# Accommodation of Freeway Merging in Environment of Mixed Vehicle Technologies

by

Afshin Pakzadnia

A thesis submitted to the Faculty of Graduate and Postdoctoral Affairs in partial fulfillment of the requirements for the degree of

Doctor of Philosophy
in Civil Engineering

Carleton University
Ottawa, Ontario

## Abstract

The connected autonomous vehicle (CAV) is the most significant breakthrough in the automobile industry since the wide adoption of automobiles as a mode of transportation. These vehicles can respond faster, drive more precisely within their lane, and keep gaps shorter than driver-operated vehicles (DVs). Therefore, they can improve traffic operations and reduce collisions resulting from human errors. However, shorter gaps on the freeway right lane (FRL) can create difficulty for on-ramp vehicles to merge onto the freeway. In addition, there is a transition period from all DVs to all CAVs. As a result, there would be a mixed traffic environment including DVs and CAVs, which might necessitate different merging management strategies.

This study proposes eight possible solutions to address the merging problems by providing acceptable gaps or resolving the conflicts between merging and mainline vehicles in a mixed traffic environment. These strategies are then evaluated based on different measures to determine which merging solution is most effective for each traffic condition. Average travel times and the capacity drop are used as traffic performance measures, while safety measures include the percentage of vehicles with low merging speed (VLMS) and probability of non-compliance (PNC) of merging manoeuvre.

The behaviour of CAVs and performance merging strategies are modelled using Vissim v2020, internal programing, and a MATLAB program. The simulation results indicate that when the CAV penetration rate is between 0% and 100%, most proposed strategies outperform the base condition of do-nothing. The traffic performance changes depending on the CAV penetration rate and the type of traffic management strategy.

The results of the safety measure for most strategies based on the VLMS index indicate that at low traffic volumes, increasing CAV penetration rate reduces VLMS, thereby improving safety. At high traffic volume, some strategies such as dissolving platoons and ramp metering show better performance. For the PNC measure, most strategies have lower PNC and better expected safety performance than the base strategy. Furthermore, increasing the CAV penetration rate reduces PNC. Finally, a regression analysis between PNC and the existing collision database demonstrated a correlation between PNC and collision frequency.

## Acknowledgements

I would like to thank my supervisor, Professor Yasser Hassan, for expanding my knowledge in the transportation field and advice encouragement. Your support, guidance and advice through this project are greatly appreciated.

I would also like to thank my colleague Dr. Bashar Dhahir, who helped me provide a program to extract traffic data from Vissim simulation results and Mr. Saad Roustom for internal programing Vissim for communication vehicle’s ability.

Furthermore, I would like to thank the Ministry of Transportation of Ontario for providing the resources for the required traffic data. Finally, financial support by the Natural Sciences and Engineering Research Council (NSERC) and Transport Canada’s Program to Advance Connectivity and Automation in the Transportation System (ACATS) is gratefully acknowledged.

Afshin Pakzadnia

## Dedication

To my dear parents, who have always believed and encouraged me to be where I am today.

To my wife and my son, who have been a constant source of support and patience.

# Table of Contents

## List of Tables

## List of Figures

## List of Acronyms

AASHTO = American Association of State Highway and Transportation Officials.

ACC = Adaptive Cruise Control Vehicle. A vehicle that uses radar or LiDar sensors to automatically control and adjust the gap distance between itself and a lead vehicle.

AV = Autonomous Vehicle, a driverless vehicle controlled by data collected from cameras, sensors, GPS, and LiDar.

BSM = Basic Safety Message that connected vehicles can exchange. These messages include information on speed, direction, location, and braking conditions.

CACC = Cooperative Adaptive Cruise Control. The CACC comprises ACC sensors and a communication system that transfers real kinematic data from the host vehicle (speed, acceleration/deceleration, and location) to the following vehicle, which can immediately respond to updated data from the lead vehicle.

AACC = Autonomous Adaptive Cruise Control.

CAV = Connected Autonomous Vehicle. A driverless vehicle uses communication and intelligent systems to control its movement.

CV = Connected vehicle. A vehicle that can communicate with other connected vehicles and roadway infrastructure through a DSRC or another communication system.

DSRC = Dedicated Short-Range Communication. A wireless system that can transfer BSM messages to connected vehicles travelling within a range of approximately 300 m, depending on the environment and presence of physical barriers.

DV = Driver-operated vehicle.

EV = Electric vehicle.

FRL = Freeway Right Lane.

LiDar = Light Detection and Ranging. Operates in much the same way as radar, though it uses light instead of microwaves.

PNC = Probability of non-compliance.

SCL = Speed Change Lane.

TTS = Total Travel Spent

VLMS = Vehicles with Low Merging Speed

VMT = Vehicle Miles Traveled

WHO = World Health Organization.

## Preface

The following dissertation is an integrated thesis including two articles, one published and the other is under review for publication in a technical journal. These articles were co-authored, and although this work was accomplished in cooperation, I was responsible for conducting research, acquiring the data, analyzing the results, and writing the document presented in this article. The first article has been published in the Canadian Journal of Civil Engineering as:

Pakzadnia, A., S. Roustom, and Y. Hassan. 2021. Accommodation of freeway merging in a mixed traffic environment including connected autonomous vehicles. Canadian Journal of Civil Engineering. 2021 (May):6. https://doi.org/10.1139/cjce-2020-0815

Chapter 3 contains an edition of this published article, adapted for formatting within the thesis. In this article, Mr. Roustom helped write some programs for the traffic simulation software based on my prepared equations to define the CAV behaviour in the simulations. He helped to simulate some of the strategies as well. CAVs vehicles. Professor Yasser Hassan, my supervisor, provided various recommendations, suggestions, and edits to the drafts. The second article is currently under review as:

Pakzadnia, A. and Y. Hassan. Expected Safety Performance of Different Freeway Merging Strategies in an Environment of Mixed Vehicle Technologies.

Chapter 4 contains a draft prepared for submission of this article. Professor Yasser Hassan, my supervisor, provided various recommendations, suggestions, and edits to the drafts.

# Chapter 1: Introduction

## 1.1 Background

In Canada, motor vehicles and roadway networks are the primary mode of transportation for travelling passengers and goods (Transport Canada 2020). Canada has more than 25.4 million registered motor vehicles and more than 1.13 million two-lane equivalent lane-kilometres of roadways (Transport Canada 2020). In 2016, the national highway system provided 161 billion vehicle kilometres of travel (Transport Canada, 2018), which demonstrates the importance of this mode of transportation. Thus, even a minor improvement to the roadway or the vehicles can significantly reduce passengers' travel times, fuel consumption, and emissions. It also can increase road safety and reduce roadway collisions.

Engineers have worked for decades on improving roadway design guidelines. Stricter regulations and higher safety standards for car manufacturers as well as inventing better intelligent traffic management systems could reduce traffic congestion and major collisions. In Canada, the efforts to improve roadways and regulations resulted in reducing more than 57% roadway fatality rate[1] from 2000 to 2019 (Transport Canada, 2019). Moreover, during this process, they also found that among the causes of collisions, human factors, such as speeding, impairment by alcohol or drugs, fatigue, and distraction, play an important role than other factors such as environmental and vehicle factors (Transport Canada, 2019). These findings were similar to the Fuller and Santo (2002) study that

[1] Fatality rate here is defined as a fatality collision per 10,000 motor vehicles registered per year (Transport Canada, 2019).

showed human errors are contributed up to 95% of collisions, causing 1.35 million deaths every year (WHO, 2018).

Along with improving safety, transportation engineers aim to reduce traffic congestion. However, due to human errors and increasing number of cars and trips, the current transportation system still has some negative effects, and drivers might encounter traffic congestion and experience stress because of taking the risk of a crash while commuting everyday. Currently, modern types of vehicles, such as connected autonomous vehicles (CAVs), are being tested to be ready for the market. Experts expect that these cars can reduce the negative effects of human behaviours, improve safety, enhance traffic management, and increase road capacity (Litman, 2015; Fagnant and Kockelman, 2015).

CAVs are expected to place profound changes in the transportation system, in particular on the traffic volume (Fagnant and Kockelman, 2015). Production of CAVs can help different groups of people, such as children, older adults, and people who will be able to use vehicles without having a driving licence (Litman, 2015). In other words, CAVs would encourage more travel than in the past, resulting in an increase in demand (Litman, 2015). Moreover, CAVs have a shorter perception-reaction time than DVs and can precisely drive with less gap distance (Fagnant and Kockelman, 2015), resulting in increasing roadway capacity. Although until current driver-operated vehicles (DVs) are entirely replaced by CAVs, the traffic environment will be a mix of different vehicles with different characteristics that may not receive the full benefits of CAVs. This mixed traffic environment will include DVs, connected vehicles (CV) without autonomous driving, autonomous vehicles (AVs) but not connected and CAVs.

This study aims to understand the behaviour of CAVs on the merging area in a mixed traffic environment and provide and evaluate possible solutions to minimize the negative effects of CAVs on the merging areas.

### 1.2 Problem Definition

A major segment of the traffic network that will be affected by AV/CAVs driving behaviour is urban freeways. Changes in the headway or gap distance among successive vehicles on the freeway can noticeably alter capacity and decrease delays. This gap distance can be shorter for CAVs than for DVs, leading to increased roadway capacity. Nevertheless, shorter gaps between vehicles in the traffic stream make lane-changing manoeuvres to become more difficult to exit from and enter mainline lanes (Fagnant and Kockelman, 2015). This problem will increase conflicts and the risk of crashes, especially at merging points in a mixed traffic environment. Figure 1.1 illustrates one type of difficulty experienced by a DV merging into a platoon of CAVs. If a CAV platoon blocks the ramp vehicles, the merging vehicle may stop at the end of SCL and wait for an acceptable gap. In this case, the high differential speed between mainline and merging vehicles can increase the probability of collision. Therefore, viable solutions must be identified to provide sufficient acceptable gaps on the mainline to reduce the conflict between merging and mainline vehicles. These solutions should allow safe and comfortable merging manoeuvres and seek to reduce the effects of traffic congestion on the mainline and ramp and maximize the capacity.

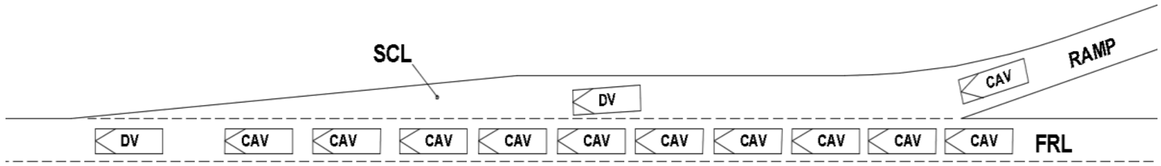



**Figure 1.1 Schematic of CAV platoon blocking on-ramp merging (FRL = freeway right lane; SCL = speed change lane).**

## 1.3 Research Objectives

This study aimed to understand the behaviour of merging vehicles adjacent to the ramp terminal for complex environments with different vehicle types (DVs and CAVs). It also provided potential solutions for safe merging manoeuvres. The assumption was that several types of vehicles would occupy roadways during the transition to solely CAVs. Thus, there would be different situations of merging manoeuvres based on the types of vehicles in the traffic stream. This study also proposed several strategies to solve the merging problems by providing acceptable gaps or resolving the conflicts between merging and mainline vehicles in mixed traffic environments. These strategies were assessed and compared to each other based on traffic performance and safety measures.

## 1.4 Research Plan

In general, for a variety of proposed merging strategies on various traffic conditions, Vissim software, along with specific internal programing, was used to simulate the behaviour of DVs and CAVs. The simulation results, such as travel time and drop in capacity evaluated the impact of strategies on traffic operation. In addition, the percentage of vehicles with low merging speed (VLMS) and the probability of non-compliance (PNC) of merging manoeuvres were used for the safety measures of proposed strategies. The VLMS percentage was an estimate of the percentage of ramp vehicles that instead of accelerating on SCL must slow down to find an acceptable gap and then merge into FRL below a specific speed threshold. This measure shows the potentially unsafe merging manoeuvres. It is expected that the collision probability would increase with increasing VLMS. The merging speeds were extracted from the Vissim simulation. PNC indicates the percentage of ramp vehicles that could not comfortably merge into the mainline. In this context, comfortable merging means not using courtesy merging, forced merging, or stopping at the end of the SCL and waiting for an acceptable gap. A MATLAB program was developed to calculate the PNC for each strategy and traffic situation in this study.

The first step in achieving the study's objectives was to review the most relevant studies from the literature review chapter. The previous studies outlined merging strategies and traffic models required for programming strategies in the Vissim simulations or the proposed MATLAB program.

The second step presented all possible and reasonable merging strategies that could resolve the merging problem in a mixed traffic environment. To evaluate the performance of strategies within the traffic simulation software, Vissim was calibrated based on the traffic characteristics of the study area. Next, the proposed strategies for the software were defined using internal programming. Finally, the results for the simulations from various traffic conditions were analyzed to determine which had better results relative to travel time, capacity drop and VLMS parameter. It should be noted that the scope of this thesis does not cover the structures and authorities for the freeway traffic management system or the specific needs to implement any management strategy. Rather, it is assumed that a traffic management system already exists to implement the selected strategies. In addition, for simulations, clear, favourable weather is assumed. Under poor weather conditions, especially in snowy weather, a longer minimum headway for CAVs may be required because vehicles need more distance to brake due to a slippery road. In addition, DVs would require to be assumed to travel at longer headways not only because of brake time on slippery roads but also because of poor visibility and required longer reaction time.

In the next step, a MATLAB program was developed to compare the expected safety performance of the various strategies using the PNC measure. This program simulated all strategies in different traffic conditions. Afterward, a 5-year collisions data from an Ottawa freeway in Ontario, Canada, was used to display the relationship between PNC and frequency of collisions at the merging areas.

## 1.5 Thesis Structure

The structure of this thesis for the remaining chapters is as follow:

- Chapter 2 covers the literature review on autonomous vehicles, driver and vehicle behaviour, traffic models, and reliability analysis.
- Chapter 3 compares traffic performance of merging strategies, presents proposed merging strategies, determines a study area for evaluating the merging strategies, defines simulation requirements such as driver behaviours for DVs and CAVs and internal Vissm programming, and discusses simulation results.
- Chapter 4 compares the expected safety performance of different merging strategies, and the safety performance of strategies applying the PNC measure. It also evaluates the relationship between PNC and number of collisions based on traffic data of existing fifteen entrance ramp terminals.
- Chapter 5 notes a summary of the conclusions and main findings. This chapter also presents some recommendations for future research.

- Appendix A includes more details and results for Chapter 3.
- Appendix B describes more details for chapter four and the MATLAB program and its functions.

# Chapter 2: Literature Review

This chapter reviews the literature about autonomous vehicles, car-following models, and merging models relevant to this study. First, the different levels of automation are defined. Next, the forecasts of market adoption of AV/CV/CAV technologies and the characteristics of these vehicles are reviewed. Then, current car-following models, merging ramp characteristics, and merging models are discussed to provide context for the proposed CAV merging model that is developed in this study. Reliability analysis for evaluation of simulation results is discussed in the last section.

## 2.1 Historical Background

The development of self-driving cars has been on car manufacturers' minds for decades, but the advent of technology has helped these vehicles become a reality. General Motors imagined these vehicles for the first time in its "Futurama exhibit of 1939" (General Motors, 1939). According to this image, by the 1960s, the gap distance between the new vehicles would be controlled by a radio system to maintain a safe distance.

The first proposed autonomous vehicles were assessed in San Diego in 1997 by National Automated Highway System Consortium (NAHSC) (Shladover, 1997). In this test, some small magnets were located under the pavement surface along the highway's centerline with 1.2m space. Magnets deliver a binary code by their arrangements of north poles. The magnetic north pole up was represented by a binary code "1," and down was represented by a binary code "0". Magnetic poles arranged up and down could deliver a message to vehicles equipped with a magnetic receiver. The binary code delivered advanced information of roadway characteristics to the drivers. This information, along with magnetic signal strength, warns of an unexpected lateral displacement, facilitates drivers to determine their longitudinal location, and navigate vehicles automatically. Eight vehicles in this test were equipped with a radio and radar system to communicate with each other and helped them drive as a platoon and keep a small gap of approximately 6.5m among them without a driver operation. The goal of this system was to propose safe automatic lane changing, platoon joining, and separation manoeuvres (Shladover, 1997).

To assess the performance of autonomous trucks and buses in 2005, the University of California, in cooperation with other transportation organizations and agencies, conducted another test (Shladover et al., 2005). The results showed that these heavy vehicles could move longitudinally and laterally using an automation system without a driver. More recently, after developing LiDar, a remote sensing technology, Google in 2019 developed its autonomous vehicle. Google's vehicle is equipped with different cameras, GPS, sensors, and a LiDar system that can help the vehicle recognize roadways, traffic signs, other vehicles, barriers, and other surrounding objectives and drive without a driver (Guizzo 2019). Google self-driving vehicles are currently testing in the United States to improve the autonomous system for all possible traffic and weather situations (Waymo, 2018).

## 2.2 Autonomous Vehicle Descriptions

AVs use different sensors such as cameras, radars, LiDar, and an intelligent system to collect and analyze their surrounding data to control some or all vehicle operation tasks. These vehicles are designed to immediately and accurately respond to required driving manoeuvres, such as changing lanes, accelerating, decelerating, adjusting speed, and merging/diverging in different traffic situations.

The driving tasks are believed can be done by AVs in a shorter reaction time than DVs and without a human mistake (Zmud et al., 2016). Along with connectivity systems, such as vehicle-to-vehicle communication (V2V), AVs also can be aware of downstream traffic flow and react to an unexpected incident in a shorter time than vehicles without connectivity and thus avoid collisions. A connectivity system also can help the transportation departments to manage traffic by ordering some commands via vehicle-to-infrastructure communication (V2I) during peak hours. The major advantages and disadvantages of autonomous vehicles are explained in the coming sections.

### 2.2.1 Advantages of Autonomous Vehicles

The advantages of autonomous vehicles can be summarized in the following points:

1- **Reduce collisions:** An estimated 1.35 million people die in automobile collisions worldwide every year (WHO, 2018). Fuller and Santo (2002) indicated that 90 to 95% of those collisions occur due to human errors. CAVs have been designed to avoid human errors, suggesting that they may help eliminate a considerable number of collisions and reduce the number of fatalities and injuries (Fagnant and Kockelman, 2015). However, it may still be too early to accept the safety benefits of autonomous driving systems. In the United States, approximately every 320,000 vehicle miles travelled (VMT) in 2015 resulted in a property-damage-only collision. There was a fatal crash for approximately every 72.0 million VMT for passenger cars (NHTSA, 2016). Google's self-driving vehicles travelled about 7 million miles from 2009 to June 2018 (Waymo, 2018) and experienced multiple collisions. One of these collisions, in February 2016, occurred because the autonomous system misunderstood the traffic situation (MacFarland, 2016). Similarly, one of Tesla's autonomous cars had a deadly crash in 2016 because it failed to recognize a white truck in front of the vehicle (Boudette, 2017), and another Tesla in autonomous mode hit and killed a woman who was walking with her bike crossing the road (BBC News, 2018). Thus, at this point, it is hard to say that autonomous vehicles are significantly safer than DVs, particularly when considering fatal collisions. However, it is evident that autonomous vehicles have the potential for considerable improvement.

2- **Increase mobility for non-drivers:** Autonomous vehicles provide a facility to allow independent travel by all non-drivers, including older adults, disabled people, and children (Fagnant and Kockelman, 2015).

3- **Increase time savings:** People using a self-driving system can rest, watch movies, perform other tasks, and enjoy their travel time or utilize it to do other tasks (Fagnant and Kockelman, 2015).

4- **Increase road capacity:** CAVs can travel close to each other, with shorter gaps between vehicles than DVs, increasing the capacity of existing roads. In addition, these vehicles can drive precisely without needing to travel in a wide lane (such as 3.7 m). As a result, more space could be saved in the existing multilane roads, which might be enough to add a new lane. Some researchers have shown that Cooperative Adaptive Cruise Control (CACC), which uses a shorter time-gap, could increase roadway throughput, reduce emissions, and fuel consumption (Ploeg et al., 2011a; Ploeg et al., 2011b; Arem et al. 2006).

5- **Mitigate congestion:** Increasing capacity, enhancing driving performance, and using connectivity to be aware of the downstream traffic situation could help reduce traffic jams.

6- **Reduce environmental impact:** It is expected that AVs will drive more steadily than human drivers, which will result in fewer and more gradual accelerations and decelerations than is typical for DVs (Talebpour and Mahmassani, 2016). Reducing the number of accelerations or decelerations reduces fuel consumption and emissions.

7- **Reduce time spent searching for parking spots:** CAVs can seek parking spots by themselves after dropping off their passengers and returning to pick them up according to a predetermined schedule. This ability helps avoid wasting passengers' time searching for a parking spot. This feature could also reduce the demand for parking in high-density urban areas because autonomous vehicles can park themselves in distant parking lots after dropping off their passengers.

8- **Reduce transportation costs for goods and increase cargo shipments:** More than 40% of the average marginal cost of trucking in 2016 was driver-related (Hooper and Murray, 2018). Thus, the cost of transportation by trucks without a driver can be lower. In addition, an autonomous truck can also operate 24/7 without stopping, except for refuelling and maintenance. Combining these factors would mean more goods can be transported more quickly and lower transportation costs.

9- **Increase the flexibility of roadway design:** Compared to DVs, CAVs have shorter stopping, decision, and passing sight distances since they use mapping data and connectivity information and have fast reaction times. In addition, as mentioned earlier, these vehicles need less width for traffic lanes because of efficient driving. As a result of these capabilities, narrower roads can be designed in areas with high land values.

10- **Reduce police staffing levels:** Self-driving systems help decrease human driving errors and illegal drivers' behaviours. Accordingly, the number of police officers required to monitor driving behaviours would be reduced relative to current levels (Chong, 2016).

