflicts.

Furthermore, we assumed that vehicles on a lane follow each other based a car following model. Particularly, the Wiedemann car following model with VISSIM's default parameters was used. Vehicles and pedestrians on conflicting movements could collide in the absence of a warning message being issued at the intersection.

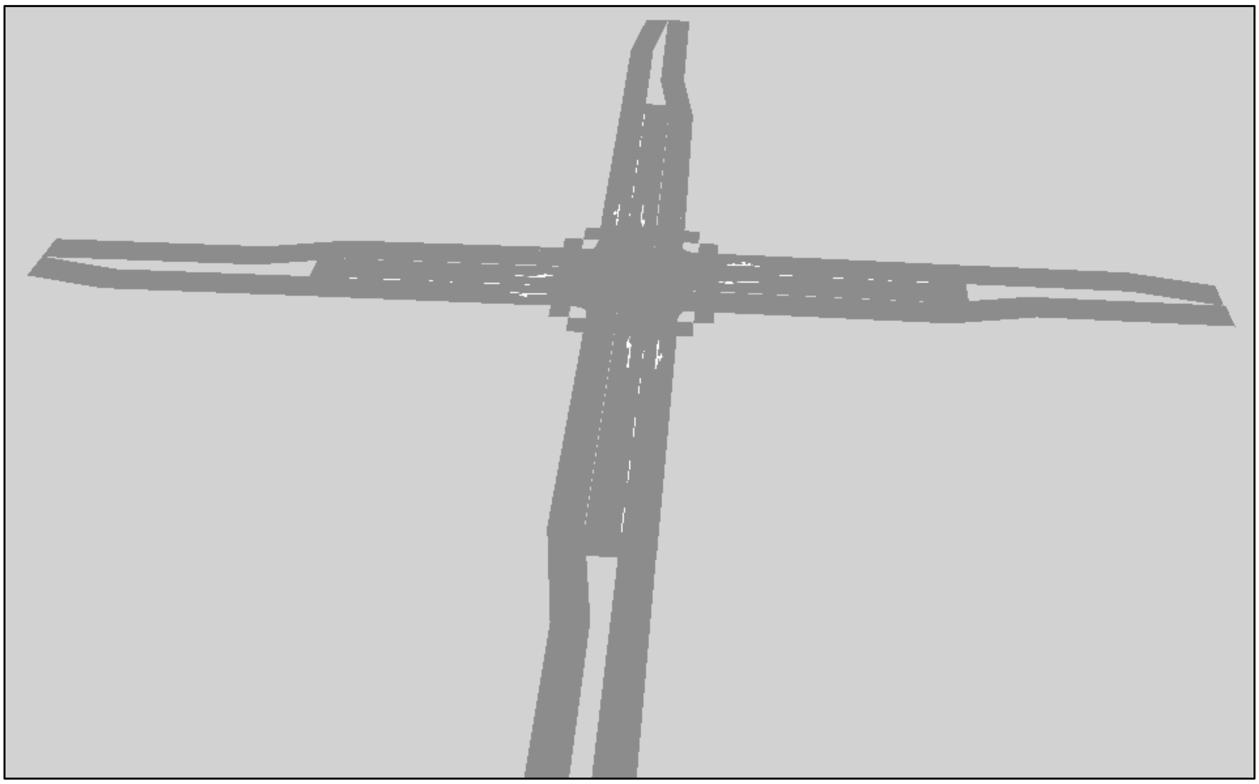

Figure 4.5: Simulation test bed

4.2.3 Simulation Scenarios

The intersection for this case study was un-controlled to increase the number of potential conflicts between vehicles and pedestrians. Such a situation helped better demonstrate the performance of the proposed algorithm. In this case study, pedestrians could move across the intersection in all directions. Vehicles could follow their preceding vehicles through behavior governed by a car following model and go straight, turn right, and turn left. The only control strategy to prevent conflicts is the proposed connected vehicle warning messages. It was expected that the proposed algorithm would address most of the possible conflicts between vehicles and pedestrians, as well as those between vehicles and other vehicles.

To compare the performance of the proposed algorithm under different conditions, several scenarios needed to be defined. Generally, a combination of two sets of scenarios, considering the volumes of vehicles and pedestrians and the penetration rates of the connections between them would indicate the performance of the algorithm in different situations.

Increasing the volumes increased the number of movements in the intersection. As a result, the number of interactions between vehicles and pedestrians increased. In this study, three volume levels at each approach of the intersection were considered: 100 veh/hr/lane, 200 veh/hr/lane, and 300 veh/hr/lane. It was assumed that the volume for pedestrians was 15 percent of the vehicular volume of the corresponding approach (i.e., 15 ped/hr/crosswalk, 30 ped/hr/crosswalk, and 45 ped/hr/crosswalk). It should be noted that the volumes at the four-leg intersection were symmetric.

