Safety Evaluation of Connected Vehicle Applications Using Micro-Simulation

by

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Abstract

Connected vehicles are on the cutting edge of automotive technology with applications expected to improve mobility and safety. Several studies have evaluated the mobility benefits of connected vehicle technology but there is little research on its impact on safety. The first objective of this study is to investigate the ability to evaluate the safety of a connected vehicle applications using surrogate safety measures through a combination of the micro-simulation model VISSIM and the Surrogate Safety Assessment Model (SSAM). Two connected vehicle applications are reviewed, considering two types of connected vehicle communications, specifically Vehicle-to-Vehicle and Vehicle-to-Infrastructure. The two applications are a cumulative travel time (CTT) intersection control algorithm connected vehicle environment, and a cooperative adaptive cruise control (CACC) application, facilitating vehicle platooning on a freeway. The CACC study investigates the improvement to the freeway segment through a simulated incident. The CTT study investigates the impacts of calibrating the micro-simulation model using real-world vehicle trajectory and conflict data. The CTT algorithm is applied to a signalized intersection and evaluated under three calibration scenarios: uncalibrated, first step calibrated for desired speed and vehicle arrival types, and second step calibrated for conflicts observed in the field. In both studies, a comparison of safety based on the number of conflicts at different time-to-collision thresholds is provided for the varying scenarios. Results show that the combination of VISSIM and SSAM provide an appropriate tool to use in the evaluation of changes in the level of safety of connected vehicle applications, specifically the CACC application and the CTT intersection control application. Calibration of the
micro-simulation model has a significant impact on the results of the safety evaluation. However, it is inconclusive whether the results are realistic with the lack of a real-world connected vehicle implementation.
Preface

This thesis is an original intellectual product of the author, M. Fyfe. The methods used expand on work conducted in the Transportation group at the University of British Columbia department of Civil Engineering. The non-connected micro-simulation model used for the cumulative travel time intersection control connected vehicle application in Section 4.1 and Section 5.1 is based on research by Essa and Sayed (2015a). Assumptions used for the micro-simulation models are based on research by Essa and Sayed (2015a), Lee et al. (2013a) and Zhao and Sun (2013).

I completed this thesis while employed at the Transportation Investment Corporation. The views and opinions within this thesis are my own and do not necessarily reflect the opinions of my employer. No special considerations were made in the interest of my employer.
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Glossary

ABS  Anti-lock Brake System
ACC  Adaptive Cruise Control
ATMS  Advanced Traffic Management System
BSM  Basic Safety Message
CACC  Cooperative Adaptive Cruise Control
COM  Component Object Model
CTT  Cumulative Travel Times
DLL  Dynamic Linked Library
DMS  Dynamic Message Sign
DR  Deceleration Rate
DSRC  Dedicated Short-Range Communications
ESC  Electronic Stability Control
FHWA  Federal Highways Administration
GPS  Global Positioning System
IEEE  Institute for Electrical and Electronics Engineers
ITS  Intelligent Transportation Systems
LOS  Level-of-Service
MAPE  Mean Absolute Percent Error
ORCI  Overall Risk Change Index
PET  Post-Encroachment Time
SAE  Society of Automotive Engineers
SSAM  Surrogate Safety Assessment Model
TTC  Time to Collision
USDOT  United States Department of Transportation
VANET  Vehicular Ad-Hoc Networks
VPH  Vehicles per Hour
V2V  Vehicle to Vehicle
V2I  Vehicle to Infrastructure
V2X  Vehicle to X
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Chapter 1

Introduction

Within transportation engineering, the primary focus in the design of any transportation facility or system is the impact to the safety of the travelling public and other road users while improving the mobility for these same users. Given the high number of vehicle crashes each year, safety remains at the forefront of critical research items for transportation engineering. The World Health Organization (2013) has stated that road collisions are the eighth leading cause of death worldwide and has reported there are approximately 1.24 million deaths and another 20-50 million non-fatal injuries on roads around the world annually.

Connected vehicles have a potential to improve transportation systems with respect to safety, mobility and sustainability; however, significant research and review of these new facilities needs to occur before there can be confidence that these systems will in fact demonstrate improvements in these areas.

Before new road designs or technologies, and applications of those technologies are implemented it is difficult to know how the transportation network will react. Traffic simulation assists by simulating what will occur on a roadway given different variables and factors. The primary types of simulations used in traffic modelling are macro-simulation, meso-simulation and micro-simulation.
Microscopic simulation (micro-simulation) involves modelling each individual vehicle, including driver behaviour, and is the type of simulation to be used for this thesis. Of the different micro-simulation software packages available, the package being used for this research is PTV VISSIM.

This chapter includes three sections. The first section provides background information on traffic safety, connected vehicles, the traffic conflict technique, micro-simulation and the Surrogate Safety Assessment Model (SSAM). The second section describes the research objectives of this thesis. The third section defines the thesis structure.

### 1.1 Background

Transportation safety carries a significant consideration when designing or implementing changes to existing or new transportation facilities. Within transportation engineering, there are three main factors when understanding the cause of a collision on a roadway: 1) the driver, 2) the vehicle, and 3) the road environment. The primary cause of collisions include driver fault (Lum and Reagan, 1995).

Within transportation infrastructure, there are limitations to what can be built due to right-of-way and allowable road space, as well as consideration for the joining roadways. Building more lanes to increase capacity is not always a possibility considering it may take years to build new infrastructure. Alternative methods of improving the capacity of roadways are needed.

To make the transportation system safer, transportation practitioners should be able to estimate the impacts of a change in design to an existing facility or the creation of a new facility within an existing network. Some components of traffic safety analysis are the identification of hazardous locations (through black spot programs), analyzing and verifying countermeasures, and, the focus of this thesis, improving road user behaviour.
1.1.1 Traffic Safety

The terms incident, accident, collision and crash are often used interchangeably when referring to traffic safety. Years of research have shown that crashes can be predicted to an extent and that they can be modelled through the use of statistical analysis (Sayed and De Leur, 2008). For this thesis the terms collision and crash will be used, and the term accident will be avoided as it suggests that the instance was random and unforeseen.

1.1.1.1 Importance of Road Safety Research

Roads are a critical part of a transportation network and they are essential to the development of a country. Roads allow for the movement of people and goods by supporting automobiles, trucks, buses, bicycles and pedestrians. Without roads there would be no ability to transport resources to build infrastructure for the development of regional or economic growth.

Road safety research is important because it helps to enhance the knowledge of road safety. To improve the safety on roads, transportation engineers and designers should have the ability to understand and evaluate the impacts of different design and operational options on a roadway. Road traffic safety research is a prime component of transportation engineering. Traffic safety is often looked at in terms of traffic “unsafety”, or the negative of safety, namely the number of injuries or fatalities resulting from traffic accidents. Traffic safety has three dimensions: exposure, risk and consequence. Road traffic safety engineering is the practice of reducing the risk of users of the road being killed or seriously injured as part of a traffic collision.

1.1.2 Connected Vehicles

Connected vehicles can be considered a new transportation facility. They involve communication between vehicles through Vehicle to Vehicle (V2V) interaction and communication between
vehicles and the infrastructure through Vehicle to Infrastructure (V2I) interaction in order to have enhanced driving applications on the roadway. The applications are intended to improve the overall mobility, safety and driving experience for individual drivers and for the road network in general. Connected vehicles are a subset of Intelligent Transportation Systems (ITS) and are a method being reviewed, currently on a limited basis, to evaluate the ability to improve the function on existing transportation facilities.

1.1.3 Micro-simulation and VISSIM

PTV VISSIM (VISSIM) is a micro-simulation model created by the German company PTV Vision. VISSIM enables modelling of various types of traffic facilities that exist on a road network, including junction geometry, motorway traffic, public transport, multimodal systems, active traffic management and emissions modelling. For motorway traffic, VISSIM allows for modeling on two levels: the driver level, and the tactical level. On the driver level, vehicles abide by the psycho-physical car following model developed by Professor Rainer Weidemann from the Karlsruhe Institute of Technology in 1974 and 1999, governing how drivers in the micro-simulation respond based on distance and difference of speed to the vehicles ahead. The car following model developed by Wiedemann (the “Wiedemann Mode”) uses random numbers and several stochastic variations to simulate behaviour of different drivers resulting in virtually no two drivers with exactly the same driving behaviour. Additionally lane changing is facilitated through a rule-based model. Both models have parameters that can be adjusted. On a tactical level, where decisions must be made far enough in advance in order to take action, VISSIM considers the geometry of the roadway and the surrounding vehicles in order to choose the appropriate lane to be travelling in. VISSIM allows for changes to properties such as the willingness to cooperate in order to realistically map the region specific to actual characteristics. Car2X, or Vehicle to X (V2X) systems can theoretically be modelled in VISSIM as they have an impact to individual vehicles.
1.1.3.1 Calibration of VISSIM

When developing a simulation, the simulation model needs to incorporate data from the real-world to ensure it properly represents reality. This process is known as calibration.

The calibration of VISSIM is considered one of the most important aspects in preparing a transportation network for simulation. Due to minimal literature and processes on calibration, many researchers and practitioners are required to use a manual trial-and-error approach for calibration to re-create situations seen in the real world as opposed to automated computer optimization of the models (Ge and Menendez, 2012).

Research has been conducted recently to demonstrate that it is important to calibrate VISSIM not only to match existing traffic conditions (e.g., arrival pattern and platoon ratio) but also with respect to safety through calibrating the driver behaviour parameters (Essa and Sayed, 2015a). Safety calibration of VISSIM can be performed using the SSAM as will be discussed in Section 1.1.4.

1.1.4 The Surrogate Safety Assessment Model

The Surrogate Safety Assessment Model (SSAM) is a software package that analyzes trajectories output from certain micro-simulation packages, namely VISSIM, PARAMICS, AIMSUM and TEXAS, in order to evaluate the road traffic conflicts observed in the simulation. SSAM acts as a post-processor as the micro-simulation models will output a trajectory file (.trj) and SSAM analyzes the vehicle-to-vehicle interactions within the trajectory file to identify conflict situations and to provide a database of all instances found within the model output. Along with conflict detection, SSAM provides surrogate safety measures as an output, as well as the classification of conflict type as either lane change, rear-end, or path crossing event and the vehicle velocity change if the event had proceeded to an incident to provide indication of the severity of the incident.
1.1.5 Traffic Conflict Technique

Observing and analyzing traffic conflicts has been regarded as an alternative method for evaluating traffic safety through using the Traffic Conflict Technique (TCT). The TCT is described by Archer (2001) as the most developed indirect method of evaluating traffic safety through registering near-collisions in real-time traffic. Some of the inhibiting factors to widespread use of the TCT are the high costs of training observers and the variability or reliability in manual collection of conflict data (Essa, 2015). Traffic conflicts have been used in safety diagnosis as a surrogate for collision data analysis as they provide insight into failure mechanisms that lead to road collisions (Amundsen and Hyden, 1977; Sayed and Zein, 1999; Tarko et al., 2009). Traffic conflicts address some of the shortcomings of collision data such as shorter collection time, more frequent occurrences and less cost to society.

1.2 Research Objectives

Simulating conflicts for road traffic safety evaluation in micro-simulation has been more common in the recent past (Essa and Sayed, 2015a,b, 2016; Shahdah et al., 2014; Wang and Stamatiadis, 2014), specifically using the SSAM. However, concerns have been raised over using simulated conflicts, primarily for two main reason (Essa, 2015; Saunier and Sayed, 2007). Firstly, because of the rules embedded within the micro-simulation models to cause vehicles to avoid collisions, making it difficult to represent unsafe conditions in the real-world. Secondly, micro-simulation models have a multitude of simulation parameters which impact the observed simulated conflicts within the model. Through calibration to real-world conditions it has been shown that these concerns can be addressed (Essa and Sayed, 2015a).

While it may be becoming more common to use the SSAM to evaluate safety through micro-simulation models, these evaluations typically involve existing transportation facilities and infrastructure. Evaluating the safety of a facility that does not exist in the real-world brings new
challenges to the use of surrogate safety measures for safety evaluations.

Connected vehicle applications are considered new transportation facilities in that there is not abundant information about the reaction of these systems to varying traffic conditions. Research has been conducted into evaluating the mobility and sustainability impacts of connected vehicle applications (Lee et al., 2013a,b; Zhao and Sun, 2013); however, the safety impacts of these facilities are rarely evaluated or quantified.

Connected vehicle applications can be separated into two categories, 1) where partial vehicle control is assumed by a computer, or 2) where driver behaviour is modified due to changes in the infrastructure, such as through navigation systems or signalized intersection control. Making use of both of these types of connected vehicle applications, the first objective of this thesis is to assess the ability for micro-simulation to be used in evaluating the change to safety of connected vehicle applications using surrogate safety measures. This will be assessed through comparison to a non-connected vehicle micro-simulation and conformance to expected results.

While connected vehicle applications can be modelled using micro-simulations, there are no widespread real-world implementations of connected vehicle applications, and therefore there are no real-world conditions to use to calibrate the micro-simulation model. Calibration is typically performed by modifying VISSIM and other parameters in the micro-simulation to emulate real-world observations. Given the two types of connected vehicle applications being investigated, modification of these parameters can be performed to represent calibration and test the sensitivity and significance of model behaviour subsequent to the changes being made. Following this, the second objective of this thesis is to demonstrate that calibration of a non-connected vehicle environment through modification of VISSIM and other parameters has a significant impact to the simulated effects of connected vehicle applications, for both safety and mobility. This will be assessed through comparison of the results after calibration to the non-connected vehicle calibrated micro-simulation and to the overall results of the uncalibrated micro-simulation.
1.3 Thesis Structure

This thesis is comprised of six chapters. This chapter presents an introduction and background to the thesis, the objectives of this research and an outline to the structure of the thesis. Chapter 2 provides a comprehensive literature review of the research areas supporting the main objectives of this thesis. The review is broad in the focus on road traffic safety research, the traffic conflict technique, Intelligent Transportation Systems, micro-simulation models of connected vehicle technologies and applications, and the work that has been done using SSAM for evaluating safety within a micro-simulation model. Chapter 3 discusses the methodology of modelling connected vehicle technologies using the VISSIM micro-simulation model and assessing the objectives under this thesis. Chapter 4 and Chapter 5 implement case studies of connected vehicle applications for the purpose of evaluating the objectives of this thesis, firstly for the uncalibrated simulations and then for a more focused view of the calibrated simulation of one of the micro-simulation models. Finally, Chapter 6 contains the summary, conclusion and areas for future research.
Chapter 2

Literature Review

This chapter outlines previous research in five main areas to provide the state of the art on which this research is based. The first area of research is about traditional road traffic safety analysis and the framework upon which advancements in traffic safety research are based. The second area of research is specific to the traffic conflict technique, outlining advancements in understanding safety and risk associated with traffic conflicts on roadways, as well as methods used for conducting studies using the traffic conflict technique. The third area of research is on Intelligent Transportation Systems (ITS) and in greater detail, Connected Vehicles and Autonomous Vehicles. The fourth area of research is specific to micro-simulation models and use of the Surrogate Safety Assessment Model (SSAM). The fifth area of research is specific to connected vehicles and the research into evaluation of connected vehicle applications using micro-simulation. Numerous studies have been found relating to the traffic conflict technique and traffic micro-simulation; therefore a reduced list of studies is presented specific to key studies that have been highly cited previously.
2.1 Traditional Road Traffic Safety Research

Traditional road traffic safety research analysis focuses on identifying hazardous areas on roadways, diagnosing safety problems, recommending safety improvement options and evaluating the economic feasibility of the safety improvement options. Traditional road traffic safety analysis is typically performed by collecting traffic safety information after collisions have occurred, primarily from historical collision reports, police reports and insurance claims (de Leur and Sayed, 2001, 2003). Studies have shown there to be shortcomings with traditional road traffic safety research methods and the data used for this research.

The Federal Highways Administration (FHWA) Venn diagram in Figure 2.1 for safety on a road, or cause of crashes, shows that 93% of crashes are caused in part by human error (Driver). By modifying the way that vehicles are driven - removing the driver and replacing it with a computer - it can cause a shift to where the majority of crashes are caused while reducing the total number of crashes.

The other key considerations for transportation facilities are mobility and sustainability (including the environment). Transport Canada (2006) undertook a study to identify the costs of congestion in major urban cities across Canada, identifying the cost annually to be between $2.3b - $3.7b in 2002 dollars. This value will have changed in more recent years. In the Metro Vancouver region, a report by HDR for the mayors council responsible for regional transportation indicates the cost of congestion in Vancouver alone equates roughly to $1.4m per year in 2015 dollars, including delay, vehicle operating and related costs, as well as business inefficiency costs and reduction in economic activity (HDR, 2015). A joint study conducted by the Texas Transportation Institute and INRIX identified the cost of congestion in the USA to be in the magnitude of $160 billion for the year 2014 (Schrank et al., 2015). Based on this information it is evident that improvements to transportation facilities and technology are required in order to reduce the cost of congestion and the impacts to society.
2.1.1 Traditional Road Traffic Safety Analysis

Traditional road traffic safety analysis typically involves collecting years of collision data to be able to evaluate conditions on a road. The level of safety of a location on a roadway is measured by the frequency of collisions by collision type: property damage, injury and fatality. A location is considered unsafe if the number of observed collisions exceeds what should be expected derived from a collision prediction model, a regression model that estimates the collision frequency for a site based on the characteristics specific to that site (Sayed and De Leur, 2008).

This is a reactive approach that has several shortcomings including poor quality collision data due to the subjective nature of collecting information, long collection periods since collisions do not occur frequently enough to produce a sufficient data set in a short period of time, and the ethical issues that arise since in order to prevent collisions, many collisions first need to occur. Alternative
methods of evaluating safety on roadways should be considered to address these shortcomings.

Hauer (2006) outlines the issues with using reported collisions as a measure for road traffic safety research, specifically that less severe collisions may not be reported and there may be bias towards a specific demographic or vehicle type more inclined to report collisions. Nicholson (1985) demonstrates through observed collision information that assumptions that are used within traditional road traffic safety research, namely the “Poisson assumption” are not always valid, showing considerable variability within the observed collision information. Hirst et al. (2004) identifies that accident risk declines over time and therefore the collision prediction models used tend to become outdated, with subsequent proposal of a correction procedure to account for errors with outdated models. de Leur and Sayed (2001) discuss the issues with using collision data and proposes the use of insurance claim reports to obtain better detail of contributing factors leading to a collision. de Leur and Sayed (2003) identify the individual obstacles with traditional road traffic safety research and attempt to provide potential solutions for each of the obstacles.

One of the key shortcomings to traditional road traffic safety research is the length of time required for collecting collision data. It is well known that collisions in traffic occur as rare and random events (Davis, 2004; Hauer, 2006; Hirst et al., 2004; Nicholson, 1985; Saunier and Sayed, 2007). Because of this it is difficult to properly evaluate the instances of collisions without taking lengthy evaluation periods. Alternative methods of collecting information are required to enable quicker response to unsafe transportation facilities.

### 2.2 Traffic Conflict Technique

Due to limitations with traditional road traffic safety analysis, alternative traffic safety research methods have been developed to address some of the shortcomings of traditional road traffic safety research. Surrogate safety measures have been used as safety measures that do not rely on reported collisions. Traffic conflicts, or near misses, address some of the shortcomings of collision data
such as shorter collection time, more frequent occurrences and less cost to society.

The traffic conflict technique involves recording the frequency and severity of conflicts between vehicles on a roadway, allowing for the immediate evaluation of unsafe driving maneuvers without having to wait for collisions to occur (Amundsen and Hyden, 1977). Traffic conflicts were originally proposed by Perkins and Harris (1968) with an objective to identify other traffic events that have a higher frequency of occurrence than collisions and can be related to collisions. The research performed by Perkins and Harris (1968) involved identifying instances where drivers take evasive maneuvers to avoid collisions, such as hard braking or the sudden changing of lanes, indicating the presence of areas with higher risk of collisions. The methodology was later named the “traffic conflict technique” (Chin and Quek, 1997; Perkins and Harris, 1968). Through the use of recorded video and standardized measures, researchers have been able to evaluate road traffic safety through traffic conflicts from a laboratory or office (Shinar, 1985).

The traffic conflict technique has many benefits as a safety surrogate in road traffic safety research. Specifically, traffic conflicts occur more frequently, they provide insights into the failure mechanism leading to road collisions, the collection period is much shorter than traditional traffic safety data collection, and the ethical dilemma of waiting for collisions to occur is no longer a factor (Chin and Quek, 1997).

### 2.2.1 Traffic Conflict Indicators

Traffic conflict indicators are the measures used to represent a conflict between road users (Essa, 2015). Traffic conflict indicators have been well documented in previous studies (Autey et al., 2012; Cunto, 2008; Ismail, 2010). The SSAM software package can be used to evaluate surrogate safety measures in conjunction with the output from the VISSIM micro-simulation model. The following sections describe some common traffic conflict indicators used in the SSAM.
2.2.1.1 Time-To-Collision (TTC)

Hayward (1972) originally defined the Time to Collision (TTC) indicator as “the time required for two vehicles to collide if they continue at their present speeds on the same path.” Amundsen and Hyden (1977) later described the TTC indicator as “an observable situation in which two or more road users approach each other in space and time to such an extent that there is a risk of collision if their movements remain unchanged.” The TTC is considered the most widely used traffic conflict indicator.

To be a useful measure, the TTC requires projection of vehicle trajectories into the future, based on information prior to the evasive maneuver taking place. This has been done using a probabilistic approach based on common motion patterns for prediction using computer vision techniques for extracting trajectory information (Saunier and Sayed, 2008; Saunier et al., 2010).

Some shortcomings of the TTC indicator are that several combinations of speeds and distance can produce the same TTC value, showing that TTC may not be a good method for determining severity of an incident, continuous measurements of TTC can require large amounts of information to be gathered about vehicle trajectories making it difficult and still time consuming, and finally the variations of the definition of the TTC may make it complicated for traffic safety practitioners to know which variation is the right one to use.

2.2.1.2 Post Encroachment Time (PET)

The Post Encroachment Time (PET) indicator is the moment in time between when the “offending” vehicle leaves the zone where a potential collision has occurred and the moment in time that the other “non-offending” vehicle arrives at that same potential collision zone (Cooper, 1984). The Post-Encroachment Time (PET) can be measured through observation of vehicle trajectories and does not require any projection of trajectories into the future.
Conflict severity is not attainable through the PET indicator as it does not require speed and distance measurements to be determined (Archer, 2004; Ismail, 2010). Another issue with the PET is that it is calculated at times even when no risk exists of a collision, typically in rear-end and merging conflict situations depending on the speed of the following vehicle in relation to the lead vehicle (Archer, 2004). Another shortcoming of the PET indicator is that it can have false readings when a vehicle takes an evasive maneuver to avoid a collision and the following vehicle never actually encroaches on into the trajectory of the lead vehicle, for example with the lead vehicle being in a queue of stationary vehicles (Shelby, 2011).

### 2.2.1.3 Maximum Speed (MaxS) and Difference in Speed (DeltaS)

The MaxS indicator is the maximum speed of either vehicle throughout the instance of the conflict and DeltaS is the difference in vehicle speeds observed at the minimum time to collision. The MaxS and DeltaS indicators are related to the severity of an incident should one occur (Gettman et al., 2008).

A shortcoming of the MaxS indicator is that speed is a scalar value and does not allow for the inclusion of direction, resulting in MaxS not being able to distinguish the severity of a head-on collision versus the minor severity of a rear-end collision (Shelby, 2011). The DeltaS indicator has the same shortcoming in that it does not represent the direction but rather only the magnitude of speeds (Shelby, 2011).

### 2.2.1.4 Change in Velocity (DeltaV)

The DeltaV indicator is the change between the conflict velocity and the postcollision velocity. It is the surrogate for the severity of the conflict and is calculated using the hypothetical collisions between the two vehicles involved in the conflict (Gettman et al., 2008). Within SSAM, DeltaV is provided for both of the vehicles (FirstDeltaV, SecondDeltaV) as well as the maximum

The DeltaV conflict indicator is not widely used. However it has demonstrated robustness where other indicators have shown issue (Shelby, 2011).

2.2.2 Challenges to the Traffic Conflict Technique

The traffic conflict technique is not without its challenges, despite the benefits discussed previously. The main challenges with respect to the traffic conflict technique are with respect to consistency, validity and reliability.

When categorizing evasive maneuvers by drivers, there are inconsistencies between field observers and the recorded conflicts are prone to errors. Additionally, a collision or conflict may occur because of the lack of an evasive maneuver, thus making it difficult to categorize the situation as a conflict or properly specify the value of the indicator being measured.

The validity of the traffic conflict technique has been criticized as there have been many studies that have failed to find an acceptable statistical correlation between the measured conflicts and measured collisions. Glennon et al. (1977) has claimed also that for every study where good correlation is shown, there is another study where poor correlations have been found. There have been studies however that show statistically significant correlations between the conflicts and the collisions (Brow, 1994; Sayed and Zein, 1999).

The reliability of conflict measures is often the main consideration in opposition to the traffic conflict technique. Primarily because of intra-rater variation, or inconsistencies in the recordings made by one field observer, as well as inter-rater variation, or the inconsistencies of interpreting and recording conflicts between different observers (Chin and Quek, 1997). Training manuals have
been developed to help avoid intra-rater variation, however observations are still subjective in nature and therefore prone to these shortcomings. Automated video analysis has made advancements in recent years through the field of computer vision and is showing to be a promising method to counteract the issues identified with manually observed conflicts (Ismail, 2010).

### 2.2.3 Computer Vision Techniques for Conflict Analysis

Automated computer vision techniques have been used more recently to perform conflict analysis, removing the subjectivity seen when manual evaluation of conflicts takes place from field observers. This technique has been employed for automatic conflict analysis in various safety applications such as before and after studies (Autey et al., 2012; Pin et al., 2015; Sayed et al., 2012, 2013).

Automated video based analysis overcomes the shortcomings of field observations both from a cost and data reliability perspective, and has proven to be more accurate in determining conflict severity. The installation of cameras is easier and less expensive than installing other detectors and the cameras can be used for other purposes, especially validating information detected by the systems.

