ENHANCING SAFE TRAFFIC OPERATIONS USING CONNECTED VEHICLES DATA AND TECHNOLOGIES

FINAL PROJECT REPORT

by

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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 mixed-use roadway networks. With this information, transportation system users can be alerted of potential conflicts prior to their occurrence, allowing them to take preventative actions, perhaps by making evasive maneuvers. A comprehensive review of the literature was made to investigate existing vehicle-to-X (V2X) safety applications. The methods to allow a sensor to communicate via both dedicated short range communications (DSRC) and Bluetooth, WiFi, or another communication protocol commonly used by mobile devices were also investigated, as were 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 published materials so far.

   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 LoRa and DSRC, and with pedestrians, bicyclists, and unconnected vehicles through cell phones and other mobile devices via Bluetooth. A 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 prediction algorithm was developed to identify unsafe conditions and to determine appropriate, CV-based safety countermeasures to be presented to system users. Finally, 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. This study found that the number of conflicts increased when penetration rates decreased. In addition, increasing volumes had a direct relationship with an increase in the number of conflicts.

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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

Acknowledgments

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 (V2X) systems communications. In a connected environment, road users (drivers and pedestrians/bicyclists) will receive warnings that inform them of potential hazards through visual displays, audible warning messages, etc. These warnings will increase roadway users' awareness of hazards and other dangerous situations they may not otherwise know about. As a result, drivers for example, 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, the safety benefits of V2X communications have not been found in published materials so far.

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 mixed-use roadway networks. With this information, transportation system users can be alerted of potential conflicts prior to their occurrence, allowing them to take preventative actions, perhaps by making evasive maneuvers. A comprehensive review of the literature was made to investigate existing V2X safety applications. The methods to allow a sensor to communicate via both dedicated short range communications (DSRC) and 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, the safety benefits of V2X communications have not been found in published materials so far. 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 LoRa and DSRC, and with pedestrians, bicyclists, and unconnected vehicles through cell phones and other mobile devices via Bluetooth. A 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 prediction algorithm was developed to identify unsafe conditions and to determine appropriate, CV-based safety countermeasures to be presented to system users. Finally, 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. This study found that the number of conflicts increased when the penetration rate of connected devices decreased. In addition, increasing the volume of pedestrians, bicyclists, and vehicles had a direct relationship with an increase in 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 was due to higher volumes of vehicles that go straight (70 percent of the total volumes of vehicles). Increasing the penetration rate reduced the number of through-movement conflicts significantly. Moreover, the number of conflicts for left turns and right turns decreased as well. Generally, the number of conflicts decreased with higher penetration rates, when the penetration rate increased among higher volumes.

1.   Introduction

In 2014, 4,884 were pedestrians killed in traffic crashes in the United States. In addition, about 65,000 pedestrians were estimated to be injured. In other words, a pedestrian is killed approximately every two hours and injured every eight minutes in the United States (NHTSA 2014). These statistics indicate the importance of targeting pedestrians in developing new traffic safety-related technologies. In this section, different factors that can influence the safety of pedestrians are discussed, and pre-crash scenarios are summarized to get a better idea about vehicle-pedestrian near-collision situations. Next, different studies that tried to address pedestrian safety by utilizing connected vehicle (CV) technologies are reviewed in order to investigate the approaches that have been used to "connect" pedestrians to vehicles and reduce the probability of accidents and injury severity.

1.1 Risk Factors in Pedestrian Crashes

A pedestrian in an incident is defined as "any person on foot, walking, running, jogging, hiking, sitting, or lying down who is involved in a motor vehicle traffic crash" (NHTSA 2014). There are several factors that can affect the probability of a crash occurring between pedestrians and motor vehicles. Generally, these factors are divided into pedestrians' characteristics, behavioral human factors, and other factors related to the physical environment. Most previous studies have tried to estimate the frequency and severity of crashes between pedestrian and vehicles by considering these three factors. In these studies, statistical analyses were utilized to find the relationship between the frequency and severity of crashes and the corresponding risk factors.

The pedestrian-related characteristics considered in such studies have often included demographic and socio-economic factors. Several studies have found that these factors have

significant effects on the occurrence of accidents. As Ukkusuri et al. (2011) showed, pedestrians in African-American or Hispanic neighborhoods in New York City experience more crashes with vehicles. In addition, they found a positive relationship between the number of crashes and the uneducated population of an area. Analysis of 217 pedestrian traffic fatalities in Seattle, Washington, between 1990 and 1995 indicated that the highest fatality rate for pedestrians was for the age group comprising people 70 years and older. In addition, males had a 50 percent higher fatality rate than females (Harruff et al. 1998). Lee and Abdel-Aty (2005) confirmed that higher age and being male had a positive association with the fatality rates and severity of accidents at urban intersections. In addition, some studies have shown that people younger than 15 years old are associated with higher probability, in terms of both frequency and severity, of accidents (Sarkar et al. 2011). On the basis of previous studies, age and sex appear to be the two most important pedestrian characteristics related to pedestrian crashes.

In addition to pedestrians' characteristics, their behavior has a significant impact on the occurrence of accidents. Alcohol involvement is one of the major causes of pedestrian crashes (Jang et al. 2013). Alcohol was a factor in 48 percent of all pedestrian crashes in the United States in 2014 (NHTSA 2014). In addition, using cell phones while crossing the road increases the probability of an accident significantly (Jang et al. 2013; Byington and Schwebel 2013). To illustrate, Nasar and& Troyer (2013) provided a hypothetical situation and asked people to cross the road when they were texting or talking on their cell phone. The results of their study showed that using a cell phone decreases pedestrian awareness significantly and increases the potential for more severe crashes when total pedestrian injuries are considered.

Factors related to the physical environment mostly concern characteristics of the road, land use, and weather and lighting conditions. For example, areas with greater numbers of

schools and commercial activities have a higher risk of pedestrian accidents (Ukkusuri et al. 2011). As Prato et al. (2012) showed, there are direct associations between the frequency of accidents and crossing the crosswalk far from the intersections, crossing from hidden places, and crossing the road at night. In addition, the width of the road has a significant effect on both the severity and frequency of accidents (Fernandes et al. 2012; Lee and Abdel-Aty 2005). Furthermore, the probability of severe accidents is greater along rural roadways and high speed urban roads (Tarko and Azam 2011). Fatality risk is higher in locations with no means of traffic or signal control than in locations that have stop signs or signal control (Sarkar et al. 2011). In terms of weather and lighting conditions, Jang et al. (2013) showed that the severity of accidents increases at nighttime, on weekends, and during periods with rainy weather. Traffic flow, the number of pedestrians, and speed limist are also important factors in pedestrian crashes. A study by Schneider et al. (2013) on 22 intersections around the campus of the University of California Berkeley showed that the risk of accidents is higher when pedestrian volumes are lower.

1.2 Pre-Crash Scenarios and Crash-Prone Areas in the Urban Network

The studies mentioned in the previous section were based on pedestrian crash data collected after the occurrence of the accidents. However, to prevent accidents from occurring, one must perceive dangerous conditions before an accident occurs between a pedestrian and an approaching vehicle. Therefore, some studies have focused on scenarios that may happen before pedestrian-vehicle accidents and have prioritized the scenarios on the basis of the harmfulness and frequency of their occurrence. Ultimately, the goal of such studies has been to prevent these crash types using solutions that apply new technologies. Jermakian and Zuby (2011) considered a five-year (2005-2009), nation-wide data set from the National Automotive Sampling System General Estimates System (NASS GES) and the Fatality Analysis Reporting System (FARS) in

the United States to develop a pedestrian detection system. They investigated factors such as vehicle movement, pedestrian movement, and driver view obstruction. On the basis of this analysis, the most critical scenario occurs when a vehicle moves straight (i.e., a though-movement) and the pedestrian crosses the road perpendicular to the path of the vehicle. The second most critical scenario in terms of frequency and severity of accident is when a vehicle goes straight and the pedestrian travels along the vehicle's path of movement. Another critical scenario happens when a vehicle is turning and the pedestrian crosses the road in the vehicle's turning path. In addition, the results indicated that most fatal vehicle-pedestrian accidents happen in non-daylight conditions and where the speed limit is higher than 40 mph.