The second important factor in the performance of the proposed algorithm was the penetration rate of the CVs in the network. If there was less communication between vehicles to vehicles and vehicles to pedestrians, a higher probability of conflicts would be expected. In this study four penetration rates were considered: 100, 75, 50, and 25 percent of the total number of vehicles and pedestrians.

4.3 Simulation Results and Discussion

In this section, the results from the simulation study based on the proposed conflict avoidance strategy described previously are presented. First, we describe the parameters that were fixed in the network. Then, the criteria used to define a situation as risky are explained, and finally, the results and their supporting discussion are provided.

4.3.1 Defining the Input Parameters

For the purpose of the analysis, the network was loaded with different volume levels, in different simulation runs. The vehicular volumes at the intersection were assumed to be symmetric, and the rates of turning and through-movements were defined before the simulation was run. In the case study, 70 percent of vehicles for each movement went straight, 15 percent of vehicles turned right, and 15 percent turned left. The volume for pedestrians was 15 percent of the volume for vehicles. Figure 4.6 shows the pre-defined volumes for each movement when the volume for each approach of the intersection is 300 veh/hr/lane.

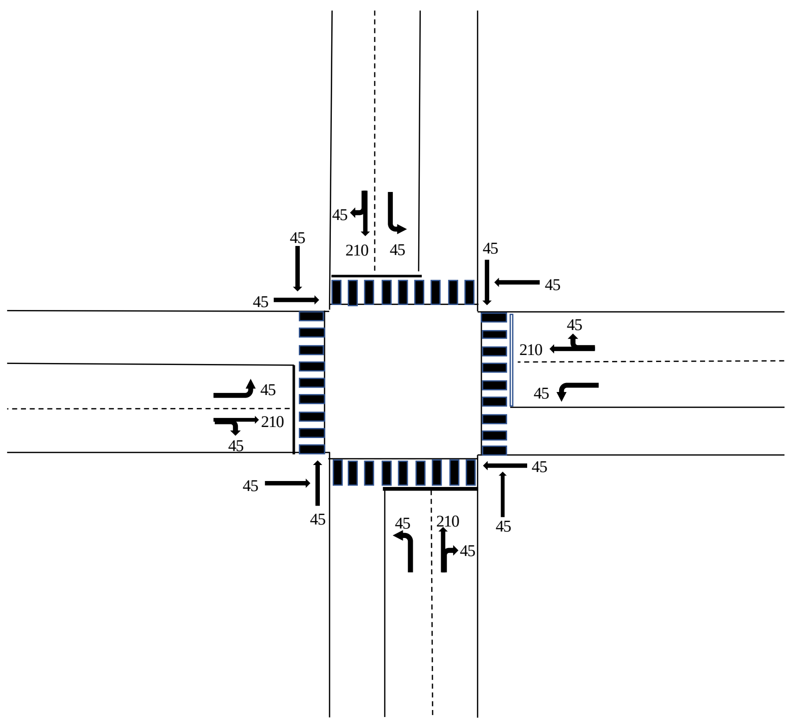

Figure 4.6: Volumes for each movement

In this case study, the users communicated with each other every 0.1 seconds, as the connected environment provides this capability. Note that smaller time steps for analyzing risk conditions give more accurate results. In addition, each of the equipped vehicles and pedestrians looked for surrounding users within a range of 100 meters. If they found an equipped vehicle, the connection occurred, and each device calculated the estimated TTC to define the risk of crash occurrence. When the TTC dropped to a value of less than the predefined threshold, then warning messages were sent to the users.

To test each of the described scenarios, several simulations were implemented to create randomness. Each scenario was repeated 10 times, which took 5 minutes. Recall that each user needed to measure the risk of a crash with the surrounding vehicles within a range of 100 meters. Therefore, several calculations necessary for this risk assessment were carried out in the underlying COM interface. As a result, the run time increased significantly for higher volumes, higher demands, and longer study durations. On the basis of the experimental results, 5 minutes was set to be the maximal simulation time for each simulation.

4.3.2 Selection of Threshold Value for Conflicts

Previous studies have suggested that the threshold for considering a conflict with respect to TTC should be 1.5 s (Gettman *et al.*, 2008; Hayward, 1972; Sayed, Brown and Navin, 1994). When the time to collision drops to less than 1.5 seconds, there is a high chance of a collision between a vehicle and a pedestrian. In general, smaller values of TTC indicate a higher risk of collision. Ultimately, when the value of TTC is equal to zero, we can say a collision has occurred.

VISSIM provides a trajectory file as an output of each simulation run that can be imported into the SSAM software. Given the predefined TTC threshold, SSAM will detect the number of conflicts and the safety measures corresponding to that conflict. On the basis of this approach, we analyzed the performance of the proposed crash risk prediction algorithm.