### 2.2.2 Disadvantages of Autonomous Vehicles

Autonomous vehicles come with some concerns, as explained below.

1- **Security and privacy concerns:** Cybersecurity and hacking are major concerns associated with CAVs. The intelligent systems of CAVs can be hacked and exploited by terrorists and other unlawful actors (Litman, 2015). In addition, vehicle connectivity systems could disclose information beyond necessary for a function or reveal location tracking data that may violate users' expectations of privacy (Litman, 2015).

2- **Moral issues:** In an unavoidable collision situation, autonomous vehicles must decide how to collide and possibly choose based on minimal harm to other road users. However, such decisions can lead to concerns on moral grounds. Goodall (2014) discussed a famous example wherein a vehicle on a bridge faces a bus crossing the road. The vehicle has three options in this situation: collide with the bus, fall into the river, or do a difficult manoeuvre to avoid colliding with the bus. Each option has a diverse set of consequences. Goodall (2014) believed that autonomous vehicles might not take the most morally correct decision in this complicated situation if the top priority for these vehicles is to protect their passengers over other road users.

3- **Problems with merging and diverging:** CAVs using a short time gap among CAVs platoon. These short gaps reduce the availability of acceptable gaps for merging vehicles. Also, the short time gaps among a CAV platoon result in difficulty in lane changing and diverging for other types of vehicles (Fagnant and Kockelman, 2015).

4- **Increase in traffic volume:** People without a driving license can travel using a CAV, and after dropping off passengers, CAVs might go home before returning to pick up their passengers. Hence, CAVs could decrease passengers' travel times but increase traffic volume.

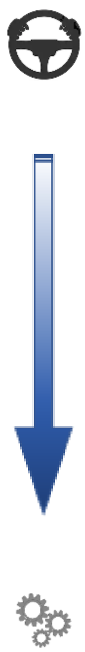
5- **Fewer jobs:** Understandably, the number of driving jobs is expected to decline with the widespread deployment of AVs/CAVs (Litman, 2015).

AVs also have the potential to affect land use and urban planning. For example, in urban areas, AVs can help to convert the land currently used for parking to other uses such as walking, cycling or transit facilities (Maurer et al., 2016). In another study, Cordera et al. (2021) found that if AVs increase the capacity of existing road networks in the urban area, they can decrease travel time and congestion and, therefore, positively impact central cities more than suburban or rural areas. However, if the increasing capacity causes an increase in demand by new users or empty AVs, the benefit of increasing capacity could vanish and cause pushing activities to the sub-urban areas and resulting in a more dispersed and scattered urban growth pattern. Moreover, AVs may impact travel pattern through the potential relocation of workers into rural or sub-urban areas due to their ability to use the commute time in other activities instead of driving.

## 2.3 Levels of Automation

The Society of Automotive Engineers (SAE, 2016) divides vehicle automation into six levels, as described in Table 2.1 This automation level system has been accepted by US National Highway Traffic Safety Administration (NHTSA, 2017), Transport Canada (2019), the Canadian Council of Ministers of Transportation and Highway Safety (Policy and Planning Support Committee, 2018) and most other transportation agencies. The levels of automation show that full vehicle automation will take time to come to the market. Consequently, in the transition period, until most cars move to L5, a variety of vehicles with different levels of automation can gradually change traffic behaviour, such as the size of gaps and merging.

**Table 2.1 Automation levels (based on SAE, 2016).**

| Automation Level | | Definition |
|---|---|---|
| L0 |  | No Automation: the vehicle is not equipped with any automated driving assistances. The driver controls all driving tasks (acceleration, braking, and steering) and is solely responsible for monitoring road conditions. |
| L1 | | Driver Assistance Automation: a driver assistance system, such as lane keeping assistance, helps the driver to steer, accelerate, or decelerate. These functions are solely usable, with drivers responsible for all control functions. |
| L2 | | Partial Automation: one or more automated functions can control two basic driving controls including acceleration/deceleration, and steering. However, the driver is still responsible for monitoring the surroundings and controlling driving operations. |
| L3 | | Conditional Automation: an automated driving system controls operation of steering, deceleration and acceleration, and monitors driving behaviour. However, the driver is ready to take over control and is anticipated to respond promptly when an unknown driving situation occurs. |
| L4 | | High Automation: an automated system executes dynamic tasks in a specific environment; immediate driver response is not required. |
| L5 | | Full Automation: an automated system controls all driving tasks under all traffic conditions without a driver's interference. |

## 2.4 Future Market for AV/CAVs

Many cars manufacturers in the world are trying to develop and improve AVs. Tesla, for instance, is testing a L4 of AVs, and their L3 vehicles are on the road in many cities and countries around the world. It is expected that tested L4 AVs could be allowed to travel on most roadways by 2030, and L5 AVs will be available in the market by 2040 (Policy and Planning Support Committee, 2018). Using a scenario analysis, Milakis et al. (2017) examined the future transportation plan of the Netherland and found that self-driving vehicles' penetration rate in the urban area would be between 1% and 11% by 2030 and 7% and 61% by 2050. Bansal and Kockelman (2017) carried a willingness-to-pay analysis and believed that if the price of AVs annually drops by 10%, more than 87% of small vehicles would be turned to L5 by 2045. The development of electric vehicles (EVs) and battery technologies could lower the AVs' cost, which is why big car manufacturers are showcasing different EV models at the moment. Arbib and Seba (2017) assumed that the combination of fully autonomous vehicles and EVs could encourage many vehicle owners to use shared mobility as a transportation service called transportation-as-a-service (TaaS) or mobility-as-a-service (MaaS). The authors expect that by 2030, 95% of passenger miles in the USA will be covered by TaaS. Private vehicles would traverse the remaining 5% of travel time, approximately 40% of all vehicles. (Arbib and Seba, 2017).

There are some barriers that self-driving vehicles must overcome before they are launched in the mainstream market. These barriers include technology, cybersecurity, privacy, and legal issues (Glancy, 2015). The technology of producing AVs/CAVs is improving, and it is anticipated to gradually reduce the cost of these vehicles (Arbib and Seba, 2017). However, security, privacy, and legal issues still remain a concern.

In terms of technology, the current wireless connectivity system uses Dedicated Short-Range Communications (DSRC), which can transmit information within a range of 300-500m (Chong, 2016). This system was supposed to be used for CAVs by 2020 (Chong, 2016). However, it seems that this system can be disrupted by high-rise buildings within a high-density area of cities' downtowns or by unwanted noise (Glancy, 2015). Based on a study by Storck and Figueiredo (2020), the Fifth-Generation network (5G) technology, which is currently available in Canada, can be a solution for communication vehicles with each other or road infrastructure. G5 can transmit enormous amounts of data faster and more securely than DSRC (Udeshi et al., 2019; Storck and Figueiredo, 2020; Kiran and Jakkala, 2020). However, a high-data transmission network and a gigantic connection system are needed to work for this system (Storck and

Figueiredo, 2020). In another study, Yastrebova et al. (2021) suggested a hybrid connectivity system for future vehicle communications. This hybrid system uses terrestrial technology such as 5G and satellites to cover communication networks for CAVs everywhere.

There are still other barriers to CAVs becoming a common vehicle, such as privacy, security, and legal concerns. For example, there are some laws and regulations for privacy policies and data protection in Canada that the car manufacturers are still required to follow (Chong, 2016). These concerns cause researchers such as Glancy (2015) to believe that the vehicle-to-everything (V2X) communication system would not be ready for the first generations of AVs. However, the AVs are connected to GPS to help find the best route to destination and may connect to the manufacturing companies to update their software (Glancy, 2015).

In summary, current DVs can be replaced by self-driving vehicles in the next 15 to 25 years. Until that time, a mixed environment of several types of vehicles such as DVs, AVs, and CAVs would be in the roadway network.

## 2.5 Driver and Vehicle Behaviour

Driving behaviour is affected by the behaviour of other drivers. Therefore, the behaviour of AVs will not be the same as DVs. For example, keeping a time gap[2] between vehicles, driving at the desired speed, using acceleration or deceleration rates, and selecting lanes on DVs are dependent on drivers' characteristics. Moreover, driver characteristics vary between different drivers or between different traffic conditions for the same driver.

[2] The term “gap” in this study means distance or time between the rear bumper of the lead vehicle to the front bumper of lag vehicles, and the term “headway” means distance or time between the front bumper of the lead to the front bumper of lag vehicles.

However, in AVs, the behaviour characteristics will be set and changed based on optimum values and the traffic conditions that provide safe and comfortable driving with minimum energy consumption. For a combination of several types of vehicles, traffic analysis requires reliable estimation values or distributions of parameters related to driving behaviour. DVs parameters can be quantified based on observing current traffic flow under different conditions, while the characteristics of AVs need to be estimated based on some AV field tests and physical laws. In the following paragraphs, the results of some fields evaluated for characteristics of DVs and autonomous vehicles are discussed.

Taieb-Maimon and Shinar, in 2001, observed DVs and found that the minimum average of DV headways was 0.66 s (±0.26), while the average comfortable headway was 0.98 s (±0.36).

The average brake reaction time was found at 0.47 s (±0.06), and they found that 10% of drivers tend to maintain a headway less than this break reaction time, which they believe would not be enough to avoid a collision in an emergency situation (Taieb-Maimon and Shinar, 2001).

Based on a field study by Treiber and Kesting (2013), the time-gap distribution was less than 1.0s in the free-flow conditions. Another study with the help of a driving simulator reported that 74% of drivers when driving at 80-120 km/h, were uncomfortable when the gap distance was less than 16.9 m, and if the gap dropped to less than 7.5 m, they felt unsafe (Larburu et al., 2010). Ayres et al. (2001) used a loop detector to collect headway data, and after analyzing the headways, found that most drivers accept a short range of 1-2 s headways during peak hours. However, the short headway time would not be enough for a driver of AVs L2 or L3 to take control of the vehicles and switch to manual drive when it drives under autonomous mode.

Adaptive Cruise Control Vehicles (ACC) and Cooperative Adaptive Cruise Control Vehicles (CACC) are two types of partially autonomous vehicles that currently drive on roads at a higher speed of 56 km/h (Nowakowski et al., 2010); hence their behaviour can be used for behaviour assumption of CVs. ACCs use different sensors such as radar that can help them automatically regulate vehicle speed, select acceleration and deceleration rates, and keep a safe gap from the front vehicle. CACCs have an ACC system plus a vehicle-to-vehicle communication system to improve ACC and reduce the gap between vehicles (Vander Werf et al., 2002). Drivers set the time gaps of these vehicles and based on the comfortability of drivers, can be a range of a minimum of 0.6 s to a high of 2.2 s (Nowakowski et al., 2010). In 2010, the International Organization for Standardization (ISO, 2010) determined ACC's minimum and maximum dynamic characteristics. Standard ISO 15622 for ACC defines minimum gap, maximum acceleration, and minimum deceleration rates at 0.8 s, 2.0 m/s$^2$, and -3.5 m/s$^{2,}$ respectively, for all operating speeds. However, drivers of ACC and CACC are allowed to set a higher gap distance, which is more comfortable for driving. For example, Tesla drivers in Model S3 can set the following distance with the front vehicle based on a scale point from 1 (closest) to 7 (longest) (Tesla, 2021). It can be expected that this option of manually selecting the gap will change automatically at the time of AV L5.

In another field study, Nowakowski et al. (2010) found that drivers preferred to set a mean gap time of 1.54 s for ACC and 0.71 s for CACC. This gap time was 1.64 s when vehicles did not use ACC and CACC systems. Ploeg et al. (2011) carried out a practical experiment of a CACC fleet, including six-passenger vehicles with a wireless communication system. They reached similar headway results compared to Nowakowski et al. (2010). The results revealed that a headway less than 0.7 s could be maintained for a string-stable behaviour and reduced to 0.5 s by optimizing the wireless system (Ploeg et al., 2011).

## 2.6 Current Car-Following Models

There are many behavioural car-following models for driver-operated vehicles. These models were developed based on traffic operations and can be categorized into three main groups: Gazis–Herman–Rothery, safety distance, and psychophysical or action point models. In the following sections, these models are shortly discussed

### 2.6.1 Gazis–Herman–Rothery Model

General Motors first described the Gazis–Herman–Rothery (GHR) model in 1958 (Brackstone and McDonald, 1999). Equation 1 shows the original form of this model, which depends on the acceleration rate, car speed, and reaction time (Panwai and Dia, 2005).

$$a_n(t) = \alpha v_n^{\beta}(t) \frac{\Delta v(t - T_R)}{\Delta x^{\delta}(t - T_R)} \tag{2.1}$$

where,

$a_n$ = acceleration of car *n* at time *t* (m/s$^2$), $\Delta v$ = relative speed (m/s), $\Delta x$ = relative distance (m), $v_n$ = speed of *n*th vehicle (km/h), $T_R$= the perception–reaction time (s), and α, β, and δ are calibration constants.

The application of this model is limited to networks for which the constant parameters are calibrated.

### 2.6.2 Safety Distance Models

Kometani and Saski first introduced the safety distance or collision-avoidance model (CA) in 1959 (Brackstone and McDonald, 1999), and then Gipps (1981) provided a refined model. These models are based on maintaining a safe following distance to avoid collision with the lead vehicle. Gipps' model's formulation has two parts, as shown in Equations 2.2 and 2.3 (Gipps, 1981).

$$v_{n(t)} + 2.5\, a_n\, R\left(1 - \frac{v_{n(t)}}{V_n}\right)\left(0.025 + \frac{v_{n(t)}}{V_n}\right)^{0.5} \tag{2.2}$$

$$d_n R + \left({d_n}^2 R^2 - d_n\left(2\left[x_{(n-1)(t)} - S_{n-1} - x_{(n)(t)}\right] - v_{(n)(t)} R - \frac{v_{n-1}(t)^2}{d}\right)\right)^{0.5} \tag{2.3}$$

where,

$a_n$ = maximum acceleration (m/s$^2$); $d_n$ = the maximum deceleration (m/s$^2$); $x_n(t)$ = position of vehicle $n$ at time $t$ (m); $R$ = the reaction time (s); $S_{n-1}$= effective length of vehicle $n$ (m), which is equal to the length of the vehicle plus a minimum space which the vehicles prefer to keep from the lead vehicle even when stationary; $V_n$ = the posted speed or desired speed of vehicle $n$ (m/s); and $v_{(n)}$ = the speed of vehicle $n$ at time $t$ (m/s).

Equation 2.2 is used for free-flow conditions, while Equation 2.3 is suitable for congested flow. The new travel speed at time $t + R$ is the minimum of these two equations (Gipps, 1981). The simulation step of this model is equal to the perception–reaction time. Gipps assumed that an additional safety margin is needed to allow for possible driver delays. He showed that this delay could be described by $R/2$ (Gipps, 1981). It should be noted that braking actions in Gipps' model use a maximum constant deceleration for all situations (Treiber and Kesting, 2013). However, using a safety margin in addition to a defined minimum gap helps simulated vehicles brake earlier and gradually reduce speed.

Another limitation feature of this model is that the reaction time for all vehicles of the same type is considered a constant. Several simulation models have implemented this model, including the UK DoT's SISTEM model, the SPEACES in Italy, INTRAS, CarSIM in the USA (Brackstone and McDonald, 1999), and AIMSUN in Spain (Mitroi et al., 2016).

### 2.6.3 Psychophysical Models

Psychophysical models, also known as action point models, are based on the driver perception of relative velocity and distance changes in the apparent size of the vehicle in front (Brackstone and McDonald, 1999). Wiedemann produced the first psychophysical model in 1974 (Treiber and Kesting, 2013). That model simulated driving behaviour based on four traffic regimes: free-flow conditions, unconscious reaction, near-minimum following, and the stationary distance between vehicles and an immediate reaction. Different acceleration functions were applied in each of these traffic regimes. The boundaries between these driving regimes were defined by nonlinear equations defined. The simulated driver changed his behaviour after reaching the boundaries of new traffic regime equations (Treiber and Kesting, 2013). The variables of these equations included speed, distance, and magnitude of the speed difference between the following vehicles (Treiber and Kesting, 2013; Mitroi et al., 2016). Vissim traffic simulation software has implemented this model.

Although the Vissim traffic simulation software with the Wiedemann model was used to evaluate merging strategies in this study, the car-following model developed for the MATLAB program in this work used Gipps' model with some modifications for CAVs. The reason is that Gipps' model required fewer parameters to be changed for its application to AVs and CAVs. In addition, the results of the two models showed similar outcomes for both software (Mitroi et al., 2016), suggesting both car-following models have almost the same accuracy. In another study, Matcha et al. (2021) evaluated different existing car-following models and indicated that the Gipps model provided better results for studying a mixed traffic environment, including DVs and CAVs.

## 2.7 Lane Changing Model

Lane changing is a manoeuvre in which a vehicle moves from the current lane to an adjacent target lane on a multilane road. There are two lane-changing types: discretionary and mandatory (Daamen et al., 2010; Kondyli and Elefteriadou, 2012). Discretionary lane changing is a movement to improve driving conditions, such as bypassing a slow vehicle, while mandatory lane-changing must be performed to continue along the travel route (Daamen et al., 2010).

A lane-changing model includes three parts: a decision model, a condition model, and a manoeuvre model (Wei et al., 2000). The decision model is based on travel destination and route plan, relative traffic conditions in the current and target lanes, and current lane type. The condition model evaluates acceptability conditions in terms of a lane change. One of the most crucial factors for this evaluation is the presence of an acceptable gap in the target lane. Finally, the lane-change manoeuvre model explains how a vehicle's speed and acceleration affect the manoeuvre task for each type of lane changing (Wei et al., 2000).

The decision model is an essential part of lane changing. Gipps (1985) found a decision tree for the lane-changing manoeuvre. In this process, the driver is supposed to answer the following questions based on their short-term or long-term aim:

- Is changing lanes physically possible and safe?

- Is lane changing mandatory because of the current lane ends, or is it desirable due to a speed advantage?
- What is the location of any permanent obstructions?
- Is there a transit lane present, and is the subject vehicle entitled to use it?
- Is there a heavy vehicle in front of the subject vehicle?
- Can the subject vehicle reach the desired speed by changing lanes?
- Does the driver need to turn to the right or left to reach their destination?

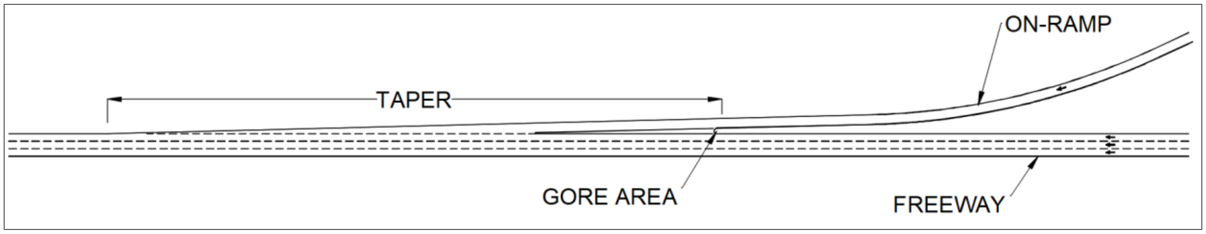
Gipps (1985) believed that a human driver answering the above questions could decide to do a lane-changing manoeuvre as the next step. Thus, it is assumed that an AV or CAV should analyze these situations, find an answer, and then make a reasonable decision regarding a lane-changing manoeuvre.

## 2.8 Freeway Merging Behaviour

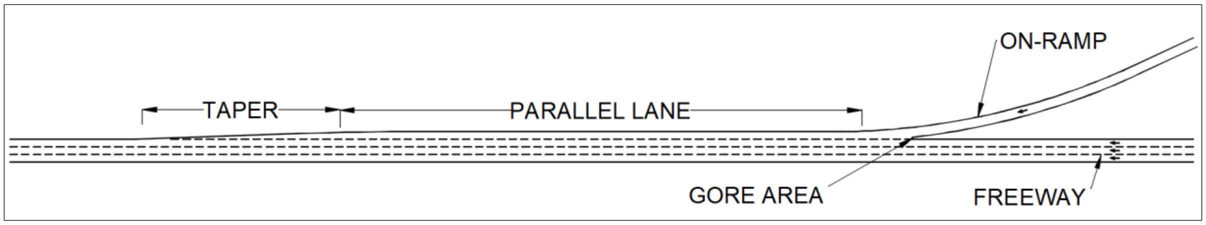
Driving a merging manoeuvre involves many minor tasks, such as searching for available gaps on the freeway right lane (FRL), evaluating gaps, adjusting speed to reach the gap, keeping distance with lead vehicles, and adjusting speed to merge into the gap. Thus, this merging manoeuvre can be stressful for drivers, especially in congested traffic, in which the available gaps are fewer than a normal traffic condition. However, a ramp with a long acceleration lane or an extended lane can help drivers find a gap at an appropriate time. The following two sections discuss the geometry of ramps and merging manoeuvre steps in detail.

### 2.8.1 Geometric Design of Merging Ramps

The American Association of State Highway and Transportation Officials (AASHTO) published the Green Book road design guideline. This guideline is used in many countries. Transportation Association of Canada also presented a Geometric Design Guideline in Canada, including some elements of the AASHTO Guideline (TAC, 2017). Both AASHTO and TAC divide merging ramps into two parts; before and after the gore area, a triangle area placed at the connection of on-ramps and freeway. The first part located before the gore area is called a ramp and connects two freeways or an arterial to a freeway. There are several types of a ramp: diagonal ramp, one quadrant ramp, loop ramp, outer connection ramp, or direct connection ramp (AASHTO, 2018). The ramp configuration determines the maximum radius of a ramp, which dictates the maximum speed on the ramp. The second part of the merging ramp located after the gore area is called the entrance terminal, a transition that facilitates ramp vehicles to accelerate and adjust their speed, search to find an acceptable available gap, and change lanes into the mainline. The entrance terminals can be classified as a limited speed change lane (SCL) or an extended lane with no clear end. The limited SCL is divided into taper and parallel acceleration lanes, as shown in Figure 2.1.