#### 2.2.3.1 Computer Vision at UBC

The Transportation Engineering group at the University of British Columbia in the department of Civil Engineering is continuously advancing research into the development of computer vision for the purposes of automated video analysis. Autey et al. (2012) provides a detailed description of the automated computer vision process for video analysis.
2.3 Intelligent Transportation Systems

Intelligent Transportation Systems (ITS) are, according to ITS Canada (2012), “[t]he application of advanced and emerging technologies (computers, sensors, control, communications, and electronic devices) in transportation to save lives, time, money, energy and the environment.” ITS are used in applications such as highway traffic monitoring, signalized intersections, on-board vehicle navigation systems, personal smartphone applications, tracking of dangerous goods and connected vehicle technologies. The key concept behind ITS is using technology to collect and disseminate information to improve the knowledge about a transportation network, improve traffic conditions, and to improve user experience.

ITS are a means of managing capacity and demand through the use of electronic systems that communicate typically with the driver through on-road infrastructure such as a Dynamic Message Sign (DMS) or on-board devices such as navigation systems. ITS is a broad topic with a wide range of applications. The primary application of ITS for the purposes of this thesis is with respect to Connected Vehicle applications and safety.

2.3.1 In-Vehicle Technologies

In-vehicle technologies involve electronic sensors and processors to collect information from the field and produce changes to driver or vehicle behaviour. Often different sensors, both active and passive, are used in detecting and tracking vehicles or other objects such as pedestrians, lane markings and traffic signs for use with in-vehicle technologies. The implementations of these systems have many applications such as adaptive cruise control, forward collision warning with pre-crash sensing, headway alert, parking sensors, blind spot sensors and brake support. Some of these technologies have benefited transportation safety in that they help to identify dangerous situations and assist the driver to take evasive action sooner to avoid a collision. Additionally, the technologies such as Anti-lock Brake System (ABS) and Electronic Stability Control (ESC)
assist by helping the driver to stay in control of the vehicle when the vehicle is skidding or braking suddenly (Transport Canada, 2011). Other technologies, such as on-board navigation systems provide a communication method to drivers to provide advance warning of traffic or incidents on the roadway and attempt to remove driver uncertainty in unfamiliar areas.

While the intended benefits of in-vehicle technologies may be safety related, driver behavioural adaptation may counteract these safety benefits, negating any improvement created by the system. Systems that are intended to make driving easier, such as adaptive cruise control, can cause drivers to focus more on secondary tasks resulting in increases to response times to hazards on the roadway creating a danger or a reduction in safety on the roadway (Rudin-Brown and Parker, 2004).

2.3.2 Safety and Behavioural Adaptation

Some safety applications of ITS in relation to in-vehicle technologies are brake assist, adaptive cruise control, pedestrian detection, blind spot detection, lane assist and collision warning system.

When safety measures are implemented within a transportation system, the primary focus is on one or multiple of exposure, crash risk and consequence. These are the typical factors being measured for any change to improve safety on the roadway; however, there are unexpected factors outside of what was intended by the engineering effect which could have adverse impacts on other factors and counteract the positive benefit of the original safety measure. The engineering effect is the anticipated change in safety level due to the factor implemented. These adverse effects are typically caused by behavioural adaptation or risk compensation which is when road users change behaviour to compensate for the safety measure. Kulmala (2010) provides an assessment of safety effects resulting from ITS, finding that measures that are more easily detected by road users, or have a greater engineering effect, generally lead more to behavioural adaptation than those that are not easily detected.

Smiley (2000) discusses the behavioural adaptation to driver condition such as age or time sensitive
driving (e.g., running late for a meeting), and on the impacts that ITS have on driving conditions. With the onset of power braking systems and improved car handling and adaptive cruise control systems, average headways are reduced while average driving speeds increase (Smiley, 2000).

In relation to behavioural adaptation, Bjørnskau (1995) proposed five hypotheses to explain behav- iournal adaptation to the implementation of any safety measures and Elvik (2004) organizes these in the following ways: 1) how easily a measure is detected, 2) antecedent behavioural adap- tion to target factors, 3) size of the engineering effect on target factors, 4) whether or not a measure primarily reduces injury severity, and 5) whether or not additional utility can be gained. Kulmala (2010) further expands on these factors and proposes the following nine-point list of ITS safety mechanisms as a framework for assessing the road safety impacts of ITS.

1. Direct in-vehicle modification of the driving task
2. Direct influence by roadside systems
3. Indirect modification of user behaviour
4. Indirect modification of non-user behaviour
5. Modification of interaction between road users
6. Modification of exposure
7. Modification of modal choice
8. Modification of route choice
9. Modification of accident consequences only

Of the nine-point list, the research as part of this thesis would be able to coordinate efforts with roadside systems to directly influence driver behaviour (e.g., through roadside messaging of incident risk). Additional points that are secondary areas that this thesis touches on are the indirect modification of user behaviour, the indirect modification of non-user behaviour, the modification of interaction between road users, modification of road user exposure and modification of route choice.
Both Kulmala (2010) and Elvik (2004) provide a general model of the causal chain as to how road safety measures influence the road safety. This model is presented in Figure 2.2.

![Figure 2.2: General Model of the causal chain for the influence of road safety measures on road safety (Elvik, 2004; Kulmala, 2010).](image)

### 2.3.3 Connected and Autonomous Vehicles

The major disruptive technology at the time of writing this thesis are related to connected and autonomous vehicles. They are components of ITS however require much greater discussion. Being a primary focus of this thesis, connected vehicles are those that include some form of communication to something other than itself. The communication can be in the form of connection with a piece of infrastructure on the side of the road, another vehicle, a combination of the two or multiple other objects. Three terms are used to describe connected vehicles: V2V, V2I, and V2X which is a more general term now used where “X” can be another vehicle, a piece of infrastructure, an on-board device or a cloud technology, or other such as the Internet.

Autonomous vehicles are those that can drive autonomously and do not require human interaction. Autonomous vehicles rely on sensors installed on the vehicle itself to detect where they are (both through Global Positioning System (GPS) and other sensors) and what is going on around them (Gibbs, 2014). When combined with software, autonomous vehicles are capable of identifying obstacles on the road, lane lines, traffic signals, pedestrians and cyclists, and other vehicles on the road. In essence, autonomous vehicles remove the need for a human driver and replace it with a
computer that is capable of doing nearly all of the same things but with a much higher frequency and faster decision and response times.

While autonomous vehicles have been touted as the future (Luettel et al., 2012), there is an inherent need for vehicles to communicate with each other as well. As an example, at the time of writing this thesis the Google Car had driven over 1.3 million miles and had been involved in less than 20 crashes. Even with the Google Self-Driving Car having the majority of accidents caused by other drivers due to human error, the first instance of a collision that is the fault of the Google Self-Driving Car could have been avoided if a form of communication between the vehicles was present. Another collision, more critical than the one reported by Google, involved Tesla’s autopilot which resulted in a fatality due to the inability for the autopilot function to see a tractor trailer, resulting in the Tesla travelling underneath the trailer while the roof of the tesla collided with the underside of the trailer. This collision could have also been avoided if there had been a communication protocol between the vehicles on the road to have prompted emergency braking in advance of the collision.

Connected vehicle technologies are the methods that vehicles can be connected whereas the applications are how those technologies are put into practice. In the following sections I will discuss some of the existing technologies and applications of connected vehicles at the time of writing this thesis.

2.3.3.1 Connected Vehicle Technologies and Applications

This thesis will distinguish between connected vehicle technologies and connected vehicle applications as follows: connected vehicle technologies are the specific pieces of hardware that enable vehicles to speak with one-another or with the surrounding infrastructure or other devices; con-

1The Google Self-Driving Car is an autonomous vehicle that has been developed by Google and at the time of this thesis being written has driven over 1.3-million miles autonomously.

2http://www.businessinsider.com/video-google-self-driving-car-slowly-hits-city-bus-2016-3

connected vehicle applications are the practice of putting to use connected vehicle technologies for real-world applications that make a change to safety, mobility or sustainability.

Connected vehicle technologies have typically been decided by the automaker with support from standards organizations such as the Institute for Electrical and Electronics Engineers (IEEE) and the Society of Automotive Engineers (SAE).

The word “connected” is often used to interpret when people or things are on and available, in constant communication with someone or something. While widespread use of the term “connected” implies it relates to the Internet, in terms of connected vehicles, there is a component that may refer to the “Internet of Things”\(^4\), although this is primarily for the infotainment component and does not relate much to transportation or traffic engineering purposes being discussed in this thesis.

There are two types of connected vehicle applications under consideration in this thesis: 1) those that communicate information to the driver in order to encourage driver action, and 2) those that communicate information to the vehicle in order to enact action. With respect to this thesis the applications to be discussed are those that intend to improve the safety or mobility of a vehicle or a road or network.

When evaluating the applications of connected vehicle and autonomous vehicle technologies they are being applied to the current vehicle network, based on existing driver behaviours. What needs to also be reviewed are the behaviours that should be anticipated to change due to the increased technologies.

With new disruptive technologies, user behaviour is often altered. An example of where technology has become disruptive is with the onset of cellular phones and the unexpected outcome that more time would be spent typing (through email and messaging applications) than speaking. The same can be expected from connected vehicle and autonomous vehicle technologies, although the

\(^4\)The Internet of Things is a combination of computers, systems, machines and other unique identifiers with the ability to communicate, transfer data, and perform tasks without requiring human-to-human or human-to-computer interaction.
outcome of behavioural changes will not fully be known until there is a widespread distribution of these vehicles on the roadways.

2.3.3.2 Social Impacts of Connected and Autonomous Vehicles

While connected and autonomous vehicles may have many practical impacts, there are indirect social impacts which should be considered.

When considering driverless vehicles, all humans travelling within these vehicles can now be classified as passengers. This creates problems of a new sort that need to be considered by auto manufacturers. A recent article published in IEEE Spectrum\(^5\) explains how nausea will be more of a common occurrence because of the lack of coordination between the eye and inner ear for the (former) drivers as they will be preoccupied performing other tasks such as reading, working, or socializing.

2.4 The VISSIM Micro-Simulation Model and SSAM

Traffic simulations are very useful to evaluate components of a road or vehicle design that have not yet been built or deployed in the real-world. Within micro-simulation models traffic conflicts can be observed. The software package called surrogate safety assessment model, referred to as SSAM, has been developed to automate the output of a simulation from four different micro-simulators: VISSIM, AIMSUN, PARAMICS and TEXAS.

Gettman et al. (2008) conducted 11 theoretical validation tests to compare the results of pairs of simulated design alternatives, and field validation on 83 intersections in order to assess the use of SSAM. The underlying principle to this study was to evaluate the ability of SSAM to distinguish between two design alternatives in a simulation. The results showed there were statistically significant differences in the total number of conflict events, number of conflicts of a certain type, and

\(^5\)http://spectrum.ieee.org/cars-that-think/transportation/self-driving/will-robocars-make-you-puke
the mean and variance of surrogate safety measures (time to collision, post-encroachment time and others). A field verification was done comparing five of the simulated intersections to those that were actually monitored in the field and the results showed a statistically significant correlation between the conflicts found in SSAM and those found in the field. It was noted in the study that volume based crash prediction correlated better with the actual crash data than the surrogate safety measures did in all cases. While the study demonstrated that SSAM would very much benefit the study of safety for facilities not yet built, the validation results were ultimately considered inconclusive and there were some recommendations for future research, such as develop a composite safety index, improve driver behaviour modelling in simulations, and investigate conflict classification criteria (Gettman et al., 2008). Essa and Sayed (2015a) demonstrated the need to calibrate VISSIM through comparison before and after the two-step calibration process, using SSAM as the second step for calibration.

Dijkstra et al. (2010) performed a study simulating conflicts at many junctions in the Netherlands (a total of 569) using the PARAMICS microscopic simulation software. Additionally, actual crash data was collected at these same junctions in the real world. The relationship between simulated conflicts and observed crashes was assessed using generalized linear models in the GENMOD procedure of the SAS software. Different log-linear models were developed by using either 1) negative binomial distribution or 2) poisson distribution. Different TTC thresholds were used in calculating the conflicts. Regression analysis was performed and both the negative binomial distribution and the poisson distribution led to similar results for goodness of fit of the models used and the significance of the variables. It was found that the number of conflicts observed at junctions and the number of passing vehicles are statistically related to the number of observed crashes for all of the junctions (Dijkstra et al., 2010).

Fan et al. (2013) developed a procedure for using SSAM and VISSIM for safety assessment at freeway merge areas. The tasks of this study were to develop VISSIM simulation models accounting for driver behaviour, and to improve consistency of simulated conflicts with manually collected
field observations through calibration of VISSIM and SSAM. The first stage of calibration consisted of reproducing volume, speed and travel time in VISSIM to that what was observed in the field. During the second stage of calibration, crucial parameters, specifically the TTC parameter as defined in SSAM, were modified to replicate what was observed in the field. The optimal TTC value was where the mean absolute percent error Mean Absolute Percent Error (MAPE) was found to be a minimum, and TTC was found to be 2.1 seconds. The two-stage calibration procedure was found to reduce the MAPE for rear-end and lane-change conflicts at freeway merge areas and showed reasonable consistency with field observations (Fan et al., 2013).

Huang et al. (2013) evaluated whether or not the combination of VISSIM and SSAM provides reasonable estimates for traffic conflicts at ten signalized intersections. Field data was collected and conflict analysis was performed manually at the observed locations. A two-stage calibration process was implemented to calibrate and validate the VISSIM simulation models and to adjust the threshold values in SSAM. The minimum TTC threshold in SSAM was calibrated to give a minimum MAPE of simulated rear-end conflicts and the minimum gap time in VISSIM was calibrated to give a minimum MAPE of simulated crossing conflicts. The results were an optimum TTC of 1.6 seconds and an optimum minimum gap of 2 seconds. Transferability of the simulation model was tested by comparing the results of simulation at two other sites using the calibrated parameters and without re-calibrating (Huang et al., 2013).

Huang et al. (2013) investigated whether performing a two-stage calibration procedure to adjust the threshold values in SSAM would benefit the simulation within VISSIM when comparing with observed conflicts. The findings showed that the two-stage approach improved the goodness-of-fit between simulated and observed conflicts and that the calibration of the SSAM thresholds were transferable when simulating other situations and comparing with observations.

Gettman et al. (2008) summarizes the research for the SSAM which was developed to combine micro-simulation and automated conflict analysis to assess the safety of traffic facilities without waiting for crashes and injuries to occur.
Evaluation of traffic micro-simulation models has shown that real world calibration is necessary. An example of the need for calibration is provided in Gomes et al. (2004) where VISSIM was calibrated for congested freeways. For the most part the default values within VISSIM provided a good fit for traffic flow on the freeway. However, Gomes et al. (2004) found there were three problem areas identified as bottlenecks in real conditions that were not being found in the model. The problem areas needed to be identified and the model needed to be calibrated to replicate these problem areas.

The conflict types included for evaluation within SSAM are as follows (Gettman et al., 2008):

**TTC** Expected time for two vehicles to collide if they remain at their present speed and on the same path.

**PET** Time lapse between end of encroachment of turning vehicle and the time that the through vehicle actually arrives at the potential point of collision.

**MaxS** The maximum speed of either vehicle throughout the conflict.

**DeltaS** The difference in speeds of the two vehicles at the minimum time to collision.

**Deceleration Rate (DR)** The initial deceleration rate of the second vehicle, the crossing or following vehicle.

**MaxD** The maximum deceleration of the second vehicle, the crossing or following vehicle.

**Conflict Type** The type of conflict: rear end, lane change or crossing.

**MaxDeltaV** The maximum change between conflict velocity and the post collision velocity for either vehicle involved in the conflict.

**FirstDeltaV / SecondDeltaV** The change between conflict velocity and the post collision velocity.
2.5 Evaluation of Connected Vehicle Applications Using Micro-Simulation

Connected vehicles have a set of basic technology which is being implemented as a standard, led by the Society of Automotive Engineers International (J2735 Surface Vehicle Standard: Dedicated Short-Range Communications (DSRC) Message Set Dictionary. 2009). Typically this technology involves dedicated short range communications (DSRC) and transmission of types of messages from V2V and V2I. The United States Department of Transportation (USDOT) has developed an ITS Standards program to work towards the harmonization of communications standards for programming and development amongst automotive and equipment manufacturers, governments and standards organizations.

Tideman and van Noort (2013) discuss the requirements put onto automotive OEMs when developing new connected vehicle technologies to ensure feasibility, robustness and effectiveness of the new technologies on the individual vehicle, small-scale scenario and traffic network levels. The authors are introducing software created by the independent research organization called TNO which provide tools to test connected vehicle systems in a simulation environment by introducing communications into the simulation of Advanced Driver Assistance Systems (ADAS). The software packages introduced are PreScan, a software for the design and testing of intelligent vehicle systems, and ITS Modeller, a microscopic traffic simulator used for evaluating the design outputs from PreScan and integration of these designs into the traffic network level. Importance is placed on the need for automotive OEMs to develop systems that meet government needs as well as to improve safety and/or mobility on roadways. A test case was performed looking at cooperative adaptive cruise control (CACC). Throughout the test case it was found that the CACC system satisfied all the local requirements and was very safe, although it created large traffic jams because the CACC system didnt take traffic efficiency into account, demonstrating that calibration is necessary when testing systems and a global view is required. An update to the design of the CACC system was implemented and overall results showed that travel time, delays and the standard devi-
ation of speed in traffic jams are reduced while the average speed in traffic jams are increased for different penetration levels (Tideman and van Noort, 2013). The study did not evaluate the safety component of the CACC system other than stating that safety was improved.

The impacts of deploying connected vehicles on the road network has been studied through micro-simulation models. Connected vehicles can communicate with each other or with the infrastructure surrounding them. Paikari et al. (2014) perform research into combining the V2V and V2I technologies to complement connected vehicle technologies, improve connected vehicle efficiency and to lead to higher safety and mobility enhancements on freeways. The authors discuss a simulation-based benefit analysis of deploying connected vehicles using DSRC. Each connected vehicle can communicate with other connected vehicles within their immediate proximity, providing recommended speed and route information while also communicating to connected roadside units which can subsequently post advisory information on highway signs to communicate with non-connected vehicles. Using PARAMICS as a micro-simulator, 15 different scenarios for varying penetration and demand loading are simulated. The evaluation of the scenarios is through safety and mobility. Mobility is measured by the average estimated point-to-point travel time. With respect to safety, a safety index is developed based on the Overall Risk Change Index (ORCI). The findings of this study are such that this specific connected vehicle technology implementation shows safety improvements and that as connected vehicle penetration increases on the roadways, so too does the efficiency on the roadways; however, the improvement in safety and mobility reaches a limit when the penetration rate gets to 40%, after which there are adverse effects (Paikari et al., 2014).

Focusing on more specific facilities, intersection management has been a topic of interest for decades. More recently the environmental factors such as pollution caused by congestion and idling associated with intersections have been considered an issue as traffic grows in a region. Jin et al. (2012) focuses on intersection management and the applications of connected vehicles for this purpose. In an advanced traffic management system specific to connected vehicles, both connected vehicles and the intersection infrastructure can take advantage of real time traffic infor-
information through the use of wireless communications. The objective of this study was to demonstrate the concept of reserving a slot in space and time for travelling through an intersection, allowing a vehicle to avoid collisions and minimize wait time. Using connected vehicle technology in a V2I communications platform it is expected that vehicles will reserve a place to travel through the intersection and the infrastructure can plan the trajectory of the vehicle in advance of it entering the intersection and in coordination with other vehicles around it. This study uses the software called SUMO (Simulation of Urban Mobility) due to its nature of handling both traffic simulation and wireless communication. Limitations to this study are the assumptions that were made, such as the assumption that all vehicles must have V2I communications. Results show that an Advanced Traffic Management System (ATMS) approach to intersection management using a reservation system for time/space within an intersection can considerably alleviate traffic congestion and reduce pollutant emissions and fuel consumption (Paikari et al., 2014). Safety was not a consideration of this study however it would be beneficial to find if collisions or conflicts are reduced by using this technology.

Chen et al. (2014) discusses the concept of connected vehicles and the transportation system using ITS as a network as opposed to for individual vehicles. This paper does not discuss simulation but does discuss the safety factors associated with connected vehicles. Some discussion was provided around driver behaviour learning (Chen et al., 2014).

Miller and Horowitz (2007) describe the simulation tool that can be used for ITS applications as it allows for vehicles to communicate with each other and with the infrastructure around the vehicles. While FreeSim allows for simulation of freeway applications including using ITS, this paper does not discuss any actual simulation or safety benefits of ITS or connected vehicles (Miller and Horowitz, 2007).

V2V communications is considered one of the key components to connected vehicles as it allows for vehicles to know and understand what other vehicles are currently doing or are about to do on a roadway. In order to enable V2V communications, a communications network must be established.
Eichler et al. (2005) discuss and demonstrate the benefits and drawbacks of Vehicular Ad-Hoc Networks (VANET) using a comprehensive simulation environment. As a means to demonstrate the benefits of a VANET, Eichler, Ostermaier, Schroth, and Kosch (2005) looks at an example of V2V traffic obstacle messaging applications for real-time traffic and safety information systems. In this example, a broken down vehicle equipped with V2V communications sends out alerts to other V2V equipped vehicles within a 250m radius whose routes are subsequently changed. The travel times and delays are measured for the V2V equipped vehicles and the non-equipped vehicles to demonstrate the benefit of a VANET (Eichler et al., 2005). The output of the simulation does not discuss safety.

Schroth et al. (2005) expand further on the importance of V2V communications on the above example using V2I communications, describing the work to quantify the possible benefits of V2V communication in connected vehicles using a combined traffic and network simulation environment where communications between vehicles affects route decisions. The concept of this work uses three logical components for the simulation: 1) traffic simulator which computes new positions periodically, 2) network simulator dedicated to imitating the full functionality of a real wireless network with complex effects of mobile communications (only a portion of the vehicles from 1 participate in 2), and 3) an application which accounts for controlling the whole simulation environment, evaluating received messages and deciding what action to be taken by the traffic simulator. The simulation run used in this paper describes an instance where there are 900 vehicles on a road network and 400 of these vehicles are equipped with vehicle-to-vehicle communication ability. A car breaks down and broadcasts the information, which is registered within the 400 connected vehicles and route choice can be made accordingly to avoid the area with the broken down vehicle. The study used CARISMA but is expected that this would be replaced by VISSIM (Schroth et al., 2005).

Highway applications for connected vehicles are equally important as highway capacity is expected to increase with improvements in this field. Looking specifically at a V2V environment, Zhao and
Sun (2013) focus on Cooperative Adaptive Cruise Control (CACC) in a micro-simulation setting to examine the benefits of platooning. CACC is the V2V communication method by communicating with the vehicle at the front of a platoon to allow for vehicles to follow each other with a closer distance, improving traffic flow capacity. The study does a comparison with different penetration percentages and different platoon sizes to demonstrate the changes in capacity on a roadway. The results show that the higher the penetration is of CACC equipped vehicles, the higher the capacity, while the capacity does not appear to change significantly based on platoon size (Zhao and Sun, 2013). It should be noted in this study that driver comfort is not considered and issues with what would need to change within a vehicle environment to ensure the comfort of drivers and passengers within the platoon are not compromised.

Ben Othmane et al. (2013) do not discuss simulation but rather presents information on the safety considerations needed for connected vehicles with respect to external malicious attacks (Ben Othmane et al., 2013).

Smith and Razo (2014) discuss the importance of V2V but put an emphasis on the V2I component. Looking to deploy a pilot project in Ann Arbor, MI, micro-simulation is used to determine the level of interaction amongst vehicles in order to best choose candidates for the pilot project. The micro-simulation was used to estimate the number of spatial and temporal locations of V2V interactions under various deployment strategies. Ultimately the micro-simulation model was able to show where and when a significant number of interactions would occur (Smith and Razo, 2014). Before a connected vehicle application is implemented as a pilot project in the field it is important to be certain that the technologies deployed will have ample opportunities to interact the way they are intended in order to allow for proper exposure and testing prior to full implementation.
Chapter 3

Methodology

To perform micro-simulation and safety evaluation of the chosen connected vehicle applications, a number of tools were utilized. This chapter outlines the tools used and a generic methodology to create the micro-simulation model for the evaluation and subsequent assessment methods. Additionally, the procedure is outlined for the two specific connected vehicle applications being reviewed as part of this thesis with underlying methodology to test the hypotheses of this thesis.

3.1 Background

VISSIM is one of the most commonly used traffic micro-simulation models. VISSIM is capable of simulating all modes of transportation and has the capabilities of defining motion characteristics of vehicles and interactions with other vehicles, allowing for evaluation on a per-vehicle basis as well as an entire transportation network.

While VISSIM allows users to customize inputs, parameters and characteristics specific to the simulation, a significant programming knowledge is required to fully make use of these capabilities. There are three methods found as part of the research for this thesis to modify the behaviour of the road traffic network in VISSIM, including both the vehicles and the infrastructure. These ways are
1) through built-in simulation parameter modification, 2) through the VISSIM COM interface, and 3) through a Dynamic Linked Library (DLL) controlling the driver behaviour. All three of these methods were reviewed and best determined which were to be employed for different connected vehicle applications. These three methods are further described below.

### 3.1.1 VISSIM Simulation Parameter Modification

Modifying the simulation parameters in VISSIM allows for varying control of driver and vehicle characteristics such as the headway time, following thresholds (in metres), and acceleration. There are over 190 distinct parameters that can be varied to the user’s preference (Essa and Sayed, 2015a).

While the modification of VISSIM parameters changes the way the micro-simulation model behaves, the changes only apply to pre-defined algorithms and vehicle behaviour based on the Wiedemann 74 and 99 driver behaviour models and the lane change models defined within VISSIM. To better evaluate connected vehicle applications, consideration should be put more on the Component Object Model (COM) interface and the DLL.

### 3.1.2 The VISSIM COM Interface

Microsoft developed a Component Object Model (COM) technology to allow communication between software, compatible with COM (Box, 1998). VISSIM is enabled with the ability to communicate through COM using multiple programming languages, including Visual Basic, MATLAB, Python, Java and C++. COM allows the control of many elements of the simulation, including some, but not all, of the simulation parameters discussed in Section 3.1.1 Other elements controllable through COM include signal heads (RED, AMBER, GREEN, etc), barrier placement, the position of a vehicle and the desired speed of a vehicle or a group of vehicles. Using COM with VISSIM also allows for enhanced reporting of information while the simulation is in progress, allowing for better insights into current vehicle operating states.
In version 5 of VISSIM there was a Car2X module which allowed for the passing of information from vehicles with the appropriate equipment flag and defines when vehicles receive information and the reaction to that information. This Car2X module was removed in subsequent versions of VISSIM and in version 7 the suggested method to use is GetByLocation. Unfortunately this method was not found to be sufficient for the implementation of connected vehicle applications within VISSIM for the purposes of this thesis. However, through additional programming all needs for evaluation of the connected vehicle applications were met.