Lenard et al. (2011) used the national accident database for Great Britain, STATS19, for the years from 2000 to 2010 to find typical accident scenarios for pedestrian accidents. They considered several factors that are associated with accident circumstances, such as speed limit, weather and light conditions, vehicle and pedestrian movements, obstructions to the line of sight, and vehicle speed. As a result of their analysis, three typical pre-crash scenarios were identified: (1) a pedestrian crosses the road when a vehicle is moving straight without any obstruction in the line of sight, (2) a pedestrian crosses the road when there is an obstruction to the line of sight for the driver, and (3) an adult pedestrian crosses the road when there lighting and weather conditions are inclement. The National Traffic Safety and Environment Laboratory in Japan set up camera recorders in front of one hundred taxis in Tokyo between 2005 and 2009 to detect near-collision circumstances between vehicles and pedestrians in the real world (Matsui et al., 2011). On the basis of this study, 163 near-collision events were detected, of which about 47 percent happened in the daytime and 53 percent happened at night. In 23 percent of the cases, an adult was crossing the road in a crosswalk at the intersection during the daytime, while 29

percent of the cases happened at night. In addition, 12 percent of the near collision events happened when an adult was crossing the road outside the crosswalk in a location far from the intersection in the daytime, while 18 percent of the cases occurred at night. In other cases, a child was involved in the near collision event.

DaSilva et al. (2003) considered a pedestrian crash data set with records collected from 1995 to 1998 in the United States. The analysis was conducted using a four-year data set from the 1995-1998 NASS/GES and FARS crash databases from the National Highway Traffic Safety Administration. On the basis of this study, 10 pre-crash scenarios were defined considering vehicle maneuvers and pedestrian actions. Most of the pedestrian crashes happened away from intersections (55 percent), while 40 percent of the crashes occurred at intersections. The pre-crash scenarios considered were as follows:

- "Vehicle is going straight and pedestrian is crossing the roadway at a nonjunction (25.9%).
- Vehicle is going straight and pedestrian is crossing the roadway at intersection (18.5%).
- Vehicle is going straight and pedestrian is darting onto the roadway at nonjunction (16.0%).
- Vehicle is turning left and pedestrian is crossing the roadway at intersection (8.6%).
- Vehicle is turning right and pedestrian is crossing the roadway at intersection (6.2%).
- Vehicle is going straight and pedestrian is walking along the roadway at nonjunction (3.7%).
- Vehicle is going straight and pedestrian is darting onto the roadway at intersection (2.5%).
- Vehicle is backing up (2.5%).
- Vehicle is going straight and pedestrian is not in the roadway at non-junction (1.2%).
- Vehicle is going straight and pedestrian is playing or working in the roadway at non-junction (1.2%)."

Yanagisawa et al. (2014) used the GES, FARS, and Pedestrian Crash Data Study (PCDS) data sets for vehicle-pedestrian crashes to identify the most important pre-crash scenarios. In this study, the movements of the vehicles were divided into classes for going straight, turning right, and turning left. Additionally, the pedestrian maneuvers included improper crossing of the road, darting/ running onto the road, walking with/against traffic, and being inattentive. It was shown that the frequency of vehicle-pedestrian crashes was relatively high when the vehicle was turning, but the severity was less because the vehicle was traveling at a lower speed. However, crashes involving vehicles that traveled straight (i.e., through-movements) had the highest fatality rates.

To define pre-crash scenarios, Yanagisawa et al. (2014) also took into account the physical setting of the roadway in the crashes. The possible locations of vehicle-pedestrian crashes were considered as follows: intersection and non-intersection. Although most of the accidents happened at intersections (50 percent in the GES data set), the injuries were less severe because the vehicles in such crashes typically traveled at lower speeds. On the other hand, most of the fatal crashes occurred at non-intersection locations (69 percent in GES and 81 percent in FARS) because of the vehicles' higher speeds. On the basis of the GES statistics, 44 percent of crashes at intersections occurred in the crosswalk, while 90 percent of crashes at non-intersection locations occurred outside of the crosswalk. The fatality rate of crashes outside of the crosswalk was significantly higher, as two thirds and 92 percent of fatalities at intersections and non-intersection locations, respectively, occurred outside of the crosswalk. In addition, the roadway profile was considered in the crash data sets. About 92 percent and 77 percent of the crashes occurred on straight and level roads, respectively.

As a result of these analyses, Yanagisawa et al. (2014) proposed four pre-crash scenarios to cover the most frequent and injury-prone crashes between pedestrians and vehicles. Figure 1.1 shows these four scenarios. Scenario 1 is the most common case in all vehicle-pedestrian crashes, in which a vehicle goes straight on a level road and the pedestrian crosses the roadway. This scenario can be considered for both intersection and non-intersection locations. In scenario 2 the vehicle turns right and the pedestrian crosses the roadway. Scenario 3 is similar to scenario 2, but the vehicle turns left. In scenario 4 the pedestrian is walking in the same direction as the vehicle is moving. Although scenario 4 does not occur as frequently as the others, it results in a highly fatal outcome. In these scenarios, the pedestrian may cross the road through a crosswalk or be outside of it.

Scenario 1   Scenario 2
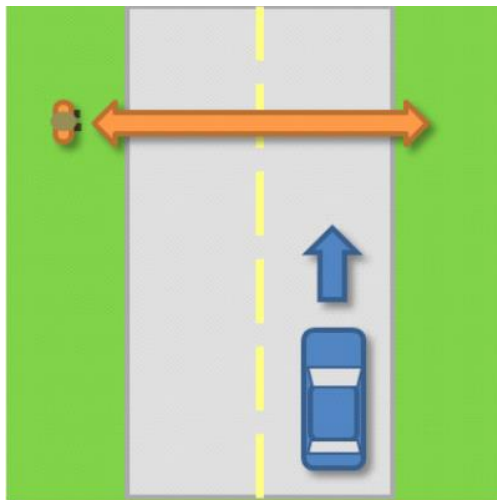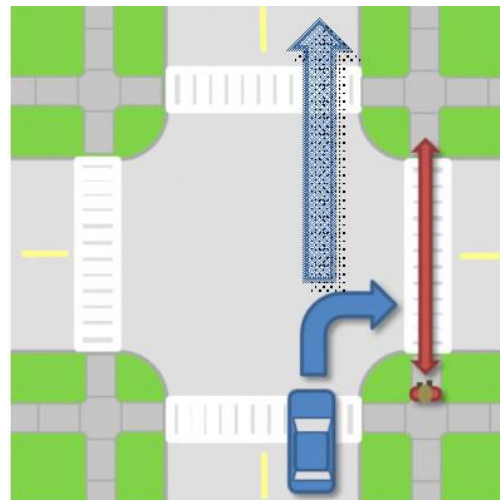
Scenario 3	Scenario 4
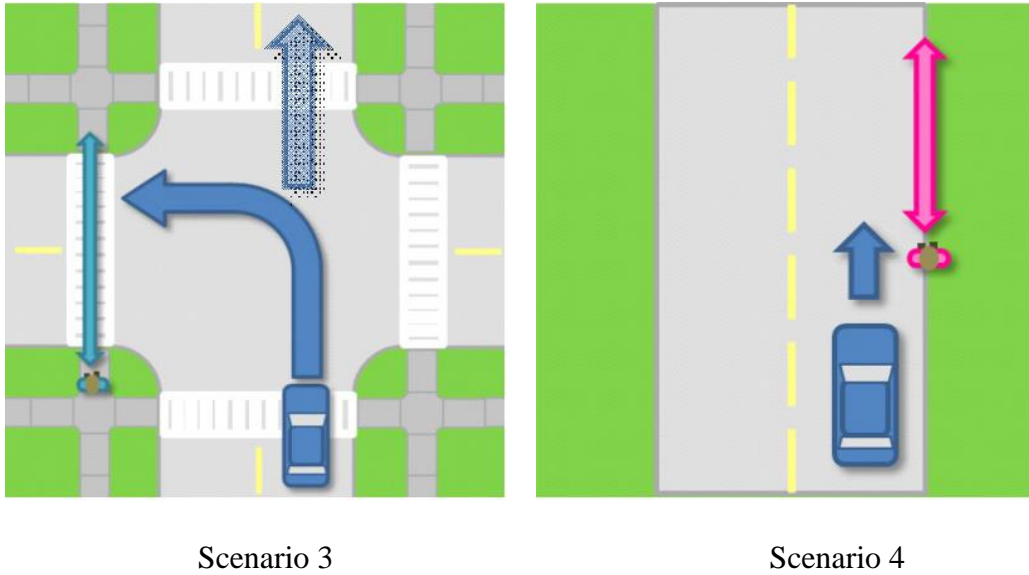
Figure 1.1 The most common pre-crash scenarios (Yanagisawa et al. 2014)