(a) Taper Acceleration Lane.




(b) Parallel Acceleration Lane.

**Figure 2.1 Configurations of acceleration SCL.**

AASHTO Green Book defined the length of SCL based on the ramp and freeway design speeds (AASHTO, 2018). However, this length must be adjusted based on the mainline gradient. Canadian geometric guideline suggests the length of SCL be the same as in the Green Book; however, instead of a specific value for SCL length, the Canadian guidelines presents a range for each combination of ramp and freeway design speed. According to TAC, for high traffic volumes, the length of SCL should be selected from the higher value of the range (TAC, 2017). In terms of sight distance, drivers should be able to see the whole length of SCL from the beginning of the acceleration lane. This sight distance helps drivers manage their speeds and merging manoeuvre within limitation time for lane changing. Also, drivers should be able to see the oncoming traffic on the freeway to find an acceptable gap (TAC, 2017).

### 2.8.2 Merging Manoeuvre

In most locations, merging ramps are a limited SCL; thus, merging is mandatory for drivers. As stated before, merging action requires some driving tasks such as steering ramp curve, moving from on-ramp to acceleration SCL, accelerating on SCL to reach merging speed, finding an appropriate gap, changing lane from SCL to FRL or rejecting merging due to a problem and searching for the next available gap (Michaels and Fazio, 1989). In addition, after merging, drivers need to increase their compact following distance to the new lead vehicle on FRL and provide a normal gap (Daamen et al., 2010).

Among the above merging tasks, finding an acceptable gap is important. An available gap is measured from the rear bumper of a lead vehicle to the front bumper of its following vehicle. Marczak et al. (2013) called this distance an "offer gap." The length of an offer gap is key that makes it an accepted or a rejected gap for merging vehicles. The minimum length of an offer gap that a merging driver is willing to accept for changing lane is called the "critical gap" (Marczak et al., 2013). A critical gap's size depends on merging vehicle speed and acceleration rate, mainline lead, and lag vehicles speeds (Daamen et al., 2010; Marczak et al., 2013). In addition, drivers' behaviours can affect the critical gap length. An aggressive driver, for instance, may have a smaller threshold for the critical gap. However, aggressive drivers are also more likely to force their way onto the main road when they cannot otherwise find an acceptable gap (Kondyli and Elefteriadou, 2012).

On the other hand, Kondyli and Elefteriadou (2012) classified the merging manoeuvre based on traffic conditions into three states of varying gap acceptance behaviour: normal, courtesy, and forcing. During a normal merging manoeuvre, a driver looks for an acceptable gap among existing gaps on the FRL. The acceptable gap in this state should be larger than the critical gap. The courtesy state is a condition in which the driver of the merging vehicle could not find an acceptable gap, but the lag vehicle on the main road decelerates to create a proper gap and allow the subject vehicle to merge onto the main road. The courtesy state is a cooperative action between the merging vehicle and the vehicles on the main road. Finally, the forcing state is similar to the courtesy state in that there is no acceptable gap on the FRL. However, the driver of the merging vehicle forces his/her vehicle onto the freeway and induces the vehicle on the main road to decelerate to create an acceptable gap for merging. Freeway speed, availability of a proper gap, and traffic congestion are drivers' main factors before carrying out a forced merging manoeuvre (Kondyli and Elefteriadou, 2012).

Several researchers attempted to quantify the merging behaviour on freeway on-ramps. Kim et al. (2008) stated that in congested traffic conditions, the available time-gaps are less than 6.0 s. Using a dataset collected by a helicopter over two on-ramps in the Netherlands, Daamen et al. (2010) found that the minimum observed accepted gaps were between 0.75 to 1.0 s. They also noted that 83.5% of the time, the headway of merging cases was equal to or larger than 2.0 s. The same study also found that the merging location of most vehicles in free-flow conditions is located before the mid-point of the SCL, while the merging location under congested traffic conditions is more likely to be at the end of SCL. The study also showed that the accepted gap at the end of SCL is smaller than the accepted gap at the beginning of SCL, meaning that drivers at the end of SCL accept a shorter gap for merging (Daamen et al., 2010).

Speed and acceleration of merging vehicles are other important factors in merging manoeuvre. Fatema and Hassan (2013) and Fatema et al. (2014) noted that vehicles reach a specific merging speed to start a merging manoeuvre; vehicles need both a proper length of SCL and an adequate acceleration to get the merging speed on the SCL from ramp speed. Based on data collected earlier by Ahammed et al. (2008) on Highway

417 in Ottawa, Ontario, regression models were developed for the speed, acceleration, and gap acceptance behaviour of merging vehicles (Fatema et al., 2014; Fatema et al., 2015). It is also noted that Ahammed et al. (2008) had reported that a short acceleration SCL and tight ramp configuration along a freeway with high traffic volume tends to reduce the merging speed. The collected data also showed that the 85$^{th}$ percentile passenger car maximum acceleration measured on some acceleration lanes in the City of Ottawa was 2.0 m/s$^2$ (Ahammed et al., 2008). Fatema et al. (2014;2015), based on Ahammed et al.'s (2008) traffic database on 23 SCL, developed regression models to show the relationship between merging speed, merging location, and gap acceptance behaviour. Their gap acceptance models were separated into two parts; lead gap, which is the gap between the lead vehicle and the merging vehicle, and a lag gap, which is the gap between the merging vehicle and lag vehicle. They created a set of models to predict the lag, lead, and total accepted gaps, which is the gap between lead and lag vehicles, as shown in Equations 2.4-2.6 (Fatema et al., 2015). These accepted gap equations were used in this study for simulation DVs.

$$Lag_{gap} = 6.83 - 0.16 \times \mathrm{V}_M - 1.237 \times \mathrm{R}_d \quad (2.4)$$

$$Lead_{gap} = 4.108 - 0.089 \times \mathrm{V}_M - 0.689 \times \mathrm{R}_d \quad (2.5)$$

$$Total_{gap} = 9.563 - 0.216 \times \mathrm{V}_M - 1.322 \times \mathrm{R}_d \quad (2.6)$$

where,

$\mathrm{V}_M$ = merge speed (km/h), $\mathrm{R}_d$ = merge location divided on the length of acceleration lane (m/m)

## 2.9 Merging of Autonomous Vehicles

Due to the lack of traffic databases for CAVs, some studies have provided different algorithms that demonstrate how AVs or CAVs with autonomous and communication abilities could improve the traffic performance compared to DVs merging vehicles. These studies are mentioned in the following section. The top eight studies assumed a fully CAVs environment while the following three studies proposed strategies for a mixed environment of DVs and CAVs. These studies applied communication systems and cooperating techniques to solve the merging problem but did not consider other strategies such as dedicating a lane for CAVs or limited CAVs platoons.

Scarinci et al. (2017) developed a cooperative merging assistance concept with a communication system and ramp traffic signal. The proposed system first searched for available gaps on the mainline. If they were unacceptable, the system coordinated with mainline vehicles to slow down to create a large enough gap. Afterwards, the system, which waited behind the traffic signal, released the ramp vehicle. The simulation results of this coordination strategy indicated that both traffic congestion in the mainline and average travel time could be reduced.

Letter and Elefteriadou (2017) proposed a merging control algorithm where vehicles on the mainline and upstream of the merging area send their information (such as speed, location, acceleration, and vehicle length) to a controller located near to gore area via a V2I communication system. Based on the presence of a vehicle on the ramp and the information from mainline vehicles, the controller calculated the best merging location and vehicle trajectory in the communication range to ensure a conflict-free merge. The controller then transmitted the new trajectories and target speeds to the vehicles which then followed these new trajectories. This study revealed that when all vehicles are CAVs, the merging algorithm could reduce travel time on free-flow and high-traffic volume conditions by 7% to 61.4%, respectively.

Xie et al. (2017) formulated an optimal control strategy that assumed vehicles on the mainline could share their information and self-driving. The traffic condition and merging vehicles on the on-ramp were communicated upstream of the merging area. If a vehicle is on the ramp, a central system calculates and suggests an optimal trajectory for the mainline upstream vehicle. Next, the upstream FRL vehicles can decide to change lane or automatically adjust their speed by decelerating or accelerating or doing nothing. Nevertheless, vehicles could not change lanes 500 m before the gore area, nor could their speeds be changed 250 m before the gore area and should remain constant until they pass the merging area. Upon the pass, human drivers can take back responsibility for driving. The results of this strategy revealed safety and mobility could be improved, particularly at low and medium traffic conditions.

Wang et al. (2020) applied a conflict analysis at the ramp terminal using a vehicle-to-everything communication system. They analyzed this approach with two vehicles, believing that when all vehicles could communicate, the strategy would prevent conflict between merging ramp and approaching mainline vehicles by sending the location and speed of the mainline vehicle to the ramp vehicle. However, the efficiency of this model is related to the communication system and boots with the communication rate.

Karbalaieali et al. (2020) designed an adaptive merging algorithm based on a communication system that helped the merging vehicles to merge into the mainline in a complete CAVs environment. This algorithm avoids disrupting the main traffic flow and instead assists the ramp vehicles merging with less slowing down or waiting for merge at the end of SCL. Their simulation assumed the communication system worked within 300 m. It showed that when there is no safe gap for merging vehicles on the mainline, mainline vehicles were encouraged to provide a wide enough gap by decelerating, accelerating or changing lane to the left lane. The simulation results also showed how this algorithm could significantly reduce ramp delay without affecting the mainline on different traffic conditions (Karbalaieali et al., 2020).

Park et al. (2011) simulated a merging algorithm based on vehicle-to-vehicle and vehicle-to-infrastructure communication systems where every vehicle could access the communication system. This model is a lane-changing advisory system that selects mainline vehicles upstream of the merging area and orders them to change lane to the left line to provide a large enough gap for merging vehicles. The simulation results of this model, at a level of service C for mainline traffic, revealed that the proposed system could increase average mainline speed by 6.4%.

Zhu et al. (2021) developed an upper-level control strategy that coordinated ramp and mainline traffic flow using a communication system to merge areas. This strategy initially attempted to provide a large gap on the mainline by ordering mainline vehicles to decelerate. Meanwhile, ramp vehicles were encouraged to wait and create a platoon before SCL. As a final step, the model applies a coordination system and adjusts the speed and set merging location so that the ramp platoon can merge into the large gap. This study implies that this strategy could enhance traffic efficiency, such as travel time, at a 100% CAV penetration rate, especially at high traffic volume conditions.

Nakka et al. (2021) proposed a framework for coordinating CAVs upstream and along the merging area to help ramp vehicles smoothly merge into the mainline with less stop-and-go driving. The coordinator on this framework collects, shares, and saves vehicle information but does not enforce CAVs to decide. Instead, it encourages CAVs, through a rewards system so as to learn how to take optimal actions based on the previous experience of interactions saved in the system. The reward system encourages CAVs to achieve safe and high-speed travelling within a smooth and stable traffic flow.

Karimi et al. (2020) proposed a cooperative optimal merging manoeuvre for triplets' vehicles (lead and lag vehicles on the mainline and a merging vehicle) in a mixed DVs and CAVs environment. They first presented six different scenarios of merging combinations for these triplet mixed vehicles. Then, they prepared distinct phases for each combination that show how the trajectory of merging a CAV or DV into the mainline can be optimized through CAVs deceleration or acceleration. This study demonstrated that cooperative merging could support a smooth manoeuvre. However, it did not apply for a continuous traffic stream for mainline and ramp with different CAV penetration rates.

Sun et al. (2020) developed a deterministic ramp merging mechanism to reduce conflict at merging areas and to optimize merging manoeuvres for mixed traffic of DVs and CAVs. They proposed 13 possible scenarios for merging strategies. To optimize these merging strategies, the study assumed that DVs trajectories could be predicted for a short time and, by using connectivity and a cooperating system, could control the CAVs trajectories. Based on these assumptions, the authors prepared a model that can accelerate or decelerate FRL CAVs to allow ramp vehicles to merge into the mainline without conflict. The results of this study demonstrated that the proposed mechanism could help ramp vehicles smoothly merge into mainline in mixed traffic than a fully DVs environment. In addition, road capacity could increase by more than 15% in a fully CAV penetration rate.

Omidvar et al. (2020) also presented an optimization algorithm to maximize the average speed along with merging areas in a mixed environment of DVs and CAVs. They assumed CAVs could communicate by V2V and V2I communications. However, the behaviours of DVs were only tracked and recorded by roadside radars in the vicinity of the merging area. Their behaviour was predicted based on the recorded DV data. Next, the proposed algorithm relies on the predicted DVs and existing CAVs trajectories to calculate new trajectories for CAVs to maximize the average speed along the merging segment. Eight combinations of CAVs and DVs were assumed for merging manoeuvres, and the new trajectories facilitated merging manoeuvres by decelerating and accelerating CAVs on the mainline. Results revealed how this algorithm could decrease the average total travel time. However, this model would not optimize traffic operations when the CAV penetration rate is less than 25%.

## 2.10 Reliability Analysis

In this study, a reliability analysis using a probabilistic method was applied to evaluate the safety of merging strategies. Through a quantitative process, the reliability analysis can assess the uncertainty of a model and predict its probability of success or failure (Singh et al., 2007). The reliability analysis for safety evaluation is considered the probability of non-compliance (PNC) of merging manoeuvres for this study. PNC value shows the probability that a merging vehicle cannot comfortably merge to mainline before reaching the end of SCL. Comfortably merge refers to the ability to find an acceptable gap and merge without a forced manoeuvre or deceleration action on the acceleration speed change lane. PNC is a safety surrogate measure because uncomfortable merging can increase the collision probability. Fatema et al. (2014) and Kanteti (2019) found a relationship between frequency collisions data and PNC results in their study for merging areas.

Several methods were used for calculation reliability analysis, such as Monte Carlo simulation (MCS), the mean-value first-order second-moment method (MFOSM), and first- and second-order reliability method (FORM and SORM) (Singh et al., 2007). In Monte Carlo simulation, random values were generated for each uncertain input variable. Based on the expected accuracy, the generation of random values was often repeated many times. These input values using a specific model of the system could provide a large set of output data to determine the probability distribution of the model and infer the properties of the system (Singh et al., 2007). This study used the Monte Carlo method through a MATLAB program to develop a probabilistic model to assess each strategy's PNC of merging manoeuvres.

# Chapter 3: Comparison of Traffic Performance of Merging Strategies

This chapter is based on an article published in the Canadian Journal of Civil Engineering 2021 as "*Accommodation of Freeway Merging in a Mixed Traffic Environment Including Connected Autonomous Vehicles*."[3]

## 3.1 Introduction

The presence of CAVs in a mixed fleet environment during the transition period will give rise to some challenges. With shorter gaps between AVs and CAVs in the traffic stream compared to DVs, AVs and CAVs can form long platoons making lane changing manoeuvres more difficult. For example, such platoons forming on a freeway right lane (FRL) would block on-ramp vehicles from merging onto the freeway (Figure 1.1). This problem has the potential to increase conflicts and the risk of crashes at merging points.

Different strategies have been suggested in the literature to accommodate freeway merging in a fully CAV fleet environment and overcome the challenges of small FRL headway. Park et al. (2011) applied a lane-changing advisory algorithm using a connectivity system that encourages some FRL vehicles in the vicinity of the merge area to change lanes into the left lanes to create gaps large enough to accommodate merging vehicles. The simulation results for a traffic volume at level of service (LOS) C revealed that the strategy can produce around 6.4% increase in the average travel speed. Scarinci et al. (2017) applied a cooperative concept using a communication system between vehicles

[3] Pakzadnia, A., S. Roustom, and Y. Hassan. 2021. Accommodation of freeway merging in a mixed traffic environment including connected autonomous vehicles. *Canadian Journal of Civil Engineering*. 2021 (May):6. https://doi.org/10.1139/cjce-2020-0815

and road infrastructure. To release an on-ramp vehicle behind a ramp traffic signal to merge onto the mainline, the systems send a message to FRL CAVs upstream of the merge area asking them to re-arrange and increase their headways by decreasing speed to provide proper gaps for the merging vehicles. Simulation results indicated that this strategy could reduce traffic congestion on the mainline and reduce the average travel time for merging vehicles. Similarly, Karbalaieali et al. (2019) developed an adaptive algorithm in a fully CAV environment where merging vehicles can communicate with the upstream FRL CAVs to provide merging gaps by encouraging these vehicles to speed up, slow down, or change lane. The simulation results showed that using this algorithm can reduce delay for ramp vehicles and increase the travel time reliability index for the mainline. However, this merging problem has not been widely addressed in the literature for the case of a mixed traffic environment. To accommodate freeway merging manoeuvres efficiently and safely, eight viable strategies are presented as different options for traffic management in freeway merging during the period of transition from current vehicle fleet to a fully CAV fleet. These strategies are simulated in Vissim v2020 along with the do-nothing scenario to assess the comparative operational and safety performance of all proposed strategies. It should be noted that AVs without connectivity allows drivers to set different behaviour profiles (e.g., aggressive, normal, or cautious). Although such AVs have different characteristics compared to DVs (e.g., faster reaction time), their lack of connectivity makes them similar to DVs in terms of their inability to receive or send messages. Therefore, the consideration of AVs in the simulation is essentially similar to that of DVs, where more classes of vehicles can be added to the vehicle fleet with the expected AV characteristics. Therefore, this study considers the vehicle fleet to be composed only of DVs and CAVs. Although some strategies can be implemented by programming requirements in CAVs based on their location, vehicle-to-infrastructure (V2I) connectivity is the main tool to communicate the commands required for CAVs to implement the proposed strategies.

## 3.2 Methodology

As explained earlier, this study develops eight potential strategies for managing the merging process for a traffic environment assumed to be a mix of DVs and CAVs. Then, the traffic and safety performance of these strategies are evaluated using micro-simulation software to determine the optimum strategy for each traffic condition using a specific site with characteristics that represent a typical entrance ramp as the study area. In addition, Strategy 0 (S0), do nothing, is assumed as a reference condition, where vehicle automation and connectivity would help CAVs reduce their reaction time and accept shorter gaps without any traffic management protocol on speed change lanes (SCL) or FRL. Figure 3.1 illustrates the eight proposed strategies, referred to as S1–S8, described in the following sections.

### 3.2.1 S1: Allocate Large Headway for FRL CAVs

S1 involves increasing the minimum headway between successive CAVs on the entire FRL from the normal low value, which helps form tight platoons to a headway that is large enough to allow on-ramp vehicles to merge. This large CAV headway is expected to reduce the capacity of FRL at high CAV penetration rates. S1 may be effective for freeway entrances and exits with frequent short separation distances. However, it should be noted that large gaps between FRL CAVs might invite DVs from the adjacent lane to shift to the FRL within these gaps.

### 3.2.2 S2: Adjust Headways of FRL CAV Upstream of Merge Area

This strategy allows CAVs to operate with their normally small headways on FRL until they approach a merge area where CAVs start to travel with larger headways to provide adequate merging gaps. This strategy minimizes capacity reduction. The headway can be increased by vehicles in FRL decelerating or performing lane-changing manoeuvres when recognizing merge locations using V2I communication or the vehicle's GPS. Once the CAVs pass the merge areas, their headway would be restored to the original lower minimum headway. However, dissolving the CAV platoons upstream of the merge area may create a shockwave that negatively impacts the travel speed on the mainline at high traffic volumes. As in S1, DVs might change lanes to occupy the large gaps created between FRL CAVs in this strategy.

### 3.2.3 S3: Allocate Lower Desired Speed for CAVs in Merge Areas

Similar to S2, this strategy aims to dissolve FRL CAV platoons, but does so by reducing the desired speed of CAVs in the merge area, which can also be achieved using V2I communication or the vehicle's GPS. When the desired speeds are reduced to a value below the operating speed of DVs before the merge area, the gaps between the CAV platoons and DVs will increase, providing acceptable gaps for merging vehicles. The speed difference also induces some FRL DVs to change lane and move to a left lane if the next lane has acceptable gaps. Lower speeds would only be allocated for the FRL merge areas, and the original CAV desired speed would be reinstated after the merge area. This strategy requires the presence of both CAVs and DVs in traffic flow to create speed differences that lead to large gaps or prompt lane changes. Therefore, S3 is not applicable at a 100% CAV penetration rate.

### 3.2.4 S4: Prohibit CAVs on FRL

In S4, CAVs are restricted from travelling in the FRL, and only DVs can travel in the FRL, with CAVs allowed only when entering or exiting the freeway. The entire FRL is set as a CAV-restricted zone except for the segment from the gore area to the end of the SCL. However, this scenario may impact the traffic flow for the other lanes at high CAV penetration rates or may cause most DVs to travel on the FRL, thus reducing the number of large gaps. S4 can only be utilized in a mixed vehicle environment, where DVs are available to utilize the FRL.

### 3.2.5 S5: Prohibit CAVs in FRL in the Merge Area

This strategy is similar to S4, where CAVs may be restricted from travelling in the FRL in the merge area. However, unlike S4, CAVs are free to travel in the FRL before and after the merge area. This strategy requires setting a segment upstream of the gore area as a CAV-restricted zone, forcing the FRL CAVs to change lane before the merge area. However, depending on the percentage of CAVs in the traffic flow and the total traffic volume, not all FRL CAVs would necessarily be able to move away from the FRL, depending on the ability of the left lanes to absorb this traffic volumes. In addition, at high traffic volume, forcing CAVs to change lanes away from the FRL before the merge area and then returning to the FRL after the merge area may increase traffic conflicts around the merge area and reduce travel speed on the mainline.