4.3.3 Results for Safety Measures

This section provides the results and analysis of the case study based on the predefined parameters and safety measures. As previously mentioned, TTC was considered to be the safety indicator. Table 4.1 shows the number of conflicts for each of the simulated scenarios. The results show that the number of conflicts increased when the volume in the network increased. In addition, increasing the penetration rate of connected devices decreased the number of conflicts.

Table 4.1: Numbers of conflicts in different scenarios

Volume / Penetration Rate	**25%**	**50%**	**75%**	**100%**
100 veh/hr/lane	10	4	2	0
200 veh/hr/lane	22	22	15	3
300 veh/hr/lane	71	46	36	11

Three types of conflicts between vehicles and pedestrians were possible in the simulation, and they included those in which a pedestrian was crossing the road and a vehicle was going straight, turning right, or turning left. Figure 4.7 shows the movements considered in the conflict scenarios in the case study. When the penetration rate was low, a conflict between a vehicle and pedestrian most commonly occurred when vehicles were going straight and pedestrians crossed the road. In addition, the conflicts for left turn movements were more frequent than conflicts for right turn movements. However, when the penetration rates increased, the total number of conflicts decreased, as did the number of conflicts with through-movements.

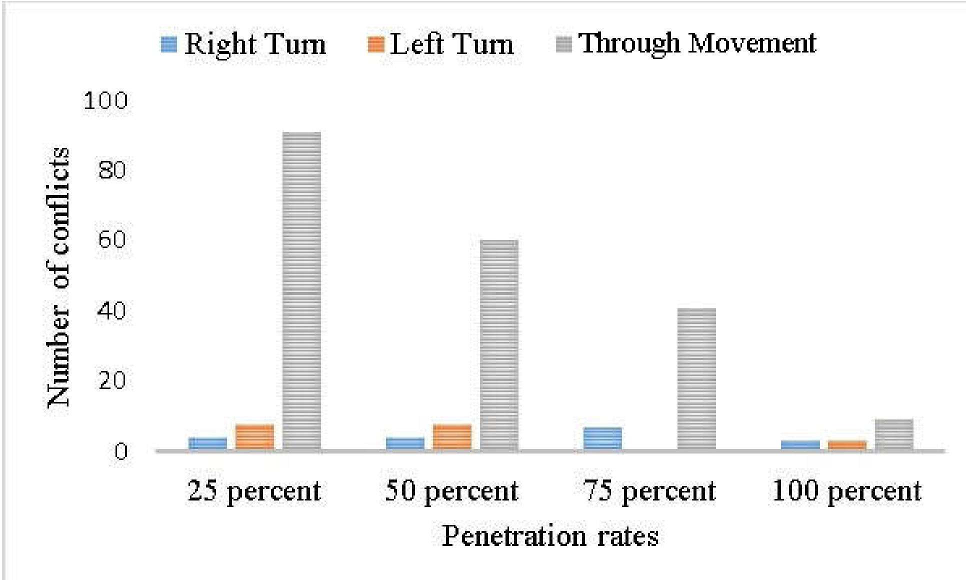

Figure 4.7: Numbers of conflicts based on movements and penetration rates

Figure 4.8 shows that increasing the volumes increased the number of conflicts for all movements. Specifically, the number of conflicts corresponding to through-movements increased substantially. The numbers of right turn and left turn conflicts also increased, but the rate of increase for right turn conflicts was higher than that for left turn conflicts.

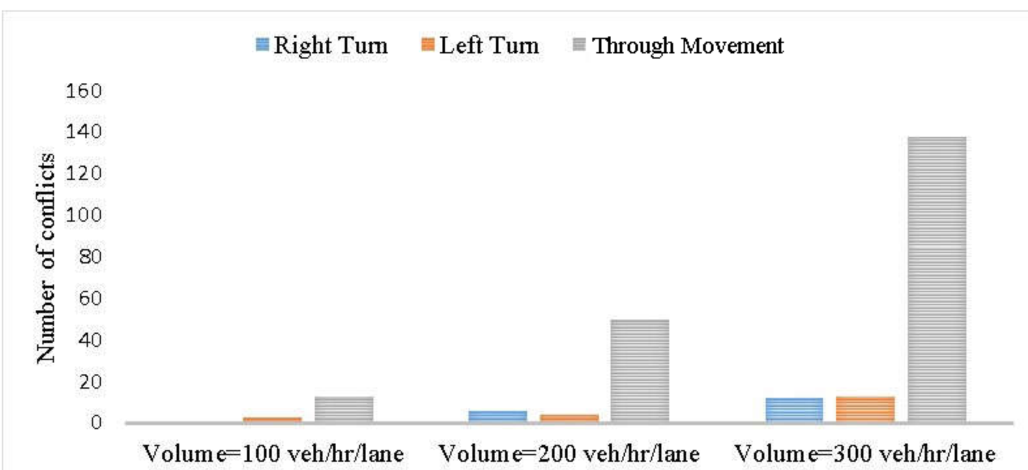

Figure 4.8: Numbers of conflicts based on the movements and volume

Figure 4.9 shows the decreasing rate of the number of conflicts based on the penetration rate for all of the different volume levels considered in the simulations. When volumes were higher, a simultaneous increase in the penetration rate of connected devices had a larger effect on decreasing the number of conflicts.