Tettamanti and Horváth (2015) outlines the use of the COM interface for VISSIM, specifically using MATLAB as the controller which is the same programming language used with the COM interface for this thesis.

### 3.1.3 The Driver Behaviour DLL

Dynamic Linked Libraries are shared libraries for use in the Microsoft Windows operating system environment. They contain code that can be used by multiple programs at the same time. VISSIM uses DLLs to supplement existing models. Specific to this thesis, the pre-existing DriverModel.DLL within the VISSIM distribution was used to supplement the driver behaviour of vehicles labelled as connected vehicles. Other DLLs include the SignalControl.DLL, SignalGUI.DLL and EmissionsModel.DLL, allowing for user defined signal controllers and emissions models.

The DriverModel.DLL allows modifications to or replacements of the car-following and lane change models. This includes defining acceleration parameters of individual vehicles, controlling the blinker and lane changes, and controlling the colour of a vehicle.

Throughout the remainder of this section, the methods defined above in Sections 3.1.1, 3.1.2 and 3.1.3 will be the referred to tools for the purpose of developing a connected vehicle environment within VISSIM.
Depending on which version of VISSIM is used there may be different needs when developing the environment. The following section outlines the framework for developing a connected vehicle environment within VISSIM version 7.

### 3.2 Framework for Developing Connected Vehicle Environments within VISSIM

There are a number of considerations in developing a connected vehicle environment in VISSIM. The primary considerations are the information being transmitted, the reactions to that information and the impacts to the road traffic network. The below generic procedure is defined to support the development and evaluation of connected vehicle environments within VISSIM. Detailed description of evaluation methodology to assess the research objectives of this thesis are provided in Sections 3.3 and 3.4.

1. Identify connected vehicle application
2. Identify connected vehicle technology
3. Determine changes within VISSIM
4. Identify tool to perform the changes within VISSIM
5. Apply changes through appropriate tool
6. Evaluation configuration
7. Run simulation
8. Evaluate simulation

Below are further definitions and explanations of each step.

#### 3.2.1 Identify Connected Vehicle Application

Connected vehicle applications can vary by location, complexity with interactions between vehicles and with infrastructure (both V2V and V2I), and purpose (e.g., reduce emissions, improve
mobility, improve safety). The connected vehicle application is the specific way that vehicles will interact with other vehicles and surrounding infrastructure. In this thesis, the two connected vehicle applications being evaluated through micro-simulation and SSAM are Cumulative Travel Time Intersection Control and Cooperative Adaptive Cruise Control.

### 3.2.2 Identify Connected Vehicle Technology

The connected vehicle technology is the specific pieces of hardware and base technology used to support the connected vehicle application. The technologies deployed are typically DSRC for communications while sending information through the Basic Safety Message (BSM). The technologies used need to be understood in order to identify where in VISSIM the modification needs to take place.

### 3.2.3 Determine Changes Within VISSIM

After the connected vehicle application and technology have been identified and understood, an evaluation needs to be undertaken as to where the changes will occur within VISSIM. This will include changes to vehicle control, infrastructure control, or driver behaviour. For example, if the driver behaviour changes due to the connected vehicle application or technology, it is possible that the reaction time will change, or if the vehicle is assuming some of the driving control, it is possible that the acceleration and deceleration driving behaviour may change.

### 3.2.4 Identify Tool to Perform the Changes Within VISSIM

The tools available for implementing connected vehicle applications in VISSIM are referenced in Section 3.1 as internal VISSIM parameters, the COM interface, and the driver behaviour model DLL. To best implement the connected vehicle application, the proper tool(s) need to be identified and used.
The VISSIM parameters should be modified if the predefined algorithms within VISSIM do not need modification but only the sensitivity of the micro-simulation itself. The VISSIM parameters will typically not be changed in isolation of the use of another tool for connected vehicle applications.

The COM interface should be used if dynamic manipulation of the internal object attributes is required. For any infrastructure control, the COM interface is most likely the tool to be used. COM can control the signal timing of a signalized intersection and the placement of barriers. With respect to vehicle control, some components can be modified such as the desired speed and some of the VISSIM parameters discussed previously; others cannot, such as the specific acceleration of a vehicle. Additionally, to implement a change to the micro-simulation model during a simulation, a break needs to be applied which has an impact on the time needed to perform the simulation, especially when multiple simulation breaks need to occur over a short period of time.

The DLL should be used to implement a connected vehicle application where control of vehicles is required. By manipulating parts of the DriverModel.DLL, the car following and lane changing driver behaviour can be modified based on user defined algorithms. Some of the specific components associated with driver behaviour that can be modified under the DLL are the desired velocity, desired acceleration, target lane / lane change initiation, and vehicle colour. Specific algorithms can be developed defining the driver behaviour. The DLL can be defined for different vehicle types making it useful for an evaluation of an incomplete market penetration of connected vehicles. It is applied for every simulation step and replaces the base driver behaviour model included within VISSIM.

Once the appropriate tool is identified, specific changes need to be introduced.
3.2.5 Apply Changes Through Appropriate Tool

After the tool is identified, there most likely will require programming to implement the connected vehicle environment. For modification of the internal VISSIM parameters only, the VISSIM GUI can be used. For the COM interface and the DLL tools, external software packages need to be used to perform the programming.

The DLL needs to be written and built as a C++ program. The base DriverModel.DLL is provided as part of the VISSIM distribution. The work done for this thesis used the Microsoft Visual Studio to develop the DLL.

Applying changes through the COM interface can be done through a selection of programming languages, including Visual Basic, C++, Python and MATLAB. COM is implemented more as a script that follows a specific series of instructions. Examples are provided as part of the VISSIM distribution.

3.2.6 Evaluation Configuration

VISSIM has options for configuring the simulation to record and output specific metrics that are determined before the simulation is run. To ensure that traffic conflicts can be evaluated using the SSAM subsequent to the evaluation, the SSAM output needs to be selected, resulting in the creation of a .trj file.

3.2.7 Run the Simulation

Given the stochastic nature of traffic, extended to micro-simulations, multiple simulation runs of the same parameters and defined algorithms need to be applied to remove any unforeseen bias caused by the random initial seed. If the COM interface is being used, VISSIM can be launched and terminated from within the script, allowing multiple simulation runs to occur while varying
the initial random seed.

### 3.2.8 Evaluate the Simulation

Evaluation of the connected vehicle application should be done for the purpose the application is intended, such as improvement in mobility, emissions or safety. Identifying how the evaluation will be performed needs to occur prior to running the simulation so that appropriate measurement tools can be input into the model and configured. This includes inputting travel time measurement points and data collection points, as well as ensuring that the appropriate selections are made under the evaluation configuration and database configuration.

Both simulations conducted under this thesis had an objective of evaluating safety using surrogate safety measures, while also evaluating mobility in the form of travel times. The two objectives of this thesis are defined in Section 1.2. To evaluate the first objective of this thesis, expectations of implementing the connected vehicle applications are defined and simulations were performed for non-connected vehicle environments as well as connected vehicle environments. The results of the connected vehicle environment are compared with the expected results and the non-connected vehicle environment results. To evaluate the second objective of this thesis, the VISSIM parameters are modified for both the non-connected vehicle environment and the connected vehicle environment. Comparisons are made between the results to demonstrate the impact of calibration through modification of VISSIM and other parameters.

The following sections describe the methodology for evaluating these connected vehicle applications through the VISSIM micro-simulation model. Evaluation can be performed using a variety of tools. This thesis uses Microsoft Access and Excel to perform the evaluation.
3.3 CTT Intersection Control Methodology

This section describes the methodology of implementing the Cumulative Travel Times (CTT) connected vehicle environment for the purposes of intersection control in VISSIM. The CTT connected vehicle application involves changes in signal timings based on the cumulative travel times of connected vehicles approaching an intersection to reduce delays at the intersection and improve overall throughput. This application involved only the control of infrastructure, specifically a traffic signal at a signalized intersection, and does not require the modification of driver behaviour of any vehicle type (connected or not).

The simulation network is based on an urban signalized intersection located in Surrey, BC, Canada at 128th Street and 72nd Avenue, commonly used in other research at the University of British Columbia (Essa and Sayed, 2015a,b, 2016; Tageldin et al., 2014). There are 4 protected-permissive left turns. To prepare the current conditions, traffic data was used from research conducted by Essa and Sayed (2015a), recorded by using 8 cameras positioned to cover areas of the 4 approaches. The intersection and associated camera locations are provided in Figure 3.1 (Tageldin et al., 2014).

Essa and Sayed (2015a) describes the process taken to extract information from the intersection such as signal timing, traffic volumes, vehicles arriving during green time, traffic composition and the number of public transit buses, average travel times, and average delay times.

To enable the connected vehicle application, the technology required was identified as the BSM. The infrastructure needs to collect the positions of all connected vehicles within the network in order to know how many connected vehicles are in each intersection approach and in turn use this information to decide which signal phase to make green while keeping other phases red.

Changes within VISSIM were identified as the signal timing of the signalized intersection. In order to implement these changes the COM interface was used, creating algorithms to identify the cumulative travel time and decide on signal phases.
The simulation was run using the COM interface in MATLAB, allowing for variation of random seed numbers to create consistency when comparing different input parameters. Evaluation was performed both for safety, using the SSAM software package, and mobility through travel time measurements.

To evaluate the first objective of this thesis for the CTT Intersection Control simulation, a non-connected vehicle environment was simulated where the intersection control is based on real-world parameters and signal timing. Expected results are that with increasing connected vehicle market penetration, rear-end conflicts will be reduced as queuing is anticipated to be reduced and the need for vehicles to change their speed (either through acceleration or deceleration) as they approach the intersection will also be reduced. To evaluate the second objective of this thesis for the CTT Intersection Control simulation, the simulation was performed through the two steps of calibration, modifying the VISSIM driver behaviour parameters and the results are evaluated through comparison with the non-connected vehicle environment.
The CTT Intersection Control simulations are discussed further in Chapter 4 and Chapter 5.

3.4 CACC Methodology

This section will describe the methodology of implementing the cooperative adaptive cruise control (CACC) connected vehicle environment in VISSIM. The CACC connected vehicle application involves vehicles cooperatively platooning through V2V communication to reduce the headway within platoons and increase overall capacity of a roadway. This application involves control of vehicles through the on-board computers, in essence modifying the driver behaviour of the specified vehicles.

The simulation environment involved creating a 4km straight section of a two-lane freeway without entrance or exit ramps.

To enable the application, the connected vehicle technology required was identified as the BSM, allowing transmission of basic vehicle information for all connected vehicles to other connected vehicles, such as the position, size, speed, heading and acceleration. Vehicle control is assumed to be through mechanical and electrical equipment installed within the vehicle.

Changes within VISSIM were identified as the acceleration determination and the overall control of the vehicle. In order to implement these changes, the DriverModel.DLL was modified to enable the connected vehicles to behave according to predefined algorithms related to acceleration and lane change. The changes made within the DriverModel.DLL were only implemented in the situation when a cooperative platoon was in place, forming or disbanding. The acceleration and lane changes were modified accordingly.

The simulation was run using the COM interface in MATLAB, allowing for variation of the random seed numbers to create consistency when comparing different connected vehicle market penetration levels. Evaluation was performed both for safety, using the SSAM software package, and
mobility through travel time measurements.

The configuration set up for the micro-simulation involved setting output of Result Attributes, specifically Delays, Nodes, Vehicle Network Performance, Vehicle travel times, and of Direct Output, specifically the Nodes (raw data), SSAM (to obtain the .trj file), and Vehicle travel times (raw data).

To evaluate the first objective of this thesis for the CACC simulation, simulation was conducted for a non-connected vehicle environment where the vehicles on the road are either manually driven or enabled with adaptive cruise control and no vehicles were equipped with the cooperative adaptive cruise control connected vehicle technology. Multiple iterations of the simulation were conducted with varying levels of connected vehicle technology. The conflicts and travel times are measured over the period of time and area around a simulated delay. Expected results are that with increasing connected vehicle market penetration, rear-end conflicts will be reduced as traffic flow will be more stable with the cooperative adaptive cruise control algorithm applied. To evaluate the second objective of this thesis for the CACC simulation, the VISSIM driver behaviour parameters and acceleration coefficients within the CACC algorithm are modified and the results are compared with the non-connected vehicle environment using the default VISSIM driver behaviour parameters and the originally chosen acceleration coefficients.

The CACC simulations are discussed further in [Chapter 4](#).
Chapter 4

Connected Vehicle Simulations Without Calibration

This chapter describes the micro-simulations of the connected vehicle environments performed without applying calibration to the simulations. It consists of two sections, one for each of the connected vehicle applications being evaluated: Cumulative Travel Time Intersection Control and Cooperative Adaptive Cruise Control.

These applications have been modelled in previous research using VISSIM and the methods used in those previous research were applied here.

4.1 Cumulative Travel Time Intersection Control

While adaptive signal control looks to improve the throughput of vehicles through intersections, there remain limitations due to technology and infrastructure constraints, namely vehicle detection methods in the field. Typical adaptive signal controllers use inductive loop detection of vehicles as they approach an intersection to make a decision of signal timing changes. However, this re-
lies still on pre-programmed signal timing, causing unnecessary delays and queuing of vehicles. If connected vehicle technologies are used in an adaptive intersection control or adaptive signal control application through Vehicle to Infrastructure (V2I) and Vehicle to Vehicle (V2V) communications, it can allow for better adaptive signal control due to the higher resolution of information available in the field. The V2I technology offers the capability of knowing with high accuracy the location of a vehicle at given time intervals. For example, Lee et al. (2013a) proposes an intersection control that is based on cumulative travel times of connected vehicles along each approach of the intersection.

The conventional way to capture travel times is by measuring the time it takes for a vehicle to travel from one point to another. Travel times are often an object of Advanced Traveller Information Systems (ATIS) for freeway applications. A literature review has revealed the difficulty of using travel times for adaptive signal control. The likely reason for this is firstly because traditional methods are unable to capture the time that a vehicle has been waiting in a queue until after that vehicle has passed the stop bar (which would be a meaningless measure in a real-time system) and secondly, because the typical time interval for averaging travel times are for longer periods of time (e.g., 5 minutes or 10 minutes) it would not be conducive to controlling a traffic signal where the total cycle length may only be between 60 to 120 seconds.

Connected vehicles are a possible solution to the inability to use travel times for adaptive intersection control. Through the use of Global Positioning Systems (GPS) and the Basic Safety Message (BSM), a standard message as part of the Dedicated Short Range Communications (DSRC) message set dictionary (SAE International, 2016) transmitted at an approximate rate of 10 times per second, the positions of all connected vehicles can be known through V2I communications to a central controller stationed at an intersection.

Cumulative travel time control has previously been proposed for intersections for the purposes of evaluating mobility through the use of connected vehicle technology (Lee et al., 2013a), accounting for the time that vehicles are approaching an intersection and the time they are waiting in a queue.
at a red light. In addition to evaluating the mobility benefits of this type of a system, sustainability in terms of emissions is also evaluated, however safety is not a consideration through that review (Lee et al., 2013a). This section proposes to evaluate the changes to the level of safety for an intersection before and after implementing a cumulative travel time control algorithm based on the TCT and using SSAM.

Lee et al. (2013a) performs a review of the applicability of intersection control for a connected vehicle environment implemented within VISSIM, looking at varying penetration levels of connected vehicles and evaluating the performance of the intersection through mobility measures.

This study evaluates a similar application of a CTT algorithm for adaptive intersection control, however the focus is on evaluating safety improvements using SSAM for adaptive intersection control in a connected vehicle environment. The evaluation is performed using varying connected vehicle penetration levels. Using a micro-simulation model of an intersection developed through research at the University of British Columbia (Essa and Sayed, 2015a,b, 2016; Tageldin et al., 2014), the CTT algorithm is put in place for varying connected vehicle market penetration levels and a comparison is conducted against the non-CTT implementation.

### 4.1.1 CTT MATLAB Implementation

To introduce the CTT algorithm for a connected vehicle environment within VISSIM, the COM interface is used through MATLAB.

The intersection being considered contains 8 approaches in total, an equivalent of one per through movement and one per left-turn movement, including a signal phase for each of the approaches. Figure 4.1 (Lee et al., 2013a) illustrates the intersection layout and the signal phase numbering.

When calculating cumulative travel times there were four phases used, combining two approaches of the intersection for each phase (Phase 1: Approaches 2 and 6; Phase 2: Approaches 4 and 8; Phase 3: Approaches 1 and 5; Phase 4: Approaches 3 and 7).
There was no found mechanism within VISSIM and the MATLAB COM interface to prompt the change of a traffic signal to cycle through all pre-programmed phases, such as when a signal is changing to red there would be a yellow phase and an all-red phase prior to the next green phase being activated. The capability found was that it only allows the manual change of a signal group to another phase upon the next break in the simulation. Therefore, manual intervention was required. Signal phases were manually coded into the MATLAB script and were chosen based on the cumulative travel times calculated. When a change in signal phases was required through the algorithm, it prompted the appropriate yellow and all-red phases to execute the signal change. Tettamanti and Horváth (2015) provides a reference to the different numeric values to set the signalization state.

The signal times used for both the non-CTT signal control and the CTT signal control are presented in Table 4.1. For reference, where All Red Time is “N/A” it is because the signal timing is set up in the real world to have a protected/permissive left turn phase, while the CTT All Red Time has a value as there could be a phase in the CTT simulation where the left turn phase does not flow into the corresponding through phase green time and therefore there needs to be sufficient time for
clearing of the intersection before the next phase turns green. The CTT Min Green Time is set at the update interval used for calculation of the cumulative travel times (in Lee et al. (2013a) the update interval was 5s).

### Table 4.1: Signal Timing Values

<table>
<thead>
<tr>
<th>Appr. #</th>
<th>Green Time</th>
<th>Yellow Time</th>
<th>All Red Time</th>
<th>CTT Min Green Time</th>
<th>CTT Yellow Time</th>
<th>CTT All Red Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>7s</td>
<td>4s</td>
<td>N/A</td>
<td>Update Int.</td>
<td>4s</td>
<td>2s</td>
</tr>
<tr>
<td>2</td>
<td>33s</td>
<td>4s</td>
<td>2s</td>
<td>Update Int.</td>
<td>4s</td>
<td>2s</td>
</tr>
<tr>
<td>3</td>
<td>7s</td>
<td>4s</td>
<td>N/A</td>
<td>Update Int.</td>
<td>4s</td>
<td>2s</td>
</tr>
<tr>
<td>4</td>
<td>23s</td>
<td>4s</td>
<td>2s</td>
<td>Update Int.</td>
<td>4s</td>
<td>2s</td>
</tr>
<tr>
<td>5</td>
<td>7s</td>
<td>4s</td>
<td>N/A</td>
<td>Update Int.</td>
<td>4s</td>
<td>2s</td>
</tr>
<tr>
<td>6</td>
<td>33s</td>
<td>4s</td>
<td>2s</td>
<td>Update Int.</td>
<td>4s</td>
<td>2s</td>
</tr>
<tr>
<td>7</td>
<td>7s</td>
<td>4s</td>
<td>N/A</td>
<td>Update Int.</td>
<td>4s</td>
<td>2s</td>
</tr>
<tr>
<td>8</td>
<td>23s</td>
<td>4s</td>
<td>2s</td>
<td>Update Int.</td>
<td>4s</td>
<td>2s</td>
</tr>
</tbody>
</table>

#### 4.1.2 CTT Algorithms

The algorithm controlling the traffic signal works through collecting vehicle information for all connected vehicles within the specific region around the intersection. For the purposes of this thesis, the region where connected vehicle information is collected is between the stop bar and 140m up the approach at each approach of the intersection. For the left turn movements the entire turning bay is less than 140m in length and therefore the whole turning bay is used for a collection region.

At the predefined time interval, the VISSIM COM GetAll command is used to collect information of all vehicles within the network. On a vehicle-by-vehicle basis, the information similar to what would be received in a BSM is reviewed to determine the precise location of each vehicle. When the vehicle’s position is determined to be on the approach within 140m of the intersection, the specific time interval is added to the cumulative travel time for that intersection approach.

An example is presented in Figure 4.2 and Table 4.2. Where if the time-step is 5s, following the NEMA phase numbering scheme presented in Figure 4.1, for each time step the CTT is provided.
and a graphical indication through red circles is shown where the signal phase would change.

**Table 4.2: CTTs to Demonstrate Signal Timing Change**

<table>
<thead>
<tr>
<th>Time Step</th>
<th>Appr. 2</th>
<th>Appr. 6</th>
<th>Appr. 4</th>
<th>Appr. 8</th>
<th>Appr. 1</th>
<th>Appr. 5</th>
<th>Appr. 3</th>
<th>Appr. 7</th>
<th>Signal Phase</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>15</td>
<td>0</td>
<td>5</td>
<td>0</td>
<td>20</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>3</td>
</tr>
<tr>
<td>2</td>
<td>30</td>
<td>25</td>
<td>25</td>
<td>5</td>
<td>25</td>
<td>0</td>
<td>0</td>
<td>5</td>
<td>1</td>
</tr>
<tr>
<td>3</td>
<td>45</td>
<td>60</td>
<td>45</td>
<td>10</td>
<td>0</td>
<td>5</td>
<td>0</td>
<td>15</td>
<td>1</td>
</tr>
<tr>
<td>4</td>
<td>20</td>
<td>70</td>
<td>65</td>
<td>20</td>
<td>0</td>
<td>10</td>
<td>0</td>
<td>25</td>
<td>1</td>
</tr>
<tr>
<td>5</td>
<td>0</td>
<td>45</td>
<td>85</td>
<td>30</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>35</td>
<td>2</td>
</tr>
<tr>
<td>6</td>
<td>0</td>
<td>30</td>
<td>110</td>
<td>45</td>
<td>0</td>
<td>5</td>
<td>0</td>
<td>45</td>
<td>2</td>
</tr>
<tr>
<td>7</td>
<td>5</td>
<td>50</td>
<td>70</td>
<td>15</td>
<td>0</td>
<td>15</td>
<td>0</td>
<td>25</td>
<td>2</td>
</tr>
<tr>
<td>8</td>
<td>10</td>
<td>80</td>
<td>5</td>
<td>20</td>
<td>0</td>
<td>35</td>
<td>10</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>9</td>
<td>20</td>
<td>130</td>
<td>15</td>
<td>15</td>
<td>0</td>
<td>50</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>10</td>
<td>10</td>
<td>115</td>
<td>25</td>
<td>30</td>
<td>0</td>
<td>40</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>11</td>
<td>5</td>
<td>100</td>
<td>35</td>
<td>45</td>
<td>0</td>
<td>55</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>12</td>
<td>15</td>
<td>55</td>
<td>45</td>
<td>65</td>
<td>0</td>
<td>50</td>
<td>0</td>
<td>5</td>
<td>2</td>
</tr>
<tr>
<td>13</td>
<td>55</td>
<td>0</td>
<td>55</td>
<td>90</td>
<td>25</td>
<td>30</td>
<td>0</td>
<td>10</td>
<td>2</td>
</tr>
</tbody>
</table>

**Figure 4.2:** CTT Demonstration for instance of Signal Change, with circles identifying the times at which the signals change due to combination of cumulative travel times
4.1.3 CTT Data Collection and Analysis

The micro-simulation model was run 5 times with varying initial seeds each for the non-connected vehicle environment as well as for each connected vehicle market penetration level in the connected vehicle environment, applying the CTT algorithm. As will be discussed further in Chapter 5, evaluations are conducted where calibration has taken place. Data is collected for the East and West movements of the intersection as these are the movements that the micro-simulation model was calibrated with (Essa and Sayed, 2015a). The mobility data was collected by measuring travel times at each approach to the intersection until the vehicle has completed its travel through the stop bar at the intersection. Conflict information is collected through the .trj file saved from the VISSIM micro-simulation for analyzing using SSAM.