### 3.2.6 S6: Restrict the Size of CAV Platoons

In S6, the size of the CAV platoons is limited to a specific number of vehicles to prevent long platoon formation with small intra-platoon headways on the FRL. The gap between successive restricted platoons would then accommodate merging manoeuvres.

The maximum platoon size is set based on the on-ramp traffic volume and the required frequency of acceptable gaps in the FRL. This frequency would, in turn, depend on the freeway traffic volume and the percentages of DVs and CAVs. A V2I system can recognize the traffic volumes of the freeway and ramp and authorize the maximum size of a platoon of CAVs. This strategy can be effective at high CAV penetration rates, where frequent large gaps are created between frequent limited-size platoons. However, at high traffic volumes and low CAV penetration rates, the gaps between CAV platoons are likely to be occupied by DVs.

### 3.2.7 S7: Use Ramp Metering for Ramp Vehicles

In S7, a traffic signal is set on the ramp to control the flow of on-ramp vehicles. Ramp vehicles are only allowed to merge on the freeway when an acceptable gap is available in the FRL. Because Since DVs do not have a connectivity system, a camera or pavement sensor can check and detect the availability of acceptable merging gaps in the FRL upstream of a ramp terminal. The location of the instruments is determined based on the average speed of the freeway and travel time of the ramp vehicle from the ramp traffic signal to the merging point. This strategy prioritizes traffic on the mainline and causes the least interruption to the mainline traffic. Therefore, it is expected to be appropriate if the merging traffic is relatively low, whereas a high ramp traffic volume could produce significant delays and long queues on the ramp. Another benefit of this strategy for mainline traffic is that ramp metering reduces the probability of ramp vehicles merging at low speed.

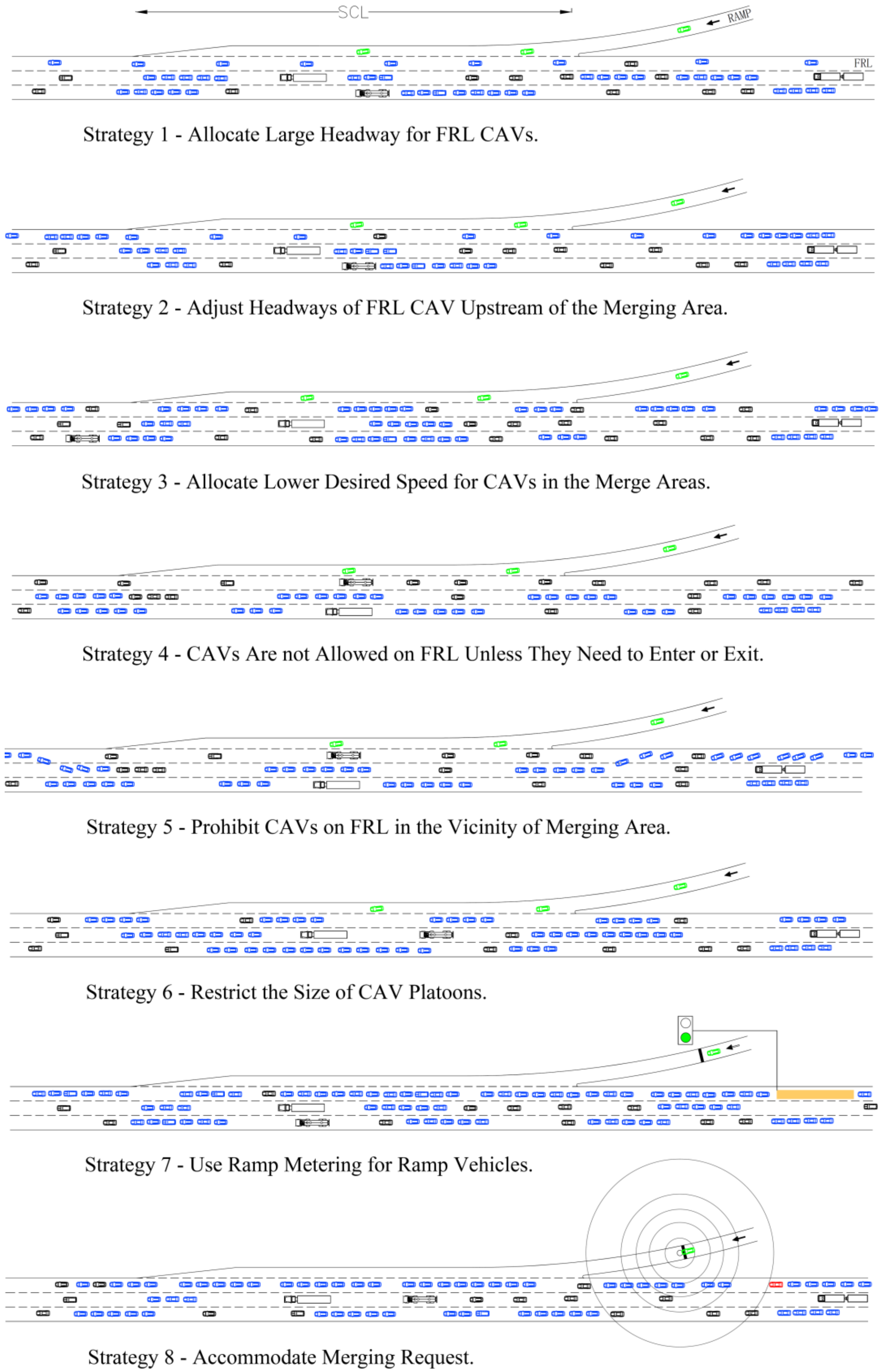



**Figure 3.1 Configuration of proposed strategies.**

### 3.2.8 S8: Accommodate Merging Requests

In S8, the CAVs on the ramp communicate with the CAVs on the FRL to request merging. Because ramp DVs lack the connectivity required to make such a request, sensors may be required on the ramp to send merging requests, especially at low CAV penetration rates. When a ramp-vehicle requests merging with the FRL and there is no sufficient gap between the FRL CAVs, some CAVs will try to change lanes. If a lane change is not possible, the CAV platoons try to create larger headways among vehicles within the platoon by accelerating or decelerating individual CAVs. In simulating this strategy, Vissim allows courtesy merging, but it is not necessarily performed by all vehicles. In addition, Vissim does not use vehicle connectivity for traffic management. Therefore, an external Python script was created to set the V2I communications and the characteristics of the CAVs in the platoon once a merging accommodation is requested. Similar to S1, S2, and S6, it is possible that a larger gap created in the FRL to accommodate a merging vehicle is occupied by a DV shifting from an adjacent lane, particularly in high traffic volumes[4].

## 3.3 Traffic Microsimulation

Traffic microsimulation in PTV Vissim with an external COM interface programming was performed to evaluate the performance of each strategy. Vissim v2020, used in this study, was capable of directly simulating all strategies using internal

[4] S8 or cooperative merging strategy is a highly complex strategy. In this strategy, CAVs need to communicate directly or through roadside infrastructures to other CAVs. In both ways, a traffic control centre is required to define the rules of this traffic management strategy in different traffic conditions. In addition, enforcing CAVs to obey the cooperating merging rules may require providing and approving new traffic laws and regulations. Until that, the CAVs might only voluntarily cooperate to provide an acceptable gap for merging vehicles. Therefore, tasks other than vehicle automation are required to implement this strategy, which is beyond this study.

parameters except for S7, which required the development of a signal control logic using VisVap, and S8, which required a COM interface to process the merging requests and command CAVs to accommodate them.

The simulation results were analyzed to assess the efficiency of each strategy based on traffic performance measures, including travel time and traffic volume, which cannot be accommodated by the road segment. In addition, the percentage of vehicles with a low merging speed (VLMS) was extracted as a surrogate safety measure to identify potentially unsafe merging manoeuvres. The VLMS percentage was estimated as the percentage of merging vehicles that slow down on the SCL to merge on the freeway below a specific speed threshold. This behaviour is generally not expected for drivers who attempt to accelerate while merging onto the FRL, and the potential for collisions is expected to increase with an increase in VLMS[5].

All eight strategies plus S0 (do-nothing) were simulated. Traffic parameters affecting traffic operations include

- Traffic volume:
  - Different freeway traffic volumes were selected for the simulations, based on the thresholds of LOS D and E. These thresholds were calculated as 2,100 and 2,400 pc/h/ln, respectively, according to the Highway Capacity Manual (TRB, 2016)[6]. In addition, as the capacity of freeway segments is expected to increase with increasing CAV penetration rate, a 20% increase in the LOS E threshold, resulting in a volume of 2,880 pc/h/ln, was selected as the new LOS, named E*.

[5] See Appendix A. Section A.9 presents the relationship between the percentage of PNC and percentage of VLMS
[6] See Appendix A. Section A.1 presents the calculation of maximum traffic volume for LOS D and E.

- Two values of ramp traffic volumes (400 and 1,300 pc/h)[7] were selected to correspond to high and low merging volumes on the main freeway within the City of Ottawa, Canada, used as the study area for this study (Ahammed et al. 2008).

- The design speed of the freeway is 110 km/h.
- Preliminary results indicated that the performance was not very sensitive to changes in the ramp design speed. Therefore, ramp design speeds of 40 and 80 km/h were used to provide a wide range of possible design ramp speeds.
- Four different CAV penetration rates were considered: 25, 50, 75, and 100%. A 0% CAV penetration rate was also considered in S0 (do-nothing) to represent the current conditions as a basis for comparison.
- Three traffic arrival types based on random simulation seeds (22, 32, and 42) were selected for the simulation runs.

Consequently, 48 different scenarios (three freeway volumes × two ramp volumes × two ramp speeds × four CAV penetration rates) were simulated for each strategy, except S3–S5. As explained earlier, a 100% CAV penetration rate was not relevant to these strategies. For S3–S5, only four CAV penetration rates were simulated resulting in 36 scenarios. An additional 0% CAV penetration rate was simulated for S0, resulting 180 simulation runs corresponding to 60 different S0 scenarios. Therefore, 1,224 simulation runs[8] corresponding to 408 simulation scenarios were performed in this study.

[7] See Appendix A. Table A.1 in Section A.2 presents the combinations of assigned traffic volumes for simulations.
[8] See Appendix A. Table A.2 in Section A.2 presents the numbers of the different simulation runs.

## 3.4 Study Site

Highway 417 is the main freeway in the City of Ottawa, Canada, with a posted speed limit of 100 km/h. The freeway on-ramp from St. Laurent northbound to Highway 417 westbound (Figure 3.2) was used as the typical ramp entrance in this study. The ramp terminal comprises a loop ramp and 295 m tapered SCL. Because the SCL length matches the TAC (2017) design guidelines, the results of this study should be applicable to many similar locations. It should be noted that the ramp design is controlled by the ramp design speed and is reflected in the vehicle operating speed on the ramp and beginning of the SCL. By considering taking the ramp design speed as a variable in the simulation scenarios, the results would not be restricted to the loop ramp design of the study site. Finally, there are six freeway lanes at the selected site (three per direction), and it is expected that increasing the number of lanes will not have a significant effect on the generality of the results.

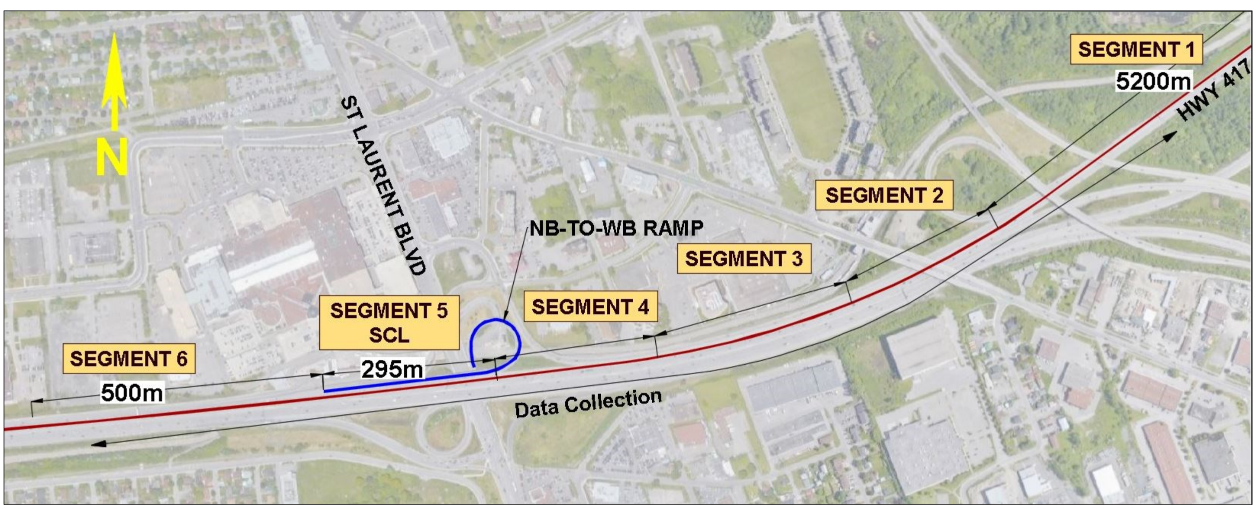



**Figure 3.2 Plan of the study site (Maps data: Google © 2021 CNES Airbus Maxar Technologies).**

As shown in Figure 3.2, the study section was divided into six segments for simulation strategies.

- The first is 5.2 km long and ends 900 m before the ramp area to provide enough distance for a minimum of four CAVs to form a platoon. The length was calculated based on a 35 pc/mi/ln (22 pc/km/ln) density at LOS D with an average headway distance of approximately 46 m.
- The next three segments are also upstream of the SCL and function as spaces to manage CAV traffic behaviour and change the minimum headway or desired speed depending on the selected management strategy. The segments are explained in the following section.
- The fifth segment, which is 295 m long, is along with the SCL.
- The sixth segment is downstream of the SCL and is 500 m long, which is slightly longer than the HCM recommendation for a merge influence area of 450 m (TRB 2016). This distance allows CAVs to resume their original driving behaviour.

## 3.5 Simulation Requirements

To simulate the proposed strategies, the default traffic behaviour parameters in the simulation software were calibrated based on the study by Wang and Gu (2019) and the local traffic behaviour[9]. In addition, as explained earlier, S7 and S8 required external programming for traffic management. This section explains all the requirements implemented to run the simulations for this study. Each simulation was run for one hour following a 15 min warm-up period.

---

[9] See Appendix A. Section A.3 presents the detailed procedure of Vissim calibration.

### 3.5.1 Vehicle and Driver Behaviour Characteristics

This study considered only passenger cars[10] in the simulations and parameters to be calibrated for DVs or predicted for CAVs. The distribution of vehicle lengths was selected based on the distribution of vehicle models representing the top 31 selling vehicles in Canada over a 12-month period between February 2018 and 2019. Together, these vehicles accounted for almost 56% of the total Canadian vehicle sales in this period, while each of the remaining 240 vehicles accounted for less than 1% of sales. Based on the lengths of these vehicles, vehicles in the simulation were categorized into seven groups, as listed in Table A. 5[11]

The minimum reaction time and headway for DVs, 0.5 and 1.0 s, respectively, were selected based on the work of Taieb-Maimon and Shinar (2001). For CAVs, Ploeg et al. (2011) noted that a minimum headway within a CAV platoon can be less than 0.5 s when the wireless link is optimized. The 0.5 s value was used as the minimum CAV headway for this study. The driving behaviour of the DVs and CAVs was modified to allow courtesy merging in the simulation.

The desired speed on the mainline lanes of this study area for the DVs was chosen based on the speed distribution of the sample collected from the UAV videos (Figure A.1[12]). A normal speed distribution was assumed for ramp vehicles, with the mean

---

[10] Heavy CAVs can act the same as small CAVs. For example, they can keep a specific following gap. However, heavy vehicles have different acceleration and deceleration rates than small vehicles. Therefore, heavy vehicles may need more time for some driving manoeuvres, such as lane changing, braking, or reaching the desired speed. Thus, in some strategies such as S1, S2, and S6 where a specific headway would be assigned for CAVs, the heavy vehicle headway may require longer than passenger CAVs. Moreover, for S5 and S8 where a lane changing may be required to provide an acceptable gap for merging vehicles, the lane changing time for heavy vehicles must be considered longer than the required time for passenger CAVs.

[11] See Appendix A. Section A.5.

[12] See Appendix A. Figure A.1 in Section A.3 presents the cumulative speed distribution of mainline vehicles on a Highway 417 segment.

and standard deviation for the design speeds (40 and 80 km/h) estimated based on a previous study on Highway 417[13] (Fatema and Hassan, 2013).

### 3.5.2 Traffic Management in S7 and S8

As explained earlier, S7 uses ramp metering to allow on-ramp vehicles to merge on the freeway when an appropriate gap is detected in the FRL. This control strategy was built in simulation using VisVAP, a user-friendly tool for defining signal control logic using the vehicle actuated programming language. The flowchart created for S7 in VisVAP causes the ramp traffic signal to open when the detector on FRL detects a minimum gap of 0.8 s (equivalent to 1.0 s headway), allowing a single vehicle to pass and complete a merging manoeuvre[14]. The minimum 0.8 s gap was determined to be optimal by trial and error.

A collaborative merging model was developed to simulate S8, which uses vehicle connectivity to send a merge request and provide an acceptable gap for the merging vehicle in a mixed traffic environment (Figure A.3[15]). The model was translated into a COM interface program using Python.

### 3.5.3 Management of Traffic Behaviour on FRL

Depending on the control strategy selected, some vehicle parameters are varied on FRL compared to the other freeway lanes (cross-sectional variation) and/or at the merge area compared to upstream and downstream of the merge area (longitudinal variation). To avoid shockwaves, longitudinal variations in vehicle parameters on the FRL are introduced

---

[13] See Appendix A. Table A.4 in Section A.4 presents the predicted mean speeds and standard deviations for ramp and mainline.
[14] See Appendix A. Figure A.2 in Section A.6 presents the flowchart of ramp metering in VisVap.
[15] See Appendix A. Figure A.3 in Section A.7 presents the flowchart of collaborative merging model utilizing vehicles' connectivity.

gradually within different segments upstream of the merge area (as described in Table 3.1). The assumed values in Table 3.1 are explained as follows.

- A selected headway of 2.0 s for S1 and S2 can be an acceptable gap for CAVs at an average speed of 100 km/h based on a CAV lane change model and the laws of kinematics.
- An acceptable headway of 2.0 s for the merge area on the FRL can be provided for S3 by a 9 km/h speed differential between DVs and CAVs within 900 m at an average CAV speed of 100 km/h.
- In S5, a 600 m segment is required to allow a high CAV volume to switch lanes before the merge area. Shorter segments will not allow CAVs to change lanes safely without creating shock waves.
- The platoon size for ramp traffic volumes of 400 and 1,300 pc/h is assumed as follows:
    - The average headway for a traffic volume of 400 pc/h is 9.0 s, which means there should be an available gap for merging vehicles every 9.0 s on the FRL. Based on the average car length and operating speed on the freeway, a platoon of 14 vehicles could provide sufficient gaps to accommodate ramp vehicles.
    - The average headway for a traffic volume of 1,300 pc/h is 2.77 s; thus, the size of the platoon on the FRL is assumed to be two vehicles.
- The headway detector in S7 was placed 190 m from the gore point to allow ramp vehicles to build enough speed to merge with the FRL vehicles.

- A 200 m segment was used in S7 to prevent right lane changes and disturbances in headway detection. Any vehicle that merges onto the FRL after the detector cannot be detected.

**Table 3.1 Segment accommodations for simulation strategies.**

| Strategy | Segment 2 (300 m) | Segment 3 (300 m) | Segment 4 (300 m) | Note |
|---|---|---|---|---|
| **S1** | $h_{min}$ for segment 1, 2, 3, 4, and 450m after segment 5 is set to 2.0 s. | | | After gore area, along with segment 5 and 450 m after that the $h_{min}$ for FRL is set to 0.5 s. $h_{min}$ for other freeway lanes is set to 0.5 s. |
| **S2** | Increase $h_{min}$ from 0.5 to 1.0 s | Increase $h_{min}$ from 1.0 to 1.5 s | Increase $h_{min}$ from 1.5 to 2.0 s | Gradually dissolving CAV platoon on FRL upstream the merge area. After gore area, 0.5 s $h_{min}$ is restored |
| **S3** | Reduce max. desired speed of CAVs by 3.0 km/h | Reduce max. desired speed of CAVs by another 3.0 km/h | Reduce max. desired speed of CAVs by another 3.0 km/h | Gradually increase speed differential between CAVs and DVs upstream of the merge area. After the merge area, the speed differential will be removed. |
| **S4** | CAVs are not allowed to use FRL upstream the gore area | | | At the merge area, merging CAVs will merge into FRL and use it until they have chance to change to the freeway middle lane. |
| **S5** | CAVs use the FRL as a travel lane | CAVs are not allowed to travel on the FRL | | After the merge area, CAVs can use the FRL as a travel lane. |
| **S6** | Max. platoon size is set to 14 vehicles for ramp traffic volume of 400 pc/h, while for ramp traffic volume of 1300 pc/h, max. platoon size is set to 2 vehicles. | | | The gap between CAV platoons is set to 1.8 s, an acceptable gap for merging vehicles. |
| **S7** | 700 m: no accommodations | | 200 m: no left lane changes are allowed into the FRL. | Headway detector was located 190 m before gore point on FRL and traffic signal was located 20 m before gore point on the entrance ramp. |
| **S8** | No accommodations | 600 m: CAVs can receive merging requests and decide to decelerate, accelerate, or switch lanes to provide an acceptable gap for merging vehicles. | | A merging vehicle can request for an acceptable gap from CAVs on FRL, based on the communication system. |

- A 600 m segment before the merge area is required in S8 to allow CAVs to decide whether they need to accelerate, decelerate, or switch lanes without causing shockwaves. The length is also required for CAVs to safely switch lanes.