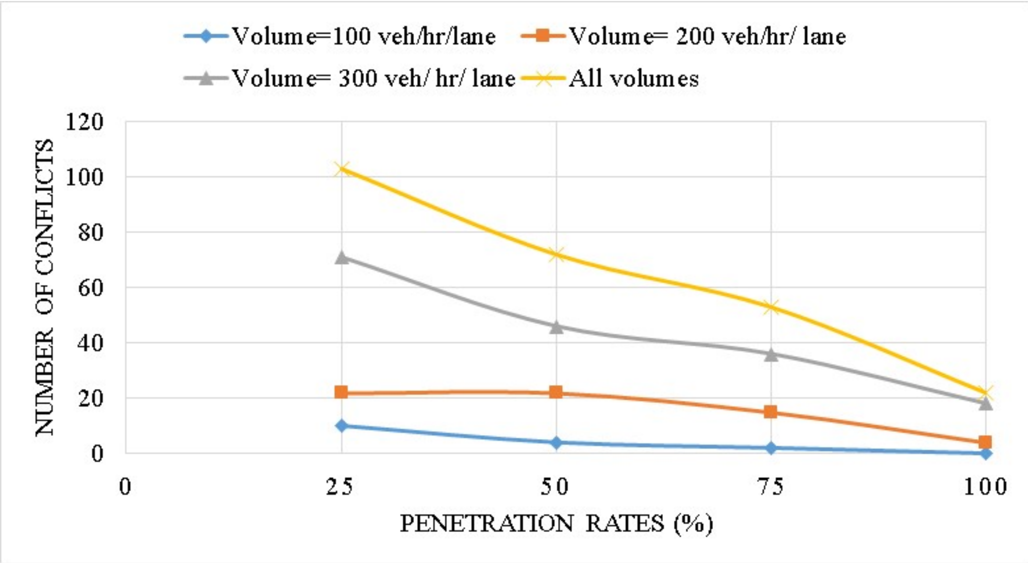

Figure 4.9: Relationship between the number of conflicts with penetration rates for different volumes

4.4 Summary

To summarize, the simulation network was tested under different scenarios, including different penetration rates and volumes. Each case was tested several times, and the results were compared. The findings were that the number of conflicts increased when the penetration rate of connected devices decreased. In addition, increasing volumes had a direct relationship with an increase in the number of conflicts.

In the simulation study, the number of conflicts between through-moving vehicles and pedestrians crossing the road was the highest. This was due to the higher volumes of vehicles that went straight (70 percent) than made turning movements. Increasing the penetration rate of connected devices reduced the number of through-moving conflicts significantly. The number of conflicts involving left turns and right turns also decreased. Generally, the number of conflicts decreased more rapidly when the penetration rate of connected devices increased among higher volumes.

5.0 Sensor Installation and Field Test at the Test Bed

As mentioned in Chapter 3, a large component of this project involved establishing a test bed in which the sensors developed in this project could be tested in a real-world setting. Initially, the plan was to install sensors along Montlake Blvd., near the University of Washington campus, but ultimately, for a variety of reasons mentioned in Chapter 3, the final plan involved instrumenting SR 522, just north of Seattle. The following sections describe the sensor installation and analysis of the data collected by the sensors during an initial period following their installation.

5.1 Sensor Installation

The sensor installation for this project occurred over a span of two days. On October 3, 2018, five MUST-II sensors were installed at the five intersections along SR 522 listed in Chapter 3. Each sensor was installed in a metal case similar to that shown in Figure 5.1, and each case was mounted on a light pole at the respective intersection on the eastbound side of SR 522. Each MUST-II was able to collect MAC addresses from mobile devices via Bluetooth or WiFi, as well as timestamp information at each of the five intersections. Such information could be used to determine the volume of sampled devices, as well as speed and travel time between the intersections. Additionally, as previously mentioned, the MUST-II sensors could serve as base stations to transmit data from the Smart Road Stickers back to the research team’s servers.