Table 4.3: Travel times at varying connected vehicle market penetration levels for the uncalibrated micro-simulation model after implementing the CTT algorithm

<table>
<thead>
<tr>
<th>Vehicle Type</th>
<th>No CTT</th>
<th>10% CTT</th>
<th>30% CTT</th>
<th>50% CTT</th>
<th>70% CTT</th>
<th>90% CTT</th>
<th>100% CTT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Avg. CV (s)</td>
<td>N/A</td>
<td>17.4</td>
<td>16.9</td>
<td>16.0</td>
<td>15.7</td>
<td>15.1</td>
<td>15.0</td>
</tr>
<tr>
<td>Avg. Non-CV (s)</td>
<td>24.3</td>
<td>22.7</td>
<td>19.0</td>
<td>17.3</td>
<td>16.5</td>
<td>15.7</td>
<td>N/A</td>
</tr>
<tr>
<td>Avg. All Vehicles (s)</td>
<td>24.3</td>
<td>20.0</td>
<td>18.0</td>
<td>16.6</td>
<td>16.1</td>
<td>15.4</td>
<td>15.0</td>
</tr>
</tbody>
</table>

Table 4.4: Travel time improvements at varying connected vehicle market penetration levels for the uncalibrated micro-simulation model compared with the no-CTT micro-simulation after implementing the CTT algorithm

<table>
<thead>
<tr>
<th>Vehicle Type</th>
<th>10% CTT</th>
<th>30% CTT</th>
<th>50% CTT</th>
<th>70% CTT</th>
<th>90% CTT</th>
<th>100% CTT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Avg. CV</td>
<td>-28%</td>
<td>-30%</td>
<td>-34%</td>
<td>-35%</td>
<td>-38%</td>
<td>-38%</td>
</tr>
<tr>
<td>Avg. Non-CV</td>
<td>-7%</td>
<td>-22%</td>
<td>-29%</td>
<td>-32%</td>
<td>-35%</td>
<td>N/A</td>
</tr>
<tr>
<td>Avg. All Vehicles</td>
<td>-18%</td>
<td>-26%</td>
<td>-31%</td>
<td>-34%</td>
<td>-37%</td>
<td>-38%</td>
</tr>
</tbody>
</table>
Figure 4.3: Travel time improvements at varying connected vehicle market penetration levels for the uncalibrated micro-simulation model compared with the no-CTT micro-simulation after implementing the CTT algorithm

Figure 4.4: Rear-end Conflicts for the uncalibrated micro-simulation model at varying connected vehicle penetration levels
Table 4.5: Time-to-Collision Conflicts at varying connected vehicle market penetration levels for the uncalibrated micro-simulation model after implementing the CTT algorithm

<table>
<thead>
<tr>
<th>TTC Threshold</th>
<th>0% CTT</th>
<th>10% CTT</th>
<th>30% CTT</th>
<th>50% CTT</th>
<th>70% CTT</th>
<th>90% CTT</th>
<th>100% CTT</th>
</tr>
</thead>
<tbody>
<tr>
<td>≤ 0.5</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>≤ 0.6</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>≤ 0.7</td>
<td>4</td>
<td>4</td>
<td>2</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>≤ 0.8</td>
<td>4</td>
<td>5</td>
<td>2</td>
<td>3</td>
<td>5</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>≤ 0.9</td>
<td>5</td>
<td>6</td>
<td>2</td>
<td>4</td>
<td>6</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>≤ 1.0</td>
<td>7</td>
<td>7</td>
<td>4</td>
<td>4</td>
<td>8</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>≤ 1.1</td>
<td>8</td>
<td>9</td>
<td>5</td>
<td>6</td>
<td>9</td>
<td>9</td>
<td></td>
</tr>
<tr>
<td>≤ 1.2</td>
<td>10</td>
<td>12</td>
<td>8</td>
<td>11</td>
<td>16</td>
<td>14</td>
<td>14</td>
</tr>
<tr>
<td>≤ 1.3</td>
<td>12</td>
<td>16</td>
<td>12</td>
<td>16</td>
<td>21</td>
<td>21</td>
<td>20</td>
</tr>
<tr>
<td>≤ 1.4</td>
<td>14</td>
<td>22</td>
<td>20</td>
<td>24</td>
<td>28</td>
<td>30</td>
<td>26</td>
</tr>
<tr>
<td>≤ 1.5</td>
<td>18</td>
<td>29</td>
<td>27</td>
<td>33</td>
<td>35</td>
<td>36</td>
<td>33</td>
</tr>
<tr>
<td>≤ 1.6</td>
<td>24</td>
<td>38</td>
<td>40</td>
<td>41</td>
<td>46</td>
<td>45</td>
<td>42</td>
</tr>
<tr>
<td>≤ 1.7</td>
<td>29</td>
<td>49</td>
<td>56</td>
<td>53</td>
<td>61</td>
<td>55</td>
<td>56</td>
</tr>
<tr>
<td>≤ 1.8</td>
<td>59</td>
<td>85</td>
<td>90</td>
<td>84</td>
<td>92</td>
<td>83</td>
<td>85</td>
</tr>
<tr>
<td>≤ 1.9</td>
<td>87</td>
<td>123</td>
<td>136</td>
<td>127</td>
<td>134</td>
<td>120</td>
<td>125</td>
</tr>
<tr>
<td>≤ 2.0</td>
<td>107</td>
<td>143</td>
<td>159</td>
<td>147</td>
<td>156</td>
<td>143</td>
<td>146</td>
</tr>
<tr>
<td>≤ 2.1</td>
<td>122</td>
<td>163</td>
<td>180</td>
<td>168</td>
<td>177</td>
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<td>164</td>
</tr>
<tr>
<td>≤ 2.2</td>
<td>139</td>
<td>181</td>
<td>193</td>
<td>183</td>
<td>192</td>
<td>169</td>
<td>177</td>
</tr>
<tr>
<td>≤ 2.3</td>
<td>153</td>
<td>196</td>
<td>208</td>
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<td>205</td>
<td>183</td>
<td>190</td>
</tr>
<tr>
<td>≤ 2.4</td>
<td>165</td>
<td>209</td>
<td>224</td>
<td>214</td>
<td>221</td>
<td>196</td>
<td>202</td>
</tr>
<tr>
<td>≤ 2.5</td>
<td>187</td>
<td>230</td>
<td>243</td>
<td>235</td>
<td>241</td>
<td>211</td>
<td>221</td>
</tr>
<tr>
<td>≤ 2.6</td>
<td>205</td>
<td>252</td>
<td>265</td>
<td>257</td>
<td>264</td>
<td>229</td>
<td>245</td>
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<td>≤ 2.7</td>
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<td>281</td>
<td>299</td>
<td>290</td>
<td>295</td>
<td>260</td>
<td>274</td>
</tr>
<tr>
<td>≤ 2.8</td>
<td>260</td>
<td>318</td>
<td>335</td>
<td>326</td>
<td>335</td>
<td>294</td>
<td>308</td>
</tr>
<tr>
<td>≤ 2.9</td>
<td>305</td>
<td>364</td>
<td>384</td>
<td>372</td>
<td>378</td>
<td>334</td>
<td>348</td>
</tr>
<tr>
<td>≤ 3.0</td>
<td>353</td>
<td>416</td>
<td>432</td>
<td>420</td>
<td>420</td>
<td>371</td>
<td>394</td>
</tr>
</tbody>
</table>

Table 4.6: Time-to-Collision Conflicts at varying connected vehicle market penetration levels for the uncalibrated micro-simulation model compared with the no-CTT micro-simulation after implementing the CTT algorithm (negative percent change indicates improvement)

<table>
<thead>
<tr>
<th>TTC Threshold</th>
<th>10% CTT</th>
<th>30% CTT</th>
<th>50% CTT</th>
<th>70% CTT</th>
<th>90% CTT</th>
<th>100% CTT</th>
</tr>
</thead>
<tbody>
<tr>
<td>≤ 0.5</td>
<td>-50%</td>
<td>0%</td>
<td>-50%</td>
<td>50%</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td>≤ 1.0</td>
<td>8%</td>
<td>-48%</td>
<td>-40%</td>
<td>13%</td>
<td>20%</td>
<td>5%</td>
</tr>
<tr>
<td>≤ 1.5</td>
<td>62%</td>
<td>48%</td>
<td>81%</td>
<td>95%</td>
<td>100%</td>
<td>80%</td>
</tr>
<tr>
<td>≤ 2.0</td>
<td>35%</td>
<td>49%</td>
<td>38%</td>
<td>46%</td>
<td>34%</td>
<td>37%</td>
</tr>
<tr>
<td>≤ 2.5</td>
<td>23%</td>
<td>30%</td>
<td>25%</td>
<td>29%</td>
<td>13%</td>
<td>18%</td>
</tr>
<tr>
<td>≤ 3.0</td>
<td>18%</td>
<td>22%</td>
<td>19%</td>
<td>19%</td>
<td>5%</td>
<td>11%</td>
</tr>
</tbody>
</table>
4.1.4 Evaluation of Results

When considering the cumulative travel time intersection control application for a connected vehicle environment, it is expected that both mobility and safety will be improved. The intention of the application is to reduce wait times at the intersection and thus reduce queuing and the opportunity for rear-end conflicts to occur. As the connected vehicle market penetration increases, travel times are expected to further improve and rear-end conflicts are expected to further be reduced.

The results for the travel times and safety evaluation are discussed in the following sections.

4.1.4.1 Mobility Evaluation

Due to the adaptive nature of the cumulative travel time algorithm, travel time improvements are observed at all connected vehicle market penetration levels for both connected vehicles and non-
connected vehicles. The connected vehicles see a consistent travel time improvement of 28% to 38% with greater travel time improvements at higher connected vehicle market penetration levels. The non-connected vehicles see improvements with a greater range of between 7% and 35%, with higher connected vehicle market penetration levels showing greater travel time improvements. The travel time improvements for the combined connected vehicles and non-connected vehicles range between 18% and 38% improvement with higher connected vehicle market penetration levels showing the greater travel time improvements.

Lower connected vehicle market penetration levels will result in non-connected vehicles waiting for longer periods of time until the traffic signal is activated for their respective signal phase.

Lee et al. (2013a) demonstrated travel time savings of 34% at 100% connected vehicle market penetration when the CTT algorithm is applied compared with the instance when the CTT algorithm is not applied. The intersection volume used by Lee et al. (2013a) to achieve these results is approximately 3,000 Vehicles per Hour (VPH). Comparing the results of this study with a travel time improvement of approximately 38% for a 5s time-step and 100% connected vehicle market penetration and an uncalibrated micro-simulation model, it shows that the algorithms perform fairly similarly with the currently applied algorithm showing a greater improvement in travel times. At varying connected vehicle market penetration levels, travel time improvements presented in this study show less variability and overall higher improvement than the results seen in Lee et al. (2013a). The algorithms used at lower connected vehicle market penetration levels are different in that Lee et al. (2013a) uses a Kalman filter to account for non-connected vehicle cumulative travel time estimates while this study focuses only on connected vehicles when determining the cumulative travel times and does not account for non-connected vehicles.

The results when evaluating mobility follow what is expected when the connected vehicle technology is applied, specifically that travel times are improved.
4.1.4.2 Traffic Conflicts Evaluation

Table 4.6 and Figure 4.5 show that at no calibration the simulated level of safety based on the modeled surrogate safety measures is typically worse when the CTT algorithm is applied, with conflicts acting as surrogates for a higher probability of incidents occurring (TTC ≤1.5s) having over a 90% increase in the number of simulated rear-end conflicts. At lower connected vehicle market penetration levels (e.g., 10% CTT or 30% CTT), there is higher variability with respect to number of conflicts observed at lower TTC thresholds, however at greater than 50% CTT connected vehicle market penetration, there are no observed reduction in the number of simulated conflicts compared with the non-connected vehicle environment. The total intersection volume of the micro-simulation model used is approximately 3,000 VPH.

These results do not align with what is expected, specifically that conflicts will be reduced at higher connected vehicle market penetration levels. This is likely due to the combination of the aggressive nature of the drivers within the VISSIM micro-simulation due to the default driver behaviour parameters and more frequent signal changes at higher connected vehicle market penetrations resulting in more changes to speed and acceleration as vehicles approach the intersections, and overall more conflicts identified.

4.2 Cooperative Adaptive Cruise Control

Cooperative Adaptive Cruise Control (CACC) is an application of V2V communication for the purpose of controlling vehicles to improve capacity on the roadway. It works like Adaptive Cruise Control (ACC) in that it allows a vehicle to follow the vehicle in front of it and adjust speed based on that lead vehicle’s behaviour. However, it expands on ACC by relying on the lead vehicle to “tell” the following vehicle what it is doing rather than having the following vehicle “sense” what the lead vehicle is doing. CACC allows for platoons of vehicles to form with short headways in order to increase capacity on the roadway. A challenge with reducing headways is that shorter
headways typically result in a higher risk of rear-end collisions.

The objective of this study is to investigate the ability to evaluate the safety of a connected vehicle application of a CACC algorithm applied to a freeway segment by using surrogate safety measures as described currently in the SSAM and conflict analysis through a combination of the micro-simulation model VISSIM and the SSAM software packages.

4.2.1 Simulation Development

A micro-simulation model was developed to perform a safety evaluation of a CACC application. Within this micro-simulation, three vehicle types are included: Manually driven vehicles (Manual Vehicles), ACC equipped and enabled vehicles, and CACC equipped and enabled vehicles. All vehicles present in the micro-simulation are single occupant vehicles.

Research has shown that the objective of CACC vehicles is to increase capacity through reducing the headway between vehicles. The headways used in this thesis for ACC and CACC vehicles are based on recommendations from research by Zhao and Sun (2013) and Van Arem et al. (2006). The headway time initially used for manual vehicles is the default value within VISSIM of 0.9s.

To distinguish the different vehicle types within the simulation, colours have been applied based on the vehicle type. Manual vehicles are blue, ACC vehicles are green and CACC vehicles are red. As will be discussed further, two additional colours (black and white) are used to distinguish when a CACC vehicle is in a platoon and whether it is following or leading the platoon. An example of the colours associated with the vehicles in the micro-simulation is provided in Figure 4.6. The lane configuration in the simulation is a 4-km long two lane freeway section with no access or egress. This configuration was used to provide a simplified simulation and for consistency in comparison with previous research conducted by Zhao and Sun (2013).

To simulate V2V communications and to change the way the vehicles react, the VISSIM driver be-
haviour model was modified. A DLL was created both for the CACC and the ACC vehicle types to simulate the computer controlling the vehicles rather than having a human driver in control. Within VISSIM, the DLL assumes control of certain parameters and allows for user defined or user programmed values for specific parameters such as following distance, acceleration/deceleration, and lane change behaviour to be applied to each VISSIM time step. Within this micro-simulation, the CACC vehicles are required to behave in conjunction with the leading vehicle and with each other, therefore the DLL identifies a vehicle to lead a platoon and causes other surrounding CACC equipped vehicles to accelerate or decelerate and change lanes at an appropriate time in order to join and continue in a platoon of CACC vehicles.

This simulation assumes that all CACC platoons will form and stay in the left lane, considered the fast lane. The vehicle inputs into the simulation have a speed distribution around 100 km/h, defined within VISSIM, and the vehicles that form a platoon will conform to the desired speed of the lead vehicle. The CACC algorithm used to calculate acceleration of a following vehicle in order to form a platoon is based on Zhao and Sun (2013) and Van Arem et al. (2006). The acceleration model used for this simulation is as shown in Equations 4.2.1 and 4.2.2

\[
a_c = k_a * a_p + k_v * (v_p - v_f) + k_s * (s - v * t_d) \quad \text{(4.2.1)}
\]

\[
a = max[a_{\text{min}}, min(a_c, a_{\text{max}})] \quad \text{(4.2.2)}
\]

Where:
\( a_c \) is the control acceleration with the linear function;

\( a \) is the acceleration in the next step of the objective vehicle;

\( a_p \) is the acceleration of the preceding vehicle;

\( v_p \) is the speed of the preceding vehicle;

\( v_f \) is the speed of the following vehicle;

\( s \) is the current space between the objective vehicle and its preceding vehicle;

\( a_{\text{max}} \) is the maximum allowed acceleration;

\( a_{\text{min}} \) is the maximum allowed deceleration;

\( k_a, k_v \) and \( k_s \) are constant gains, all greater than zero.

Equations 4.2.1 and 4.2.2 are used for simulating ACC vehicles as well through removing the \( k_a \) and \( a_p \) terms.

In order to design the micro-simulation of the CACC technology, algorithms were developed to guide changes to driver behaviour based on vehicle type and position with respect to lane and surrounding vehicles. These algorithms are categorized into three states: 1) normal driving state, 2) lead platoon state, and 3) join platoon state.

4.2.2 Driving States

Normal Driving State

The Normal Driving State is when the vehicle is not controlled by adaptive cruise control or cooperative adaptive cruise control. No additional control is applied and all vehicles in this state behave as manually driven vehicles.
**Lead Platoon State**

The Lead Platoon State is when the CACC vehicle has been designated as a leader of the platoon. In this state, the lead vehicle will drive using adaptive cruise control towards the vehicle in front of it, using $k_a = 0$ and $t_d = 1.4$ from Equation 4.2.1. If there is no vehicle immediately in front, it will drive as a manually driven vehicle. The lead platoon state initiates a vehicle colour change to black to visually distinguish in the micro-simulation that the vehicle is leading the platoon.

**Join Platoon State**

The Join Platoon State is when the CACC vehicle is in the process of joining a platoon or is currently in a platoon, but is not leading the platoon. The CACC vehicle when it is in the Join Platoon state uses the values of $k_a = 1$ and $t_d = 0.5$ from Equation 4.2.1. The join platoon state initiates a vehicle colour change to white to visually distinguish that the vehicle is joining or has joined a platoon.

**4.2.3 CACC Driver Behaviour Algorithms**

There are a few scenarios that would account for a vehicle forming or entering into a CACC platoon. There are also specific requirements that must be met in order for this to occur. These scenarios and requirements form the logic of when vehicle platoons are formed and when they disband. The logic is described below:

- If a CACC vehicle is in the left lane, it checks the vehicle type in front of it and behind it.
  - if the vehicle in front of it is not a CACC vehicle, it flags itself as being able to be a lead vehicle.
  - if the vehicle behind it is a CACC vehicle, it initiates a platoon and becomes a lead vehicle.
– if the vehicle in front of it is a CACC vehicle, it requests to join a platoon with that vehicle. VISSIM is limited within the DLL to find information about near vehicles for up to two upstream and two downstream, on up to two lanes on both sides of the current lane. This limits the ability within the DLL to model driver behaviour up to the lead vehicle rather than simply the vehicle in front of the vehicle in question.

• If a CACC vehicle is in the right lane, it checks the vehicle type to the left of it and in front and behind it.

  – if the vehicle to the left and in front of it is not a CACC vehicle, it continues to drive with the system defined driver behaviour model.

  – if the vehicle to the left and in front of it is a CACC vehicle, it would like to join a platoon:

    * If the vehicle type to the left and behind it is not a CACC vehicle, it changes lanes and joins the platoon behind the CACC platoon vehicle.

    * If the vehicle type to the left and behind it is a CACC vehicle, it waits until the end of the CACC platoon to change lanes and join the CACC platoon. Within the DLL, ideally we would like to limit platoon size to 6 vehicles, with 5 gaps; however, the limitations with finding information about nearby vehicles limits the ability to do this.

• If a platoon is already formed and a vehicle would like to exit the platoon, that vehicle notifies the lead vehicle and then initiates the exit manoeuver.

For each vehicle, the DLL collects information for each time step in order to change the driver behaviour based on surrounding vehicles.

### 4.2.4 CACC Data Collection and Analysis

A total of ten penetration levels for CACC equipped vehicles were simulated with five simulation runs of identical vehicle volumes with varying initial seeds to randomize the simulation, generating
fifty (50) simulation runs in total. For each CACC penetration level, the ACC vehicle penetration remains at 10%. The penetration of the three vehicle types in these simulations are presented in Table 4.7.

Table 4.7: CACC Simulation Input Connected Vehicle Penetrations

<table>
<thead>
<tr>
<th>Vehicle Type</th>
<th>No CV</th>
<th>10% CV</th>
<th>20% CV</th>
<th>30% CV</th>
<th>40% CV</th>
<th>50% CV</th>
<th>60% CV</th>
<th>70% CV</th>
<th>80% CV</th>
<th>90% CV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manual</td>
<td>90%</td>
<td>80%</td>
<td>70%</td>
<td>60%</td>
<td>50%</td>
<td>40%</td>
<td>30%</td>
<td>20%</td>
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<td>0%</td>
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<tr>
<td>ACC</td>
<td>10%</td>
<td>10%</td>
<td>10%</td>
<td>10%</td>
<td>10%</td>
<td>10%</td>
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<td>30%</td>
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<td>50%</td>
<td>60%</td>
<td>70%</td>
<td>80%</td>
<td>90%</td>
</tr>
</tbody>
</table>

For the simulated freeway, a basic freeway segment was used as defined in the Highway Capacity Manual (Highway Capacity Manual, 2000) with a total vehicle volume of 3,300 per hour for a one hour period, simulating an uninterrupted level of service of between B and C. In these conditions, at the default simulation parameters, VISSIM shows no rear-end conflicts when evaluated through SSAM. To provide a meaningful evaluation, a traffic delay was simulated by inserting a very slow moving vehicle into the right hand lane.

The simulation was run for each CACC connected vehicle penetration level. For each CACC connected vehicle penetration level, 5 simulations were run with different initial seeds, beginning at 1 and being incremented by 20 for each subsequent simulation. The length of the simulations were 4,600 seconds, with 1,000 seconds seed time for the simulation to become in a steady state. The slow moving vehicle was inserted in the right hand lane at the 2,600 second mark, inside of a 750m section where data was collected for evaluation purposes.

The travel time of each vehicle was captured through the 750m section where the traffic delay was simulated. Additionally, a trajectory file (.trj) was produced for each simulation run which was evaluated through conflict analysis using SSAM. The mobility and safety evaluations are performed based on the period of time when the traffic delay was prominent, between 2,600 seconds and 3,000 seconds. The simulation was evaluated for travel time and safety measures of improvement for each CACC penetration level where CACC vehicles were included in the simulation.
Results are presented in Table 4.8 and Table 4.9 for mobility and in Table 4.10 and Table 4.11 with respect to traffic conflicts. Improvements for travel times are measured against the total travel time observed with no CACC equipped vehicles present, and for traffic conflicts it is compared with the total rear-end conflicts observed during where there are no CACC equipped vehicles present. Improvements are measured only over the period of time when the traffic delay was simulated.

Table 4.8: Travel times per connected vehicle market penetration level

<table>
<thead>
<tr>
<th>Vehicle Type</th>
<th>No CV</th>
<th>10% CV</th>
<th>20% CV</th>
<th>30% CV</th>
<th>40% CV</th>
<th>50% CV</th>
<th>60% CV</th>
<th>70% CV</th>
<th>80% CV</th>
<th>90% CV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total TT</td>
<td>73.5</td>
<td>66.8</td>
<td>68.3</td>
<td>72.2</td>
<td>68.3</td>
<td>68.0</td>
<td>61.7</td>
<td>47.0</td>
<td>45.2</td>
<td>37.9</td>
</tr>
<tr>
<td>Man. TT</td>
<td>72.3</td>
<td>70.7</td>
<td>72.7</td>
<td>74.7</td>
<td>74.9</td>
<td>73.4</td>
<td>65.7</td>
<td>49.4</td>
<td>47.1</td>
<td>N/A</td>
</tr>
<tr>
<td>ACC TT</td>
<td>74.8</td>
<td>69.3</td>
<td>69.2</td>
<td>76.7</td>
<td>68.3</td>
<td>69.8</td>
<td>64.3</td>
<td>50.2</td>
<td>48.7</td>
<td>40.6</td>
</tr>
<tr>
<td>CACC TT</td>
<td>N/A</td>
<td>60.5</td>
<td>63.0</td>
<td>65.4</td>
<td>61.8</td>
<td>60.7</td>
<td>55.0</td>
<td>41.3</td>
<td>39.8</td>
<td>35.1</td>
</tr>
<tr>
<td>Total SD</td>
<td>11.8</td>
<td>10.5</td>
<td>13.3</td>
<td>12.2</td>
<td>10.4</td>
<td>13.1</td>
<td>8.9</td>
<td>6.8</td>
<td>7.1</td>
<td>4.1</td>
</tr>
<tr>
<td>Man. SD</td>
<td>11.2</td>
<td>11.0</td>
<td>13.2</td>
<td>10.4</td>
<td>9.8</td>
<td>15.3</td>
<td>9.6</td>
<td>5.7</td>
<td>7.8</td>
<td>N/A</td>
</tr>
<tr>
<td>ACC SD</td>
<td>13.6</td>
<td>8.8</td>
<td>14.9</td>
<td>14.2</td>
<td>8.1</td>
<td>11.0</td>
<td>6.1</td>
<td>7.0</td>
<td>4.7</td>
<td>3.4</td>
</tr>
<tr>
<td>CACC SD</td>
<td>N/A</td>
<td>10.6</td>
<td>12.9</td>
<td>11.0</td>
<td>10.4</td>
<td>11.9</td>
<td>7.8</td>
<td>4.3</td>
<td>5.9</td>
<td>2.6</td>
</tr>
</tbody>
</table>

Figure 4.7: Average Travel Times Per CACC Penetration Level and Per Vehicle Type
Figure 4.8: Percent Change in Travel Times Per CACC Market Penetration Level Compared with The Average Travel Time for No CACC

Figure 4.9: Rear-End conflicts by time-to-collision threshold
### Table 4.9: Percent change in travel times per connected vehicle market penetration level compared with No CACC micro-simulation

<table>
<thead>
<tr>
<th>Vehicle Type</th>
<th>10% CV</th>
<th>20% CV</th>
<th>30% CV</th>
<th>40% CV</th>
<th>50% CV</th>
<th>60% CV</th>
<th>70% CV</th>
<th>80% CV</th>
<th>90% CV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total</td>
<td>9%</td>
<td>7%</td>
<td>2%</td>
<td>7%</td>
<td>8%</td>
<td>16%</td>
<td>36%</td>
<td>40%</td>
<td>49%</td>
</tr>
<tr>
<td>Manual</td>
<td>4%</td>
<td>1%</td>
<td>-2%</td>
<td>-2%</td>
<td>0%</td>
<td>11%</td>
<td>33%</td>
<td>38%</td>
<td>N/A</td>
</tr>
<tr>
<td>ACC</td>
<td>6%</td>
<td>6%</td>
<td>-4%</td>
<td>7%</td>
<td>5%</td>
<td>13%</td>
<td>32%</td>
<td>35%</td>
<td>45%</td>
</tr>
<tr>
<td>CACC</td>
<td>18%</td>
<td>14%</td>
<td>11%</td>
<td>16%</td>
<td>17%</td>
<td>25%</td>
<td>44%</td>
<td>47%</td>
<td>52%</td>
</tr>
</tbody>
</table>