## 3.6 Collecting Simulation Data

Detailed vehicle trajectories containing the values of different variables such as speed and travel lane are collected every 0.5 s for each vehicle in the simulations. In addition, data were collected for travel time for each vehicle along a 2,300 m segment of the freeway (1,600 m before and 700 m after the gore point) and on an 895 m length of the ramp (195 m before and 700 m after the gore point). As mentioned earlier, the average travel time for both mainline and ramp vehicles and the percentage of merging vehicles with merging speed below a specific threshold (VLMS) were selected as performance measures to evaluate and compare the traffic operation and safety of the different strategies. Finally, the difference between the traffic volume assigned upstream of the merge area and the actual number of vehicles counted downstream the merge area serves as a measure of the unaccommodated traffic demand. This measure, referred to as the drop in road capacity, is estimated for each simulation run.

## 3.7 Results and Discussion

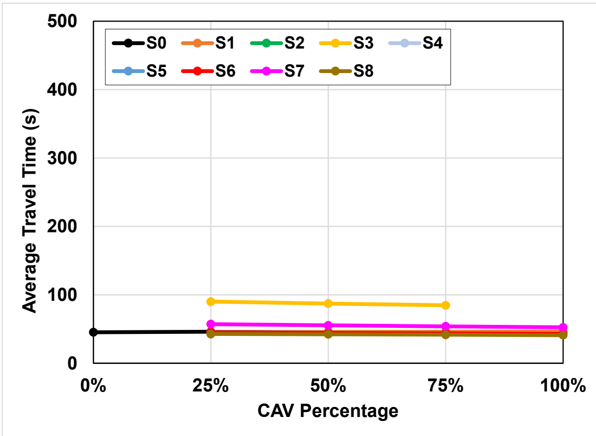
This section summarizes the main findings based on the average results of the three seed numbers for each simulation scenario.

### 3.7.1 Average Ramp Travel Time

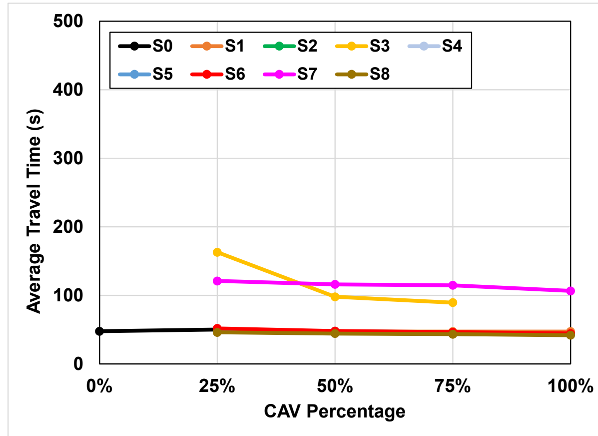
Figure 3.3 presents the results of the average travel times for ramp vehicles for all strategies (S0–S8) simulated with a ramp design speed of 40 km/h[16] at LOS D, E, and E*. The main findings are as follows.

- In general, at LOS D, most strategies had similar ramp travel times, with values almost independent of the CAV penetration rate. In this scenario, S3 had noticeably higher ramp travel time regardless of the ramp traffic volume. S7 was expected to increase the ramp travel time, and this trend was confirmed for low freeway traffic volumes, with almost all other strategies outperforming S7.
- As the freeway traffic volume increases, the differences between scenarios become more pronounced, particularly in cases with a high ramp traffic volume. Even in these cases, as the CAV penetration rate increases, the ramp travel time generally decreases, and all strategies ultimately converge to a narrow range of ramp travel time at 100% CAV penetration. This is because CAVs can use smaller gaps to merge. Additionally, 100% CAV penetration increases the number of vehicles in the CAV platoons and the frequency of large headways between these CAV platoons. It is also noted that, as the freeway traffic volume increases, S7 starts to perform better than the other strategies.
- At LOS E and E* with high ramp traffic volume. S2 outperforms other strategies for ramp travel time, S2 also outperforms S1 at high ramp traffic volumes, as the CAV desired headway on FRL is restored to a low value after the merge area in S2.

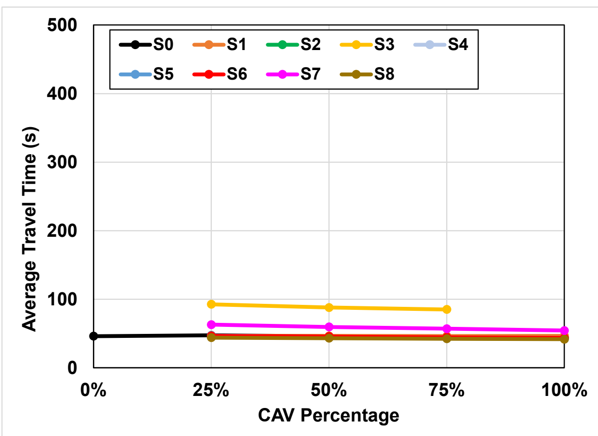
[16] See Appendix A. Figure A.4 in Section A.8 presents the average ramp travel time results for 80 km/h ramp design speed.



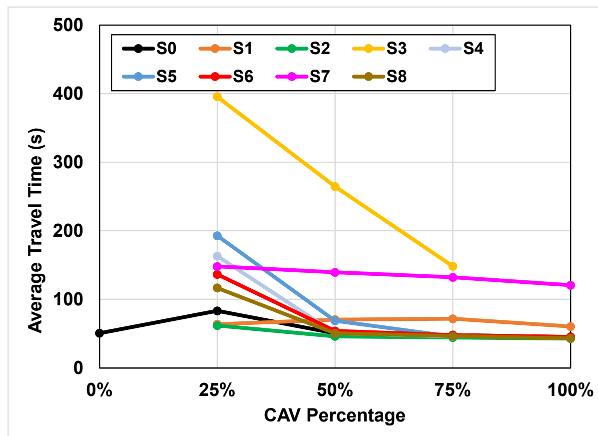

(a) LOS D, ramp volume = 400 pc/h.



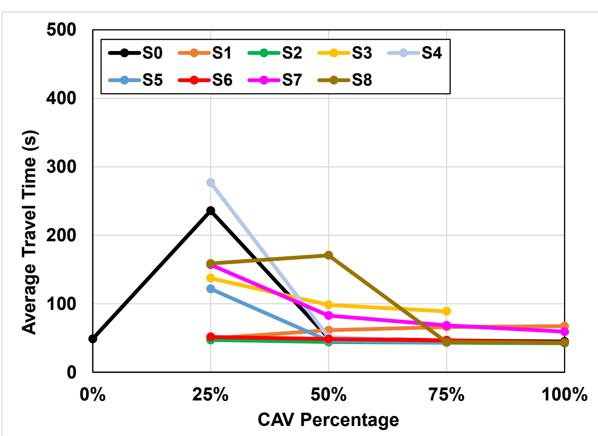

(b) LOS D, ramp volume = 1,300 pc/h.



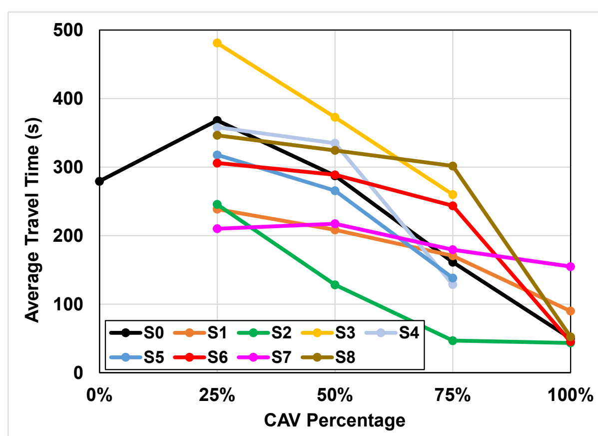

(c) LOS E, ramp volume = 400 pc/h.




(d) LOS E, ramp volume = 1,300 pc/h.




(e) LOS E*, ramp volume = 400 pc/h.




(f) LOS E*, ramp volume = 1,300 pc/h.

**Figure 3.3 Average travel time for ramp vehicles (40 km/h ramp design speed).**

This reduction in desired headway can help reduce the travel time for merging vehicles that do not have to adjust their behaviour if they stay on the FRL.

- At LOS E* and 25% CAV penetration rates, most strategies show better results than S0. However, with the increasing ramp traffic volume and CAV penetration rate, only S2 and S5 outperformed S0. S1 and S3, which impose more restrictions on the CAVs in the FRL even after the merge area, do not perform as well as S2 and S5; as in the former strategies, merging vehicles must adapt their behaviour to restrictions beyond the merge area.
- S4 and S5 were expected to have the lowest ramp travel times, as the FRL would be free from platoons with small intra-headways around the merge area, however, the results of the simulation show that this was not the case. This phenomenon may be owing to the increased DV volume in the FRL to balance the traffic volumes on all mainline lanes in S4. As the CAV penetration rate increases, the ramp travel time in S4 decreases, because fewer DVs were available in the traffic stream to occupy the FRL. However, this improvement in ramp travel time is likely to occur at the expense of a higher travel time for freeway traffic. For S5, the conflicts resulting from the CAVs shifting back to the FRL after the merge area may reduce the FRL operating speed. Creating another segment for the FRL after the merge area where CAVs are not allowed to switch back for a certain length might enhance the performance of S5.
- In high traffic volume conditions, the minimum DVs headway of 1.0s is not adequate for merging vehicles, and there are insufficient acceptable gaps among DVs. However, in S5, which aimed to prevent CAVs on FRL only in the vicinity

of the merge area, DVs do not have enough time to switch lanes onto the FRL to re-balance traffic lanes in the vicinity of the merge area, so there were fewer DVs on FRL and more acceptable gaps than in the S4 scenario.

- Increasing the design speed of the ramp from 40 km/h to 80 km/h resulted in a slightly lower travel time for ramp vehicles in most scenarios.

### 3.7.2 Average Freeway Travel Time

Figure 3.4 summarizes the results of the average travel time for freeway vehicles (referred to as the freeway travel time) for a ramp design speed of 40 km/h[17]. Similar to ramp travel time, most strategies had very close results for freeway travel time at LOS D, with values almost independent of the CAV penetration rate. Again, S3 had a noticeably higher freeway travel time regardless of the ramp traffic volume, which is expected given the reduction in the CAVs' desired speed on the FRL.

- Again, the differences between the scenarios become more pronounced as the freeway traffic volume increases, especially when a high ramp traffic volume is also present. Even in these cases, as the CAV penetration rate increases, the freeway travel time generally decreases, and all strategies ultimately converge to a narrow range of freeway travel time at 100% CAV penetration apart from some strategies at LOS E*.
- At LOS D and E, S8 slightly outperforms the other strategies for the mainline vehicles. This may not be an expected outcome; however, but the small difference

[17] See Appendix A. Figure A.5 in Section A.8 presents the average freeway travel time results for 80 km/h ramp design speed.

between most strategies does not appear substantial and may not indicate an actual trend.

- For a high freeway traffic volume (LOS E*), different strategies appear to be favourable at different CAV penetration levels.
- Generally, S7 has the lowest freeway travel time because ramp metering prioritizes travel on the freeway mainline lanes. For example, for LOS E*, 1,300 pc/h ramp volume, and 25% CAV penetration rate, S7 produces the lowest ramp and freeway average travel times with a difference of over 170 s when compared to S0 for the ramp travel time (an approximately 45% reduction) and 80 s for the freeway travel time (48% reduction). However, not all on-ramp vehicles were able to merge because of the queue building behind the traffic signal, and at a high ramp traffic volume and LOS E*, approximately 60% of the ramp vehicles (780 out of 1,300 vehicles) were not able to merge onto the FRL.
- The worst performing strategies were S1, S3, and S5. S1 performed poorly overall, especially at a CAV penetration rate of 25% a with high ramp traffic volume, which may have resulted from the need for FRL CAVs to keep adjusting their speed to maintain the 2.0 s minimum headway when a ramp vehicle merges onto the FRL. S5 had the worst results at LOS E* and a high CAV penetration rate because of the congestion created by the shifting of the CAVs to the freeway middle and left lanes. S4 offered better freeway travel time results on high traffic volumes than S5 because there are fewer lane-changing conflicts.

### 3.7.3 Drop of Road Capacity[18]

As previously mentioned, the drop in road capacity was estimated as the difference between the traffic volume assigned upstream of the merge area and the actual number of vehicles counted in the simulation downstream of merge area.

Table 3.2 summarizes the simulated results of the percentage drop in capacity for both the freeway mainline lanes and ramp. For each combination of LOS on the freeway mainline and ramp traffic volume, the maximum drop in capacity for CAV penetration rates of 25% and 50% is shown as the value for low CAV penetration (L), whereas the maximum value for CAV penetration rates of 75% and 100% is shown as the value for high CAV penetration (H). Higher capacity drops are experienced with low CAV penetration.

### 3.7.4 Vehicles with Low Merging Speed

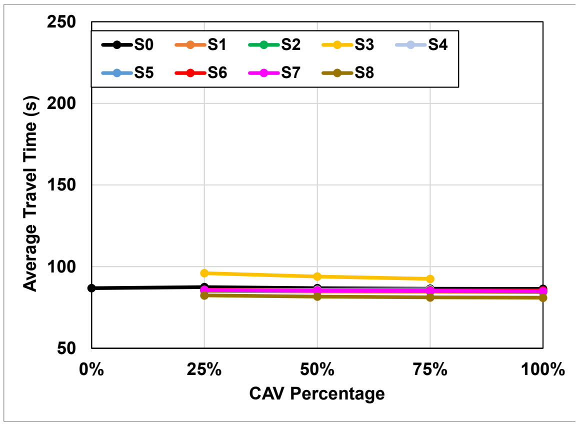
As noted earlier, the percentage of VLMS is analyzed as a surrogate safety measure to assess the relative safety performance of the proposed strategies. A low merging speed or speed reduction at the merging point is an unexpected driver behaviour that creates a potentially unsafe high-speed differential between the merging vehicle and other vehicles on the FRL. Therefore, a high percentage of VLMSs is expected to indicate a poor merging strategy. Figure 3.5 illustrates the percentage of VLMS for a ramp design speed of 40 km/h[19]. The threshold for these graphs is a merging speed of 30 km/h. The main observations from these graphs can be summarized as follows:

---

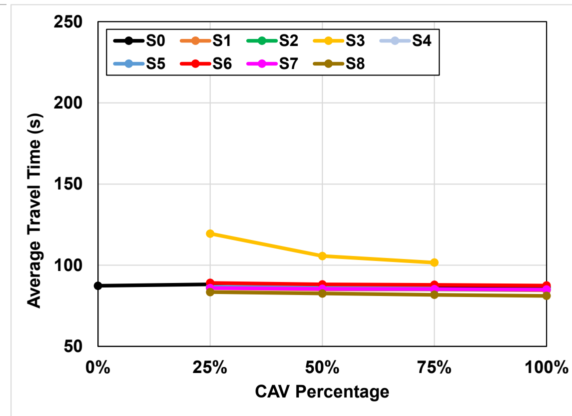
[18] This thesis was focused on evaluating different strategies under different traffic conditions, including demand volume. Capacity is defined as a maximum hourly flow rate under a sustainable condition. Therefore, this is not a capacity in terms of the maximum volume that can travel through the section, but it is observed throughput for the scenarios under different conditions.

[19] See Appendix A. Figure A.6 in Section A.8 presents the percentage VLMS, speed threshold of 30 km/h for 80 km/h ramp design speed.

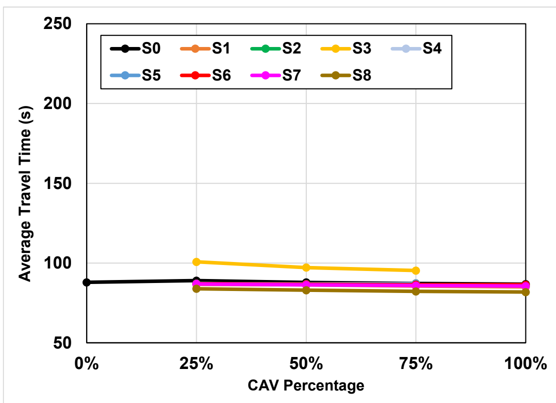
- Similar to the travel time results, most strategies had very close results of VLMS at LOS D, with the exception of S3.
- In almost all scenarios, the worst performing strategy was S3, with the difference being more pronounced at high ramp traffic volumes. Most of the other strategies performed slightly better than S0. At a 100% CAV penetration rate, all the strategies show similar results.
- In general, most ramp vehicles were able to merge at a speed higher than the selected threshold of 30 km/h in S7, as ramp metering in this strategy allowed merging only when an acceptable gap was detected in the FRL. The released ramp vehicle could utilize the SCL to speed up before merging into the available gap.
- For LOS E and E*, a spike in VLMS is noted for most strategies, depending on the traffic volumes on the freeway and ramp, including S0 at 25% or 50% CAV penetration. For most strategies, this spike diminishes at 100% CAV penetration. This trend matches the trends of ramp and freeway travel times, which also spike for some strategies at low CAV penetration, and then decrease when the whole vehicle fleet is a CAV.
- At a high traffic volume (LOS E*), many strategies are noticeably more favorable than S0. For example, for a ramp traffic volume of 400 pc/h, S1, S2, S5, and S7 have at least a 5% lower VLMS than S0. This difference is approximately 60% for S2 and 55% for S1 and S7 at 25% CAV penetration.



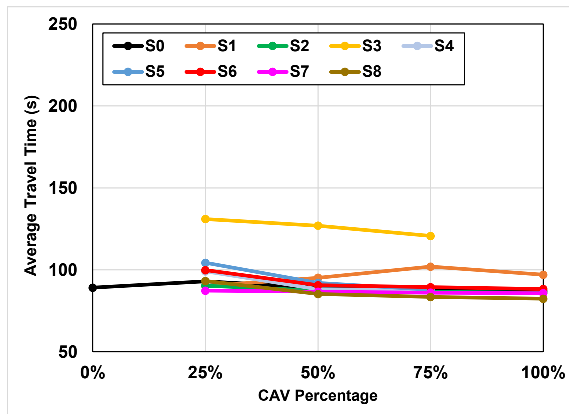

(a) LOS D, ramp volume 400 pc/h.



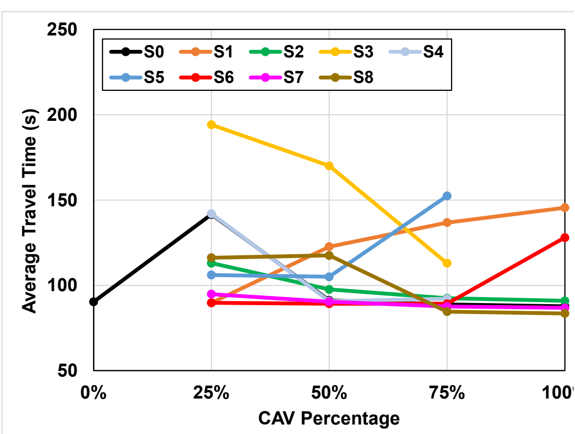

(b) LOS D, ramp volume 1,300 pc/h.



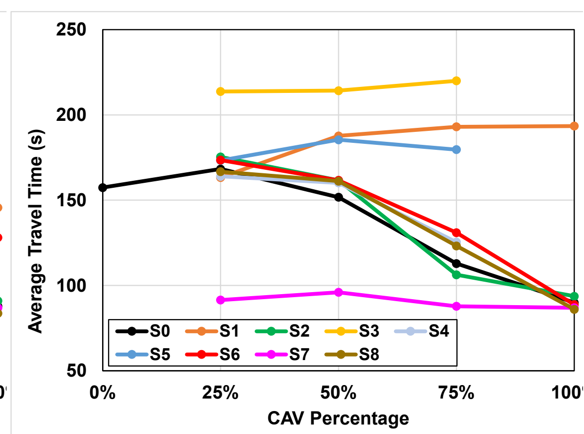

(c) LOS E, ramp volume 400 pc/h.




(d) LOS E, ramp volume 1,300 pc/h.




(e) LOS E*, ramp volume 400 pc/h.




(f) LOS E*, ramp volume 1,300 pc/h.

**Figure 3.4 Average travel time for freeway vehicles (40 km/h ramp design speed).**

**Table 3.2. Drop in freeway mainline and ramp capacity (ramp design speed 40 km/h).**

| Mainline LOS | D | | | | E | | | | E* | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Ramp traffic volume (pc/h) | 400 | | 1300 | | 400 | | 1300 | | 400 | | 1300 | |
| CAV penetration | L | H | L | H | L | H | L | H | L | H | L | H |
| S0 | -/- | -/- | -/- | -/- | -/- | -/- | -/- | -/- | 4/6 | 6/- | 8/46 | -/3 |
| S1 | -/- | -/- | -/- | -/- | -/- | -/- | -/23 | 1/- | 6/- | -/- | 12/23 | 16/6 |
| S2 | -/- | -/- | -/- | -/- | -/- | -/- | -/- | -/- | 1/- | -/- | 11/24 | -/- |
| S3 | -/- | -/- | 1/- | -/- | -/- | -/- | -/47 | -/2 | 11/1 | -/- | 14/57 | 12/22 |
| S4 | 2/- | -/- | -/- | -/- | -/- | -/- | -/5 | -/- | 7/5 | -/- | 11/45 | 4/7 |
| S5 | -/- | -/- | -/- | -/- | -/- | -/- | -/14 | -/- | 5/3 | 5/- | 13/38 | 9/8 |
| S6 | -/- | -/- | -/- | -/- | -/- | -/- | -/2 | -/- | 7/- | 15/- | 12/38 | 13/36 |
| S7 | -/- | -/- | -/39 | -/37 | -/- | -/- | -/50 | -/44 | 5/2 | -/- | 6/65 | -/58 |
| S8 | -/- | -/- | -/- | -/1 | -/- | -/- | -/6 | -/1 | 5/6 | -/- | 11/45 | 1/41 |

Low and high CAV penetration refer to rates of up to 50% and greater than 50%, respectively; numbers in each cell are the percentage of capacity drop for mainline/ramp; values < 1% are replaced with "-."