Figure 5.1: Metal case mounted on a light pole for MUST-II installation

The second day of the sensor installation took place on Thursday, November 8, 2018. On that date, STAR Lab researchers installed two Smart Road Stickers along the Burke Gilman trailside to the northeast and southwest of the trail's intersection with SR 104. To avoid any hazard to trail users as well as obstacles in the trail's clear zone, the sensors were installed on sign posts as shown in Figure 5.2 and Figure 5.3. The components of the Smart Road Sticker, as shown in Figure 3.2, were placed in a plastic waterproof case that could be installed on the sign posts, with a larger solar panel mounted atop the sign posts.

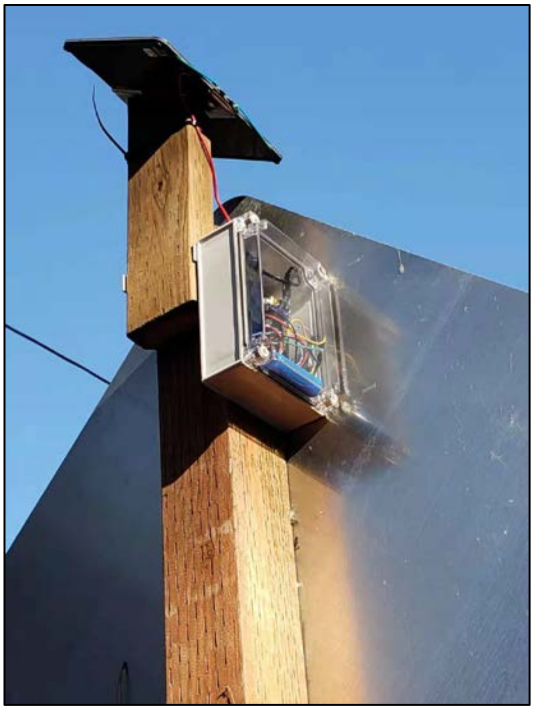

Figure 5.2: Smart Road Sticker in its case and a solar panel mounted on the northeast side of the trail

Figure 5.3: Smart Road Sticker in its case and a solar panel mounted on the southwest side of the trail

Because of a variety of constraints related to the safety and timing of the installation, the only data collected via the sensor installation along SR 522 were from the MUST-II sensors. That is to say, the safety algorithms and mobile app functionality/communication with the Smart Road Stickers, as described in Chapter 4, were not further tested at the SR 522 test bed. The research team hopes to further test the functionality of the Smart Road Stickers at the test bed in early 2019.

5.2 Data Analysis from Sensor Installation

Initial data collection and analysis for the data from the MUST-II sensors took place between October 17, 2018, and November 3, 2018. It is important to understand that the number of detections at each intersection was not the true volume but was indeed correlated with the true volume. The MUST-II sensors detected MAC addresses from mobile devices via Bluetooth and WiFi; therefore, the sensors could not determine the following:

(1) what mode of travel the device was associated with (e.g., vehicle vs. pedestrian),

(2) whether or not multiple detected MAC addresses were from the same vehicle (i.e., duplicate detections), or

(3) the exact location of the mobile device being detected beyond knowing that it was within the sensor's detection range at the given intersection.

With regard to the last point, this means that at a given intersection, it was not possible to tell which approach the detected device was on, nor which lane it was in; hence, the direction of travel could not be inferred when the data from only one detector were inspected.

For initial data analysis, the main focus was on the volumes of detected devices. The total numbers of detections per intersection per day by the five installed MUST-II sensors are shown in Figure 5.4. Each plot shows three time series of data: (1) the "Total" series shows the total number of detections across Bluetooth and WiFi; (2) the “Bluetooth” series shows the total number of detections via Bluetooth; and (3) the “WiFi” series shows the total number of detections via WiFi. Since each mobile device would likely be detected multiple times at a given intersection because the MUST-II was sensing at a frequency of multiple times per second, the number of unique detections was likely a more useful metric. This number was in essence the number of unique MAC addresses (and in turn mobile devices) detected at each intersection, each day, via Bluetooth or WiFi; these data are shown in Figure 5.5. From the figures, it can clearly be seen that in general, the number of devices detected via WiFi was much higher than the number detected via Bluetooth. This is not surprising, as in order for a device to be detected via Bluetooth, it must be in the “discoverable” mode.