### Table 4.10: Rear-end TTC conflicts at varying connected vehicle (CV) penetration levels

<table>
<thead>
<tr>
<th>TTC Threshold</th>
<th>NO CV</th>
<th>10% CV</th>
<th>20% CV</th>
<th>30% CV</th>
<th>40% CV</th>
<th>50% CV</th>
<th>60% CV</th>
<th>70% CV</th>
<th>80% CV</th>
<th>90% CV</th>
</tr>
</thead>
<tbody>
<tr>
<td>≤ 0.5</td>
<td>8</td>
<td>12</td>
<td>12</td>
<td>20</td>
<td>16</td>
<td>12</td>
<td>8</td>
<td>18</td>
<td>12</td>
<td>6</td>
</tr>
<tr>
<td>≤ 0.6</td>
<td>12</td>
<td>12</td>
<td>16</td>
<td>24</td>
<td>20</td>
<td>20</td>
<td>12</td>
<td>22</td>
<td>19</td>
<td>10</td>
</tr>
<tr>
<td>≤ 0.7</td>
<td>17</td>
<td>20</td>
<td>28</td>
<td>28</td>
<td>24</td>
<td>27</td>
<td>16</td>
<td>26</td>
<td>23</td>
<td>10</td>
</tr>
<tr>
<td>≤ 0.8</td>
<td>26</td>
<td>29</td>
<td>38</td>
<td>32</td>
<td>32</td>
<td>32</td>
<td>22</td>
<td>31</td>
<td>29</td>
<td>14</td>
</tr>
<tr>
<td>≤ 0.9</td>
<td>32</td>
<td>42</td>
<td>46</td>
<td>40</td>
<td>38</td>
<td>42</td>
<td>26</td>
<td>35</td>
<td>33</td>
<td>20</td>
</tr>
<tr>
<td>≤ 1.0</td>
<td>50</td>
<td>59</td>
<td>56</td>
<td>45</td>
<td>44</td>
<td>52</td>
<td>34</td>
<td>44</td>
<td>38</td>
<td>24</td>
</tr>
<tr>
<td>≤ 1.1</td>
<td>73</td>
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<td>71</td>
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<td>46</td>
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<td>103</td>
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<td>62</td>
<td>76</td>
<td>51</td>
<td>58</td>
<td>46</td>
<td>28</td>
</tr>
<tr>
<td>≤ 1.3</td>
<td>129</td>
<td>149</td>
<td>131</td>
<td>85</td>
<td>71</td>
<td>87</td>
<td>58</td>
<td>66</td>
<td>55</td>
<td>32</td>
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<tr>
<td>≤ 1.4</td>
<td>184</td>
<td>190</td>
<td>167</td>
<td>102</td>
<td>86</td>
<td>100</td>
<td>67</td>
<td>70</td>
<td>59</td>
<td>44</td>
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<td>248</td>
<td>226</td>
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<td>124</td>
<td>115</td>
<td>114</td>
<td>79</td>
<td>80</td>
<td>69</td>
<td>48</td>
</tr>
<tr>
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<td>88</td>
<td>90</td>
<td>76</td>
<td>54</td>
</tr>
<tr>
<td>≤ 1.7</td>
<td>387</td>
<td>339</td>
<td>315</td>
<td>211</td>
<td>176</td>
<td>162</td>
<td>99</td>
<td>101</td>
<td>84</td>
<td>66</td>
</tr>
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<td>412</td>
<td>377</td>
<td>260</td>
<td>221</td>
<td>195</td>
<td>116</td>
<td>109</td>
<td>98</td>
<td>71</td>
</tr>
<tr>
<td>≤ 1.9</td>
<td>560</td>
<td>494</td>
<td>443</td>
<td>319</td>
<td>268</td>
<td>224</td>
<td>137</td>
<td>118</td>
<td>108</td>
<td>78</td>
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<tr>
<td>≤ 2.0</td>
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<td>582</td>
<td>529</td>
<td>387</td>
<td>327</td>
<td>272</td>
<td>162</td>
<td>129</td>
<td>118</td>
<td>96</td>
</tr>
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<td>676</td>
<td>624</td>
<td>462</td>
<td>408</td>
<td>331</td>
<td>189</td>
<td>148</td>
<td>134</td>
<td>106</td>
</tr>
<tr>
<td>≤ 2.2</td>
<td>910</td>
<td>781</td>
<td>725</td>
<td>563</td>
<td>487</td>
<td>383</td>
<td>232</td>
<td>174</td>
<td>155</td>
<td>122</td>
</tr>
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<td>≤ 2.3</td>
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<td>891</td>
<td>847</td>
<td>680</td>
<td>579</td>
<td>458</td>
<td>275</td>
<td>199</td>
<td>176</td>
<td>135</td>
</tr>
<tr>
<td>≤ 2.4</td>
<td>1,207</td>
<td>1,014</td>
<td>987</td>
<td>822</td>
<td>696</td>
<td>552</td>
<td>326</td>
<td>219</td>
<td>204</td>
<td>147</td>
</tr>
<tr>
<td>≤ 2.5</td>
<td>1,395</td>
<td>1,191</td>
<td>1,130</td>
<td>986</td>
<td>841</td>
<td>663</td>
<td>390</td>
<td>250</td>
<td>224</td>
<td>176</td>
</tr>
<tr>
<td>≤ 2.6</td>
<td>1,595</td>
<td>1,383</td>
<td>1,318</td>
<td>1,169</td>
<td>1,020</td>
<td>811</td>
<td>495</td>
<td>291</td>
<td>250</td>
<td>194</td>
</tr>
<tr>
<td>≤ 2.7</td>
<td>1,855</td>
<td>1,620</td>
<td>1,547</td>
<td>1,408</td>
<td>1,234</td>
<td>976</td>
<td>586</td>
<td>349</td>
<td>293</td>
<td>217</td>
</tr>
<tr>
<td>≤ 2.8</td>
<td>2,178</td>
<td>1,919</td>
<td>1,804</td>
<td>1,759</td>
<td>1,444</td>
<td>1,168</td>
<td>722</td>
<td>415</td>
<td>352</td>
<td>250</td>
</tr>
<tr>
<td>≤ 2.9</td>
<td>2,483</td>
<td>2,266</td>
<td>2,167</td>
<td>2,112</td>
<td>1,719</td>
<td>1,390</td>
<td>881</td>
<td>494</td>
<td>409</td>
<td>303</td>
</tr>
<tr>
<td>≤ 3.0</td>
<td>2,856</td>
<td>2,690</td>
<td>2,631</td>
<td>2,521</td>
<td>2,129</td>
<td>1,692</td>
<td>1,107</td>
<td>655</td>
<td>512</td>
<td>369</td>
</tr>
</tbody>
</table>
Table 4.11: Percent Change to Rear-end TTC conflicts at varying connected vehicle (CV) penetration levels Compared With No CACC

<table>
<thead>
<tr>
<th>TTC Threshold</th>
<th>10% CV</th>
<th>20% CV</th>
<th>30% CV</th>
<th>40% CV</th>
<th>50% CV</th>
<th>60% CV</th>
<th>70% CV</th>
<th>80% CV</th>
<th>90% CV</th>
</tr>
</thead>
<tbody>
<tr>
<td>TTC ≤ 0.5</td>
<td>50%</td>
<td>50%</td>
<td>150%</td>
<td>100%</td>
<td>50%</td>
<td>0%</td>
<td>125%</td>
<td>50%</td>
<td>-25%</td>
</tr>
<tr>
<td>TTC ≤ 1.0</td>
<td>18%</td>
<td>13%</td>
<td>-10%</td>
<td>-12%</td>
<td>4%</td>
<td>-32%</td>
<td>-11%</td>
<td>-24%</td>
<td>-52%</td>
</tr>
<tr>
<td>TTC ≤ 1.5</td>
<td>-9%</td>
<td>-16%</td>
<td>-50%</td>
<td>-54%</td>
<td>-54%</td>
<td>-68%</td>
<td>-68%</td>
<td>-72%</td>
<td>-81%</td>
</tr>
<tr>
<td>TTC ≤ 2.0</td>
<td>-14%</td>
<td>-22%</td>
<td>-43%</td>
<td>-51%</td>
<td>-60%</td>
<td>-76%</td>
<td>-81%</td>
<td>-83%</td>
<td>-86%</td>
</tr>
<tr>
<td>TTC ≤ 2.5</td>
<td>-15%</td>
<td>-19%</td>
<td>-29%</td>
<td>-40%</td>
<td>-52%</td>
<td>-72%</td>
<td>-82%</td>
<td>-84%</td>
<td>-87%</td>
</tr>
<tr>
<td>TTC ≤ 3.0</td>
<td>-6%</td>
<td>-8%</td>
<td>-12%</td>
<td>-25%</td>
<td>-41%</td>
<td>-61%</td>
<td>-77%</td>
<td>-82%</td>
<td>-87%</td>
</tr>
</tbody>
</table>

Figure 4.10: Percent Change in Rear-End Conflicts by TTC Threshold for varying CACC Market Penetration Level Compared with No CACC (negative percentage indicates improvement)

4.2.5 Evaluation of Results

The results of the micro-simulation model are evaluated based on two measures of improvement: 1) Improvement to mobility, and 2) Reduction in simulated traffic conflicts as a surrogate for safety. Expected results are that at higher connected vehicle market penetrations both travel times and simulated rear-end conflicts will be reduced.
4.2.5.1 Mobility Evaluation

The mobility of the different penetration levels are evaluated based on the network travel times. Figure 4.7 displays a visual representation of the travel times for varying CACC connected vehicle market penetration levels for the different vehicle types and the average travel times between all vehicles. Figure 4.8 displays a visual representation of travel time improvements compared with the total average travel time with no CACC vehicles present at varying CACC penetration levels for Manual Vehicles, ACC vehicles, CACC vehicles and the average for all vehicles. The results show that as the penetration level of CACC vehicles increases the average travel time reduces, thus improving mobility. Additionally, Table 4.8 outlines the travel times for each vehicle type at each CACC connected vehicle market penetration level, as well as the standard deviations for these travel times. The standard deviations are shown to be reduced at higher CACC connected vehicle market penetration levels, indicating more reliable travel time through the area of congestion.

Comparison of mobility results show that the improvements vary by vehicle type and CACC penetration rate. Travel times for the total network (including all vehicle types) as well as for individual vehicles types are compared with the No CACC penetration rate travel time for the network. At all CACC penetration rates there are savings for the CACC equipped vehicles. Consistent travel time savings are seen for all vehicle types after the CACC penetration rate reaches 60% indicating that this is the point at which mobility improvements become essentially saturated. At a 90% CACC penetration rate, the total network sees improvements to travel times by nearly 50%.

4.2.5.2 Traffic Conflicts Evaluation

Rear-end conflicts were the measure used to identify safety improvements under the connected vehicle environment for a CACC application when a delay in traffic is observed. Rear-end conflicts are evaluated at TTC thresholds of 0.5s to 3.0s, in 0.5s increments, with lower TTC thresholds representing a higher conflict severity (higher probability of a collision occurring).
Table 4.11 provides the change in traffic conflicts based on the percent change in rear-end conflicts for different TTC thresholds compared to the No-CACC micro-simulation.

Figure 4.10 provides a visual summary of the improvement in the total number of conflicts for each CACC penetration level. As the CACC penetration level increases, there is an increase in the improvement to the total number of conflicts observed compared to the scenario with no CACC equipped vehicles. After a 60% CACC penetration level is reached, the improvements over the scenario where no CACC equipped vehicles are present appear to level off for higher TTC thresholds (2.0s and above), demonstrating that the safety improvements do not follow a linear trend at higher CACC penetration levels. At lower TTC thresholds, there is volatility throughout the different CACC market penetration levels, likely due to the lower absolute number of simulated conflicts resulting in larger percentage changes.

Because of the nature of the CACC vehicles, headways of 0.5s are being used which increases the likelihood of measuring rear-end conflicts at very low TTC thresholds while they may not be actual rear-end conflicts as they are instances accounted for in the acceleration model described in Equation 4.2.1.

4.2.6 Micro-Simulation Sensitivity Analysis

Sensitivity analysis was performed on the driver behaviour parameters and the acceleration coefficients to evaluate the variability of the micro-simulation model when these components are modified.

4.2.6.1 Driver Behaviour Parameters

VISSIM contains many driver behaviour parameters (about 190). There are 30 specific parameters related to driver behaviour. In a study conducted by Essa and Sayed (2015a), sensitivity analysis was performed in order to determine the most important driver behaviour parameters related to
safety. While Essa and Sayed (2015a) looked specifically at intersections, some of the parameters are still relevant to the CACC simulations and therefore additional modeling is conducted in order to evaluate the differences and sensitivities based on changing these parameters.

Sensitivity analysis has been performed in previous research on the VISSIM driver behaviour parameters, specifically those that affect the aggressiveness and defensiveness on the roadway for freeway applications (Gomes et al., 2004; Habtemichael and Picado-Santos, 2013; Hadi et al., 2007). The VISSIM driver behaviour parameters are important for calibration purposes to ensure that the micro-simulation model adequately represents conditions in the real world. Modifying these parameters can have a significant effect on the outcome of the micro-simulation. Habtemichael and Picado-Santos (2013) demonstrates that there is significant impact to safety when VISSIM parameter CC1 is modified. The VISSIM parameter CC1 is the headway parameter and is said to have the most influence over freeway capacity (Gomes et al., 2004). The default VISSIM CC1 value is 0.9s. Hadi et al. (2007) analyses the the change in capacity of a roadway in VISSIM when modifying the CC1 parameter and reviews the capabilities of different micro-simulators to simulate an incident.

The two driver behaviour parameters that affect the safety distance in VISSIM are CC0 and CC1. The safety distance is given by Equation 4.2.3

\[
dx_{safe} = CC0 + CC1 \times speed
\]  

(4.2.3)

CC0 is the parameter that determines the stopped distance, or the distance that a vehicle maintains behind a stopped vehicle on a freeway, with a default value in VISSIM of 1.5m. CC1 is the parameter that specifies headway, with a default value in VISSIM of 0.9s. At higher speeds the CC1 parameter is the dominant component of Equation 4.2.3 and is the parameter that is being modified to demonstrate the changes to the outcomes of the micro-simulation model as part of the input parameter sensitivity analysis.
Gomes et al. (2004) suggests that with reasonable values of $dx_{safe}$, the freeflow speed and the default value for CC0, CC1 is calculated to be 1.5s. Habtemichael and Picado-Santos (2013) demonstrates the changes in the safety through rear-end conflicts at CC1 values ranging between 0.5s and 1.3s. Hadi et al. (2007) demonstrates the changes in capacity at CC1 values ranging from 0.5s to 1.5s.

Within this study sensitivity analysis is performed on the simulated conflicts when changing the CC1 value to identify whether the improvements found with the default CC1 value in VISSIM of 0.9s hold when CC1 is changed. The CC1 parameter is varied between 0.7s and 1.5s and results are presented as a comparison to the default VISSIM Parameter of 0.9s for CACC market penetration rates ranging from 0% to 90% for the TTC $\leq 1.5s$. Comparison results for travel times and rear-end conflicts are presented in Tables 4.12 and 4.13, and Tables 4.14 through 4.21 respectively.

**Table 4.12: Travel Time Variations Based on Varying CC1 Parameter**

<table>
<thead>
<tr>
<th>CC1 Parameter</th>
<th>NO CACC</th>
<th>10% CACC</th>
<th>30% CACC</th>
<th>50% CACC</th>
<th>70% CACC</th>
<th>90% CACC</th>
</tr>
</thead>
<tbody>
<tr>
<td>CC1 = 0.7</td>
<td>65</td>
<td>61</td>
<td>63</td>
<td>54</td>
<td>47</td>
<td>38</td>
</tr>
<tr>
<td>CC1 = 1.1</td>
<td>81</td>
<td>75</td>
<td>78</td>
<td>70</td>
<td>57</td>
<td>36</td>
</tr>
<tr>
<td>CC1 = 1.3</td>
<td>83</td>
<td>84</td>
<td>86</td>
<td>75</td>
<td>54</td>
<td>37</td>
</tr>
<tr>
<td>CC1 = 1.5</td>
<td>92</td>
<td>89</td>
<td>89</td>
<td>79</td>
<td>63</td>
<td>38</td>
</tr>
</tbody>
</table>

**Table 4.13: Travel Time Variations Based on Varying CC1 Parameter Value Compared with Default VISSIM Parameter (Reductions are Improvements)**

<table>
<thead>
<tr>
<th>CC1 Parameter</th>
<th>No CACC</th>
<th>10% CACC</th>
<th>30% CACC</th>
<th>50% CACC</th>
<th>70% CACC</th>
<th>90% CACC</th>
</tr>
</thead>
<tbody>
<tr>
<td>CC1 = 0.7</td>
<td>12%</td>
<td>9%</td>
<td>13%</td>
<td>20%</td>
<td>1%</td>
<td>0%</td>
</tr>
<tr>
<td>CC1 = 1.1</td>
<td>-11%</td>
<td>-12%</td>
<td>-7%</td>
<td>-3%</td>
<td>-22%</td>
<td>4%</td>
</tr>
<tr>
<td>CC1 = 1.3</td>
<td>-13%</td>
<td>-25%</td>
<td>-20%</td>
<td>-10%</td>
<td>-15%</td>
<td>2%</td>
</tr>
<tr>
<td>CC1 = 1.5</td>
<td>-25%</td>
<td>-33%</td>
<td>-23%</td>
<td>-16%</td>
<td>-34%</td>
<td>-1%</td>
</tr>
</tbody>
</table>

**Table 4.14: Rear-End Conflicts for 0.7s Headway at Varying CACC Penetration Levels**

<table>
<thead>
<tr>
<th>TTC Threshold</th>
<th>No CACC</th>
<th>10% CACC</th>
<th>30% CACC</th>
<th>50% CACC</th>
<th>70% CACC</th>
<th>90% CACC</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\leq 0.5$</td>
<td>29</td>
<td>24</td>
<td>14</td>
<td>12</td>
<td>17</td>
<td>8</td>
</tr>
<tr>
<td>$\leq 1.0$</td>
<td>110</td>
<td>96</td>
<td>87</td>
<td>49</td>
<td>43</td>
<td>34</td>
</tr>
<tr>
<td>$\leq 1.5$</td>
<td>415</td>
<td>321</td>
<td>276</td>
<td>127</td>
<td>84</td>
<td>60</td>
</tr>
<tr>
<td>$\leq 2.0$</td>
<td>1023</td>
<td>755</td>
<td>667</td>
<td>336</td>
<td>148</td>
<td>90</td>
</tr>
<tr>
<td>$\leq 2.5$</td>
<td>1869</td>
<td>1493</td>
<td>1338</td>
<td>713</td>
<td>350</td>
<td>168</td>
</tr>
<tr>
<td>$\leq 3.0$</td>
<td>2233</td>
<td>2010</td>
<td>1496</td>
<td>646</td>
<td>483</td>
<td>331</td>
</tr>
</tbody>
</table>
Table 4.15: Rear-End Conflicts for 0.7s Headway Compared with Default VISSIM Parameter

<table>
<thead>
<tr>
<th>TTC Threshold</th>
<th>No CACC</th>
<th>10% CACC</th>
<th>30% CACC</th>
<th>50% CACC</th>
<th>70% CACC</th>
<th>90% CACC</th>
</tr>
</thead>
<tbody>
<tr>
<td>≤ 0.5</td>
<td>267%</td>
<td>100%</td>
<td>-30%</td>
<td>0%</td>
<td>-4%</td>
<td>33%</td>
</tr>
<tr>
<td>≤ 1.0</td>
<td>121%</td>
<td>64%</td>
<td>93%</td>
<td>-6%</td>
<td>-4%</td>
<td>42%</td>
</tr>
<tr>
<td>≤ 1.5</td>
<td>67%</td>
<td>42%</td>
<td>122%</td>
<td>11%</td>
<td>6%</td>
<td>25%</td>
</tr>
<tr>
<td>≤ 2.0</td>
<td>52%</td>
<td>30%</td>
<td>73%</td>
<td>24%</td>
<td>15%</td>
<td>-6%</td>
</tr>
<tr>
<td>≤ 2.5</td>
<td>34%</td>
<td>25%</td>
<td>36%</td>
<td>8%</td>
<td>40%</td>
<td>-4%</td>
</tr>
<tr>
<td>≤ 3.0</td>
<td>-22%</td>
<td>-25%</td>
<td>-41%</td>
<td>-62%</td>
<td>-26%</td>
<td>-10%</td>
</tr>
</tbody>
</table>

Table 4.16: Rear-End Conflicts for 1.1s Headway at Varying CACC Penetration Levels

<table>
<thead>
<tr>
<th>TTC Threshold</th>
<th>No CACC</th>
<th>10% CACC</th>
<th>30% CACC</th>
<th>50% CACC</th>
<th>70% CACC</th>
<th>90% CACC</th>
</tr>
</thead>
<tbody>
<tr>
<td>≤ 0.5</td>
<td>4</td>
<td>8</td>
<td>24</td>
<td>20</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>≤ 1.0</td>
<td>62</td>
<td>37</td>
<td>42</td>
<td>36</td>
<td>37</td>
<td>28</td>
</tr>
<tr>
<td>≤ 1.5</td>
<td>249</td>
<td>153</td>
<td>100</td>
<td>71</td>
<td>66</td>
<td>52</td>
</tr>
<tr>
<td>≤ 2.0</td>
<td>565</td>
<td>381</td>
<td>260</td>
<td>150</td>
<td>112</td>
<td>79</td>
</tr>
<tr>
<td>≤ 2.5</td>
<td>1150</td>
<td>894</td>
<td>686</td>
<td>353</td>
<td>195</td>
<td>125</td>
</tr>
<tr>
<td>≤ 3.0</td>
<td>2333</td>
<td>2194</td>
<td>1805</td>
<td>916</td>
<td>543</td>
<td>281</td>
</tr>
</tbody>
</table>

Table 4.17: Rear-End Conflicts for 1.1s Headway Compared with Default VISSIM Parameter

<table>
<thead>
<tr>
<th>TTC Threshold</th>
<th>No CACC</th>
<th>10% CACC</th>
<th>30% CACC</th>
<th>50% CACC</th>
<th>70% CACC</th>
<th>90% CACC</th>
</tr>
</thead>
<tbody>
<tr>
<td>≤ 0.5</td>
<td>-50%</td>
<td>-33%</td>
<td>20%</td>
<td>67%</td>
<td>-56%</td>
<td>33%</td>
</tr>
<tr>
<td>≤ 1.0</td>
<td>24%</td>
<td>-37%</td>
<td>-6%</td>
<td>-31%</td>
<td>-17%</td>
<td>17%</td>
</tr>
<tr>
<td>≤ 1.5</td>
<td>0%</td>
<td>-32%</td>
<td>-20%</td>
<td>-38%</td>
<td>-17%</td>
<td>8%</td>
</tr>
<tr>
<td>≤ 2.0</td>
<td>-16%</td>
<td>-35%</td>
<td>-33%</td>
<td>-45%</td>
<td>-13%</td>
<td>-17%</td>
</tr>
<tr>
<td>≤ 2.5</td>
<td>-18%</td>
<td>-25%</td>
<td>-30%</td>
<td>-47%</td>
<td>-22%</td>
<td>-29%</td>
</tr>
<tr>
<td>≤ 3.0</td>
<td>-18%</td>
<td>-18%</td>
<td>-28%</td>
<td>-46%</td>
<td>-17%</td>
<td>-24%</td>
</tr>
</tbody>
</table>

Table 4.18: Rear-End Conflicts for 1.3s Headway at Varying CACC Penetration Levels

<table>
<thead>
<tr>
<th>TTC Threshold</th>
<th>No CACC</th>
<th>10% CACC</th>
<th>30% CACC</th>
<th>50% CACC</th>
<th>70% CACC</th>
<th>90% CACC</th>
</tr>
</thead>
<tbody>
<tr>
<td>≤ 0.5</td>
<td>12</td>
<td>8</td>
<td>4</td>
<td>8</td>
<td>12</td>
<td>11</td>
</tr>
<tr>
<td>≤ 1.0</td>
<td>60</td>
<td>41</td>
<td>35</td>
<td>24</td>
<td>40</td>
<td>25</td>
</tr>
<tr>
<td>≤ 1.5</td>
<td>265</td>
<td>153</td>
<td>88</td>
<td>54</td>
<td>68</td>
<td>55</td>
</tr>
<tr>
<td>≤ 2.0</td>
<td>613</td>
<td>398</td>
<td>232</td>
<td>115</td>
<td>111</td>
<td>84</td>
</tr>
<tr>
<td>≤ 2.5</td>
<td>1158</td>
<td>871</td>
<td>596</td>
<td>248</td>
<td>201</td>
<td>143</td>
</tr>
<tr>
<td>≤ 3.0</td>
<td>2233</td>
<td>2010</td>
<td>1496</td>
<td>646</td>
<td>483</td>
<td>331</td>
</tr>
</tbody>
</table>

Table 4.19: Rear-End Conflicts for 1.3s Headway Compared with Default VISSIM Parameter

<table>
<thead>
<tr>
<th>TTC Threshold</th>
<th>No CACC</th>
<th>10% CACC</th>
<th>30% CACC</th>
<th>50% CACC</th>
<th>70% CACC</th>
<th>90% CACC</th>
</tr>
</thead>
<tbody>
<tr>
<td>≤ 0.5</td>
<td>50%</td>
<td>-33%</td>
<td>-80%</td>
<td>-33%</td>
<td>-33%</td>
<td>89%</td>
</tr>
<tr>
<td>≤ 1.0</td>
<td>20%</td>
<td>-30%</td>
<td>-21%</td>
<td>-54%</td>
<td>-10%</td>
<td>3%</td>
</tr>
<tr>
<td>≤ 1.5</td>
<td>7%</td>
<td>-32%</td>
<td>-29%</td>
<td>-53%</td>
<td>-15%</td>
<td>14%</td>
</tr>
<tr>
<td>≤ 2.0</td>
<td>-9%</td>
<td>-32%</td>
<td>-40%</td>
<td>-58%</td>
<td>-13%</td>
<td>-12%</td>
</tr>
<tr>
<td>≤ 2.5</td>
<td>-17%</td>
<td>-27%</td>
<td>-40%</td>
<td>-63%</td>
<td>-20%</td>
<td>-19%</td>
</tr>
<tr>
<td>≤ 3.0</td>
<td>-22%</td>
<td>-25%</td>
<td>-41%</td>
<td>-62%</td>
<td>-26%</td>
<td>-10%</td>
</tr>
</tbody>
</table>
Table 4.20: Rear-End Conflicts for 1.5s Headway at Varying CACC Penetration Levels

<table>
<thead>
<tr>
<th>TTC Threshold</th>
<th>No CACC</th>
<th>10% CACC</th>
<th>30% CACC</th>
<th>50% CACC</th>
<th>70% CACC</th>
<th>90% CACC</th>
</tr>
</thead>
<tbody>
<tr>
<td>≤ 0.5</td>
<td>4</td>
<td>4</td>
<td>8</td>
<td>8</td>
<td>4</td>
<td>16</td>
</tr>
<tr>
<td>≤ 1.0</td>
<td>52</td>
<td>44</td>
<td>28</td>
<td>24</td>
<td>24</td>
<td>32</td>
</tr>
<tr>
<td>≤ 1.5</td>
<td>215</td>
<td>152</td>
<td>77</td>
<td>45</td>
<td>50</td>
<td>55</td>
</tr>
<tr>
<td>≤ 2.0</td>
<td>576</td>
<td>418</td>
<td>210</td>
<td>105</td>
<td>92</td>
<td>84</td>
</tr>
<tr>
<td>≤ 2.5</td>
<td>1043</td>
<td>833</td>
<td>450</td>
<td>226</td>
<td>159</td>
<td>134</td>
</tr>
<tr>
<td>≤ 3.0</td>
<td>2077</td>
<td>1734</td>
<td>1032</td>
<td>477</td>
<td>366</td>
<td>317</td>
</tr>
</tbody>
</table>

Table 4.21: Rear-End Conflicts for 1.5s Headway Compared with Default VISSIM Parameter

<table>
<thead>
<tr>
<th>TTC Threshold</th>
<th>No CACC</th>
<th>10% CACC</th>
<th>30% CACC</th>
<th>50% CACC</th>
<th>70% CACC</th>
<th>90% CACC</th>
</tr>
</thead>
<tbody>
<tr>
<td>≤ 0.5</td>
<td>-50%</td>
<td>-67%</td>
<td>-60%</td>
<td>-33%</td>
<td>-78%</td>
<td>167%</td>
</tr>
<tr>
<td>≤ 1.0</td>
<td>5%</td>
<td>-25%</td>
<td>-38%</td>
<td>-54%</td>
<td>-46%</td>
<td>33%</td>
</tr>
<tr>
<td>≤ 1.5</td>
<td>-13%</td>
<td>-33%</td>
<td>-38%</td>
<td>-60%</td>
<td>-38%</td>
<td>14%</td>
</tr>
<tr>
<td>≤ 2.0</td>
<td>-15%</td>
<td>-28%</td>
<td>-46%</td>
<td>-61%</td>
<td>-29%</td>
<td>-13%</td>
</tr>
<tr>
<td>≤ 2.5</td>
<td>-25%</td>
<td>-30%</td>
<td>-54%</td>
<td>-66%</td>
<td>-36%</td>
<td>-24%</td>
</tr>
<tr>
<td>≤ 3.0</td>
<td>-27%</td>
<td>-36%</td>
<td>-59%</td>
<td>-72%</td>
<td>-44%</td>
<td>-14%</td>
</tr>
</tbody>
</table>

Figure 4.11: Percent Change in Rear-End Conflicts by TTC Threshold for varying CACC Market Penetration Level at a 0.7s Headway Compared with Default VISSIM Headway Parameter
Figure 4.12: Percent Change in Rear-End Conflicts by TTC Threshold for varying CACC Market Penetration Level at a 1.1s Headway Compared with Default VISSIM Headway Parameter

Figure 4.13: Percent Change in Rear-End Conflicts by TTC Threshold for varying CACC Market Penetration Level at a 1.3s Headway Compared with Default VISSIM Headway Parameter
4.2.6.2 Acceleration Coefficients

The second task for sensitivity analysis was to modify the acceleration coefficients provided in Equation 4.2.1, namely $k_a$, $k_v$, and $k_s$. For this sensitivity analysis the hardcoded values within the DLL are modified for each set of simulation runs. The values used within the base simulations are as were used by Zhao and Sun (2013) as $k_a = 1.0$, $k_v = 0.58$, and $k_s = 0.1$. Four additional comparisons are conducted as described below, keeping $k_a$ constant at 1.0. These differences in acceleration coefficients were chosen based on the sensitivity analysis performed in Van Arem et al. (2006). The additional four different combinations of acceleration coefficients used are as follows:

**Comparison 1:** $k_a=1.0$, $k_v=1.00$, and $k_s=0.1$

**Comparison 2:** $k_a=1.0$, $k_v=2.00$, and $k_s=0.1$

**Comparison 3:** $k_a=1.0$, $k_v=0.58$, and $k_s=0.2$

**Comparison 4:** $k_a=1.0$, $k_v=0.58$, and $k_s=0.3$
Comparisons were performed at a 50% CACC penetration level to demonstrate the sensitivity of the acceleration parameters on safety through rear-end conflicts, and travel times. The difference in travel times and rear-end conflicts results are presented in Table 4.22 comparing the modified acceleration comparisons with the initial values used.