Environmental factors were considered for these four scenarios in the available data sets. The analysis showed that about 80 percent of these scenarios happen under normal (i.e., non-adverse) weather conditions. More than 50 percent of cases for scenario 1, scenario 2, and scenario 3 occur under daylight conditions, but 61 percent of the cases for scenario 4 happen in dark conditions. In addition, the surface condition of the road is dry for more than 80 percent of crashes under all scenarios (Yanagisawa et al. 2014).

2.   Literature Review

A comprehensive review of the literature focusing on the best available technologies and methodologies for ensuring cyber security and protecting user privacy is presented in this chapter. On the basis of the literature review, a preliminary system architecture was developed for the communication node (CN) device and mobile application described in the following chapters.

2.1 V2X Safety Application

Connected vehicle (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 communications. 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 would 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 current 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 and others 2005). These are helping to reduce the probability of collisions occurring and near-collision events significantly. In fact, several types of warning messages, such as forward collision warnings, lane change warnings, do-not-pass warnings, and control loss warnings, already make drivers aware of crash-prone situations. Although V2V communication provides effective tools to reduce the number and severity of the crashes, it cannot address all possible types of crashes. Thus, V2I communication that makes use of roadside equipment such as signal controllers is considered to be another means to improve safety through CV technologies. For example, Maile et al. (2008) developed a cooperative intersection collision avoidance system to warn drivers about violation of stop signs

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or traffic signals. Moreover, the information from signalized crosswalks can be sent to approaching vehicles as a warning message to make drivers aware of the presence of pedestrians in the crosswalk (ITERIS, 2017).

2.2 Senor Detecting Technologies

Even though V2V and V2I communications address a significant number of kinds of crashes, a gap remains in terms of connecting drivers and pedestrians, bicyclists, and motorists to each other. Thus, V2X communication is needed. In addition to applications of V2X communications, some studies have tried to detect the presence of pedestrians near vehicles by using sensors to avoid an accident when a vehicle moves forward and the emergency braking system is available. Yanagisawa et al. (2014) developed a pedestrian crash avoidance/mitigation (PCAM) system to detect a pedestrian in front of a vehicle with radar and a camera. This system applies the brake automatically when a 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 accidents between vehicles and pedestrians and extracted detailed information in terms of safety factors and injury severity. Then, the accident scenarios were reconstructed in a simulator while the brake assist system and antilock braking system features were added to vehicles. In most of the cases the collision could not have been avoided, but the injury severity probability and collision speed were reduced significantly.

Although efforts at using on-board sensors and computer vision techniques to activate automatic braking systems may be helpful to prevent possible collisions between vehicles and pedestrians and bicycles, their performance may not be satisfactory when visibility is poor , the

pedestrian is far from the detecting device, or the pedestrian is not in the line of sight of the sensor. V2X technology may provide the opportunity to fill this gap by using DSRC or cellular network technologies, especially as smart phones are becoming more prevalent among people within all age groups.

2.3 Communication System for Delivering the Warning Message

Wu et al. (2014) developed a communication system between vehicles and smart phones that used DSRC technology through a collaboration between Honda and Qualcomm. In addition, information about the position of the pedestrian was extracted from smart phone's GPS and inertial system, and the pedestrian's path was predicted by 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 communication between drivers and pedestrians, a warning message can be sent to drivers, pedestrians, or both parties. Hussein et al. (2016) indicated that sending the warning messages to both the pedestrian and vehicle led to better safety performance. Anaya et al. (2014) assumed that only pedestrians would receive the warning and would have to take proper crash mitigation actions. The study investigated the performance of the developed application V2ProVu, which applies Wi-Fi communications, measures the risk of the situation, and sends the proper warning message to the pedestrian's smart phone. The results of the study indicated that blockage between the vehicle and pedestrian reduced the performance of the application. In

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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 the error of the GPS data from cell phones was about 10 meters for 95 percent of the observations, although the error for longitudinal position was less than 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 sending them. David and Flach (2010) provided some criteria for filtering unnecessary messages. For example, a warning message will be sent to pedestrians when their movement directions are toward the street. In addition, assuming the maximum speed for a pedestrian will indicate whether he/she will get to the collision point before the car's passing and whether the message should be sent. More sophisticated filters may 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 Algorithm

The occurrence of an accident 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, currently developed crash prediction models are designed to estimate the frequency or severity of accidents on the basis of the safety factors explained in section 2.1. In addition, the predictions from such models may not be highly accurate. 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 accidents.

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 the 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 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. Gettman and Head (2003) developed a software application called the Surrogate Safety Assessment Model (SSAM) to detect a conflict between a pair of vehicles and analyze the outcomes of a simulation directly by using the trajectories of the vehicles. SSAM calculates several surrogate safety measures automatically and provides the results for the total study period. The surrogate measures shown as outcomes of SSAM are 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 possible collisions between vehicles and pedestrians, TTC is most commonly selected as the safety surrogate measure, and risk estimation algorithms are defined on the basis of this measure. The general framework for risk estimation with smartphones or on-board units in vehicles for each time step in different studies is shown in Figure .1 (Wu et al. (2014); Hussein et al. (2016); Anaya et al. (2014); Sugimoto et al. (2008); David & Flach (2010)). The onboard units in vehicles and smartphones 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 is estimated. TTC can be calculated on the basis of Eqs. **Error! Reference source not found.** and **Error! Reference source not found.** 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 to react and brake with maximum deceleration until the vehicle stops completely.
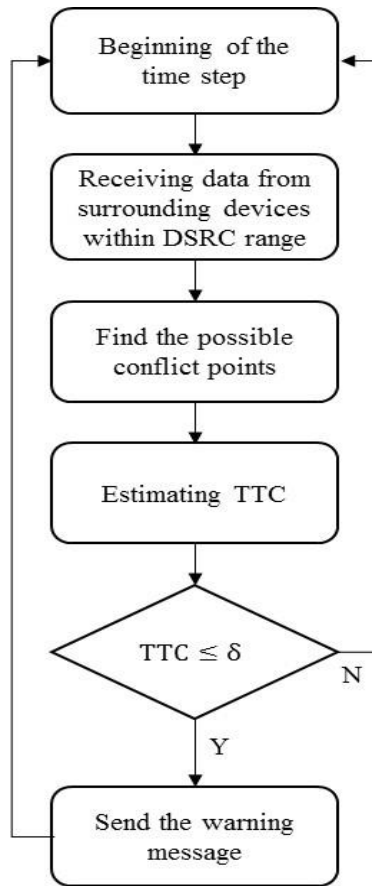
Figure 2.1 Risk estimation framework

2.5 Simulation Technologies and Methods in a CV Environment

Many types of traffic flow simulation (TFS) tools exist (e.g., VISSIM, Paramics, Aimsun, SUMO, etc.), but none of them is able to simulate the entire communication process. Certain communication network simulation (CNS) tools exist as well (e.g., NS2, Qualnet, Jist/SWANS, GloMosim, etc.), but none of them is 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).