Figure 5.4: Total number of detections per intersection per day

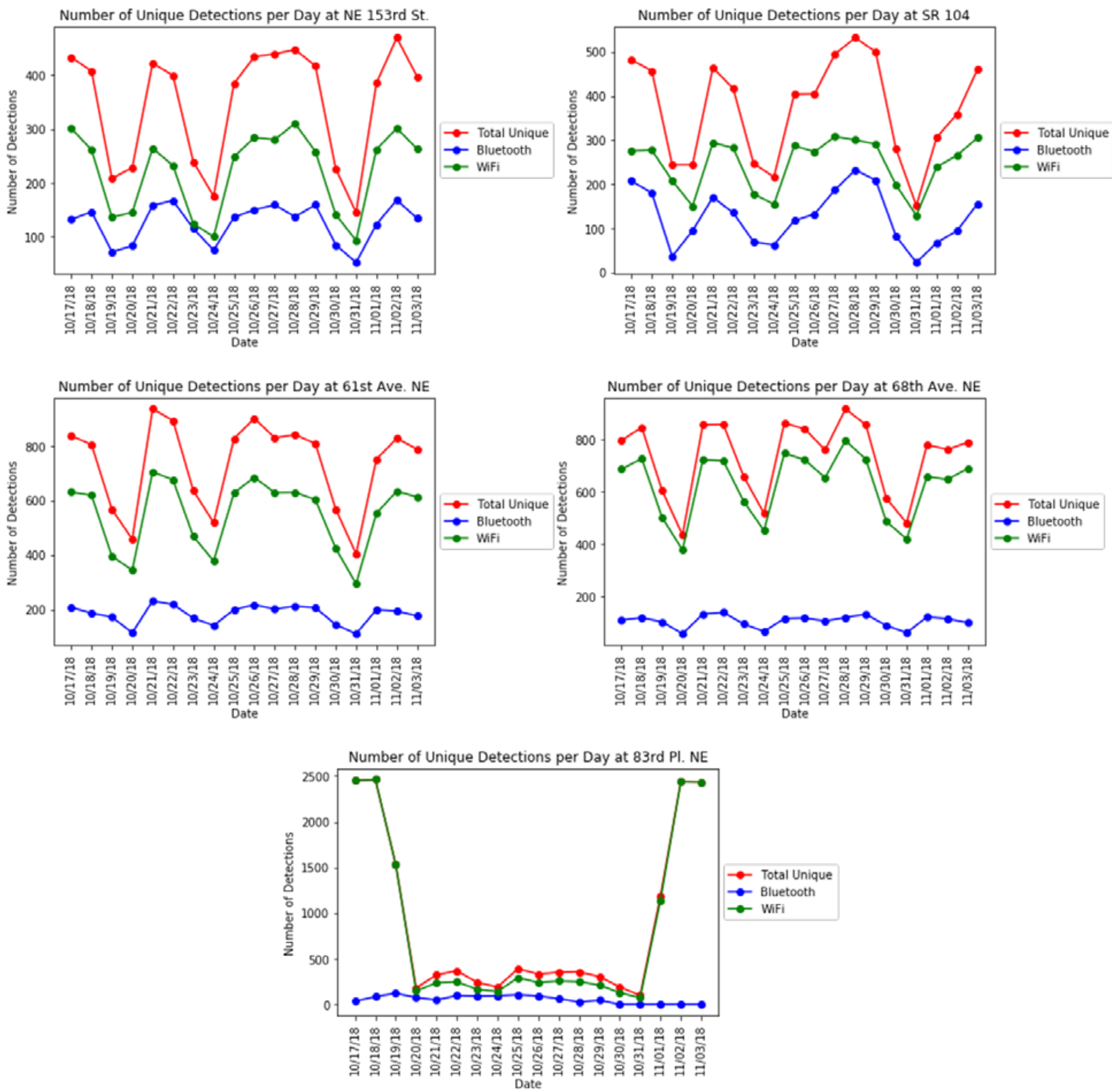

Figure 5.5: Number of unique detections per intersection per day

A summary and deeper dive into the detection data are shown in Table 5.1. The table shows summary statistics for the number of unique detections at each intersection computed across all days between October 17 and November 23, 2018. From the data, it can be seen that in considering the average number of unique detections across Bluetooth and WiFi, the number of detections increased traveling eastbound between the intersections, with the highest average number of daily detections of approximately 880 at the 83rd Pl. NE intersection. It can also be seen that the number of daily detections via Bluetooth was consistently lower than the number of devices detected over WiFi. On average, the numbers of WiFi detections were higher than corresponding Bluetooth detections by a factor of 1.78 to 15.09.

Table 5.1: Daily summary statistics of unique MUST-II detection data

	Total				
	NE 153rd St.	**SR 104**	**61st Ave. NE**	**68th Ave. NE**	**83rd Pl. NE**
Average	347	370	734	732	880
Standard Deviation	106	113	159	145	906
Minimum	145	151	404	434	98
Maximum	469	532	936	915	2462
	Bluetooth				
	NE 153rd St.	**SR 104**	**61st Ave. NE**	**68th Ave. NE**	**83rd Pl. NE**
Average	125	125	183	106	55
Standard Deviation	35	61	34	23	42
Minimum	52	22	110	57	0
Maximum	168	232	231	139	121
	WiFi				
	NE 153rd St.	**SR 104**	**61st Ave. NE**	**68th Ave. NE**	**83rd Pl. NE**
Average	222	245	551	627	825
Standard Deviation	73	58	126	123	939
Minimum	93	129	294	377	72
Maximum	310	308	705	795	2462