Table 4.22: Changes to Travel Times and Rear-End Conflicts for CACC Acceleration Parameters at 50% CACC Penetration

<table>
<thead>
<tr>
<th>Measure</th>
<th>Comparison 1</th>
<th>Comparison 2</th>
<th>Comparison 3</th>
<th>Comparison 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total TT</td>
<td>2%</td>
<td>7%</td>
<td>1%</td>
<td>0%</td>
</tr>
<tr>
<td>Man. Vehicle TT</td>
<td>2%</td>
<td>8%</td>
<td>0%</td>
<td>2%</td>
</tr>
<tr>
<td>ACC Vehicle TT</td>
<td>1%</td>
<td>7%</td>
<td>1%</td>
<td>-2%</td>
</tr>
<tr>
<td>CACC Vehicle TT</td>
<td>1%</td>
<td>6%</td>
<td>3%</td>
<td>2%</td>
</tr>
<tr>
<td>Rear-end ≤ 3.0s</td>
<td>-21%</td>
<td>-11%</td>
<td>-22%</td>
<td>-43%</td>
</tr>
<tr>
<td>Rear-end ≤ 2.0s</td>
<td>-11%</td>
<td>-8%</td>
<td>-25%</td>
<td>-54%</td>
</tr>
<tr>
<td>Rear-end ≤ 1.5s</td>
<td>-11%</td>
<td>-10%</td>
<td>-21%</td>
<td>-56%</td>
</tr>
</tbody>
</table>

4.2.7 Sensitivity Analysis Evaluation

Results of the travel time and safety improvements are presented in Tables 4.8 through 4.22 and in Figures 4.7 through 4.14.

4.2.7.1 Mobility Evaluation

When modifying the driver behaviour parameters within VISSIM, system wide travel times are improved at lower CACC penetration levels for a headway time (CC1) of 0.7, but improvements deteriorate at 70% CACC penetration level when compared with the same CACC penetration levels and using the default VISSIM driver behaviour parameter value. At higher headway times, the travel time savings show disimprovements as the CC1 value increases, travel times get longer and disimprovements become greater. The results of this sensitivity analysis are expected as increasing the CC1 value is in essence causing the driver behaviour to be less aggressive while decreasing the CC1 value causes the driver behaviour to be more aggressive.
When modifying the acceleration coefficients under Equation 4.2.1, only the 50% CACC penetration level was evaluated. It was found that improvements to travel times vary, but not significantly (less than 10% for all scenarios) indicating that the acceleration parameters for the CACC equipped vehicles do not greatly impact the overall travel time of the system.

### 4.2.7.2 Traffic Conflicts Evaluation

When evaluating the results of the sensitivity analysis, shorter headway times have significant impacts to the safety evaluation results. Comparisons are made for different headway times and different CACC penetration levels compared with the same CACC penetration level for the default VISSIM driver behaviour parameter for headway time. Headway times longer than the default VISSIM parameter (i.e., 1.1s, 1.3s and 1.5s) show improvements over the default VISSIM value for nearly all CACC penetration levels. At higher CACC penetration levels the improvements are generally not as great as with lower CACC penetration levels, primarily due to the reduction in manually driven vehicles within the simulation that are affected by the changes to the headway parameters.

The acceleration coefficients chosen based on [Zhao and Sun (2013)](#) and [Van Arem et al. (2006)](#) produce less rear-end conflicts than when compared with modifications of the acceleration coefficients at TTC thresholds of $\leq 1.5s$ and greater. Varying the acceleration coefficients demonstrate worsening with respect to to rear-end conflicts at all TTC thresholds measured, specifically 1.5s, 2.0s and 3.0s, indicating the acceleration coefficients chosen are a good choice when applying the CACC algorithm from a safety perspective.
Chapter 5

Calibrated Connected Vehicle Simulations

This chapter describes the micro-simulation of a connected vehicle environment after calibration to real-world conditions. Of the two connected vehicle micro-simulations detailed in Chapter 4, the cumulative travel time intersection control connected vehicle environment was developed using a real-world intersection with real traffic information that has been used for calibration. The cooperative adaptive cruise control connected vehicle environment is a theoretical implementation without any readily available real-world conditions that can be used for calibration purposes.

To demonstrate that calibration of a non-connected vehicle environment through modification of VISSIM and other parameters has a significant impact to the simulated effects of connected vehicle applications, for both safety and mobility, modifications to the parameters were implemented using results of a two-step calibration procedure conducted by Essa and Sayed (2015a), firstly applying calibration parameters for delay and arrival rates, and secondly applying calibration parameters for observed conflicts.
5.1 Cumulative Travel Time Intersection Control

The evaluation of the CTT algorithm in relation to connected vehicles was performed in Section 4.1 using the default VISSIM parameters with no calibration conducted. This section will serve to perform the micro-simulation after the first step calibration and second step calibration, calibrating for delays and arrival rates, and for observed conflicts respectively. The objective of this review is to determine if calibrating the micro-simulation model provides a better representation of the real world than not calibrating the micro-simulation model.

Essa and Sayed (2015a) calibrated the VISSIM micro-simulation model using a two step process. Section 4.1 provided the uncalibrated comparison. In this section, the comparisons are performed at two stages: 1) First Step Calibration focusing on delays and arrival rates compared with real-world delays, and 2) Second Step Calibration focusing on VISSIM safety parameters to correlate with observed conflicts in the field.

5.1.1 Intersection First Step Calibration

The first step calibration aims to ensure that the field measured parameters are represented within the simulation. There are many parameters that can be used for this calibration, however it is very difficult to optimize many parameters at once. The calibration parameters used are based on research by Essa and Sayed (2015a), in which the average delay per vehicle was selected to be optimized, primarily as it is the key measure for evaluating the Level-of-Service (LOS) for signalized intersections (Highway Capacity Manual, 2000). Dummy intersections were introduced to obtain appropriate arrival times to the East and West approaches. The first step calibration is a calibration step commonly performed in micro-simulation as it is required in order to obtain reasonable results from the simulation.
5.1.2 Intersection Second Step Calibration

The second step calibration is intended to enhance the correlation between conflicts seen in the field and in the simulation. Essa and Sayed (2015a) performed the second step calibration through sensitivity analysis on VISSIM parameters to understand which have the biggest effect on the simulated rear-end conflicts with subsequent analysis performed through a genetic algorithm to determine the best values. Essa and Sayed (2015a) found the most important six parameters to be CC0 (standstill distance), CC1 (headway time), CC4 & CC5 (negative and positive following thresholds), the reduction factor for safety distance close to stop line, start upstream of stop line, and desired deceleration. These six parameters will be considered as the safety-related parameters for signalized intersections as they affect the desired safety distance between each pair of consecutive vehicles.

Subsequent to the evaluation without calibrating the micro-simulation model, previously discussed in Chapter 4, to evaluate the effects of calibration, evaluation of delays and safety were performed on the intersection in two different scenarios using both the basic (not connected vehicle) scenario as well as the connected vehicle scenario:

1. First Step Calibrated (to account for vehicle arrival times and delays)
2. Second Step Calibrated (to account for vehicle conflicts)

The default and the calibrated parameter values used for the second calibration step are provided in Table 5.1.

### Table 5.1: Default VISSIM Driver Behaviour Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>Default</th>
<th>Calibrated Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>CC0</td>
<td>metres</td>
<td>1.50</td>
<td>2.50</td>
</tr>
<tr>
<td>CC1</td>
<td>seconds</td>
<td>0.9</td>
<td>1.3</td>
</tr>
<tr>
<td>CC4 &amp; CC5</td>
<td></td>
<td>± 0.35</td>
<td>± 0.25</td>
</tr>
<tr>
<td>Reduction factor for safety distance close to stop line</td>
<td></td>
<td>0.60</td>
<td>0.75</td>
</tr>
<tr>
<td>Start upstream of stop line</td>
<td>metres</td>
<td>100</td>
<td>110</td>
</tr>
<tr>
<td>Desired deceleration</td>
<td>m/s²</td>
<td>-2.80</td>
<td>-2.80</td>
</tr>
</tbody>
</table>
5.1.3 Automated Video-Based Computer Vision Analysis

Autey et al. (2012) and several other researchers (Saunier and Sayed, 2006, 2007, 2008; Saunier et al., 2010) describe the computer vision process for automated analysis through video capture of traffic. A detailed description of the analysis process using computer vision is shown in Figure 5.1 (Tageldin et al., 2014).

![Figure 5.1: Process outlining computer vision methodology for automated video analysis (Tageldin et al., 2014)](image)

Essa and Sayed (2015a) details the evaluation on the intersection under review, explaining how the volumes, signal timing and calibration was conducted using computer vision. A visual representation of the conflicts observed for the calibration dataset is presented in Figure 5.2.

5.1.4 CTT Data Collection and Analysis

Data is collected for the East and West movements of the intersection as these are the movements calibrated by Essa and Sayed [5]. The mobility data was collected by measuring travel times at each approach to the intersection until the vehicle has completed its travel through the stop bar at the intersection. Conflict information is collected through the .trj file saved from the VISSIM micro-simulation for analyzing using SSAM.

During the calibration phase of this micro-simulation, the model was run for two scenarios: 1) first step calibrated, and 2) second step calibrated, both for the non-CTT algorithm being applied as well as the CTT algorithm being applied. Subsequent to the second step calibration being performed,
<table>
<thead>
<tr>
<th>Section 1</th>
<th>Section 3</th>
<th>Section 5</th>
<th>Section 7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Field Conflicts</td>
<td>Field Conflicts</td>
<td>Field Conflicts</td>
<td>Field Conflicts</td>
</tr>
<tr>
<td>Simulated Conflicts</td>
<td>Simulated Conflicts</td>
<td>Simulated Conflicts</td>
<td>Simulated Conflicts</td>
</tr>
</tbody>
</table>

**Figure 5.2:** Heat maps of calibration data set using Computer Vision and simulated conflicts used for calibration (Essa and Sayed, 2015a)
additional CTT applied micro-simulations were performed at varying time-step intervals in order to evaluate sensitivities to when the signal controller updates, as well as at varying connected vehicle penetration levels to evaluate the connected vehicle application without perfect market penetration. The resulting rear-end conflicts are presented in Table 5.6 and Table 5.7 and the rear-end conflict improvements are presented in Table 5.8 and Table 5.9. Graphical representations of the rear-end conflicts and improvements are presented in Figures 5.5 and 5.6, and Figures 5.7 and 5.8 respectively.

**Table 5.2:** Travel times at varying connected vehicle market penetration levels for the first step calibrated micro-simulation model after implementing the CTT algorithm

<table>
<thead>
<tr>
<th>Vehicle Type</th>
<th>No CTT</th>
<th>10% CTT</th>
<th>30% CTT</th>
<th>50% CTT</th>
<th>70% CTT</th>
<th>90% CTT</th>
<th>100% CTT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Avg. CV (s)</td>
<td>N/A</td>
<td>18.0</td>
<td>16.7</td>
<td>15.9</td>
<td>15.2</td>
<td>15.0</td>
<td>14.9</td>
</tr>
<tr>
<td>Avg. Non-CV (s)</td>
<td>26.0</td>
<td>22.6</td>
<td>18.7</td>
<td>16.6</td>
<td>15.8</td>
<td>15.8</td>
<td>N/A</td>
</tr>
<tr>
<td>Avg. All Vehicles (s)</td>
<td>26.0</td>
<td>20.3</td>
<td>17.7</td>
<td>16.3</td>
<td>15.5</td>
<td>15.4</td>
<td>14.9</td>
</tr>
</tbody>
</table>

**Table 5.3:** Travel times at varying connected vehicle market penetration levels for the second step calibrated micro-simulation model after implementing the CTT algorithm

<table>
<thead>
<tr>
<th>Vehicle Type</th>
<th>No CTT</th>
<th>10% CTT</th>
<th>30% CTT</th>
<th>50% CTT</th>
<th>70% CTT</th>
<th>90% CTT</th>
<th>100% CTT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Avg. CV (s)</td>
<td>N/A</td>
<td>18.6</td>
<td>17.4</td>
<td>16.7</td>
<td>15.7</td>
<td>15.2</td>
<td>15.3</td>
</tr>
<tr>
<td>Avg. Non-CV (s)</td>
<td>25.8</td>
<td>22.8</td>
<td>19.3</td>
<td>18.0</td>
<td>16.7</td>
<td>16.2</td>
<td>N/A</td>
</tr>
<tr>
<td>Avg. All Vehicles (s)</td>
<td>25.8</td>
<td>20.7</td>
<td>18.3</td>
<td>17.4</td>
<td>16.2</td>
<td>15.7</td>
<td>15.3</td>
</tr>
</tbody>
</table>

**Table 5.4:** Travel time improvements at varying connected vehicle market penetration levels for the first step calibrated micro-simulation model compared with the no-CTT micro-simulation after implementing the CTT algorithm

<table>
<thead>
<tr>
<th>Vehicle Type</th>
<th>10% CTT</th>
<th>30% CTT</th>
<th>50% CTT</th>
<th>70% CTT</th>
<th>90% CTT</th>
<th>100% CTT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Avg. CV</td>
<td>-31%</td>
<td>-36%</td>
<td>-39%</td>
<td>-41%</td>
<td>-42%</td>
<td>-43%</td>
</tr>
<tr>
<td>Avg. Non-CV</td>
<td>-13%</td>
<td>-28%</td>
<td>-36%</td>
<td>-39%</td>
<td>-39%</td>
<td>N/A</td>
</tr>
<tr>
<td>Avg. All Vehicles</td>
<td>-22%</td>
<td>-32%</td>
<td>-37%</td>
<td>-40%</td>
<td>-41%</td>
<td>-43%</td>
</tr>
</tbody>
</table>
Figure 5.3: Travel time improvements at varying connected vehicle market penetration levels for the first step calibrated micro-simulation model compared with the no-CTT micro-simulation after implementing the CTT algorithm.

Figure 5.4: Travel time improvements at varying connected vehicle market penetration levels for the second step calibrated micro-simulation model compared with the no-CTT micro-simulation after implementing the CTT algorithm.
Table 5.5: Travel time improvements at varying connected vehicle market penetration levels for the second step calibrated micro-simulation model compared with the no-CTT micro-simulation after implementing the CTT algorithm

<table>
<thead>
<tr>
<th>Vehicle Type</th>
<th>10% CTT</th>
<th>30% CTT</th>
<th>50% CTT</th>
<th>70% CTT</th>
<th>90% CTT</th>
<th>100% CTT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Avg. CV</td>
<td>-28%</td>
<td>-33%</td>
<td>-35%</td>
<td>-39%</td>
<td>-41%</td>
<td>-41%</td>
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<tr>
<td>Avg. Non-CV</td>
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<td>-25%</td>
<td>-30%</td>
<td>-35%</td>
<td>-37%</td>
<td>N/A</td>
</tr>
<tr>
<td>Avg. All Vehicles</td>
<td>-20%</td>
<td>-29%</td>
<td>-33%</td>
<td>-37%</td>
<td>-39%</td>
<td>-41%</td>
</tr>
</tbody>
</table>

Table 5.6: Time-to-Collision Conflicts at varying connected vehicle market penetration levels for the first step calibrated micro-simulation model after implementing the CTT algorithm

<table>
<thead>
<tr>
<th>TTC Threshold</th>
<th>No CTT</th>
<th>10% CTT</th>
<th>30% CTT</th>
<th>50% CTT</th>
<th>70% CTT</th>
<th>90% CTT</th>
<th>100% CTT</th>
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<td>8</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>1</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>≤ 0.6</td>
<td>11</td>
<td>4</td>
<td>5</td>
<td>4</td>
<td>3</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>≤ 0.7</td>
<td>14</td>
<td>5</td>
<td>7</td>
<td>5</td>
<td>5</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>≤ 0.8</td>
<td>17</td>
<td>9</td>
<td>8</td>
<td>6</td>
<td>6</td>
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<td>6</td>
</tr>
<tr>
<td>≤ 0.9</td>
<td>20</td>
<td>10</td>
<td>10</td>
<td>7</td>
<td>8</td>
<td>6</td>
<td>8</td>
</tr>
<tr>
<td>≤ 1.0</td>
<td>29</td>
<td>13</td>
<td>13</td>
<td>9</td>
<td>11</td>
<td>8</td>
<td>10</td>
</tr>
<tr>
<td>≤ 1.1</td>
<td>38</td>
<td>19</td>
<td>18</td>
<td>12</td>
<td>13</td>
<td>10</td>
<td>14</td>
</tr>
<tr>
<td>≤ 1.2</td>
<td>48</td>
<td>26</td>
<td>26</td>
<td>18</td>
<td>19</td>
<td>16</td>
<td>19</td>
</tr>
<tr>
<td>≤ 1.3</td>
<td>59</td>
<td>34</td>
<td>34</td>
<td>27</td>
<td>27</td>
<td>22</td>
<td>25</td>
</tr>
<tr>
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<td>42</td>
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<td>35</td>
<td>31</td>
<td>34</td>
</tr>
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<td>41</td>
</tr>
<tr>
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<td>59</td>
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<td>52</td>
<td>55</td>
</tr>
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<td>90</td>
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<td>149</td>
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<td>138</td>
<td>126</td>
<td>117</td>
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<tr>
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<td>181</td>
<td>172</td>
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<td>164</td>
<td>149</td>
<td>138</td>
</tr>
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<td>185</td>
<td>172</td>
<td>155</td>
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<td>230</td>
<td>221</td>
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<td>205</td>
<td>188</td>
<td>174</td>
</tr>
<tr>
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<td>244</td>
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<td>224</td>
<td>207</td>
<td>192</td>
</tr>
<tr>
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<td>283</td>
<td>269</td>
<td>247</td>
<td>244</td>
<td>229</td>
<td>211</td>
</tr>
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<td>278</td>
<td>259</td>
<td>241</td>
</tr>
<tr>
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<td>335</td>
<td>309</td>
<td>305</td>
<td>284</td>
<td>266</td>
</tr>
<tr>
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<td>542</td>
<td>396</td>
<td>376</td>
<td>346</td>
<td>336</td>
<td>323</td>
<td>299</td>
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<tr>
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<td>424</td>
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<td>380</td>
<td>362</td>
<td>341</td>
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<tr>
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<td>432</td>
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<td>496</td>
<td>469</td>
<td>436</td>
</tr>
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</table>
Table 5.7: Time-to-Collision Conflicts at varying connected vehicle market penetration levels for the second step calibrated micro-simulation model after implementing the CTT algorithm

<table>
<thead>
<tr>
<th>TTC Threshold</th>
<th>No CTT</th>
<th>10% CTT</th>
<th>30% CTT</th>
<th>50% CTT</th>
<th>70% CTT</th>
<th>90% CTT</th>
<th>100% CTT</th>
</tr>
</thead>
<tbody>
<tr>
<td>≤ 0.5</td>
<td>5</td>
<td>2</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
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<td>3</td>
<td>4</td>
<td>3</td>
<td>2</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
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<td>8</td>
<td>7</td>
<td>5</td>
<td>6</td>
</tr>
<tr>
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<td>22</td>
<td>14</td>
<td>11</td>
<td>10</td>
<td>9</td>
<td>6</td>
<td>7</td>
</tr>
<tr>
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<td>14</td>
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<td>10</td>
<td>8</td>
<td>10</td>
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<td>12</td>
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<td>75</td>
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<tr>
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<td>218</td>
<td>155</td>
<td>135</td>
<td>121</td>
<td>100</td>
<td>92</td>
<td>92</td>
</tr>
<tr>
<td>≤ 2.3</td>
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<td>146</td>
<td>124</td>
<td>112</td>
<td>113</td>
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<td>197</td>
<td>186</td>
<td>151</td>
<td>137</td>
<td>139</td>
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<tr>
<td>≤ 2.5</td>
<td>395</td>
<td>288</td>
<td>247</td>
<td>231</td>
<td>187</td>
<td>175</td>
<td>172</td>
</tr>
<tr>
<td>≤ 2.6</td>
<td>481</td>
<td>344</td>
<td>289</td>
<td>269</td>
<td>222</td>
<td>207</td>
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<td>322</td>
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<td>243</td>
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<td>403</td>
<td>384</td>
<td>319</td>
<td>291</td>
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<td>520</td>
<td>485</td>
<td>408</td>
<td>379</td>
<td>390</td>
</tr>
</tbody>
</table>

Table 5.8: Time-to-Collision Conflicts at varying connected vehicle market penetration levels for the first step calibrated micro-simulation model compared with the no-CTT micro-simulation after implementing the CTT algorithm

<table>
<thead>
<tr>
<th>TTC Threshold</th>
<th>10% CTT</th>
<th>30% CTT</th>
<th>50% CTT</th>
<th>70% CTT</th>
<th>90% CTT</th>
<th>100% CTT</th>
</tr>
</thead>
<tbody>
<tr>
<td>≤ 0.5</td>
<td>-56%</td>
<td>-88%</td>
<td>-50%</td>
<td>-71%</td>
<td>-88%</td>
<td>-88%</td>
</tr>
<tr>
<td>≤ 1.0</td>
<td>-57%</td>
<td>-68%</td>
<td>-61%</td>
<td>-69%</td>
<td>-67%</td>
<td>-73%</td>
</tr>
<tr>
<td>≤ 1.5</td>
<td>-50%</td>
<td>-46%</td>
<td>-44%</td>
<td>-56%</td>
<td>-49%</td>
<td>-60%</td>
</tr>
<tr>
<td>≤ 2.0</td>
<td>-40%</td>
<td>-30%</td>
<td>-33%</td>
<td>-38%</td>
<td>-38%</td>
<td>-44%</td>
</tr>
<tr>
<td>≤ 2.5</td>
<td>-41%</td>
<td>-29%</td>
<td>-37%</td>
<td>-41%</td>
<td>-40%</td>
<td>-46%</td>
</tr>
<tr>
<td>≤ 3.0</td>
<td>-40%</td>
<td>-28%</td>
<td>-37%</td>
<td>-41%</td>
<td>-41%</td>
<td>-46%</td>
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</tbody>
</table>
**Figure 5.5:** Rear-end Conflicts for the first step calibrated micro-simulation model at varying connected vehicle penetration levels

**Figure 5.6:** Rear-end Conflicts for the second step calibrated micro-simulation model at varying connected vehicle penetration levels
Figure 5.7: Rear-end conflicts improvements for the first step calibrated micro-simulation model at varying connected vehicle penetration levels compared with no-CTT algorithm applied.