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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.   Development of the CN 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 related to pedestrians to drivers of motor vehicles (Sugimoto et al., 2008; Hisaka and Kamijo, 2011). Although these efforts have made initial strides in the V2X arena, they have 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. We feel 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 preventative actions to avoid conflicts.

3.1 Smart Road Sticker Design for Bluetooth Detection

The goal of this portion of the project was to develop a solar-energy driven, small, and lightweight communication node (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 another suitable cellular communication protocol. This would allow for 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 between vehicles, infrastructure, and non-motorized users, the sensors would be able to transmit information from one sensor to another. With a small, and relatively inexpensive sensor, multiple sensors could be easily installed in

critical areas to overcome issues of transmission range and 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.
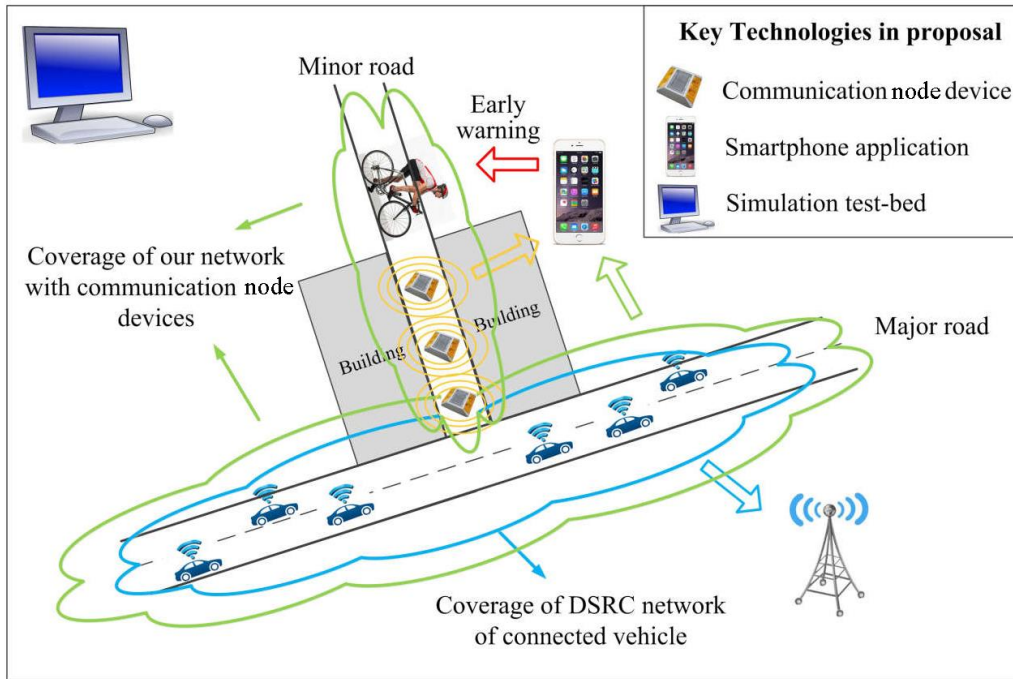

Figure 3.1 Illustration of the CN device application in a vision-restricted street scenario

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 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 techniques 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 exterior and inner structure of the SRS are shown in figures 3.2 and 3.3. The detection time for one interval is 5

seconds, and the maximum number of devices able to be detected at once is 10. 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
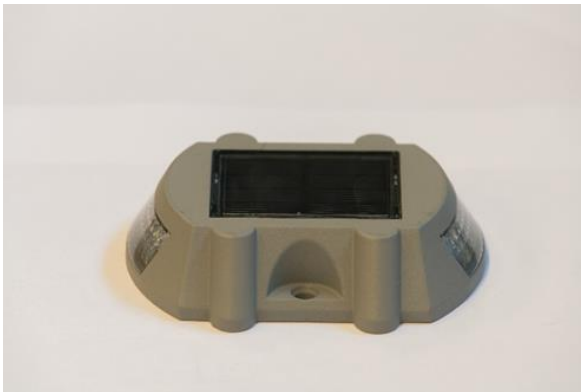
detection interval.
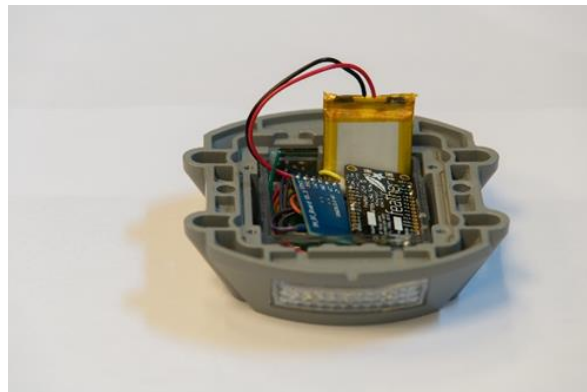

Figure 3.2 Exterior of the SRS   **Figure 3.3** Inner structure of the SRS

3.2 Software Development

Once a 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 have the application

installed on their phones or other mobile devices. Such information will comprise warnings

about potential conflicts that may 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 for transmission of safety information to a larger percentage of the traveling

population, regardless of their mode, because at least in the present time, non-motorized users do

not have DSRC-capable devices. Existing research, such as Roodell (2009), has addressed the

communication of safety information in a connected vehicle environment between a 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 were important issues to address in designing the mobile application.

The software can be categorized into two types: mobile phone application and 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 listens to the LoRa receiver port and filters the data received. Only Bluetooth MAC address registered in the system re displayed. The interfaces of the Android and PC applications are shown in figure 3.4. In order to guarantee cyber security and privacy, Bluetooth MAC addresses are encrypted in the mobile and PC applications, as they are technically personally identifying information.
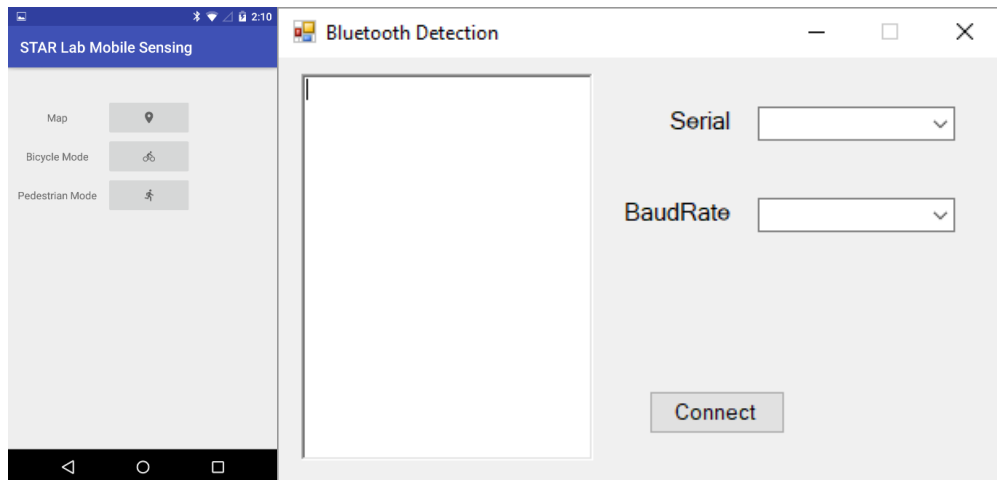
Figure 3.4 Interface of the Android and PC applications

3.3 Experiment Results

Experiments were done from several perspectives, including 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 will send data to the receiver and PC via LoRa. The coded MAC address of the detected device will then be