Another part of the initial analysis of the MUST-II data sought to compare the number of device detections to the annual average daily traffic (AADT). Along SR 522, WSDOT publicly reports AADT data at three locations via its online Traffic GeoPortal (WSDOT, 2017); the most recent values reported are from 2017 and they are the total volumes for both directions of travel:

- West of SR 104: 42,000 vehicles per day;
- East of 68th Ave. NE: 47,000 vehicles per day; and
- West of 68th Ave. NE: 38,000 vehicles per day.

As data on the directional distribution of volume along SR 522 was not available, an assumption was made that 50 percent of the AADT traveled in each of the two possible directions. In considering the total number of daily unique device detections, it was observed that MUST-II detections accounted for between 1.76. percent of the daily eastbound volume (at the SR 104 count station) to as high as 3.86 percent of the daily eastbound volume (at the count station west of 68th Ave. NE). Bluetooth detections accounted for between 0.44 percent and 0.56 percent of total eastbound daily volume, while WiFi detections accounted for 1.16 percent and 3.30 percent of total eastbound daily volume.

The final part of the initial analysis of the MUST-II data involved computation of travel times between the subject intersections. For this analysis, there are a few important things to note. First, results are only presented for the eastbound direction of travel along SR 522, as the detection range of the MUST-II was such that vehicles traveling westbound with mobile devices along SR 522 were essentially out of detection range. Next, the sample size used to compute the travel times was often quite small, and therefore was based on both Bluetooth and WiFi detections. To compute travel times between intersections, the same MAC address had to be detected at multiple intersections within a given time window set to filter out extraneous travel times (e.g., someone detected at an intersection stopped to eat dinner at a restaurant for one hour before driving past the next intersection with a MAC address detector). Furthermore, it was possible that a vehicle could drive past multiple intersections with detectors without being detected at all of them, depending on a number of considerations including proximity to the detector, whether their Bluetooth setting was in the discoverable mode, etc. Finally, it is important to note that because SR 522 is signalized, the travel times would often include control delay.

Travel times were computed between the subject intersections for weekdays (Monday-Friday) between October 17, 2018 and November 3, 2018 during the hours of 5:00 AM through 8:00 PM (the very early and late hours of the day had fewer device detections). The travel times in seconds computed between intersections equipped with MUST-II sensors during the AM and PM peak periods are shown in Table 5.2, and average travel times by hour of the day are shown in Figure 5.6. Because ground-truth travel time data were unknown, it is difficult to draw conclusions about the validity of the results. Again, the sample sizes used to compute the travel times were often quite small, in many cases fewer than five measurements, meaning the results must be interpreted with caution. Nonetheless, the point here was to demonstrate the functionality of the MUST-II sensors. In examining Figure 5.6, one can see some trends of AM and PM peak periods, although further analysis and data collection are both needed and warranted. The work presented here on travel times is but a preliminary analysis of the data collected via the MUST-II. Work for the future is described in the conclusions.

Table 5.2: Travel times (sec) computed between intersections along SR 522 eastbound for weekday peak periods

Intersections	AM (7-10)	PM (3-6)
NE 153rd St. to SR-104	343.15	243.90
SR-104 to 61st Ave. NE	158.06	173.85
61st Ave. NE to 68th Ave. NE	190.73	231.23
68th Ave. NE to 83rd Pl. NE	316.53	258.11