- The proposed strategies S2 and S7 can reduce VLMS by approximately 75% at LOS E* and a ramp traffic volume of 1,300 pc/h, including 75% of CAVs.
- S8 at LOS E* and 400 ramp traffic volume with a 50% CAV penetration rate shows a high VLMS value compared with S0. This is due to the relatively high volume of DVs on the FRL that do not receive a merging request and do not adjust their behaviour to accommodate this request.

### 3.7.5 General Notes

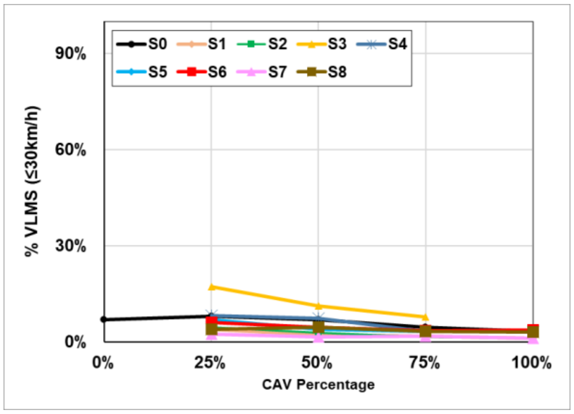
It is believed that an increase in CAV adoption or penetration rate would increase road capacity (Fragnant and Kockelman 2015). However, at high traffic volumes (more than the current threshold of LOS E), the presence of CAVs at relatively low penetration rates (up to 50%) can create traffic congestion in merge areas and reduce travel speeds for both ramp and freeway vehicles. As shown in Figure 3.3 and 4, both ramp and freeway vehicles experience a spike in travel time at a 25% CAV penetration rate with a high freeway traffic volume (LOS E*) if no traffic management is applied. This spike diminishes as the CAV penetration rate increases.

Based on the results of the freeway and ramp travel times, the do-nothing alternative (S0) can be acceptable for LOS D and E. However, S0 may lead to safety issues at LOS E with high ramp traffic volumes when the CAV penetration rate is low (up to 50%). A management strategy should be adopted to improve the travel time and safety for LOS E* and a CAV penetration rate below 100%. The best strategies that can be implemented for different combinations of traffic volumes and CAV penetration rates are summarized in Table 3.3[20].

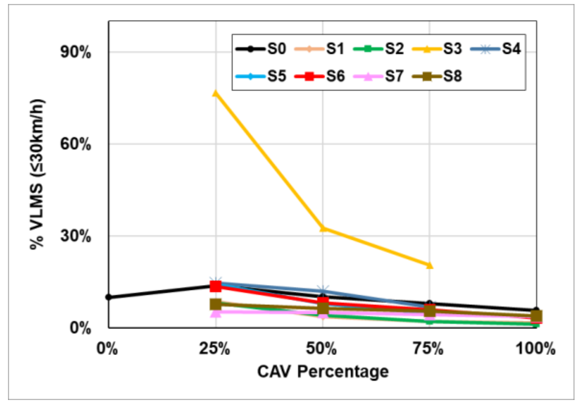
### 3.8 Conclusions

It is expected that CAVs will have very short reaction times, allowing them to form platoons with minimal gaps. Although this travel pattern is expected to increase road capacity, it will cause complications for vehicles merging from on-ramps to freeways. Eight different strategies were proposed to create acceptable merging gaps in the FRL or resolve the expected merging conflicts. Simulations of these strategies were tested with different CAV penetration rates, mainline LOS, and ramp volumes. Different measures of performance were compared, including average travel time, unaccommodated demand on the freeway mainline and ramp, and the percentage of ramp vehicles that merge below a specific speed threshold (VLMS).

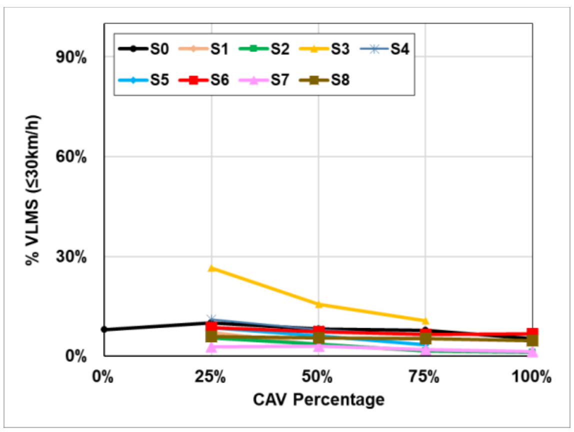
[20] The capacity drop measure indicates that due to a high traffic volume in LOS E* and restrictions imposed by some strategies, all assigned vehicles to the system may not pass through the merging area within the simulation time. This problem might happen because of traffic congestion and a shockwave. The vehicles that could not pass through the merging section might be queuing upstream of the merging area or be in the simulator's memory waiting for an opportunity to be released to the system, and in the end, they were taken into account as a capacity drop. Therefore, those strategies that can not allow all assigned traffic volumes to pass through the merging area in specific traffic conditions, such as high traffic volumes, would not be considered a solution for that scenario during transition time.



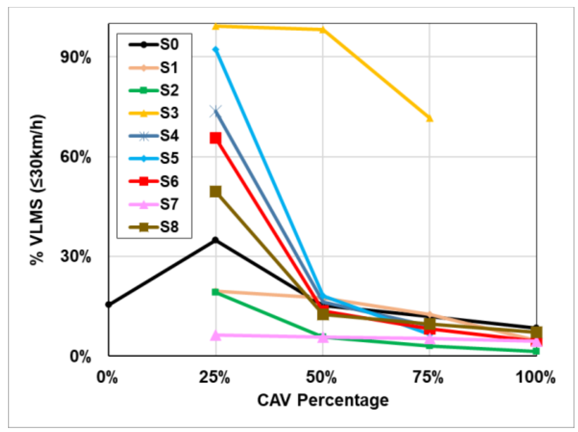

(a) LOS D, ramp volume 400 pc/h.



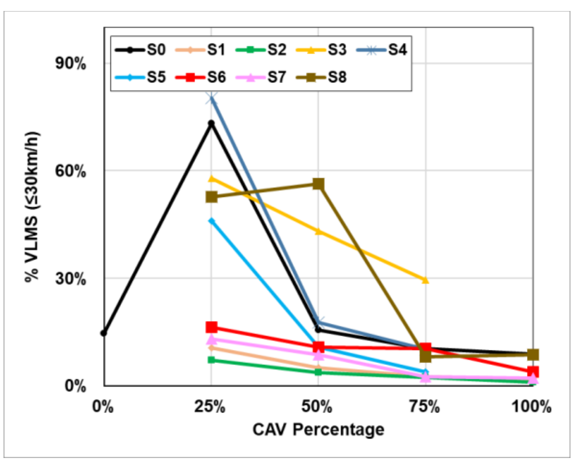

(b) LOS D, ramp volume 1,300 pc/h.



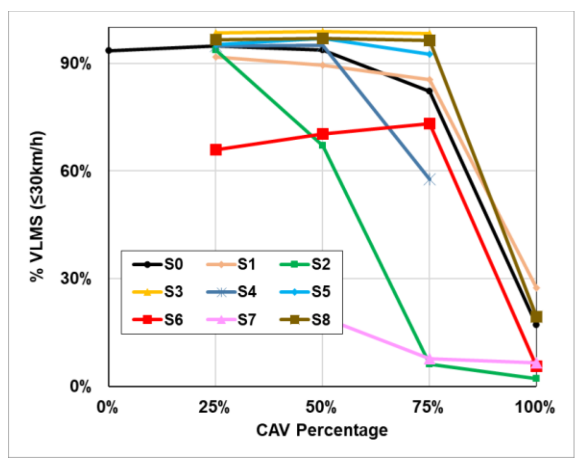

(c) LOS E, ramp volume 400 pc/h.




(d) LOS D, ramp volume 1,300 pc/h.




(e) LOS E*, ramp volume 400 pc/h.




(f) LOS E*, ramp volume 1,300 pc/h.

**Figure 3.5 Percentage VLMS, speed threshold of 30 km/h (40 km/h ramp design speed).**

**Table 3.3 Summary of feasible strategies for different traffic conditions.**

| Mainline LOS | D | | E | | E* | |
|---|---|---|---|---|---|---|
| Ramp traffic volume | L | H | L | H | L | H |
| **(a) Based on freeway travel time.** | | | | | | |
| Low CAV% | S1, 2, 4, 5, 6, 7 and 8 | S2, 5, 7 & 8 | S1, 2, 4, 5, 6, 7 and 8 | S2, 7 and 8 | S2, 6 and 7 | S7 |
| High CAV% | | | S1, 2, 6, 7 and 8 | | S7 and 8 | S2 and 7 |
| **(b) Based on ramp travel time.** | | | | | | |
| Low CAV% | S8 | | | S2 | S1, 2, 5 and 6 | S1, 2, 5, 6 and 7 |
| High CAV% | | | | | S 2, 5 and 8 (after CAV 75%). | S2 |
| **(c) Based on freeway capacity drop** | | | | | | |
| Low CAV% | S1, 2, 3, 5, 6, 7 and 8 | S1, 2, 4, 5, 6, 7 and 8 | S1, 2, 3, 4, 5, 6, 7 and 8 | S1, 2, 3, 4, 5, 6, 7and 8 | S2 | S7 |
| High CAV% | S1, 2, 3, 4, 5, 6, 7 and 8 | | | S2, 3, 4, 5, 6, 7 and 8 | S1, 2, 3, 4, 7and 8 | S2 and 7 |
| **(d) Based on ramp capacity drop** | | | | | | |
| Low CAV% | S1, 2, 3, 4, 5, 6,7 and 8 | S1, 2, 3, 4,5 ,6 and 8 | S1, 2, 3, 4, 5, 6, 7 and 8 | S2 | S1, 2, 3, 5, 6 and 7 | S1, 2, 4, 5, 6 and 8 |
| High CAV% | | S1, 2, 3, 4, 5 and 6 | | S1, 2, 4,5 and 6 | S1, 2, 3, 4, 5, 6, 7 and 8 | S2 |
| **(e) Based on VLMS** | | | | | | |
| Low CAV% | S1, 2, 4, 5, 6, 7 and 8 | S1, 2, 5, 6, 7 and 8 | S1, 2, 5, 6, 7 and 8 | S1, 2 and 7 | S1, 2, 5, 6 and 7 | S1, 2, 6 and 7 |
| High CAV% | S1, 2, 4, 5, 7 and 8 | S1, 2, 6, 7 and 8 | S1, 2, 4, 5 and 7 | S2, 6, 7 and 8 | S1, 2, 5 and 7 | S2, 4, 6 and 7 |

Low and high CAV penetration refer to rates up to 50% and greater than 50%, respectively.

The results indicate that the operational performance is affected by the CAV penetration rate and the implemented traffic management strategy. For relatively low freeway and ramp traffic volumes, the do-nothing strategy (S0) performs well in terms of all performance measures considered. If traffic volumes increase beyond LOS E, other strategies become more viable, particularly during the period of the vehicle fleet transition with a CAV penetration rate below 100%.

Platoon dissolving strategies are effective for low ramp and freeway traffic volumes. However, ramp metering had the lowest freeway travel times, with the differences being more pronounced for high traffic volumes. However, as this strategy prioritizes the mainline traffic flow, ramp vehicles might become heavily congested because of the traffic signal queue. Utilizing vehicle connectivity to process merging requests in S8 generally outperforms other strategies at LOS D and E in terms of the travel time of freeway vehicles, which is comparable with previous studies (Park et al. 2011; Scarinci et al. 2017; Karbalaieali et al. 2019).

The 2.0s desired headway for CAVs in S1 and S2, and between successive platoons in S6, is assumed based on a freeway operating speed of 100 km/h. However, at high traffic volumes of LOS E or E*, the operating speed drops below 100 km/h, and the 2.0s headway may not be sufficient for merging vehicles. One solution is to set the desired headway in these strategies using a dynamic method that calculates the desired headway based on the measured freeway operating speed. However, increasing the desired headway because of the reduced operating speed can further aggravate the congestion when the CAVs reduce their speeds to maintain a higher desired headway, and would increase the probability of more DVs changing lanes within these relatively large headways.

Traffic microsimulations do not completely assess operational safety. In this study, the percentage of VLMS was used as a surrogate measure of safety for several reasons. Future work should also evaluate safety performance with another surrogate measure, such as the probability of non-compliance, which correlates with collision frequency at freeway entrance ramps (Fatema and Hassan 2013).

Finally, this study considers a freeway segment with only one merging ramp. These travel conditions are close to those of rural freeways, where the ramp density is low enough for traffic at one interchange and is affected by disturbances at the previous interchange.

# Chapter 4: Comparing the Expected Safety Performance of Different Merging Strategies

This chapter is based on an under review article as "*Expected Safety Performance of Different Freeway Merging Strategies in an Environment of Mixed Vehicle Technologies*." [21]

## 4.1 Introduction

Merge areas on freeways are usually areas with a high probability of traffic collisions (Ahammed et al., 2008). During the merging manoeuvre, drivers have to consider different tasks such as accelerating, finding an available gap, keeping a safe distance with front and back vehicles, and adjusting speed after merging action. These multiple driving tasks could increase driver errors and probability of collisions. New vehicle technologies such as connected autonomous vehicles (CAVs) can help improve traffic safety through different actions, including reducing the reaction time, automatically adjusting vehicle speed and controlling vehicle distance to the lead vehicle, finding available gaps on the freeway and evaluating if they are acceptable for merging, and deciding on the optimal time for a safe merging manoeuvre.

However, CAVs are also expected to travel closer to other vehicles compared to driver-operated vehicles (DVs) and can create platoons with very short intra-platoon gaps. This travel pattern on the freeway right lane (FRL) may prevent or reduce opportunities of merging vehicles to find acceptable gaps to merge onto the freeway.

[21] Pakzadnia, A. and Y. Hassan. Expected safety performance of different freeway merging strategies in an environment of mixed vehicle technologies.

Different studies developed optimization merging models to manage cooperative merging for a mixed traffic environment, including DVs and CAVs, for merging areas (Karimi et al. 2020; Sun et al. 2020; Omidvar et al. 2020). These optimization models used a connectivity system to manage the FRL CAVs trajectories through decelerating or accelerating orders to provide a large enough gap for merging vehicles. These studies showed that merging models using a connectivity system could help reduce conflict between on-ramp vehicles and the FRL vehicles and make a smooth merging manoeuvre for merging vehicles. In terms of safety measures, a field test by Hayat et al. (2014) indicated that merging assistance systems on a connected vehicle (CV) could minimize the conflicts among vehicles at the merging area and reduce collisions. Moreover, Zhu and Tasic (2021) introduced a merging conflict model to evaluate the safety impact of autonomous vehicles (AVs) at the merging area. They found that increasing AV penetration rates can increase the safety of merging manoeuvres and reduce the probability of frequency and severity of the critical merging events.

In this chapter, reliability analysis is used to comparatively assess the safety implications of the different strategies to manage freeway merging using a more established surrogate safety measure. Reliability analysis assesses the uncertainty inherent in a system and estimates its probability of failure (Singh et al. 2007). This type of analysis allows for a quantitative evaluation for merging manoeuvres that offers a probability of merging failure. In the context of freeway merging, the probability of non-compliance (PNC) of merging manoeuvres is the term used to reflect the probability of merging failure and is used as the surrogate safety measure in this chapter. PNC indicates the likelihood that a merging vehicle cannot comfortably merge onto the freeway within the length of the speed change lane (SCL). This situation can happen when a vehicle reaches the end of SCL without finding an acceptable gap and has to stop, slow down, or perform a forced merge. While this is not equivalent to a collision, which is the manifestation of failure in a highway system, the resulting manoeuvres have the potential to increase the probability of a collision.

Fatema and Hassan (2013), Fatema et al. (2014), Fatema et al (2015), and Kanteti (2019) used PNC as a surrogate safety measure to evaluate the expected safety performance of the design elements at entrance ramp terminals for a fleet of DVs. They also found a relationship between collision frequencies at entrance ramp terminals and PNC results in their study areas. This study uses the same surrogate measure but applies it to the proposed merging strategies in a mixed fleet of CAVs and DVs. To calculate the PNC, a MATLAB program was developed to simulate the merging strategies and estimate PNC as the percentage of ramp vehicles that travel to the end of the SCL without finding an acceptable merging gap.

This following sections briefly describe the eight merging strategies and then explain the research methodology including the MATLAB program used to simulate the merging manoeuvres and estimate PNC and the traffic models assumed in the program. Then, the characteristics of the study area are described, the analyzed traffic characteristics are presented, and the PNC results are discussed. The study also uses the negative binomial regression[22] to establish the relationship between PNC as estimated in this chapter and observed collision frequencies.

[22] See Appendix B. Section B.10 Negative binominal regression

## 4.2 Merging Strategies

As mentioned in chapter three, eight merging strategies are proposed as solutions to eliminate or reduce the conflicts expected at freeway merging due to CAV platooning in a mixed traffic environment. The eight strategies were assessed in comparison to each other and to a base condition called S0, which is a do-nothing strategy, at different CAV penetration rates based on different traffic performance measures using traffic micro-simulation (Pakzadnia et al. 2021). The comparison accounted for different site conditions based on traffic volumes on the freeway and ramp and based on the entrance ramp geometric design as reflected in the ramp design speed. The results indicated that the operational performance, in terms of average travel time and capacity, is affected by the traffic volume, ramp speed, CAV penetration rate, and the implemented traffic management strategy. Furthermore, most strategies in all traffic conditions showed better traffic operation results than S0, confirming the advantages of managing freeway merging in a mixed CAV environment. The results also showed that the best-performing strategy varies depending on the site conditions and CAV penetration rate.

## 4.3 Methodology

As mentioned earlier, the safety performance of these strategies is assessed in this chapter based on PNC as a surrogate safety measure using a simulation program developed in MATLAB. This program uses specific gap acceptance and car-following models for DVs and CAVs.

### 4.3.1 Simulation Program

To compare the expected safety performance associated with each merging strategy at different traffic and geometric conditions, such as traffic volume, ramp speed, and CAV penetration rate, a MATLAB program was developed to simulate traffic operation under the different merging strategies. The program comprises a number of functions to generate the freeway and ramp traffic based on Poisson arrival, update the speed and location data for all vehicles based on a modified Gipps' model at a small-time step, estimate acceptable gaps for the merging vehicle whether it is a CAV and DV, compare the available and acceptable gaps for each ramp vehicle, and allow the ramp vehicle to merge if the available gap is greater than or equal to the acceptable gap.

A ramp vehicle that does not have an acceptable gap for merging continues driving on the SCL while comparing the available and acceptable gaps at small time steps until it can merge or reaches the end of SCL. At the end of the simulation, PNC is estimated as the ratio of the number of ramp vehicles that cannot merge onto the FRL to the total number of ramp vehicles. The traffic parameters, such as traffic volume, speed, acceleration, deceleration, reaction time, and minimum headway, are defined by the user for each vehicle type. Figure B.1[23] is a flowchart for the developed program.

### 4.3.2 Traffic Models in Simulation

The behaviour of CAVs differs from that of DVs. For example, CAVs have a faster reaction time and accept a shorter gap for merging than DVs. This section presents three traffic models used in this study for a mixed traffic environment and incorporated in

[23] See Appendix B. Figure B.2 illustrates MATLAB program frame work.

the MATLAB program: car-following, gap acceptance, and cooperative merging utilizing connectivity in S8.

### 4.3.3 Car-Following Model

There are many car-following models, among which Gipps (1981) model is one of the most famous, most straightforward, and relatively accurate models. Gipps (1981) presented the following equation to estimate the updated vehicle speed for each time step based on two primary considerations: acceleration and deceleration:

$$v_{(n)(t+R)} = \min \{v_{n(t)} + 2.5\, a_n\, R \left(1 - \frac{v_{n(t)}}{V_n}\right) \left(0.025 + \frac{v_{n(t)}}{V_n}\right)^{0.5}, d_n(R/2 + F_d) + (d_n{}^2 (\frac{R}{2} + F_d)^2 - d_n(2\left[x_{(n-1)(t)} - S_{n-1} - x_{(n)(t)}\right] - v_{(n)(t)}R - \frac{v_{n-1}(t)^2}{d^{\wedge}})^{0.5}\} \tag{4.1}$$

where,

$a_n$ = maximum acceleration (m/s$^2$); $R$ = reaction time, which is assumed to be constant for all vehicles in each category (DVs or CAVs); $V_n$ = desired speed of vehicle *n* (m/s) ; $v_{n(t)}$ = speed of vehicle *n* at time *t* (m/s); $d_n$ = maximum deceleration of the lead vehicle, which has a negative value (m/s$^2$); $x_{(n)(t)}$ = position of vehicle *n* at time *t*; $S_{n-1}$ = effective length of vehicle *n* (m), which is equal to the length of the vehicle plus a margin value which the vehicles prefer to keep from the lead vehicle even when stationary; $d^{\wedge}$ = maximum deceleration of the following vehicle that wishes to undertake based on the estimation of the lead vehicle's braking (m/s$^2$); and $F_d$ = safety time margin because of possible delay time, which was assumed by Gipps to be equal to *R*/2.

Gipps’ model was originally developed for DVs and was incorporated in this study as developed for the DVs in the mixed vehicle fleet. The same model is also proposed in this study to simulate CAVs in the vehicle fleet after adjusting two factors, which are reaction time ($R$) and safety margin ($F_d$), to better reflect the CAV driving behaviour. Ideally, all factors should be calibrated using databases with information on CAV traffic. However, with the lack of such a public database, the coefficients are assumed to be the same as in Gipps' original model.