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 was walking past the SRS) are shown in figure 3.5.
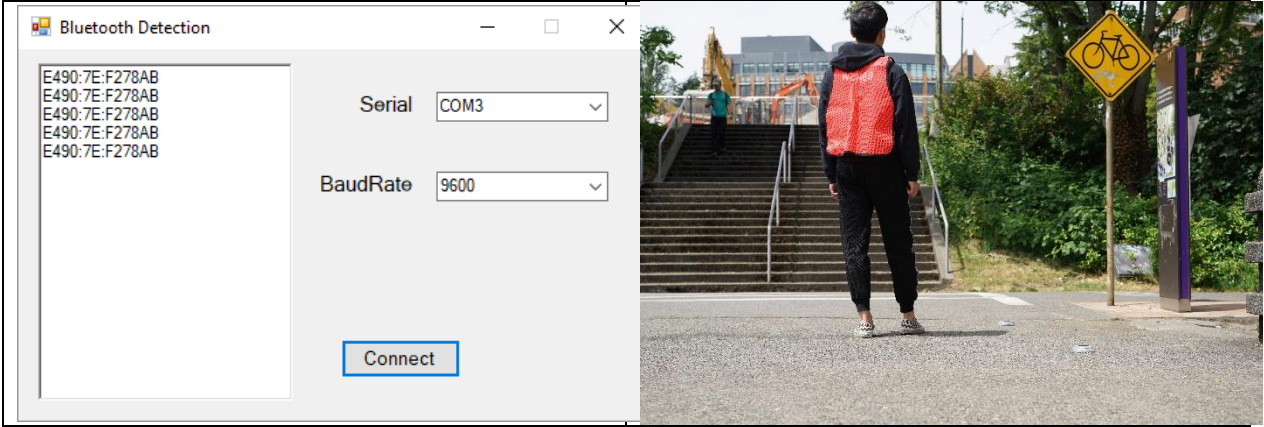
Figure 3.5 Detection results and experiment scene

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 3.6.

Table 3.1 The 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 3.6. Maximum effective detection distance (8 m from the SRS)

4. Crash Prediction Algorithm

To estimate the risk of collision between pedestrians and vehicles, a framework is needed make the proper connection between devices. This framework should use information such as current position and speed from smartphones and onboard units in vehicles 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 to be a surrogate measure of risky situations for potential crossing and rear-end conflicts. In this chapter, we propose a general framework based on the assumption that smartphone devices and onboard units will provide accurate data about the positions and speeds of pedestrians and vehicles. First, the means of conflict point estimation and the approach to finding it are discussed. Then, the time to collision is estimated, and finally the proposed algorithm is presented.

4.1 Computations to Find the Conflict Point

To find the conflict point between two vehicles or a vehicle and a pedestrian, we used the information collected from the onboard units in the vehicles and smartphones. The longitude and latitude positions and the direction of the movements were 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 (4.1) and (4.2).
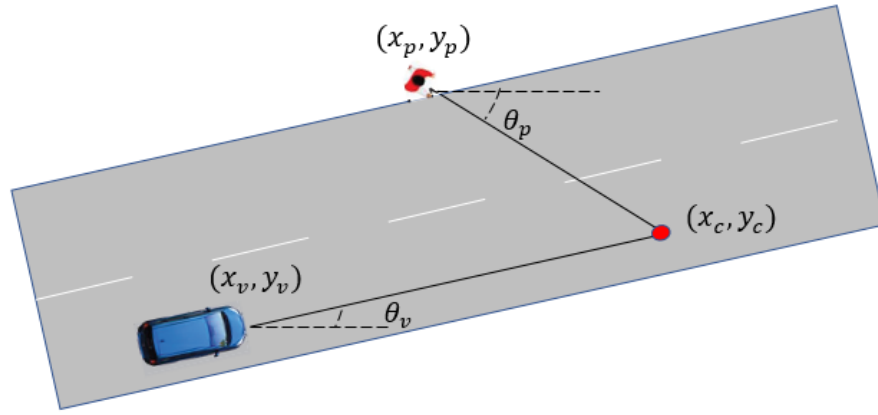
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Figure 4.1 Finding the collision point

$$x_c = \frac{(y_v - y_p) - (x_v \tan(\theta_v) - x_p \tan(\theta_p))}{\tan(\theta_p) - \tan(\theta_v)} \tag{4.1}$$

$$y_c = \frac{(x_v - x_p) - (y_v \cot(\theta_v) - y_p \cot(\theta_p))}{\cot(\theta_p) - \cot(\theta_v)} \tag{4.2}$$

4.2 Computations for Time to Collision

Finding conflict points may be helpful for finding the frequency of conflict situations, but it does not include the severity of the potential conflict. Therefore, time to collision was introduced to measure the severity of the conflict situation. TTC indicates the time at which two vehicles or a vehicle and a pedestrian would collide if they continued their movement with their current speeds and paths. Lower values of TTC indicate more severe possible conflicts. If TTC drops below a given threshold value, the safety risk approaches a critical condition, and users should take action to prevent a crash. The value of TTC can be calculated on the basis of the speed and distance to the conflict point for each of the users. Equation (4.3) shows the measurement of TTC for crossing conflicts. However, this formulation is not appropriate for

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rear-end collisions. Thus equation (4.4) was introduced for rear-end cases. Rear-end and

crossing conflicts are shown in Figure 4..2 (a) and (b), respectively.

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

(4.3)

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

(4.4)

where

x_1 = Location of vehicle 1.

x_2 = Location of 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.

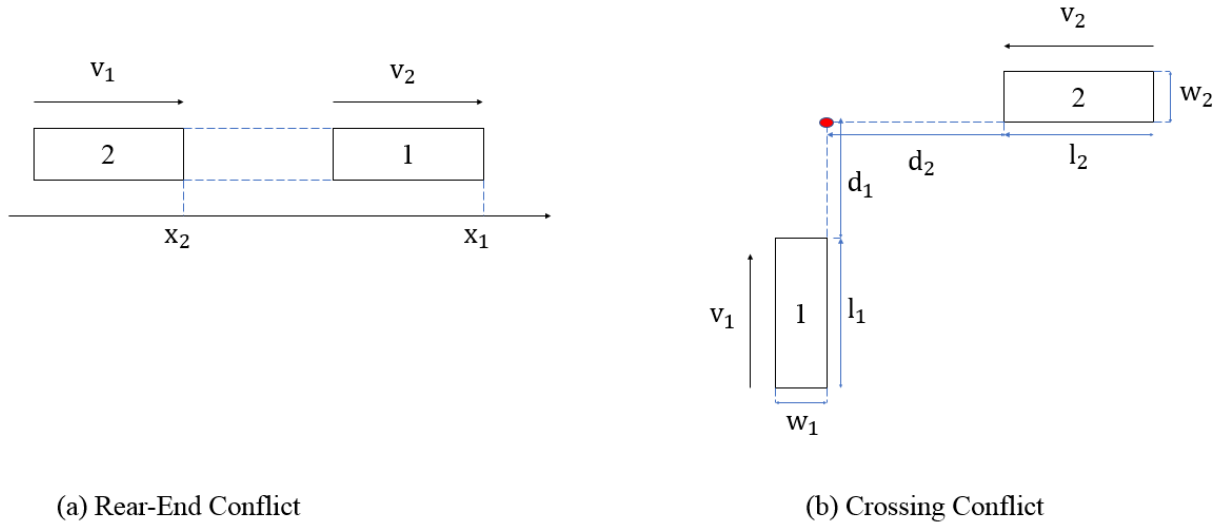(a) Rear-End Conflict   (b) Crossing Conflict

Figure 4.2 Rear-end and 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 brake (t_{br}). In addition, we can consider a safe distance between vehicles and pedestrians that should not be violated (t_{safe}). Equation (4.5) indicates the minimum time (δ) that a driver or a pedestrian needs to react to avoid the collision.

$$\delta = t_p + t_{br} + t_{safe} \tag{4.5}$$

We assume that at a critical time, the user's reaction with braking 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 (4.6) 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. As such, the braking time for vehicles and pedestrians can be calculated with equations (4.7) and (4.8), respectively. However, because pedestrians travel at lower speeds, we can assume that they stop instantaneously. Note that the speed of pedestrians is assumed to be maximum in order to consider the worst case. The unit of the time, speed, and deceleration rates in all proposed equations are, , $\frac{m}{s}$, and $\frac{m}{s^2}$, respectively.