Figure 5.8: Rear-end conflicts improvements for the second step calibrated micro-simulation model at varying connected vehicle penetration levels compared with no-CTT algorithm applied.
Table 5.9: Time-to-Collision Conflicts at varying connected vehicle market penetration levels for the second step calibrated micro-simulation model compared with the no-CTT micro-simulation after implementing the CTT algorithm

<table>
<thead>
<tr>
<th>TTC Threshold</th>
<th>10% CTT</th>
<th>30% CTT</th>
<th>50% CTT</th>
<th>70% CTT</th>
<th>90% CTT</th>
<th>100% CTT</th>
</tr>
</thead>
<tbody>
<tr>
<td>≤ 0.5</td>
<td>-60%</td>
<td>-20%</td>
<td>-80%</td>
<td>-40%</td>
<td>-40%</td>
<td>-40%</td>
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<tr>
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<td>-43%</td>
<td>-45%</td>
<td>-78%</td>
<td>-59%</td>
<td>-59%</td>
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</tr>
<tr>
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<td>-49%</td>
<td>-53%</td>
<td>-70%</td>
<td>-63%</td>
<td>-65%</td>
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<td>-53%</td>
<td>-53%</td>
<td>-57%</td>
<td>-58%</td>
</tr>
<tr>
<td>≤ 3.0</td>
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<td>-40%</td>
<td>-50%</td>
<td>-52%</td>
<td>-57%</td>
<td>-58%</td>
</tr>
</tbody>
</table>

5.1.5 CTT Comparison with Lower Intersection Volume

The evaluation for the CTT algorithm has been conducted thus far at a total hourly intersection volume of approximately 3,000 vehicles per hour. A supplementary review was conducted to investigate how the algorithm performs under lower intersection volumes. The intersection volume used for this review was approximately 2,400 vehicles per hour. The results are presented in Tables 5.10, 5.5, 5.12 and 5.13 and Figures 5.9, 5.10 and 5.11.

Table 5.10: Travel times at varying connected vehicle market penetration levels for the second step calibrated micro-simulation model after implementing the CTT algorithm at a lower intersection volume

<table>
<thead>
<tr>
<th>Vehicle Type</th>
<th>No CTT</th>
<th>10% CTT</th>
<th>30% CTT</th>
<th>50% CTT</th>
<th>70% CTT</th>
<th>90% CTT</th>
<th>100% CTT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Avg. CV (s)</td>
<td>N/A</td>
<td>16.3</td>
<td>17.2</td>
<td>16.4</td>
<td>15.9</td>
<td>15.4</td>
<td>15.2</td>
</tr>
<tr>
<td>Avg. Non-CV (s)</td>
<td>24.8</td>
<td>23.4</td>
<td>19.8</td>
<td>18.8</td>
<td>17.5</td>
<td>16.9</td>
<td>N/A</td>
</tr>
<tr>
<td>Avg. All Vehicles (s)</td>
<td>24.8</td>
<td>19.8</td>
<td>18.5</td>
<td>17.6</td>
<td>16.7</td>
<td>16.2</td>
<td>15.2</td>
</tr>
</tbody>
</table>

Table 5.11: Travel time improvements at varying connected vehicle market penetration levels for the second step calibrated micro-simulation model compared with the no-CTT micro-simulation after implementing the CTT algorithm at lower intersection volume

<table>
<thead>
<tr>
<th>Vehicle Type</th>
<th>10% CTT</th>
<th>30% CTT</th>
<th>50% CTT</th>
<th>70% CTT</th>
<th>90% CTT</th>
<th>100% CTT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Avg. CV</td>
<td>-34%</td>
<td>-31%</td>
<td>-34%</td>
<td>-36%</td>
<td>-38%</td>
<td>-39%</td>
</tr>
<tr>
<td>Avg. Non-CV</td>
<td>-6%</td>
<td>-20%</td>
<td>-24%</td>
<td>-30%</td>
<td>-32%</td>
<td>N/A</td>
</tr>
<tr>
<td>Avg. All Vehicles</td>
<td>-20%</td>
<td>-25%</td>
<td>-29%</td>
<td>-33%</td>
<td>-35%</td>
<td>-39%</td>
</tr>
</tbody>
</table>
**Figure 5.9:** Travel time improvements at varying connected vehicle market penetration levels for the second step calibrated micro-simulation model compared with the no-CTT micro-simulation after implementing the CTT algorithm at lower intersection volume.

**Figure 5.10:** Rear-end Conflicts for the second step calibrated micro-simulation model at varying connected vehicle penetration levels at a lower intersection volume.
**Table 5.12:** Time-to-Collision Conflicts at varying connected vehicle market penetration levels for the second step calibrated micro-simulation model after implementing the CTT algorithm at a lower intersection volume

<table>
<thead>
<tr>
<th>TTC Threshold</th>
<th>0% CTT</th>
<th>10% CTT</th>
<th>30% CTT</th>
<th>50% CTT</th>
<th>70% CTT</th>
<th>90% CTT</th>
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<td>4</td>
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<td>7</td>
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</table>

**Table 5.13:** Time-to-Collision Conflicts at varying connected vehicle market penetration levels for the second step calibrated micro-simulation model compared with the no-CTT micro-simulation after implementing the CTT algorithm at a lower intersection volume

<table>
<thead>
<tr>
<th>TTC Threshold</th>
<th>10% CTT</th>
<th>30% CTT</th>
<th>50% CTT</th>
<th>70% CTT</th>
<th>90% CTT</th>
<th>100% CTT</th>
</tr>
</thead>
<tbody>
<tr>
<td>≤ 0.5</td>
<td>-50%</td>
<td>0%</td>
<td>-50%</td>
<td>-33%</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td>≤ 1.0</td>
<td>-53%</td>
<td>-43%</td>
<td>-63%</td>
<td>-73%</td>
<td>-43%</td>
<td>-67%</td>
</tr>
<tr>
<td>≤ 1.5</td>
<td>-36%</td>
<td>-33%</td>
<td>-51%</td>
<td>-56%</td>
<td>-41%</td>
<td>-54%</td>
</tr>
<tr>
<td>≤ 2.0</td>
<td>-35%</td>
<td>-29%</td>
<td>-40%</td>
<td>-40%</td>
<td>-38%</td>
<td>-42%</td>
</tr>
<tr>
<td>≤ 2.5</td>
<td>-36%</td>
<td>-30%</td>
<td>-33%</td>
<td>-39%</td>
<td>-39%</td>
<td>-40%</td>
</tr>
<tr>
<td>≤ 3.0</td>
<td>-38%</td>
<td>-35%</td>
<td>-35%</td>
<td>-41%</td>
<td>-43%</td>
<td>-44%</td>
</tr>
</tbody>
</table>
5.1.6 Evaluation of Results

The following sections describe the changes to mobility with respect to travel times and to surrogate safety measures through the traffic conflict technique for the first step and second step calibrated micro-simulation models at varying connected vehicle market penetrations.

5.1.6.1 Mobility Evaluation

In all connected vehicle penetration levels the travel times for both connected vehicles and non-connected vehicles improve. For the first step calibrated micro-simulation model, at a 10% connected vehicle market penetration the connected vehicles show a 31% reduction in travel times while the non-connected vehicles show a 13% reduction in travel times. The improvements for connected vehicles grow to 39% reduction at the 50% connected vehicle market penetration level and then grow slowly to 43% reduction in travel time at the 100% connected vehicle market penetration level. The non-connected vehicle travel time improvements have a significant improvement
between 10% connected vehicle market penetration and 30% connected vehicle market penetration levels, from 13% reduction in travel times to 28% reduction in travel times. The improvements again grow to 36% reduction in travel times at the 50% connected vehicle market penetration level, but slow to 39% reduction for 70% and 90% connected vehicle market penetration levels.

Reviewing the travel time improvements after the second step calibration is performed, there is again an improvement for both connected and non-connected vehicles at all connected vehicle market penetration levels evaluated when compared with the non-connected vehicle environment. The improvements follow a similar trend to what was seen for the first-step calibrated micro-simulation as well as what was seen in the uncalibrated micro-simulation.

At a lower total intersection volume, the results differ from the higher intersection volume for lower connected vehicle market penetration levels; however, the travel time improvements follows a similar trend at higher connected vehicle market penetration levels.

While at lower connected vehicle penetration rates there are imperfect conditions for detection, the results demonstrate that even in these conditions (specifically 10% and 30%) there are still significant travel time improvements through the intersection for both connected and non-connected vehicles.

While the results vary slightly in comparisons with the non-connected environment for both the first step and second step calibration micro-simulations, the absolute travel times for the varying connected vehicle market penetration rates are relatively unchanged throughout the different levels of calibration, indicating that calibration does not have a large impact on travel times. Total intersection volume has a more significant impact on travel times at lower connected vehicle market penetration levels with respect to variability in savings, but at higher market penetration levels the results are relatively consistent regardless of the intersection volumes evaluated. The larger impact with respect to travel time improvements occurs due to the CTT algorithm itself in conjunction with higher connected vehicle market penetration levels.
Reviewing the results presented by Lee et al. (2013a), a comparison of travel time improvements with exposure shows that as the hourly intersection volume increases the improvements to travel times when applying the CTT algorithm increase as well. Comparing the results of this study with a travel time improvement of approximately 43% and 41% for a 5s time-step and 100% connected vehicle market penetration and at the first step and second step calibrated micro-simulation models, it shows that the algorithm used in conjunction with the calibrated micro-simulation models perform better by 7-9% with the currently applied algorithm showing a greater improvement in travel times. Similar to the uncalibrated micro-simulation model evaluations, at varying connected vehicle market penetration levels, travel time improvements presented in this study show less variability and overall higher improvement than the results seen in Lee et al. (2013a). Evaluating the lower total intersection volume shows similar results to Lee et al. (2013a) in that the travel time improvements are less pronounced at lower intersection volumes. Within this study the travel time improvements at a lower intersection volume remain more stable than those seen in Lee et al. (2013a).

5.1.6.2 Traffic Conflicts Evaluation

In all the connected vehicle environments evaluated, significant improvements to the number of conflicts observed were seen at all connected vehicle penetration levels, for both the first step and second step calibrated micro-simulation models.

The TTC conflicts were analyzed at varying thresholds (e.g., $\leq 0.5s$ up to $\leq 3.0s$) to evaluate the differences in output from each micro-simulation. When the first step calibration was applied the improvements in TTC conflicts remain relatively stable for each connected vehicle market penetration at the TTC threshold of $\leq 2.0s$ and above, ranging between 28% and 46% improvement with higher improvements seen with the higher connected vehicle market penetration levels. At lower TTC thresholds, the improvements are greater, ranging between 44% and 88%, but have significantly higher variation within individual connected vehicle market penetration levels.
With the second step calibration applied, results are similar to what was seen after the first step calibration but with more improvement over the no-connected vehicle scenario, improvements ranging between 39% and 63%. At lower TTC thresholds the improvements have a very large range, between 20% and 80% improvement. Within the individual connected vehicle market penetration levels, there are at times significant ranges of improvements, such as at the 30% connected vehicle level where the range is between 20% improvement at a TTC threshold of \( \leq 0.5 \text{s} \) and 53% improvement at a TTC threshold of \( \leq 1.5 \text{s} \). At higher connected vehicle market penetration levels, greater than 70%, the improvements over the non-connected vehicle environment are more consistent with each other, indicating that, with respect to TTC rear-end conflicts, at higher connected vehicle market penetration levels (70% and above) the intersection will behave in a relatively stable manner whereas there is more volatility at lower connected vehicle market penetration levels.

At the lower intersection volume, traffic conflict improvements follow a similar trend to at the higher intersection volume with a TTC threshold of \( \leq 2.0 \text{s} \) remaining relatively consistent with higher TTC thresholds within each connected vehicle market penetration level, ranging between 29% and 44% improvement. At lower TTC thresholds (\( \leq 1.5 \text{s} \) and less) the variation is greater, ranging between 0% improvement and 73%. This is due to there being significantly less traffic conflicts at the lower TTC thresholds (\( \leq 1.5 \text{s} \) and below) compared with higher TTC thresholds.

Essa and Sayed (2015a) performed a calibration against field measured conflicts and determined that after the first step calibration there was already a significant improvement to appropriately simulating conflicts due to calibrating the arrival rate and patterns limiting the exposure to vehicle interactions similar to what are seen in the field. When comparing the results of the second step calibrated simulations against the first step calibrated simulations, the observations are consistent with the trends seen in Essa and Sayed (2015a) although the magnitude of improvements have higher variation.

Overall the results of the traffic conflicts evaluation demonstrate that calibration, through modification of VISSIM parameters, has a significant impact on the simulated rear-end conflicts.
Chapter 6

Summary, Conclusion and Future Research

This chapter contains three parts. Firstly, an overall review of the thesis is provided including a summary of the results from Chapters 4 and 5. Following the summary, a conclusion is presented. Finally, future research is recommended.

6.1 Summary

This thesis investigates the ability of using the VISSIM micro-simulation model to evaluate the safety of connected vehicle applications in conjunction with the SSAM software package and conflict analysis through a combination of VISSIM and SSAM, as well as to investigate if calibration of the micro-simulation model provides a better representation of the real world than not calibrating the micro-simulation model. Two connected vehicle applications were chosen for the investigation, one involving a cooperative adaptive cruise control (CACC) connected vehicle application to support vehicle platooning through V2V communications, the other involving a cumulative travel time (CTT) intersection control connected vehicle application to support more efficient travel through an intersection using V2I communications. An overall review of the methodology of implementing a micro-simulation model of a connected vehicle application was presented with two examples.
provided for the two micro-simulation models used in this thesis.

Case studies were performed for the individual connected vehicle applications. For the CACC micro-simulation model, the ability to evaluate the safety of a CACC connected vehicle environment on a freeway using VISSIM micro-simulation and the Surrogate Safety Assessment Model (SSAM) was investigated. Micro-simulations through VISSIM were performed at varying CACC penetration levels. This study demonstrates that SSAM in combination with VISSIM is an appropriate tool to evaluate the level of safety of a connected vehicle application for cooperative adaptive cruise control on a freeway segment. Through sensitivity analysis it was demonstrated that the simulated conflicts results vary, sometimes significantly depending on calibration parameter values as well as acceleration coefficient values from within the CACC algorithm.

For the CTT micro-simulation model, the ability to evaluate safety after applying a CTT algorithm to a signalized intersection through the use of connected vehicle technology was investigated. After initial investigation, the micro-simulation model was evaluated through a two-step calibration process, first for vehicle arrival rates and second for observed traffic conflicts. Micro-simulations through VISSIM were performed at three levels: Uncalibrated, first step calibrated, and second step calibrated. The different stages of calibration show significant variation in the number of conflicts observed, as well as throughout the changes in connected vehicle penetration levels. It was found that calibrating the micro-simulation model to real-world non-Connected Vehicle conditions had a significant impact on the modeled safety improvements when the connected vehicle environment is applied, however it is inconclusive whether the results are realistic or not as the CTT application is not in practice in the field to compare to.

6.2 Conclusion

The VISSIM micro-simulation model in conjunction with the SSAM software package is useful for evaluating simulated traffic conflicts for traffic facilities.
Both micro-simulation models of the connected vehicle applications reviewed demonstrates the potential to evaluate the changes in safety on a transportation network with the connected vehicle applications in place through the use of surrogate safety measures. The two applications involved different communication types, 1) V2V communication for the CACC connected vehicle application, and 2) V2I communication for the CTT connected vehicle application.

A general procedure has been outlined to describe the process required for simulating a connected vehicle application with the VISSIM micro-simulation model. Specific examples are provided for both applications, focusing on the separate connected vehicle communication types.

Results from the specific connected vehicle application simulations demonstrate that, through evaluation with the combination of the VISSIM micro-simulation model and the SSAM software package, implementing connected vehicle applications result in promising observable changes to simulated traffic conflicts indicating that implementing the connected vehicle applications will result in a change to the level of safety on a roadway.

Throughout the implementation of the connected vehicle applications into a VISSIM micro-simulation model, it was found that the VISSIM micro-simulation model would benefit from updated modules enabling better modelling of connected vehicle applications.

### 6.2.1 CACC Conclusion

The cooperative adaptive cruise control (CACC) application demonstrated that V2V communications and the control of vehicles results in a significant reduction in the number of simulated conflicts, with varying results depending on the market penetration of connected vehicles with the CACC technology on the roadway. The range of improvements with respect to mobility, through travel time measurements, is between 10% (at lower CACC penetration levels) and 50% (at the 90% CACC penetration level) when evaluated through an incident causing delays on the roadway.
While the results of the CACC connected vehicle application are promising, the VISSIM driver behaviour parameters show to have a moderate affect to the travel times, ranging from a decrease of 20% for a more aggressive headway, to an increase of 34% at less aggressive headways, when compared with the default VISSIM headway driver behaviour parameter. With respect to conflict analysis, significant variations are found when the headway parameter is changed, generally improving at higher headway values (i.e., 1.1s and above) and disimproving at lower headway values (i.e., 0.7s). This implies that calibration of the micro-simulation model to real-world conditions will be necessary to be able to have a realistic understanding of the benefits of implementing the CACC connected vehicle application.

Ultimately without a real-world implementation of the CACC application it is unknown if the results of the micro-simulation model are accurate or not.

### 6.2.2 CTT Conclusion

The cumulative travel time intersection control connected vehicle application (CTT) demonstrated that V2I communications and the integration with the control of a signalized intersection results in general in a reduction of the number of simulated conflicts, with varying results depending on the market penetration of the connected vehicles on the roadway and the level of calibration of the micro-simulation model.

The micro-simulation was run for three calibration scenarios: 1) no calibration (default VISSIM parameters), 2) first step calibrated for arrival rates (through the use of dummy signals), and 3) second step calibrated for SSAM conflicts (through the modification of driver behaviour parameters). The simulated travel times were found not to vary significantly throughout the different levels of calibration. The simulated rear-end conflicts had significant variation based on the level of calibration at varying connected vehicle market penetration levels. For the uncalibrated simulation, there was a significant increase, at times of 100%, to the number of simulated rear-end conflicts.
when the CTT algorithm was implemented compared with the no-CTT scenario. The first and second step calibrations demonstrate an improvement to the number of simulated rear-end conflicts at all connected vehicle market penetration levels, with higher market penetration levels showing in general more of an improvement to the number of simulated conflicts than the lower market penetration levels.

Evaluating the simulation at a lower total intersection volume (approximately 2,400 vehicles per hour), after the second step calibration was applied, demonstrates similar results to the higher total intersection volume (approximately 3,000 vehicles per hour), with the difference being an overall less number of total conflicts at all connected vehicle market penetration levels and a resulting lower level of improvement.

In general the CTT algorithm in conjunction with a connected vehicle environment results in an improvement to simulated travel times and conflicts and the improvements to the simulated traffic conflicts is greater at higher total intersection volumes. The use of video analysis to analyze real-world conflicts through computer vision enables for a better representation to the real-world conditions for calibrating the micro-simulation model and have a direct impact to the simulated conflicts within the micro-simulation model.

While the results of the calibrated micro-simulation model are promising after implementing the CTT connected vehicle environment, without a real-world implementation of the CTT algorithm in conjunction with the connected vehicle environment it is unknown if the results of the micro-simulation are realistic.
6.3 Future Research

6.3.1 CACC Future Research

Within this study the evaluation focused only on one type of conflict (rear-end) with one safety measure indicator used (TTC). It would be beneficial to review other safety measures in conjunction with the TTC, such as the maximum and relative speeds of the vehicles involved in order to understand severity of the conflicts.

Future work with the CACC algorithm should be compared with real-world results of actual deployments similar to the experimental evaluation performed by Ploeg et al. (2011) in order to better calibrate the micro-simulation for large scale deployment of the connected vehicle application.

6.3.2 CTT Future Research

Within this study, the evaluation focused only on one type of conflict (rear-end) with one safety measure indicator used (TTC). It would be beneficial to review other safety measure indicators to understand the severity of the conflicts, such as the maximum and relative speeds of the two vehicles involved in the conflict (MaxS and DeltaS measures respectively).

Specific to the connected vehicle application, more work is required to further the advancement of this research by applying the Kalman filtering technique as was done in Lee et al. (2013a) and comparing the level of safety through SSAM at varying connected vehicle penetration levels with the Kalman filter applied compared with the current methodology not accounting for non-connected vehicles. Additionally, evaluating at multiple intersection volumes will provide a better indication as to what impacts the volumes have on the level of safety of the CTT algorithm.

This specific CTT algorithm was applied to only a single intersection. It would be useful to transfer the algorithm to another intersection, similar to work done by Essa and Sayed (2015b) to investi-
gate the performance at different locations with different traffic patterns.

The update interval was kept at a relatively short time frame for the evaluation of the CTT algorithm (5s). It would be useful to evaluate this at longer update intervals (e.g., 10s or 15s) to see at what point do the safety benefits decrease.

Finally, the distance of detection should be reviewed and analyzed to determine an optimal distance from the intersection. In this study we used 140m; however it may be found that shortening or extending this distance could improve the safety of the CTT application.


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Appendix A

Cumulative Travel Time Intersection

Control Background Code

A.1 MATLAB Code for Micro-Simulation

The following is the applicable MATLAB code used for running the simulation and measuring the cumulative travel time of each approach to the intersection as well as calling the function to evaluate the phase with the highest cumulative travel time and control the intersection as required.

```matlab
% Access during simulation
%=======================================================================

% Defines the time interval for checking cumulative travel time (Lee 2013
% looks at 5 seconds)
% time_int = 5;

%C Create a matrix to keep track of all vehicle cumulative travel times.
CVehicle_Matrix = zeros(8000, 1);
NCVehicle_Matrix = zeros(8000, 1);

%C Create a matrix to keep track of all vehicles in each approach, and
% connected vehicles in each approach
CVehicle_Appr_Matrix = zeros(8, 1);
NCVehicle_Appr_Matrix = zeros(8, 1);

% Set Signal Controller
SC_number = 1;
```
for Vehicle_Comp = 1:6
    set(Vissim.Net.VehicleInputs.ItemByKey(1), 'AttValue', 'VehComp(1)', Vehicle_Comp_Arry3(Vehicle_Comp));
    set(Vissim.Net.VehicleInputs.ItemByKey(2), 'AttValue', 'VehComp(1)', Vehicle_Comp_Arry1(Vehicle_Comp));
    set(Vissim.Net.VehicleInputs.ItemByKey(3), 'AttValue', 'VehComp(1)', Vehicle_Comp_Arry1(Vehicle_Comp));
    set(Vissim.Net.VehicleInputs.ItemByKey(4), 'AttValue', 'VehComp(1)', Vehicle_Comp_Arry1(Vehicle_Comp));
end

for Vehicle_Comp = 1:6
    for i = 1:6
        set(Vissim.Net.VehicleInputs.ItemByKey(1), 'AttValue', 'VehComp(1)', Vehicle_Comp_Arry3(Vehicle_Comp));
        set(Vissim.Net.VehicleInputs.ItemByKey(2), 'AttValue', 'VehComp(1)', Vehicle_Comp_Arry1(Vehicle_Comp));
        set(Vissim.Net.VehicleInputs.ItemByKey(3), 'AttValue', 'VehComp(1)', Vehicle_Comp_Arry1(Vehicle_Comp));
        set(Vissim.Net.VehicleInputs.ItemByKey(4), 'AttValue', 'VehComp(1)', Vehicle_Comp_Arry1(Vehicle_Comp));
    end
end

for Random_Seed = 1:5
    Random_Seed_Array = [1 2 4 1 6 1 8 1];
    set(Vissim.Simulation, 'AttValue', 'RandSeed', Random_Seed_Array(Random_Seed));
end
CVehicle_Matrix(veh_number) = CVehicle_Matrix(veh_number) + time_int;

CTT_Array(str2num(vgl_lane(1))) = CTT_Array(str2num(vgl_lane(1))) +
   CVehicle_Matrix(veh_number);

end
end
end

CTT_Array_Old = CTT_Array;
signalphase = Evaluate_CTT_Signal_Timing(CTT_Array, signalphasel); signalphasel = signalphase;

Yellow_Time = 4;
Red_Clearance = 2;
switch signalphase
% Set the Signal Group according to the phase with highest cumulative travel time based on
   signalphase function.
case 1
   Signal_Group = [3 1 6 5 4 2 9 10];
case 2
   Signal_Group = [6 5 3 1 4 2 9 10];
case 3
   Signal_Group = [4 2 3 1 6 5 9 10];
case 4
   Signal_Group = [9 10 3 1 6 5 4 2];
end
for sg=1:8
   SignalGroup(sg) = SignalController.SGs.ItemByKey(Signal_Group(sg));
end
Current_State = {get(SignalGroup(1), 'AttValue', 'State'), ...
   get(SignalGroup(2), 'AttValue', 'State'), ...
   get(SignalGroup(3), 'AttValue', 'State'), ...
   get(SignalGroup(4), 'AttValue', 'State'), ...
   get(SignalGroup(5), 'AttValue', 'State'), ...
   get(SignalGroup(6), 'AttValue', 'State'), ...
   get(SignalGroup(7), 'AttValue', 'State'), ...
   get(SignalGroup(8), 'AttValue', 'State')};

% % Set the state of a signal controller:
Phase = [3 3 1 1 1 1 1 1];

% Find the index of Current_State where the signal is green
if any(ismember(Current_State, 'GREEN')) == 0
   index = find(ismember(Current_State, 'GREEN'));
end
% Set the signal timing, checking first the green phase
if index(1) == 1 % DO NOTHING – Signal is already as it should be.
else
% This will be changed to yellow for the yellow_time, then red,
% the all_red time will pass, then the phase desired will be
% set to green using the following for loop.
Phase=ones(8,1);
Phase(index) = 4;
Sim_break_at = (timestep)+1;
timestep=timestep+1;
CurrentPhase = get(SignalGroup(index(1)), 'AttValue', 'State');
set(Vissim.Simulation, 'AttValue', 'SimBreakAt', Sim_break_at);
Vissim.Simulation.RunContinuous;
set(SignalGroup(index(1)), 'AttValue', 'State', Phase(index(1)));
set(SignalGroup(index(2)), 'AttValue', 'State', Phase(index(2)));
Phase=ones(8,1);
Sim_break_at = (timestep)+4;
timestep=timestep+4;
CurrentPhase = get(SignalGroup(index(1)), 'AttValue', 'State');
end
A.2 MATLAB Code for Cumulative Travel Time Calculation

The following is MATLAB code to evaluate the cumulative travel times of each of the approach combinations for the four signal phases and output the phase with the highest cumulative travel time.

```matlab
function [signalphase] = Evaluate_CTT_Signal_Timing( x, y )

sp1 = x(1) + x(2);
sp2 = x(3) + x(4);
sp3 = x(5) + x(7);
sp4 = x(6) + x(8);
signalphasearray=[sp1 sp2 sp3 sp4];

[signalphasesum, Index] = max(signalphasearray);

if Index == y
    signalphase = Index;
    return
end

if Index == 1
    Non_Index_Array = [2 3 4];
end
if Index == 2
    Non_Index_Array = [1 3 4];
end
```