### 4.3.4 Gap Acceptance Model

Models are already available in the literature to estimate the minimum acceptable gap ($G_{A,min}$) for DVs. Based on data collected from different SCLs, Fatema et al. (2015) and Alyamani and Hassan (2021) provided different sets of models to predict lead, lag, and total (distance between lead and lag vehicles) accepted gaps for merging manoeuvres. In this chapter, Equations (4.2) and (4.3) by Fatema et al. (2015) were selected to model merging gap acceptance as they were developed using data at the same study area and were used in this simulation to estimate the minimum lag and lead acceptable gaps for DVs:

$$Lag_{gap} = 6.863 - 0.167 \times V_M - 1.237 \times R_d \tag{4.2}$$

$$Lead_{gap} = 4.108 - 0.089 \times V_M - 0.689 \times R_d \tag{4.3}$$

where,

$V_M$ = merge speed (km/h) and $R_d$ = merge location divided by the length of SCL (m/m).

The acceptable gap for a CAV merging between two successive CAVs on the FRL can be evaluated based on the need for the merging vehicle to adjust speed to match the speed of the FRL vehicles while maintaining a minimum gap from the nearest vehicle at the end of the merging manoeuvre. Figure 4.1 shows a schematic of the merging manoeuvre for the two cases where the speed of the merging vehicle ($V_R$) is less or greater than the speed of lead FRL vehicle ($V_F$). First, the time of the merging manoeuvre ($t$) is equal to the time required for the CAV to adjust the speed from $V_R$ to $V_F$, which can be written as:

$$t = \frac{V_F - V_R}{a} \tag{4.4}$$

where,

$a$ = CAV acceleration (m/s$^2$), $V_R$ = speeds of merging vehicle (m/s), $V_F$ = speed of the FRL vehicles (m/s)

The model is then based on the logic that at the end of the merging manoeuvre the merging vehicle keeps a minimum distance for safety issues to the lead and lag FRL vehicles, which is equal to the vehicle speed multiplied by the reaction time. By relating speed and distance, the minimum acceptable gap ($G_{A,min}$) can be estimated as follows:

$$S_{1a} = R \times V_R \tag{4.5}$$

$$S_{1b} = R \times V_F \tag{4.6}$$

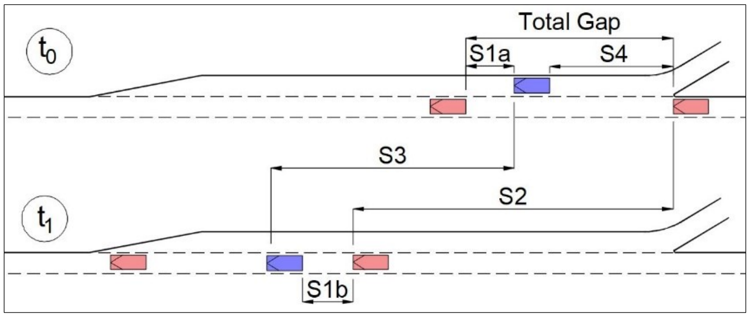
$$S_2 = V_F \times t \tag{4.7}$$

$$S_3 = 0.5 \times a \times t^2 + V_R \times t \tag{4.8}$$

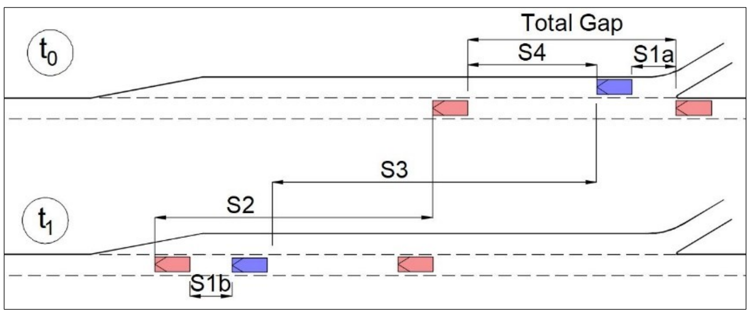
$$G_{A,min} = \begin{cases} S_{1a} + S_{1b} + S_2 + L - S_3 & V_R < V_F \\ S_{1a} + S_{1b} + S_3 + L - S_2 & V_R > V_F \end{cases} \tag{4.9}$$

where,

$L$ = length of the merging vehicle (m) and $R$ = reaction time (s).




(a) $V_R < V_F$.




(b) $V_R > V_F$.

**Figure 4.1 Minimum accepted gap for CAVs.**

For example, a CAV merging onto a freeway with a driving speed of 100 km/h for both merging and the FRL vehicles, $G_{A,min}$ is approximately 17.1 m or less than 1.0s (assuming $R$ = 0.2 s and $L$ = 6 m). Therefore, at high CAV penetration rates and an operating speed of 100 km/h, short gaps of 2.0 s would be acceptable for most merging manoeuvres. The 2.0 s headway threshold was applied to set the FRL CAV headway in S1 and S2 and headway between the FRL CAV platoons for S6. Also, to create a platoon, it is assumed that if a CAV is within 20.0 s distance to a front CAV, without any vehicle between them, it uses the maximum acceleration to reach posted speed and create a platoon with the front CAV.

### 4.3.5 Cooperative Merging Model for S8

In strategies S0-S7, the traffic management does not utilize the connectivity system to request an accommodation from the FRL CAVs. Rather, the merging vehicle searches available gaps on the FRL for an acceptable gap. If the available gap is equal to or greater than the acceptable gap, the vehicle can merge and join the FRL traffic. As indicated in the previous section, the acceptable gap in the simulation is estimated based on specific factors, including the types and speeds of the ramp vehicle, lead and lag FRL vehicles.

For S8, the connectivity system among CAVs and between CAVs and the road infrastructure is utilized in a traffic management scheme to facilitate the merging manoeuvres. If the lead or lag FRL vehicle is a CAV and the available gap is not acceptable for the merging vehicle, a merging request is processed via the connectivity system. Subsequently, the FRL CAV will either accelerate, change lane, or decelerate to provide an acceptable gap for the merging vehicle.

The cooperative merging procedure to provide an acceptable gap is prioritized in the order of: 1) acceleration of the lead vehicle, 2) lane change by the FRL vehicle(s) to the freeway second lane (FSL), and 3) deceleration of the lag vehicle. The reason is that an acceleration by the lead vehicle, if the front vehicle has enough distance to do so, does not conflict with the path of any other vehicle, and in turn has the lowest potential negative impact on safety and traffic performance. Deceleration by the lag vehicle is assumed to have the highest potential negative impacts on both safety and operation because of the potential of a rear-end collision or shockwaves. The procedures of merging manoeuvres for these three accommodation manoeuvres are presented schematically in Figure 4.2 and can be explained as follows:

*Acceleration method:* In the first priority manoeuvre, the connectivity system recognizes that the lead vehicle is a CAV (vehicle 2 in Figure 4.2a) and orders it to accelerate to provide a large enough gap to allow the ramp vehicle to merge onto the FRL if the acceleration can be performed safely. The required additional time for the available gap to become an acceptable gap, which is estimated based on the type of lag FRL vehicle and merging vehicle, can be expressed by Equation (4.10).

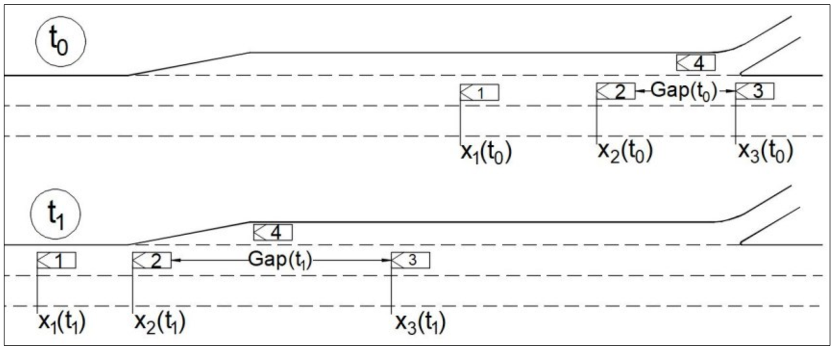
$$\begin{aligned} Required\ additional\ gap\ time &= Acceptable\ Gap - Available\ Gap \\ &= Gap\ (t_1) - Gap(t_0) \end{aligned} \tag{4.10}$$

If all lead, lag and merging vehicles are CAVs, the acceptable gap is calculated based on the model in Equation (9). If the merging vehicle is CAV, but the lag vehicle is DV, the acceptable lag gap is calculated based on the model in Equation (4.2). The time at which the merging vehicle reaches the end of SCL while travelling at constant speed can be computed using Equation (4.11). The lead FRL CAV needs to provide an acceptable gap for the merging vehicle by this time.

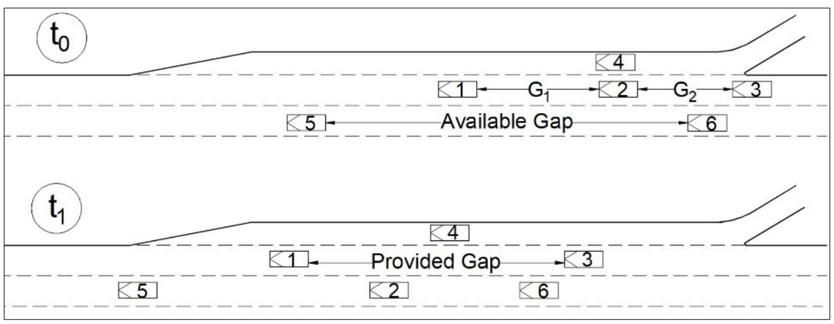
$$t_1 = t_0 + \frac{x_{end\ of\ SCL} - x_4(t_0)}{v_4(t_0)} \tag{4.11}$$

where,

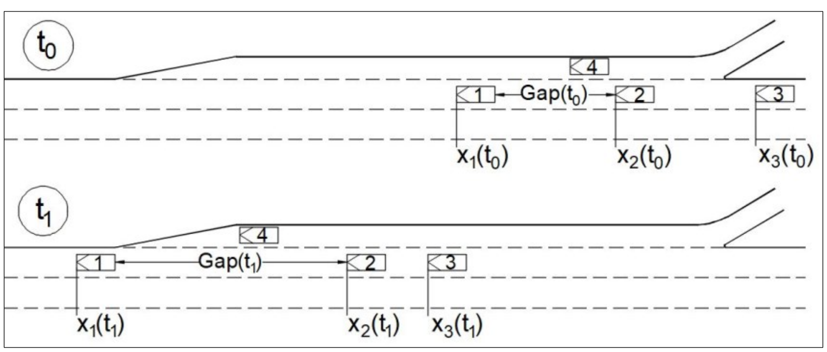
$t_0$ = time at which the merging vehicle searches for an available gap, $t_1$ = the latest time that the merging vehicle can merge onto the FRL, $v_i(t_j)$ = speed of vehicle $i$ at time $j$, and $x_i(t_j)$ = location of vehicle $i$ at time $j$,




(a) Acceleration manoeuvre for providing accepted gap.




(b) Lane changing for providing accepted gap.




(c) Deceleration manoeuvre for providing accepted gap.

**Figure 4.2 Traffic management to provide gap for S8.**

The additional gap time between the lead and lag FRL vehicles at the time $t_1$ is created by the lead vehicle acceleration and is estimated using Equation (4.12). In this equation, the speed of CAV lead vehicle $(v_2)$ at $t_1$ $(v_2(t_1))$ is set based on maximum acceleration as shown in Equation (4.13). In addition, it is assumed that while the lead vehicle is accelerating to provide an acceptable gap, both the ramp and lag vehicles are driving at constant speeds.

$$Additional\ gap\ time \leq \frac{((v_2(t_1) + v_2(t_0))/2 - v_3(t_0)) \times (t_1 - t_0)}{v_3(t_0)} \tag{4.12}$$

$$v_2(t_1) = v_2(t_0) + a \times (t_1 - t_0) \leq v_{max} \tag{4.13}$$

where,

$a$ = maximum acceleration.

For this manoeuvre to be executed, the available gap at $t_1$ needs to be greater than the acceptable gap for merging and the distance between the lead vehicle and the vehicle in front of it (vehicle 1 in Figure 4.2a) greater than the CAV safe distance. This safe distance is equal to the reaction time multiplied by the lead vehicle speed, as shown in t Equation (4.14).

$$x_1(t_1) - l_1 - x_2(t_1) \geq R \times v_2(t_1) \tag{4.14}$$

where,

$R$ = reaction time, and $l_i$ = the length of vehicle $i$.

*Lane-change manoeuvre method:* If the lead vehicle cannot accelerate due to a close vehicle ahead, the second priority manoeuvre for providing an acceptable gap would be a lane change. In this procedure, the connectivity system first checks if an acceptable gap is available in the FSL and orders a CAV on the FRL to change the lane to FSL. As illustrated in Figure 4.2b, if the available gaps on the FRL, $G_1$ and $G_2$, are less than the acceptable gap for merging, and if the closest vehicle to merging vehicle on the FRL (vehicle 2) is a CAV, then the merging vehicle can merge onto the FRL if the following two conditions are met.

- An available gap on the FSL indicates that vehicle 2 could change lane from the FRL to FSL.
- By lane-changing for vehicle 2, the provided gap on the FRL is large enough for the merging ramp vehicle.

*Deceleration method:* In this last option, the connectivity system recognizes that the lag vehicle (vehicle 2 in Figure 4.2c) is a CAV and orders it to decelerate to provide a large enough gap to allow the ramp vehicle to merge onto the FRL. The additional gap time between the lead and lag FRL vehicles at time $t_1$ can be estimated as shown previously in Equations (4.10) and (4.11) while noting the different vehicle notations. The additional gap time that the decelerating lag vehicle can provide within the available time (by the time the merging vehicle reaches the end of SCL) can be expressed by Equation (4.15).

$$Additional\ gap\ time \leq \frac{((v_1(t_0) - (v_2(t_1) + v_2(t_0))/2) \times (t_1 - t_0)}{(v_2(t_0) + v_2(t_1))/2} \tag{4.15}$$

The lag vehicle speed at time $t_1$ can be formulated as:

$$v_2(t_1) = v_2(t_0) - d \times (t_1 - t_0) \tag{4.16}$$

The spacing between the lag FRL vehicle and its following vehicle (vehicle 3 in Figure 4.2c), which should be bigger than the safe distance at $t_1$ as shown in Equation (4.17). The ramp vehicle can merge into the provided gap, if it is greater than the acceptable gap.

$$x_2(t_1) - l_2 - x_3(t_1) \geq R \times v_3(t_1) \tag{4.17}$$

If one of the above procedures works, in the stated order of priorities, the ramp vehicle can merge onto the FRL. Otherwise, the ramp vehicle would count as a failed merge manoeuvre.

### 4.4 Study Corridor and Simulation Attributes

Having developed the simulation program in MATLAB to determine PNC associated with each merging strategy under a specific set of geometric and traffic conditions, the merging strategies were examined using the same site used to assess the operational performance of the merging strategies representing a typical merging ramp geometry in Ottawa, Canada. The merging ramp is located on Highway 417 at the St Laurent Boulevard interchange. This freeway has three lanes in each direction with a posted speed of 100 km/h. The merging loop ramp on westbound-to-northbound has a 295-m tapered SCL. The study section to control the simulation strategies is divided into four main segments (Figure 4.3).

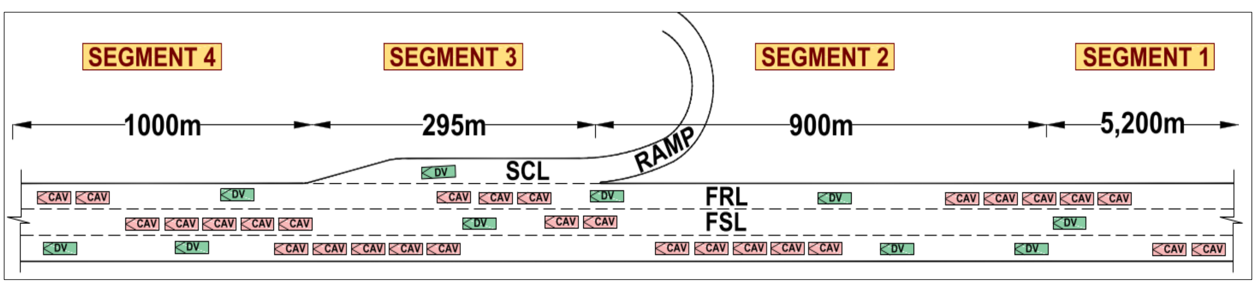



**Figure 4.3 Study area.**

- Segment 1 is selected 5.2-km-long enough to make time for CAVs to create a long platoon.
- Segment 2 is selected 900 m long and divided into three (3×300 m) sub-segments to allow gradual change of vehicles' speeds or headways for S2 and S3 (Pakzadnia et al. 2021).

- The third segment extends along with the SCL that is 295 m.
- Segment 4 is selected a 1000 m long downstream of the SCL to comply with approximately two times of HCM recommendation for merge influence area, which is 450 m (TRB 2016). This distance allows CAVs to resume their original driving behaviour after the merging area. In the developed simulation, the merging vehicles would drive on this segment on the freeway and may impact the speeds and available gaps on the FRL within Segment 3.

## 4.5 Simulation Parameters

Simulating the strategies in the developed program requires specific values for different road conditions, traffic conditions, and driving parameters for DVs and CAVs. Table 4.1 provides a summary of the parameters and the values used in this study, which are the same as those used in assessing the operational performance by Pakzadnia et al. (2021). The justifications for these assumptions were explained in more detail and can be summarized as follows:

- Different CAV penetration rates were used to cover the range from low CAV adoption to all-CAV vehicle fleet. In addition, the case of zero CAV penetration rate is considered in the base strategy (S0).
- Design speeds mean travelling speeds, and standard deviations for both freeway and ramp were assumed based on local conditions and to cover a range of ramp design speeds.

**Table 4.1 Vehicle and traffic characteristics using MATLAB simulations.**

| Feature | Assumed values | | | | |
|---|---|---|---|---|---|
| Road functional class | Urban freeway, including three main lanes | | | | |
| Speed | Design speed | DVs | | CAVs | |
| | | $\mu_v$ | $\sigma_v$ | $\mu_v$ | $\sigma_v$ |
| Freeway speed (km/h) | 110 | 105.50 | 10.57 | 100 | 5.0 |
| Ramp speed (km/h) | 40 | 36.60 | 3.21 | 30.0 | 1.5 |
| | 80 | 73.50 | 6.0 | 70.0 | 3.5 |
| Traffic volume of the freeway | See Table 4.2. | | | | |
| Traffic volume of the ramp | 400, and 1300 pc/ln/h | | | | |
| CAV penetration rates | 25%, 50%, 75%, and100% | | | | |
| Simulation time | Warm up:15 min and Main simulation: 60 min | | | | |
| Timestep | 0.1 s | | | | |
| Min. headway (s) | DVs = 1.0 and CAVs = 0.5 | | | | |
| Min. reaction time (s) | DVs = 0.5 and CAVs = 0.2 | | | | |
| Safety margin | Reaction time/2 | | | | |
| Max. acceleration rate | 2.0 m/s2 | | | | |
| Max. deceleration rate | -3.0 m/s2 | | | | |
| Start location freeway vehicles | 5,200 m before gore point | | | | |
| Start location ramp vehicles | 250 m before gore point | | | | |
| End of simulation lane | 1000 m after the end of SCL | | | | |
| Length of vehicles | 4.27 m (6%), 4.53 m (15%), 4.64 m (26%), 4.75 m (11%), 4.9 m (6%), 5.81 m (21%), 6.1 m (15%) | | | | |

- Traffic volumes on the freeway mainline lanes were set at the upper threshold for LOS D and E (TRB 2016). An additional volume was assumed as LOS E*, which corresponds to 20% increase over LOS E to account for the expected capacity increase with CAV adoption. However, restricting CAVs from travelling in the FRL in S4 and S5 would affect the traffic volume traversing the freeway segment on each lane. Therefore, for these two strategies, traffic volumes on the FRL for each set of conditions were extracted from the traffic micro-simulation results, as shown in Table 4.2.

- Taieb-Maimon and Shinar (2001) suggested 0.5 s for minimum reaction time ($R$) and 1.0 s for the minimum headway for DVs. For CAVs, Ploeg et al. (2011) and Ghiasi et al. (2017) assumed 0.7 s and 0.3 s respectively for minimum headway. In this study, a mid-value of 0.5 s is applied as a minimum CAV headway.

**Table 4.2. Assumed traffic volumes on FRL for different strategies.**

| Strategy | LOS | Ramp volume | CAV% | | | | |
|---|---|---|---|---|---|---|---|
| | | | 0%[b] | 25% | 50% | 75% | 100%[c] |
| S0, S1, S2, S3[a], & S6-S8 | D | 400/1,300 | | | 2,100 | | |
| | E | 400/1,300 | | | 2,400 | | |
| | E* | 400/1,300 | | | 2,880 | | |
| S4[a,c] | D | 400 | - | 2,785 | 2,383 | 1,563 | - |
| | | 1300 | - | 2,572 | 2,432 | 1,852 | - |
| | E | 400 | - | 2,476 | 2,025 | 1,350 | - |
| | | 1300 | - | 2,430 | | | - |
| | E* | 400/1300 | - | 2,450 | 2,009 | 1,310 | - |
| S5[a,c] | D | 400 | - | 2,700 | 2,215 | 1,585 | - |
| | | 1300 | - | 2,500 | 2,310 | 1,795 | - |
| | E | 400 | - | 2,075 | 1,620 | 1,110 | - |
| | | 1300 | - | 2,000 | | | - |
| | E* | 400/1300 | - | 1,780 | 1,400 | 874 | - |

Note:

[a] S3, S4 and S5 are not valid strategies for 100% CAV penetration rate.