$$MaxD = a_0 + bv \tag{4.6}$$

$$t_{br}^v = \left| \frac{1}{b} \ln(1 + \frac{b}{a_0} v) \right| \tag{4.7}$$

$$t_{br}^{p} = \left| \frac{v_{max}^{p}}{a_p} \right| \tag{4.8}$$

The safe time (t_{safe}) for vehicles and pedestrians can be calculated on the basis of equations (4.9) and (4.10). 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 keeps its current speed and path. Equation (4.11) shows this value, where d is the remaining distance. Assuming that δ_v and δ_p are the critical times for the vehicle and pedestrian, respectively, then 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 in order to prevent a collision.

$$t_{safe}^{v} = \frac{d_{safe}}{v} \tag{4.9}$$

$$t_{safe}^{p} = \frac{d_{safe}}{v_{max}^{p}} \tag{4.10}$$

$$TTCP = \frac{d}{v} \tag{4.11}$$

4.3 Proposed Crash Prediction Algorithm

In this section, the developed algorithm to predict safety risk and prevent collisions is described. This framework considers V2V and V2X communications to be the vehicles that are connected to each other and are connected to pedestrians and bicyclists as well. The objective of the algorithm is to warn users and give them sufficient time to avoid a collision. Figure shows how the algorithm identifies risky conditions and sends warning messages to users.
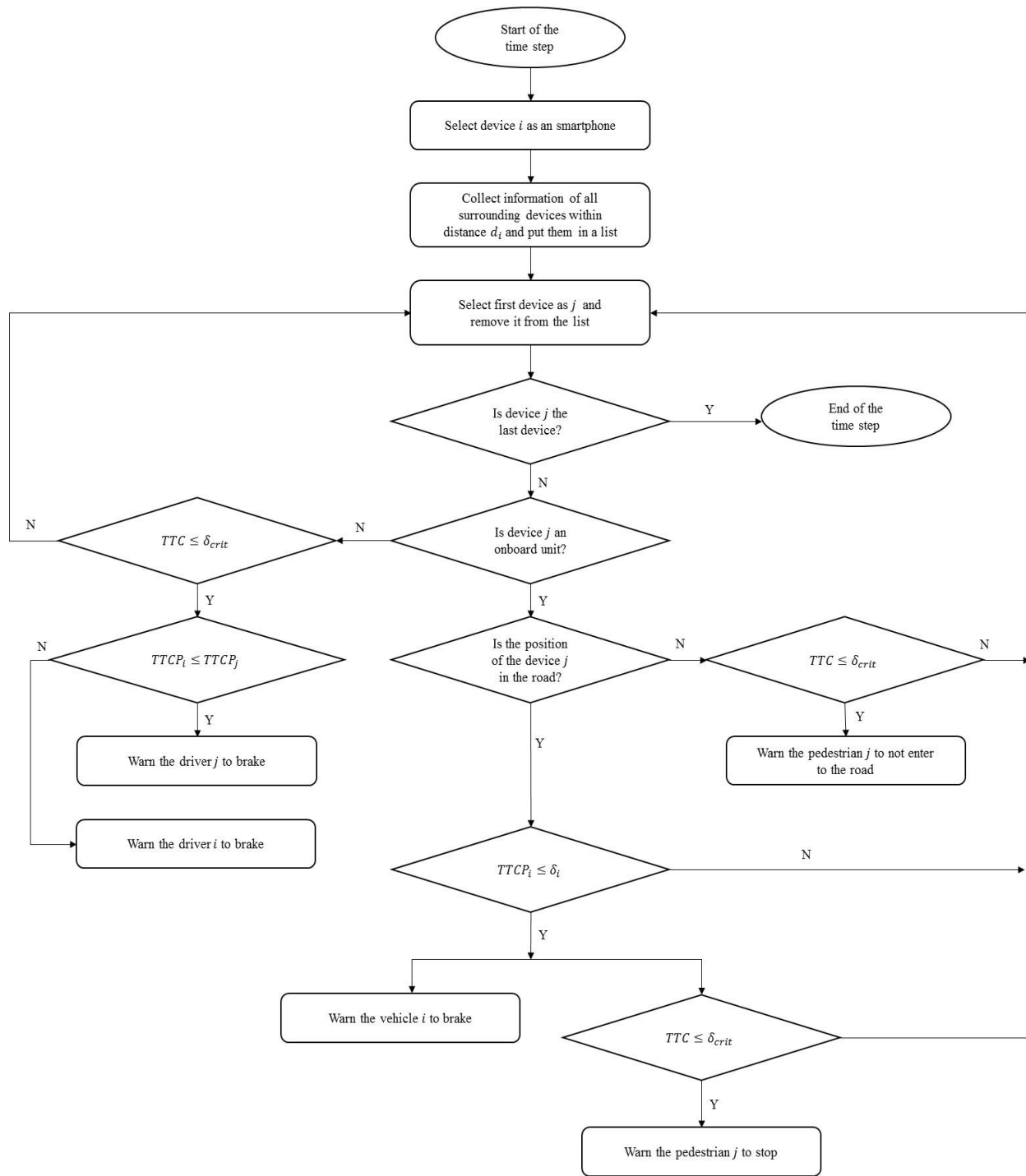
Figure 4.3 Algorithm for preventing collisions between vehicles and pedestrians

In the proposed algorithm, it is assumed that at each time step the onboard unit in the

vehicle (device i) collects the information (position and speed) of the surrounding devices,

including the other vehicle's onboard units and smartphones, within a certain range of distance that DSRC technology covers. However, because smartphones can be connected to vehicles through the cellular network, this range is accordingly less. Device j among all surrounding devices is 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 are 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.

If device j is a pedestrian, 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 gets to the critical distance ($TTCP_i \leq \delta_i$), then the warning message is 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 also considered in this algorithm. In such situations, the warning message continues to be sent to the driver while warning messages are also sent to the pedestrian to stop or take appropriate action. When the risky condition is resolved, the warning messages stop. On the other hand, if the pedestrian is on the sidewalk and there is a risky condition when $TTC \leq \delta_{crit}$, then the warning message is sent to the pedestrian to stop moving forward and stay on the sidewalk until the risky condition is resolved.

When device j is an onboard unit in a vehicle, the interaction can be different. In this case, when the risk of collision is detected as $TTC \leq \delta_{crit}$, the warning message is 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 farther one will yield to it. It is assumed that vehicles will start to reduce their speed with the maximum deceleration rate as described in the previous

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section when the warning message is sent to them. The value of the new speed can be estimated

with equation (4.12). 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.

$$v_{t+1} = v_t + MaxD.\Delta t \qquad (4.12)$$

5.   Simulation Evaluation Approach

To investigate the effectiveness of the proposed safety performance algorithm, there was a need to simulate the approach. Simulation provided the opportunity to evaluate the ability of the approach to reduce the number of collision and pre-collision situations on the basis of different settings. In this study, the VISSIM microscopic simulator was used because it provides the required tools to simulate CV conditions and corresponding interactions between vehicles and pedestrians. The simulation test bed was created in VISSIM, and different scenarios were tested within it. This chapter describes the procedures for creating the test bed and the tested scenarios.

5.1 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 interaction with vehicles. VISSIM provides the ability to export the results of the simulation as input to the Surrogate Safety Assessment Model (SSAM). VISSIM also provides the ability to take control of the vehicles and pedestrians with external logic through the COM interface. The latter feature of this software was desirable for the purposes of this study because V2X communication provides more information to drivers that could be used to enhance the reactiosn of drivers and pedestrians in unsafe situations.