A.2 MATLAB Code for Cumulative Travel Time Calculation

The following is MATLAB code to evaluate the cumulative travel times of each of the approach combinations for the four signal phases and output the phase with the highest cumulative travel time.

```matlab
function [signalphase] = Evaluate_CTT_Signal_Timing( x, y )

sp1 = x(1) + x(2);
sp2 = x(3) + x(4);
sp3 = x(5) + x(7);
sp4 = x(6) + x(8);
signalphasearray=[sp1 sp2 sp3 sp4];

[signalphasesum, Index] = max(signalphasearray);

if Index == y
    signalphase = Index;
    return
end

if Index == 1
    Non_Index_Array = [2 3 4];
end
if Index == 2
    Non_Index_Array = [1 3 4];
end
```
if Index == 3
    Non_Index_Array = [1 2 4];
end
if Index == 4
    Non_Index_Array = [1 2 3];
end
Index_Array = [Index 0 0 0];
Duplication = 0;
for i = 1:3
    if signalphasearray(Index) == signalphasearray(Non_Index_Array(i))
        Duplication = Duplication + 1;
        Index_Array(i+1) = Non_Index_Array(i);
    end
end
if Duplication == 0
    signalphase = Index;
    return
else
    Final_Index_Array = zeros(Duplication + 1, 1);
    Final_Index_Array(1) = Index;
    Duplication_Index = 0;
    for i = 1:4
        if Index_Array(i) == 0
            Duplication_Index = Duplication_Index + 1;
            Final_Index_Array(Duplication_Index) = Index_Array(i);
        end
    end
    msize = numel(Final_Index_Array);
    idx = randperm(msize);
    signalphase = Final_Index_Array(idx(1));
    return
end
Appendix B

Cooperative Adaptive Cruise Control

Background Code

B.1 C++ DLL CACC Driver Behaviour Model

The following is the C++ code for the Dynamic Linked Library to replace the driver behaviour model for the CACC vehicles.

```cpp
#include "CACCPlatooningModel.h"

double current_speed = 0.0;
double desired_acceleration = 0.0;
double desired_lane_angle = 0.0;
l.long active_lane_change = 0;
l.long original_active_lane_change = 0;
l.long rel_target_lane = 0;
double desired_velocity = 0.0;
double original_desired_velocity = 0.0;
l.long turning_indicator = 0;
```
| long vehicle_color = CMYK(255, 255, 255, 255);
| double lead_vehicle_distance = 999.0;
| double tail_vehicle_distance = 999.0;
| double left_lead_vehicle_distance = 999.0;
| double left_tail_vehicle_distance = 999.0;
| double right_lead_vehicle_distance = 999.0;
| double right_tail_vehicle_distance = 999.0;
| double lead_vehicle_distance2 = 999.0;
| double tail_vehicle_distance2 = 999.0;
| double left_lead_vehicle_distance2 = 999.0;
| double left_tail_vehicle_distance2 = 999.0;
| double right_lead_vehicle_distance2 = 999.0;
| double right_tail_vehicle_distance2 = 999.0;
| double lead_vehicle_speed_difference = -99.0;
| double lead_vehicle_length = 0.0;
| double ka = 1.0;
| double kv = 0.58;
| // double kv = 1.0;
| // double kv = 2.0;
| double ks = 0.1;
| // double ks = 0.2;
| // double ks = 0.3;
| double ac = 0.0;
| double ap = 0.0;
| double vp = 0.0;
| double vf = 0.0;
| double s = 0.0;
| double v = 0.0;
| double td = 0.5; // 0.5s gap.
| double amin = -3.0;
| double amax = 2.0;
| long lead_platoon = 0;
| long join_platoon = 0;
| long vehicle_category = 0;
| long lead_vehicle_category = 0;
| long tail_vehicle_category = 0;
| long right_lead_vehicle_category = 0;
| long right_tail_vehicle_category = 0;
| long left_lead_vehicle_category = 0;
| long left_tail_vehicle_category = 0;
| long lead_vehicle_category2 = 0;
| long tail_vehicle_category2 = 0;
| long right_lead_vehicle_category2 = 0;
| long right_tail_vehicle_category2 = 0;
| long left_lead_vehicle_category2 = 0;
| long left_tail_vehicle_category2 = 0;
| long vehicle_lane = 0;

//==========================================================================
BOOL APIENTRY DllMain(HANDLE hModule,
DWORD ul_reason_for_call,
LPVOID lpReserved)
{
    switch (ul_reason_for_call) {
    case DLL_PROCESS_ATTACH:
    case DLL_THREAD_ATTACH:
    case DLL_THREAD_DETACH:
    case DLL_PROCESS_DETACH:
        break;
    }
    return TRUE;
}
//==========================================================================

DRIVERMODEL_API int DriverModelSetValue( long type,
```c
long index1,
long index2,
long long_value,
double double_value,
char *string_value
{
    /* Sets the value of a data object of type <type>, selected by <index1> */
    /* and possibly <index2>, to <long_value>, <double_value> or */
    /* <*string_value> (object and value selection depending on <type>). */
    /* Return value is 1 on success, otherwise 0. */
    switch (type) {
        case DRIVER_DATA_PATH:
            case DRIVER_DATA_TIMESTEP:
                case DRIVER_DATA_TIME:
                    return 1;
        case DRIVER_DATA_VEH_ID:
            /* reset leading vehicle’s data for this new vehicle */
            lead_vehicle_distance = 999.0;
            lead_vehicle_speed_difference = -99.0;
            lead_vehicle_length = 0.0;
            return 1;
        case DRIVER_DATA_VEH_LANE:
            vehicle_lane = long_value;
            return 1;
        case DRIVER_DATA_VEH_ODOMETER:
        case DRIVER_DATA_VEH_LANE_ANGLE:
        case DRIVER_DATA_VEH_LATERAL_POSITION:
            return 1;
        case DRIVER_DATA_VEH_VELOCITY:
            current_speed = double_value;
            v_f = current_speed;
            return 1;
        case DRIVER_DATA_VEH_ACCELERATION:
        case DRIVER_DATA_VEH_LENGTH:
        case DRIVER_DATA_VEH_WIDTH:
        case DRIVER_DATA_VEH_WEIGHT:
        case DRIVER_DATA_VEH_MAX_ACCELERATION:
            return 1;
        case DRIVER_DATA_VEH_TURNING_INDICATOR:
            turning_indicator = long_value;
            return 1;
        case DRIVER_DATA_VEH_CATEGORY:
            vehicle_category = long_value;
            return 1;
        case DRIVER_DATA_VEH_PREFERRED_REL_LANE:
        case DRIVER_DATA_VEH_USE_PREFERRED_LANE:
            return 1;
        case DRIVER_DATA_VEH_DESIRED_VELOCITY:
            original_desired_velocity = double_value;
            return 1;
        case DRIVER_DATA_VEH_X_COORDINATE:
        case DRIVER_DATA_VEH_Y_COORDINATE:
            case DRIVER_DATA_VEH_TYPE:
                return 1;
        case DRIVER_DATA_VEH_COLOR:
            /* vehicle_color = long_value;*/
            vehicle_color = CMYK(255, 255, 0, 0);
            return 1;
        case DRIVER_DATA_VEH_CURRENT_LINK:
            return 0; /* (To avoid getting sent lots of DRIVER_DATA_VEH_NEXT_LINKS messages) */
            /* Must return 1 if these messages are to be sent from VISSIM! */
    }
    case DRIVER_DATA_VEH_NEXT_LINKS:
    case DRIVER_DATA_VEH_ACTIVE_LANE_CHANGE:
    case DRIVER_DATA_VEH_REL_TARGET_LANE:
    case DRIVER_DATA_NVEH_ID:
    case DRIVER_DATA_NVEH_LANE_ANGLE:
```
case DRIVER_DATA_NVEH_LATERALPOSITION:
    return 1;
case DRIVER_DATA_NVEH_DISTANCE:
    if (index1 == 0 && index2 == 1) {
        lead_vehicle_distance = double_value;
    }
    else if (index1 == 0 && index2 == -1) {
        tail_vehicle_distance = double_value;
    }
    else if (index1 == 0 && index2 == 2) {
        lead_vehicle_distance2 = double_value;
    }
    else if (index1 == 0 && index2 == -2) {
        tail_vehicle_distance2 = double_value;
    }
    if (vehicle_lane == 1) {
        if (index1 == 1 && index2 == 1) {
            left_lead_vehicle_distance = double_value;
        }
        else if (index1 == 1 && index2 == -1) {
            left_tail_vehicle_distance = double_value;
        }
        else if (index1 == 1 && index2 == 2) {
            left_lead_vehicle_distance2 = double_value;
        }
        else if (index1 == 1 && index2 == -2) {
            left_tail_vehicle_distance2 = double_value;
        }
    }
    else if (vehicle_lane == 2) {
        if (index1 == 1 && index2 == 1) {
            right_lead_vehicle_distance = double_value;
        }
        else if (index1 == 1 && index2 == -1) {
            right_tail_vehicle_distance = double_value;
        }
        else if (index1 == 1 && index2 == 2) {
            right_lead_vehicle_distance2 = double_value;
        }
        else if (index1 == 1 && index2 == -2) {
            right_tail_vehicle_distance2 = double_value;
        }
    }
    return 1;
case DRIVER_DATA_NVEH_REL_VELOCITY:
    if (index1 == 0 && index2 == 1) {
        lead_vehicle_speed_difference = double_value;
        vp = current_speed - lead_vehicle_speed_difference;
    }
    return 1;
case DRIVER_DATA_NVEH_ACCELERATION:
    if (index1 == 0 && index2 == 1) {
        ap = double_value;
    }
    return 1;
case DRIVER_DATA_NVEH_LENGTH:
    if (index1 == 0 && index2 == 1) {
        lead_vehicle_length = double_value;
        s = lead_vehicle_distance - lead_vehicle_length;
    }
    return 1;
case DRIVER_DATA_NVEH_WIDTH:
case DRIVER_DATA_NVEH_WEIGHT:
case DRIVER_DATA_NVEH_TURNING_INDICATOR:
case DRIVER_DATA_NVEH_CATEGORY:
    if (index1 == 0 && index2 == 1) {
        lead_vehicle_category = long_value;
if (index1 == 0 && index2 == −1) {
    tail_vehicle_category = long_value;
}
if (index1 == 0 && index2 == 2) {
    lead_vehicle_category2 = long_value;
}
if (index1 == 0 && index2 == −2) {
    tail_vehicle_category2 = long_value;
}
if (vehicle_lane == 2) {
    lead_platoon = 0;
    join_platoon = 0;
        if (index1 == −1 && index2 == 1) {
            right_lead_vehicle_category = long_value;
        }
        if (index1 == −1 && index2 == −1) {
            right_tail_vehicle_category = long_value;
        }
        if (index1 == −1 && index2 == 2) {
            right_lead_vehicle_category2 = long_value;
        }
        if (index1 == −1 && index2 == −2) {
            right_tail_vehicle_category2 = long_value;
        }
        if (lead_vehicle_category != vehicle_category && tail_vehicle_category == vehicle_category && tail_vehicle_distance >= −50) {
            lead_platoon = 1;
            join_platoon = 0;
        }
    else if (lead_vehicle_category == vehicle_category && tail_vehicle_category == vehicle_category && tail_vehicle_distance >= −50 && lead_vehicle_distance >= 50) {
            lead_platoon = 1;
            join_platoon = 0;
        }
        if (lead_vehicle_category == vehicle_category && lead_vehicle_distance <= 50) {
            if (lead_platoon == 0) {
                lead_platoon = 0;
                join_platoon = 1;
            } else if (lead_platoon == 1) {
                lead_platoon = 1;
                join_platoon = 0;
            }
        }
        if (lead_vehicle_category != vehicle_category && tail_vehicle_category != vehicle_category) {
            join_platoon = 0;
            lead_platoon = 0;
        }
    } else if (vehicle_lane == 1) {
    lead_platoon = 0;
    join_platoon = 0;
        if (index1 == 1 && index2 == 1) {
            left_lead_vehicle_category = long_value;
        }
        if (index1 == 1 && index2 == −1) {
            left_tail_vehicle_category = long_value;
        }
        if (index1 == 1 && index2 == 2) {
            left_lead_vehicle_category2 = long_value;
        }
        if (index1 == 1 && index2 == −2) {
            left_tail_vehicle_category2 = long_value;
        }
        else if (vehicle_lane == 1) {
            lead_platoon = 0;
            join_platoon = 0;
        }
    }
DRIVERMODEL_API int DriverModelGetValue(long type, long index1, long index2, long *long value, double *double value, char **string value)
{
    /* Gets the value of a data object of type <type>, selected by <index1>, and possibly <index2>, and writes that value to <double_value> or <string_value> (object and value selection depending on <type>). */
    /* Return value is 1 on success, otherwise 0. */

    switch (type) {
    case DRIVER_DATA_STATUS:
        original_active_lane_change = long_value;
        return 1;
    case DRIVER_DATA_ACTIVE_LANE_CHANGE:
        original_active_lane_change = long_value;
        return 1;
    case DRIVER_DATA_REL_TARGET_LANE:
        rel_target_lane = long_value;
        return 1;
        default:
        return 0;
    }
    return 0;
}
else if (join_platoon == 1) {
    desired_velocity = vp;
} else { desired_velocity = original_desired_velocity; }

* double_value = desired_velocity;
return 1;

case DRIVER_DATA_VEH_COLOR:
if (join_platoon == 1) {
    vehicle_color = CMYK(255, 255, 255, 255);
} else if (lead_platoon == 1) {
    vehicle_color = CMYK(255, 0, 0, 0);
} * long_value = vehicle_color;
return 1;

case DRIVER_DATA_WANTS_SUGGESTION:
* long_value = 1;
return 1;

case DRIVER_DATA_DESIRED_ACCELERATION:
// Acceleration is based on:
// ac = (ka * ap) + (kv * (vp - v_f)) + (ks * (s - v_f * t));
// a = max[amin, min(ac, amax)]
if (join_platoon == 1) {
    ac = (ka * ap) + (kv * (vp - v_f)) + (ks * (s - v_f * t));
    desired_acceleration = max(amin, min(ac, amax));
} else if (lead_platoon == 1) { // need to ensure that this takes into consideration the
  desired velocity as well – if the lead vehicle is faster than the desired velocity
  then this needs to not speed up to the lead vehicle for a lead_platoon vehicle.
    if (lead_vehicle_distance <= 50) {
        ac = (kv * (vp - v_f)) + (ks * (s - v_f + 1.4));
        desired_acceleration = max(amin, min(ac, amax));
    }
}

// Added a section to cause the CACC vehicles to act like ACC vehicles regardless of if they are leading a
// platoon or not.
else {
    if (lead_vehicle_distance <= 50) {
        ac = (kv * (vp - v_f)) + (ks * (s - v_f + 1.4));
        desired_acceleration = max(amin, min(ac, amax));
    }
}
* double_value = desired_acceleration;
return 1;

case DRIVER_DATA_DESIRED_LANE_ANGLE:
// * double_value = desired_lane_angle;
return 0;

case DRIVER_DATA_ACTIVE_LANE_CHANGE:
// Vehicle is in the right lane, and a vehicle immediately to the left and in front of it
// is either leading a platoon or in a platoon, and the vehicle immediately to the
// left and behind it is not in the platoon.
if (vehicle_lane == 1 && left_lead_vehicle_category == vehicle_category &&
    left_tail_vehicle_category != vehicle_category ||
    left_tail_vehicle_category ==
    vehicle_category &&
    (left_tail_vehicle_distance < -50 ||
    left_lead_vehicle_distance - left_tail_vehicle_distance > 50))) { // Make sure the distances are
    if (left_tail_vehicle_distance <= -15 && left_lead_vehicle_distance > 5 &&
        left_lead_vehicle_distance < 50) { // Make sure the distances are
        active_lane_change = 1;
    } else {
        active_lane_change = original_active_lane_change;
    }
}
B.2 C++ DLL ACC Driver Behaviour Model

The following is the C++ code for the Dynamic Linked Library to replace the driver behaviour model for the ACC vehicles.
#include "ACCPlatooningModel.h"

double current_speed = 0.0;
double desired_acceleration = 0.0;
double original_desired_velocity = 0.0;
double desired_lane_angle = 0.0;
long active_lane_change = 0;
long rel_target_lane = 0;
double desired_velocity = 0.0;
long turning_indicator = 0;
long vehicle_color = CMYK(255,255,255,255);
double lead_vehicle_distance = 999.0;
double lead_vehicle_speed_difference = -99.0;
double lead_vehicle_length = 0.0;
double ka = 0.0;
double kv = 0.58;
double ks = 0.1;
double ac = 0.0;
double ap = 0.0;
double vp = 0.0;
double vf = 0.0;
double s = 0.0;
double v = 0.0;
double td = 1.4; // 1.4 s gap.
double amin = -3.0;
double amax = 2.0;

BOOL APIENTRY DllMain (HANDLE hModule,
                       DWORD u1_reason_for_call,
                       LPVOID lpReserved)
{
    switch (u1_reason_for_call) {
        case DLL_PROCESS_ATTACH:
            case DLL_THREAD_ATTACH:
                case DLL_THREAD_DETACH:
                    case DLL_PROCESS_DETACH:
                        break;
    }
    return TRUE;
}

DRIVERMODEL_API int DriverModelSetValue (long type,
                                         long index1,
                                         long index2,
                                         long long_value,
                                         double double_value,
                                         char *string_value)
{
    /* Sets the value of a data object of type <type>, selected by <index1> */
    /* and possibly <index2>, to <long_value>, <double_value> or */
/* \<string_value\> (object and value selection depending on \<type\>). */
/* Return value is 1 on success, otherwise 0. */

switch (type) {
  case DRIVER_DATA_PATH :
  case DRIVER_DATA_TIMESTEP :
  case DRIVER_DATA_TIME :
    return 1;
  case DRIVER_DATA_VEH_ID :
    /* reset leading vehicle's data for this new vehicle */
    lead_vehicle_distance = 999.0;
    lead_vehicle_speed_difference = -99.0;
    lead_vehicle_length = 0.0;
    return 1;
  case DRIVER_DATA_VEH_LANE :
  case DRIVER_DATA_VEH_ODOMETER :
  case DRIVER_DATA_VEH_LANE_ANGLE :
  case DRIVER_DATA_VEH_LATERAL_POSITION :
    return 1;
  case DRIVER_DATA_VEH_VELOCITY :
    current_speed = double_value;
    vf = current_speed;
    return 1;
  case DRIVER_DATA_VEH_ACCELERATION :
  case DRIVER_DATA_VEH_LENGTH :
  case DRIVER_DATA_VEH_WIDTH :
  case DRIVER_DATA_VEH_WEIGHT :
  case DRIVER_DATA_VEH_MAX_ACCELERATION :
    return 1;
  case DRIVER_DATA_VEH_TURNING_INDICATOR :
    turning_indicator = long_value;
    return 1;
  case DRIVER_DATA_VEH_CATEGORY :
  case DRIVER_DATA_VEH_PREFERRED_REL_LANE :
  case DRIVER_DATA_VEH_USE_PREFERRED_LANE :
    return 1;
  case DRIVER_DATA_VEH_DESIRED_VELOCITY :
    original_desired_velocity = double_value;
    return 1;
  case DRIVER_DATA_VEH_XCOORDINATE :
  case DRIVER_DATA_VEH_YCOORDINATE :
  case DRIVER_DATA_VEH_TYPE :
    return 1;
  case DRIVER_DATA_VEH_COLOR :
    /* vehicle_color = long_value; */
    vehicle_color = CMYK(255, 0, 255, 0);
    return 1;
  case DRIVER_DATA_VEH_CURRENT_LINK :
    return 0; /* (To avoid getting sent lots of DRIVER_DATA_VEH_NEXT_LINKS messages) */
  case DRIVER_DATA_VEH_NEXT_LINKS :
  case DRIVER_DATA_VEH_ACTIVE_LANE_CHANGE :
  case DRIVER_DATA_VEH_REL_TARGET_LANE :
  case DRIVER_DATA_NVEH_ID :
  case DRIVER_DATA_NVEH_LANE_ANGLE :
  case DRIVER_DATA_NVEH_LATERAL_POSITION :
    return 1;
  case DRIVER_DATA_NVEH_DISTANCE :
    if (index1 == 0 && index2 == 1) { /* leading vehicle on own lane */
      lead_vehicle_distance = double_value;
    }
    return 1;
  case DRIVER_DATA_NVEH_REL_VELOCITY :
    if (index1 == 0 && index2 == 1) { /* leading vehicle on own lane */
      lead_vehicle_speed_difference = double_value;
      vp = current_speed - lead_vehicle_speed_difference;
    }
    return 1;
case DRIVER_DATA_NVEH_ACCELERATION :
    if (index1 == 0 && index2 == 1) {
        ap = double_value;
    }
    return 1;

case DRIVER_DATA_NVEH_LENGTH :
    if (index1 == 0 && index2 == 1) {
        /* leading vehicle on own lane */
        lead_vehicle_length = double_value;
        s = lead_vehicle_distance - lead_vehicle_length;
    }
    return 1;

case DRIVER_DATA_NVEH_WIDTH :
    case DRIVER_DATA_NVEH_WEIGHT :
    case DRIVER_DATA_NVEH_CATEGORY :
    case DRIVER_DATA_NVEH_LANE_CHANGE :
    case DRIVER_DATA_NO_OF_LANES :
    case DRIVER_DATA_LANE_WIDTH :
    case DRIVER_DATA_LANE_END_DISTANCE :
    case DRIVER_DATA_RADIUS :
    case DRIVER_DATA_MIN_RADIUS :
    case DRIVER_DATA_DIST_TO_MIN_RADIUS :
    case DRIVER_DATA_SLOPE :
    case DRIVER_DATA_SLOPE_AHEAD :
    case DRIVER_DATA_SIGNAL_DISTANCE :
    case DRIVER_DATA_SIGNAL_STATE :
    case DRIVER_DATA_SIGNAL_STATE_START :
    case DRIVER_DATA_SPEED_LIMIT_DISTANCE :
    case DRIVER_DATA_SPEED_LIMIT_VALUE :
        return 1;
    case DRIVER_DATA_DESIRED_ACCELERATION :
        desired_acceleration = double_value;
        return 1;
    case DRIVER_DATA_DESIRED_LANE_ANGLE :
        desired_lane_angle = double_value;
        return 1;
    case DRIVER_DATA_ACTIVE_LANE_CHANGE :
        active_lane_change = long_value;
        return 1;
    case DRIVER_DATA_REL_TARGET_LANE :
        rel_target_lane = long_value;
        return 1;
    default :
        return 0;
}

/*----------------------------------------*/

DRIVERMODEL_API int DriverModelGetValue (long type,
    long index1,
    long index2,
    long *long_value,
    double *double_value,
    char **string_value)
{
    /* Gets the value of a data object of type <type>, selected by <index1>, */
    /* and possibly <index2>, and writes that value to <double_value>, */
    /* <float_value> or <string_value> (object and value selection */
    /* depending on <type>). */
    /* Return value is 1 on success, otherwise 0. */

    switch (type) {
    case DRIVER_DATA_STATUS :
        *long_value = 0;
        return 1;
    case DRIVER_DATA_VEH_TURNING_INDICATOR :
        *long_value = turning_indicator;
        return 1;
return 1;
case DRIVER_DATA_VEH_DESIRED VELOCITY :
    if (lead_vehicle_distance <= 50) {
        desired_velocity = vp;
    } else {
        desired_velocity = original_desired_velocity;
    } *double value = desired_velocity;
return 1;
case DRIVER_DATA_VEH_COLOR :
    *long value = vehicle_color;
return 1;
case DRIVER_DATA_WANTS_SUGGESTION :
    *long value = 1;
return 1;
case DRIVER_DATA_DESIRED ACCELERATION :
    /*### start commenting out from here for "do nothing" */
    //double net_distance = lead_vehicle_distance - lead_vehicle_length;
    //double lead_vehicle_speed = current_speed - lead_vehicle_speed_difference;
    //double desired_distance = lead_vehicle_speed*1.4;
    //if (lead_vehicle_speed_difference > 0) {
    //    /* we are faster than the leading vehicle */
    //    if (lead_vehicle_speed > 0) {
    //        if (net_distance > desired_distance) {
    //            /* slow down to leading vehicle's speed with 1 s time gap */
    //            desired_acceleration = - lead_vehicle_speed_difference
    //                                * lead_vehicle_speed_difference
    //                                / (net_distance - desired_distance)
    //                                / 2.0;
    //        }
    //    } /* try to increase distance */
    //    desired_acceleration = - lead_vehicle_speed_difference - 1.0;
    //}
    //} /* if (lead_vehicle_speed > 0) */
    //else {
    //    /* leading vehicle is standing still */
    //    if (net_distance < 2.1) {
    //        desired_acceleration = - 9.9; /* emergency braking */
    //    }
    //    else {
    //        /* brake to standstill in 2.0 m distance */
    //        desired_acceleration = - lead_vehicle_speed_difference
    //                                * lead_vehicle_speed_difference
    //                                / (net_distance - 2.0)
    //                                / 2.0;
    //    }
    //}
    //} /* if (lead_vehicle_speed_difference > 0) */
    //else {
    //    /* accelerate to min of leading vehicle's speed and own desired speed */
    //    double new_speed = desired_velocity;
    //    if (lead_vehicle_speed < desired_velocity) {
    //        new_speed = lead_vehicle_speed;
    //    }
    //    desired_acceleration = new_speed - current_speed;
    //}
    /*### comment out until here for "do nothing" */
    if (lead_vehicle_distance <= 50){
        ac = (ka*ap) + (kv*(vp - vf)) + (ks*(s - vf*td));
        desired_acceleration = max(min(amin, min(ac, amax));
    } *double value = desired_acceleration;
return 1;
}
double value = desired_lane_angle;
return 1;
case DRIVER_DATA_ACTIVE_LANE_CHANGE :
    long value = active_lane_change;
    return 1;
case DRIVER_DATA_REL_TARGET_LANE :
    long value = rel_target_lane;
    return 1;
case DRIVER_DATA_SIMPLE_LANECHANGE :
    long value = 1;
    return 1;
    default :
    return 0;
}

DriverModelExecuteCommand (long number)
{
    switch (number) {
    case DRIVER_COMMAND_INIT :
        return 1;
    case DRIVER_COMMAND_CREATE_DRIVER :
        return 1;
    case DRIVER_COMMAND_KILL_DRIVER :
        return 1;
    case DRIVER_COMMAND_MOVE_DRIVER :
        return 1;
    default :
        return 0;
    }
}