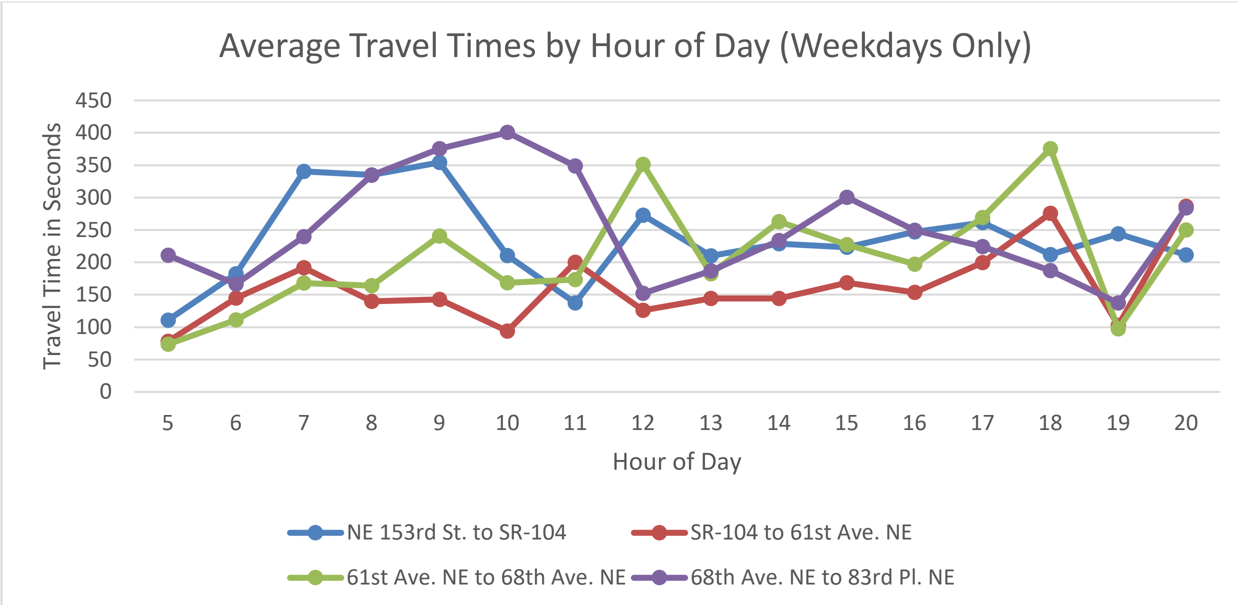

Figure 5.6: Average travel times by hour of day computed between intersections along SR 522 eastbound

6.0 Conclusions and Recommendations

6.1 Conclusions

The core contributions of this project are multi-faceted. First, a CN device known as the Smart Road Sticker was developed and tested. The SRS is capable of detecting mobile devices from both motorized and non-motorized users; hence, it has numerous applications in traffic sensing, such as collecting data on volumes, speeds, travel times, and origin-destinations. In this project, however, the focus of the SRS was to detect a mobile app that was developed to allow users to communicate with the SRS, as well as to receive pertinent safety information. The combination of the sensor and app presents a new frontier in connected vehicle research, as it allows non-motorized users without DSRC-enabled devices to take part in the equation. Namely, they can be detected and alerted of safety hazards in a manner similar to motorized users, which has the potential to greatly improve the safety of especially vulnerable travelers. Initial experiments showed that the SRS can reliably detect mobile devices from non-motorized road users who have the developed mobile app.

As a second contribution, a surrogate safety/crash risk prediction algorithm was developed for use in identifying conflicts between vehicles and pedestrians and ultimately preventing collisions between them. This algorithm relies on identifying both the estimated location of and time to collision. The performance of the algorithm was studied in a simulation test bed developed in the VISSIM traffic microsimulation platform. The simulation studied different traffic volumes and penetration rates of connected devices. From the simulation, it was observed that generally, the number of conflicts decreased with higher penetration rates of connected devices, when the penetration rate increased among higher volumes.

A final core contribution of this project was the development of a real-world test bed along SR 522 in Bothell, Washington. The test bed served as a location where the research team did and will continue to collaborate with WSDOT to test sensors under actual field conditions. In this project, a mobile sensor known as the MUST-II was installed for Bluetooth and WiFi MAC address sensing at five intersections along SR 522. In addition, two Smart Road Stickers were installed along the side of the Burke Gilman trail near a location where the trail crosses SR 104. The installation allowed the research team to investigate how their sensors work outside of a lab setting, as well as collect data on travel patterns in the Bothell area. In the near future, the team hopes to further test the mobile app and corresponding communication capabilities with the SRS in the field at the SR 522 test bed.

6.2 Recommendations for Further Study

In terms of future work, first and foremost, continued testing of the SRS and mobile app are needed in the field. Specifically, the safety alerts being generated and communicated to the mobile app of conflicts among road and trail users need to be further tested. At present, the mobile app was tested only in a smaller-scale experiment on the UW campus before deployment of the SRS in the field. The research team is working on improving the app and hopes to do further testing in the near future. Additionally, installation of Smart Road Stickers at other locations along the Burke Gilman trail would also be beneficial for increasing the sample size of detections and studying how the device functions under different conditions (e.g., different trail geometry, different lighting conditions, etc.).

Next, the team hopes to further analyze the data collected from the MUST-II sensors to compute more reliable travel times, speeds, and travel time reliability metrics, and to examine other travel patterns along SR 522. This will require (1) more data collection and (2) access to ground-truth travel time data. The team has computed similar metrics for data collected via the MUST-II sensor in Tianjin, China, and hopes to visualize the results at the test bed on the UW STAR Lab's Digital Roadway Interactive Visualization and Evaluation Network (DRIVE Net, http://www.uwdrive.net) (Ma, Wu, and Wang, 2011) in the near future. Finally, the team hopes to continue to work with WSDOT to instrument the real-world test bed site with new sensors they are continuing to develop.

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