Earlier versions of VISSIM (e.g., VISSIM 5.00 and earlier) introduced 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) have not offered this module. Moreover, using predefined modules could be limiting. The VISSIM COM interface provides the opportunity to identify traffic conditions

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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 of implementing the proposed safety performance algorithm in VISSIM is described in Figure .
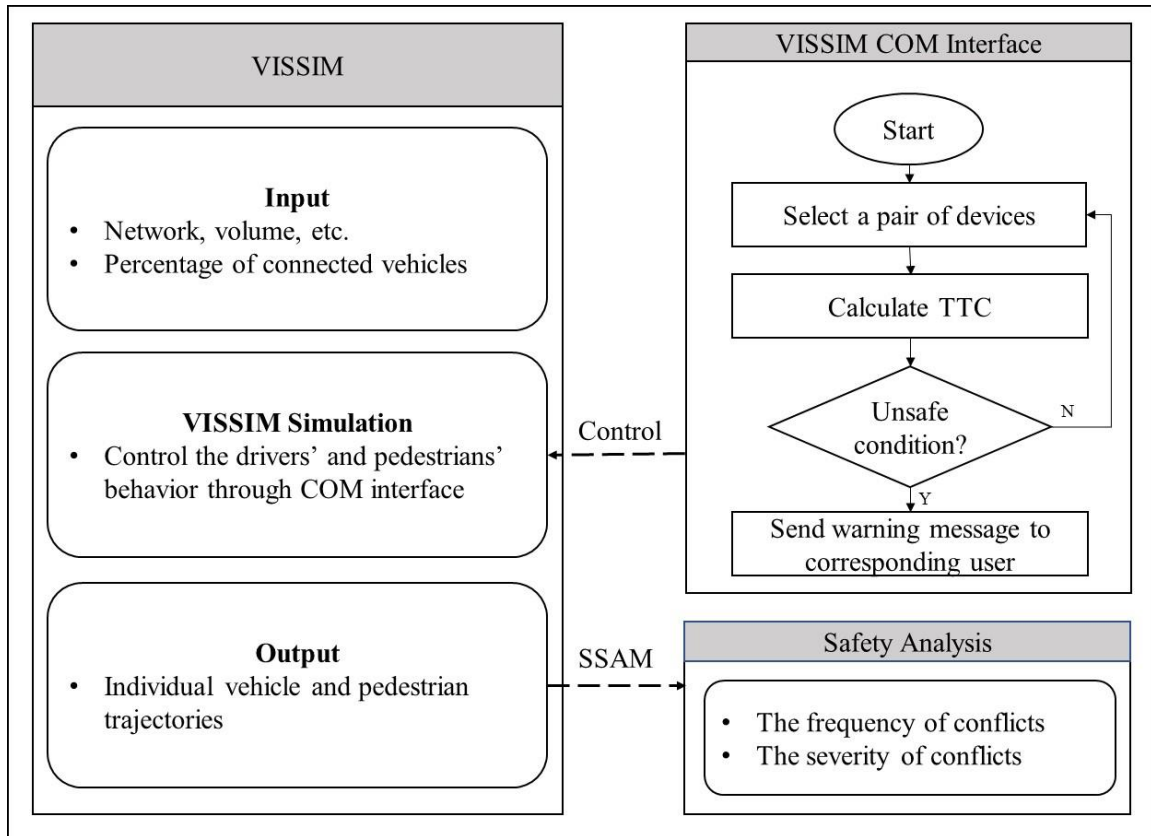

Figure 5.1 The structure of simulation with VISSIM

As shown in Figure , 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. Using the COM interface, the proposed crash prediction algorithm is implemented in order to detect risky situations by using information from vehicles and pedestrians that are connected to each other. Then, time to collision can be estimated and used as thea 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 severities, are found.

5.2 Simulation Test Bed

As previously mentioned, for this project, the simulation test bed was created in VISSIM. As the literature review showed, most collisions between vehicles and pedestrians occur in urban areas. The most frequent cases are those in which a vehicle is turning and a pedestrian is crossing the road. However, the most severe cases occur when a vehicle is going straight and a pedestrian is crossing the road. Simulating the behavior of drivers and pedestrians in an urban intersection covers most of these cases. Therefore, a network with a four-leg intersection and with both vehicle and pedestrian movements was used as the test site for investigating the V2V and V2P communications and the corresponding safety performance. Figure shows the studied network containing an intersection.

As seen in Figure 5.2, 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 was going straight, turning left, or turning right, there was potential for a vehicle to collide with pedestrians who were crossing the road. In this network, it was assumed that the speed limit for vehicles was 50 km/hr and the pedestrians moved with a maximum speed of 5 km/hr. In this study, we worked with an un-signalized intersection in order to consider the high-risk scenarios for cases when users would be both connected and unconnected.
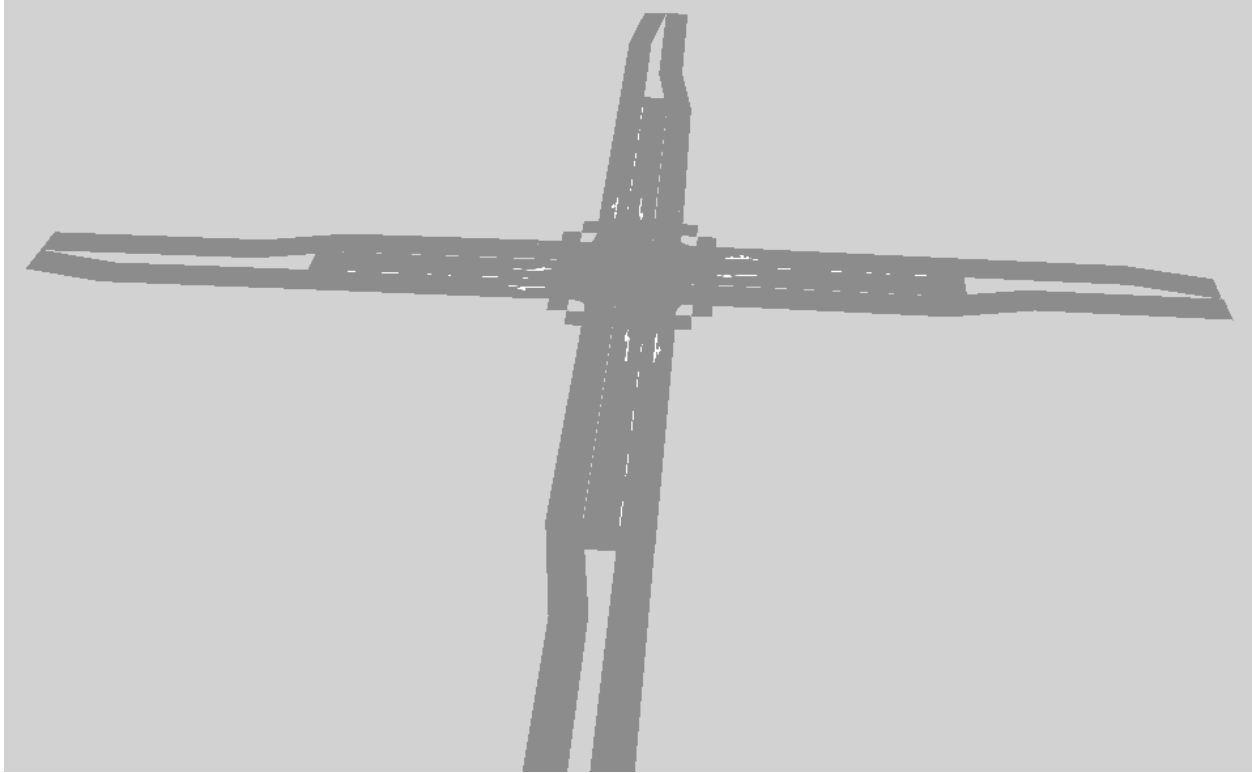
Figure 5.2 Simulation test bed

5.3 Simulation Scenarios

The intersection for this case study was unsignalized to increase the number of potential

collisions between vehicles and pedestrians. Such a situation helped to better display the

performance of the proposed algorithm. In this case study, pedestrians could move across the

intersection in all directions. Vehicles could go straight, turn right, and turn left. It was expected

that the proposed algorithm would address most of the possible collisions 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 were needed. Generally, a combination of two sets of scenarios that considered the

volume of vehicles and pedestrians and the penetration rate of the connection between them

could 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 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.

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

6.   Simulation Results and Discussions

This chapter presents the results from the simulation study based on the evaluation

approach described in previous section. 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.

6.1 Defining the Input Parameters

For the purpose of the analysis, the network was loaded with different volume levels, in

different simulation runs, as explained before. In the studied intersection, the rate of turning and

through-movements wee 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 pedestrian was 15 percent of the volume for vehicles.

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 the

risk condition gave 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 happened, 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,

warning messages were sent to users.

To test each of the described scenarios, several simulations were implemented to address

the randomness in each. Each scenario was repeated 10 times, which took 5 minutes. Recall that

each of the users needed to measure the risk of a crash with their surrounding vehicles within the

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 durations. On the basis of the experimental results, 5 minutes was set to be the maximum simulation time for each simulation.

6.2 Selection of a 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). This value indicates that 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, then 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 prediction algorithm.

6.3 Results for Safety Measures

This section provides the results and analysis of the case study based on the predefined parameters and the safety measures. As mentioned, TTC was considered to be the safety indicator.

Table **6.2** shows the number of conflicts for each of the simulated scenarios. On the basis of the results, 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 6.2 The number 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 collisions between vehicles and pedestrians were possible in the simulation, and they included those in which a pedestrian crossed the road and a vehicle was going straight, turning right, or turning left. Figure 6.1 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, conflicts for left turn movements were more frequent than conflicts for right turn movements. However, when the penetration rates increased, then the total number of conflicts, as well as the number of conflicts with through-movements, decrease.
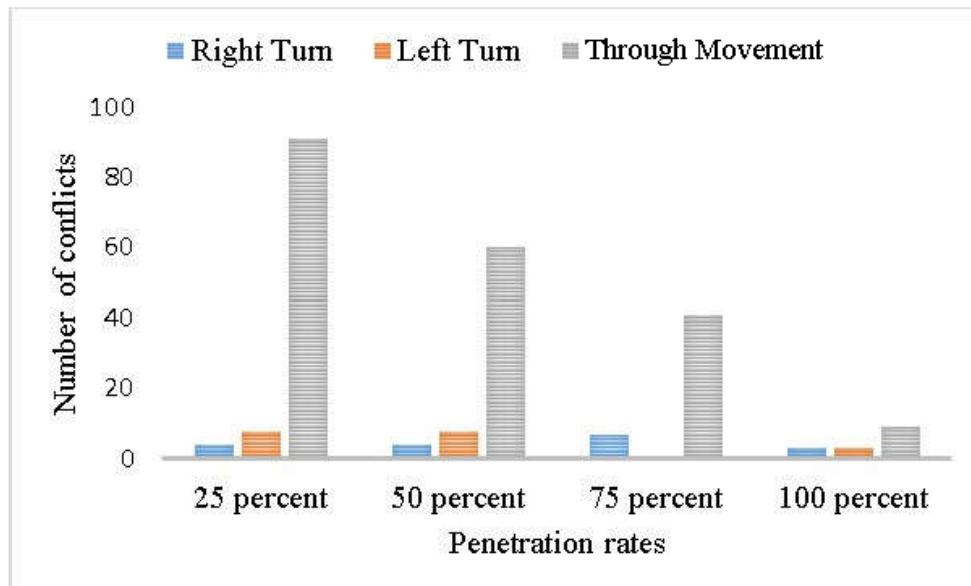
Figure 6.1 The number of conflicts based on movements and penetration rates

In addition, Figure shows that increasing volumes increased the number of conflicts for all movements. Specifically, conflicts corresponding to through-movements increased substantially in number. The number 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.
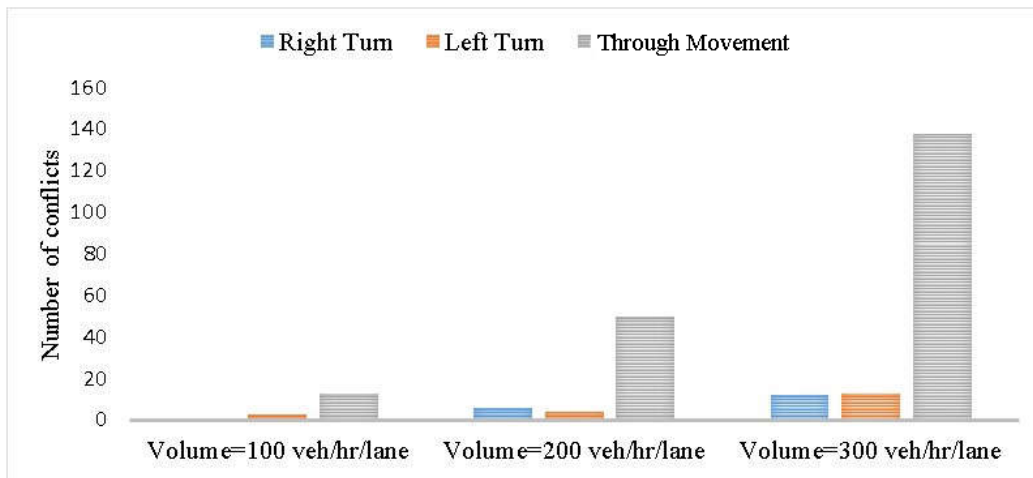

Figure 6.2 The number of conflicts based on movements and volumes

Figure shows the decreasing rates of the number of conflicts based on the penetration rate for all of the different volume levels considered in the simulations. When the volume was higher, a simultaneous increase in the penetration rate of connected devices had a larger effect on decreasing the number of conflicts.
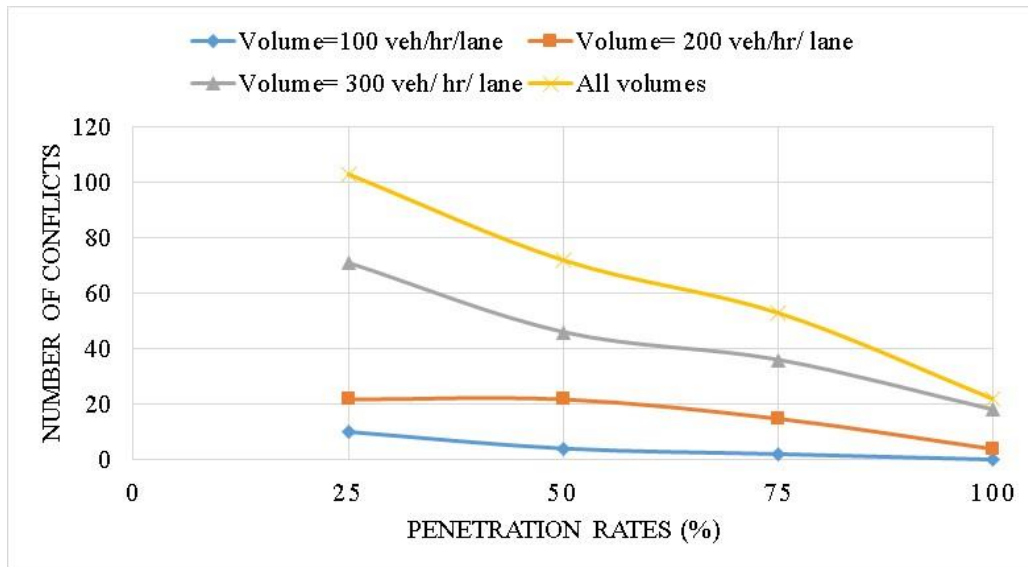
Figure 6.3 The relationship between the number of conflicts with penetration rates for different volumes

6.4 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. On the basis of the findings of this study, the number of conflicts increased when the penetration rate of connected devices decreased. In addition, increasing volumes had a direct relationship with an increasing number of conflicts.

In the simulation study, the number of conflicts between through-moving vehicles and pedestrians crossing the road was the highest. This is due to higher volumes of vehicles that went straight (70 percent) in comparison to making turns. Increasing the penetration rate of connected devices reduced the number of through-moving conflicts significantly. Moreover, the number of conflicts involving left turns and right turns decreased as well. Generally, the number of conflicts decreased more rapidly when the penetration rate of connected devices increased among higher volumes.

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