[b] Only S0 (no traffic management or do-nothing strategy) is considered for 0% CAV penetration rate.

[c] Traffic volume for S4 and S5 are assumed based on counting vehicles at Vissim simulation results.

- A safety margin for additional possible delay is added to reaction time in the car-following model. The value of safety margin is recommended half of the reaction time (Gipps 1981)
- All vehicles were considered passenger cars (PC) with vehicle length determined based on the percentages of the top-selling vehicles in Canada over a 12-month

period between February 2018 and 2019. Vehicles in the simulation were categorized into seven groups whose lengths are shown in Table 4.1.

## 4.6 Required Number of Simulation Runs

For a specific simulation scenario comprising a specific set of CAV penetration rate, traffic volumes, and design speeds, the developed program generates vehicles for one simulation hour with the parameters of individual vehicles randomly assigned based on the statistical distribution for each parameter. For example, a ramp DV would have a randomly assigned desired speed based on the mean and standard deviation associated with the specific ramp design speed, as shown in Table 4.1. To determine the required number of runs for each scenario, a large number of vehicles was simulated in a specific scenario to find the lowest number of runs that give a reasonable accuracy. Table B.1[24] represents the results of mean PNC values for this simulation scenario and different numbers of simulation runs. The results show that for simulating 5,950 ramp vehicles or more (seven runs in this case), the change in the mean is less than 1%. Thus, seven simulation runs corresponding to seven hours of traffic movements, other than the warm-up time, were selected as the number of runs to estimate PNC for each set of conditions.

Finally, the number of scenarios simulated for each strategy is a combination of three freeway traffic volumes, two ramp traffic volumes, two ramp design speeds, and three to five CAV penetration rates. As shown in Table 4.2, 0% CAV penetration rate is applied only for S0, and 100% CAV penetration rate is not applied for S3, S4 and S5. Thus, a total of 420 simulation scenarios were considered for all strategies; with each scenario simulated for seven runs.

---

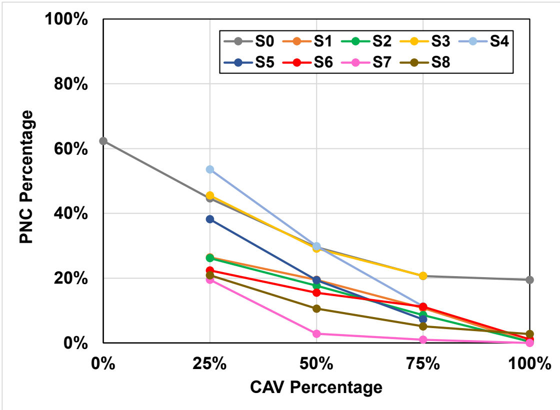
[24] See Appendix B. Table B.1 presents the mean PNC value for the different numbers of the simulation runs.

## 4.7 Simulation Results and Discussion

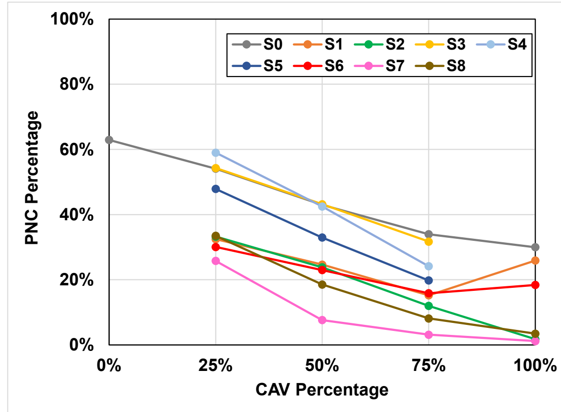
Figure 4.4 illustrates the PNC results for different strategies with various CAV penetration rates and different traffic volumes for a ramp design speed of 40 km/h. The following observations and findings can be stated:

- In general, PNC decreases with the increase of CAV penetration rate even for S0. Therefore, contrary to expectations, the adoption of CAVs should not negatively impact safety performance at entrance ramp terminals. However, this finding should be cautiously examined as forced merging in a DV environment is most often accommodated by the FRL drivers, which is not considered in the calculation of PNC. Thus, most uncomfortable or forced merging manoeuvres do not translate into collisions. Unless courtesy merging is built into CAVs, forced merging can translate into collisions at a higher frequency.
- Still, all strategies, other than S3, have lower PNC than S0 at high CVA penetration rates. The desired speed of CAVs in strategy S3 is set to be lower than DVs, resulting in more congested traffic in the FRL than in other strategies, and in turn lower probabilities of comfortable merging or higher PNC. Therefore, the merging management strategies still have the potential of improving safety at entrance ramp terminals.
- Expectedly, S7 has the lowest PNC, which is at least 20% lower PNC than S0. This strategy controls the ramp traffic volume using ramp metering, which releases vehicles to merge onto freeway only if there are acceptable gaps in the FRL. However, all ramp vehicles may not have a chance to pass the ramp metering during peak hours, and queuing at the ramp can take place.

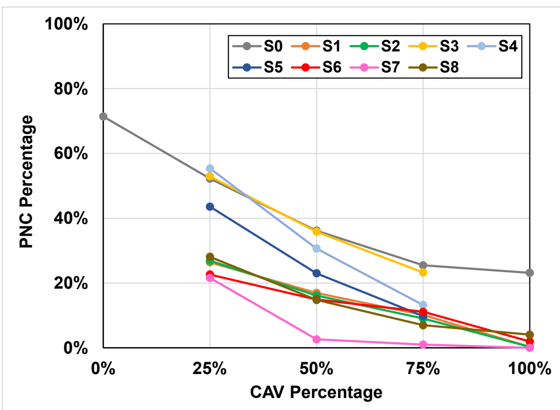
- S1, S2, and S6 have similar PNC results in most cases. However, S1 and S6 at high ramp traffic volume and high CAV penetration rates have a higher PNC than S2. This is because the large gaps created between CAVs or CAV platoons downstream the merge would require adjustments of the CAV speeds and gaps once a ramp vehicle merges onto the FRL. This adjustment can result in a shockwave on the FRL, reducing speeds and gaps on the FRL within the merge area and reducing the opportunities for ramp vehicles to merge.
- S4 and S5 restrict CAV from travelling in the FRL. However, CAVs in S5 can use the FRL before and after the merge area as a travel lane. The results of PNC for these two strategies show that S5 has better performance regarding PNC than S4, especially at low CAV penetration rates and low ramp volume. More DVs travel in the FRL in S4 at low CAV penetration rates compared to S5 resulting in fewer acceptable gaps in the FRL.



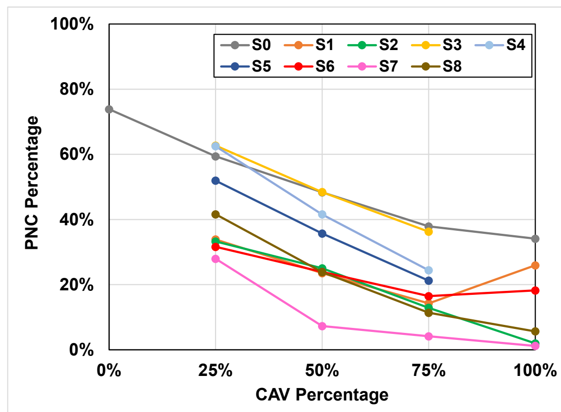

(a) LOS D, Ramp volume = 400 veh/h.



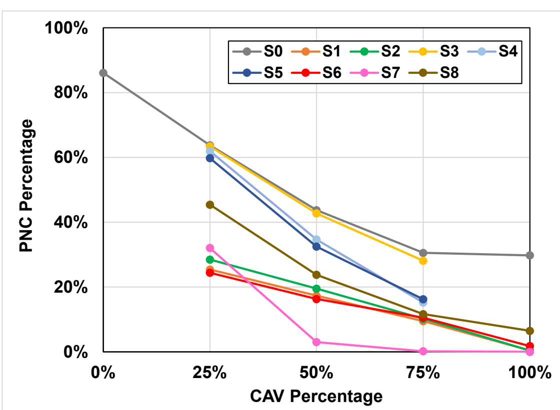

(b) LOS D, Ramp volume = 1,300 veh/h.



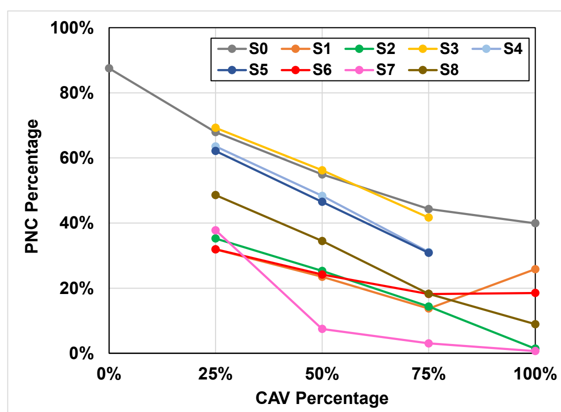

(c) LOS E, Ramp volume = 400 veh/h.




(d) LOS E, Ramp volume = 1300 veh/h.




(e) LOS E*, Ramp volume = 400 veh/h.




(f) LOS E*, Ramp volume = 1,300 veh/h.

**Figure 4.4 PNC results (40 km/h ramp design speed)[25].**

[25] See Appendix B. Figure B.2 presents the PNC results for 80 km/h ramp design speed.

- The performance of S8, in terms of PNC, improves as the CAV penetration rate increases. However, at low CAV penetration rates and high traffic volume, S1, S2, and S6 perform better than S8 because of the low volume of CAVs that can accommodate a merging request in S8.
- In general, the PNC results for 80 km/h ramp design speed show similar trends but lower values compared to the 40 km/h ramp design speed. These simulation results indicate that ramp vehicles with a high ramp design speed can merge more comfortably onto the FRL.

### 4.8 Relationship Between PNC and Collision Frequency

As mentioned earlier, previous research has shown a good relationship between the surrogate safety measure PNC and actual safety performance in terms of collision frequency at freeway entrance ramp terminals (Fatema et al. 2014; Fatema et al. 2015; Kanteti 2019). However, because this study uses different models in car-following and merging, the relationship was re-examined using traffic data and collision frequencies on fifteen merging ramps on Highway 417, Ottawa, Ontario, Canada. The collision data were collected for a five-year period between 2015 and 2019, and the Negative Binomial Regression (NBR) was applied to relate collision frequency to traffic and geometric characteristics. Each of the fifteen sites was also simulated using the developed simulation program under S0 and 0% CAV to estimate PNC at each site corresponding to current conditions. The NBR was re-applied to add PNC as an independent variable in the regression models to examine if adding PNC would improve the models. The specific procedure for data collection, simulation, and statistical modeling included the following:

- The FRL traffic volumes: Annual Average Daily Traffics (AADT) of Highway 417 up to the year 2016 are publicly available. In addition, the traffic volumes of each lane of Highway 417 were obtained from the Ministry of Transportation of Ontario (MTO) for some segments, covering some of the sites used in this analysis of the highway for specific days. Based on these data, the average ratio of traffic volume of FRL to the directional AADT in this highway with three lanes was calculated as 33.4%. This ratio was applied to estimate the FRL traffic volumes at the sites where the FRL volume was not available. In addition, a growth traffic factor was calculated based on historical traffic data to predict the traffic volume up to 2019.
- Ramp traffic volume: Traffic volumes on the ramps were obtained using the City of Ottawa's Miovision website based on the volumes recorded at the ramp terminal intersections and/or other intersections in the vicinity of selected merging ramps. At these intersections, the peak and midday traffic volumes and truck percentages were available for specific days. The City of Ottawa also provided hourly, daily, and monthly expansion factors to convert the observed volumes to AADT. Using these factors, the ratio of midday traffic to AADT was estimated as 6.3%. This ratio was used to calculate the midday traffic for FRL as well.
- Ramp length: The lengths of the SCL at the selected sites, from end of ramp controlling curve to the end of the SCL taper, were measured on Google maps. Ten out of fifteen ramps are defined as loop ramps, and others are defined as direct ramps.

- Freeway Speed: Speeds of individual freeway vehicles were assumed to follow a normal distribution. Mean speed and standard deviation for each segment of FRL were assumed based on data obtained from MTO, where were collected in 2020.
- Ramp Speed: The design speeds of ramps were estimated based on the geometry of ramps, especially ramp curvatures. Speeds of individual ramp vehicles were assumed to follow a normal distribution with the mean and standard deviation estimated based on a previous study on the same study area using the following equations (Fatema et al. 2015):

$$\mu_v = -0.287 + 0.922\, V_{85}, \quad R^2 = .99 \tag{4.18}$$

$$\sigma_v = 0.446 + 0.069\, V_{85}\,, \quad R^2 = .65 \tag{4.19}$$

where,

$\mu_v$ = mean speed (m/s); $\sigma_v$ = standard deviation of speed distribution (m/s); $V_{85}$ = 85$^{th}$ percentile speed (m/s); and $R^2$ = coefficient of determination.

- Collision data for 2015-2019 were obtained from the City of Ottawa Open-data website (2021). The website provided shapefiles for location of collisions that can be transferred to Google Earth. The collision data were collected for the ramp and mainline separately for the different collision severity levels (fatal, injury, and property damage only). Collisions on the ramp were considered from the beginning of the ramp to the beginning of SCL. Collisions on the mainline were collected along the SCL from nose width 3.0 m to the end of merging taper or 450 m, whichever is longer. This 450 m was selected as the influence area of the merging area, according to HCM (2016).

Table 4.3 summarizes the collected data, including collision frequency and the estimated PNC. The STATA 16.0 software was used to develop NBR models with and without PNC as an independent variable, as explained earlier. Table B.2 and B.3[26] present all developed collision models based on total collisions (ramp and mainline combined) and ramp-only collisions, respectively. Table 4.4 presents a summary of ten significant collisions models.

**Table 4.3 Summary of traffic data for study area.**

| No | SCL Site | No. of ramp collisions (2015-2019) | No. of freeway collisions (2015-2019) | Freeway mean speed (km/h) | Freeway standard deviation speed (km/h) | Ramp design speed (km/h) | Ramp standard deviation speed (km/h) | Length of SCL (m) | Freeway Traffic volume (veh/h) | FRL traffic volume (veh/h) | Ramp traffic volume (veh/h) | PNC |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Palladium (S-W) | 3 | 8 | 107.9 | 11.4 | 50 | 4.7 | 480 | 1,520 | 507 | 160 | 0.080 |
| 2 | Terry Fox (N-W) | 6 | 7 | 108.8 | 58.9 | 65 | 5.7 | 450 | 2,301 | 768 | 276 | 0.190 |
| 3 | Terry Fox (S-E) | 5 | 7 | 111.6 | 58.9 | 65 | 5.7 | 436 | 2,301 | 768 | 489 | 0.221 |
| 4 | Terry Fox (N-E) | 3 | 14 | 111.6 | 40.5 | 45 | 4.4 | 410 | 2,301 | 768 | 204 | 0.171 |
| 5 | Terry Fox (S-W) | 2 | 6 | 108.8 | 40.5 | 45 | 4.4 | 425 | 2,301 | 768 | 124 | 0.136 |
| 6 | Moodie (N-W) | 2 | 26 | 104.3 | 63.5 | 70 | 6.0 | 450 | 4,012 | 1,338 | 133 | 0.307 |
| 7 | Moodie (S-W) | 1 | 38 | 104.3 | 40.5 | 45 | 4.4 | 470 | 4,012 | 1,338 | 102 | 0.288 |
| 8 | Moodie (N-E) | 1 | 38 | 104.8 | 40.5 | 45 | 4.4 | 477 | 4,012 | 1,338 | 336 | 0.354 |
| 9 | Richmond (S-E) | 2 | 12 | 101.1 | 72.7 | 80 | 6.6 | 370 | 4,979 | 1,661 | 36 | 0.401 |
| 10 | Woodroffe (N-E) | 5 | 68 | 108.2 | 35.8 | 40 | 4.1 | 290 | 4,575 | 1,526 | 131 | 0.426 |
| 11 | Maitland (NS-E) | 11 | 37 | 108.2 | 45.1 | 50 | 4.7 | 295 | 4,986 | 1,663 | 581 | 0.524 |
| 12 | Vanier (N-E) | 2 | 22 | 108.2 | 35.8 | 40 | 4.1 | 360 | 5,416 | 1,806 | 397 | 0.540 |
| 13 | St Laurent (S-W) | 3 | 53 | 108.2 | 35.8 | 40 | 4.1 | 295 | 4,850 | 1,618 | 287 | 0.477 |
| 14 | Innes (E-S) | 3 | 8 | 108.2 | 35.8 | 40 | 4.1 | 360 | 3,857 | 1,286 | 430 | 0.392 |
| 15 | Innes (W-N) | 1 | 23 | 108.2 | 45.1 | 50 | 4.7 | 300 | 3,857 | 1,286 | 372 | 0.384 |

The results of developed models for total collision show that according to AIC, models including the exposure vehicle-km and ramp design speed variables, such as model number 10, have better results. For the ramp-only collision models, it seems all variables

[26] See Appendix B. Table B.2 and B.3 present the summary of collisions regression models for total collisions and for only ramp collisions.

can be significant in the different traffic situations. Adding the variable PNC helps noticeably to reduce AIC in approximately 50% of models. The changes in AIC for 20% of models are less than 1%, which is not a significant difference. In general, the results indicate a relationship between the number of collisions and PNC, and higher PNC values have higher probabilities of collisions. Thus, these models confirm that PNC is a good surrogate safety measure for freeway merging ramp areas.

**Table 4.4 Summary of the significant collision models.**

| No. | Constant | Variable 1 | | Variable 2 | | Variable 3 (PNC) | | AIC |
|---|---|---|---|---|---|---|---|---|
| | Coefficient | Coefficient | Name | Coefficient | Name | Coefficient | Name | |
| Total Collisions | | | | | | | | |
| 1 | 2.1747** | 0.0828† | Exp_FRL | | | | | 127.71 |
| 2 | 4.2673** | 0.0042 | Exp_FRL | | | 2.0454** | Log(PNC) | 123.41 |
| 3 | 2.1928** | 0.0254† | Exp_Tot | | | | | 130.27 |
| 4 | 4.4755** | -0.0021 | Exp_Tot | | | 2.1576** | Log(PNC) | 123.40 |
| 5 | -1.1967 | 2.7649* | Log(Exp_Tot) | | | | | 129.37 |
| 6 | 4.8777* | -0.2906† | Log(Exp_Tot) | | | 2.2008** | Log(PNC) | 123.38 |
| Only ramp collisions | | | | | | | | |
| 7 | 1.9558** | -0.0576† | Exp_FRL | | | | | 68.63 |
| 8 | 2.0764** | -0.1660* | Exp_FRL | | | 3.8378* | PNC | 65.02 |
| 9 | 2.4001 | -1.3143 | Log(Exp_FRL) | 0.0048 | Ramp-DS | | | 71.06 |
| 10 | 5.0282** | -6.3348** | Log(Exp_FRL) | 0.0236† | Ramp-DS | 5.6787** | PNC | 64.94 |

Note: † $p$-value ≤ 0.1; * $p$-value ≤ 0.05; ** $p$-value ≤ 0.01.

$Log(x) =$ logarithm $(x)$; $Exp\_x$= exposure in a million vehicle-km for five years = $Q\_x \times 365 \times Length\ of\ \_SCL \times 5 \times 10^{-9}$; $Q\_FRL$= AADT of FRL; Q_Tot= AADT of mainline and ramp at each merging area; $Ramp\_DS$ = ramp design speeds; $p$-value = the significance of the model parameters; AIC= Akaike information criterion. In general, a lower AIC value indicates a better model (Polus et al. 1985).

## 4.9 Conclusions

Concerns have been expressed on freeway merging at entrance ramps and expected difficulties related to the operation of CAVs. To address these concerns, different merging management strategies have been proposed to eliminate or reduce conflicts between merging ramp vehicles and FRL vehicles. This chapter comparatively assessed the expected safety performance associated with these different merging management strategies and the do-nothing option during the transition from a fully DV to a fully CAV fleet using a surrogate safety measure, referred to as the probability of non-compliance (PNC), which reflects the percentage of ramp vehicles that cannot merge onto the freeway comfortably. First, a simulation program was developed in MATLAB to simulate the merging manoeuvre and the different management strategies and to calculate the PNC value for a specific set of traffic and site conditions. Next, PNC results for 420 simulation scenarios were illustrated for the study area.

First, the results showed that safety performance, as reflected in PNC, may improve with the increase of CAV penetration rate provided that courtesy merging logic is built into CAVs. Still, most developed strategies showed a better outcome and lower PNC than the do-nothing option. Thus, it is assumed that using proposed strategies in a mixed traffic environment can be a solution to help vehicles comfortably merge onto the freeway and reduce the probability of collisions at merge areas compared to do-nothing. Finally, different collision models were examined based on the traffic data of 15 entrance ramps to show the relationship between PNC and collision frequency. The results of these collision models revealed a trend that high PNC values are related to high collision frequencies.

# Chapter 5: Conclusion and Recommendations

## 5.1 Conclusions

The CAVs are expected to fill our road network soon. They can drive with a shorter reaction time than DVs, which lets them drive closer than DVs and hold a short gap. While CAV platoons can increase road capacity, short intra-platoon gaps can block or make it difficult for merging vehicles to make their way onto freeways. To solve the problem, eight traffic management strategies were proposed to address the challenges that may arise during the transition phase from a fully DVs to a fully CAVs. These strategies attempt to create acceptable merging gaps for vehicles on the FRL or to resolve merging conflicts by regulating merging manoeuvres. The eight proposed strategies and a base condition of do-nothing were simulated for an existing ramp condition in Ottawa, Ontario, Canada using Vissim and a proposed MATLAB program. These strategies were simulated with different CAV penetration rates, mainline LOS, and ramp volumes and speeds. The geometry and traffic characteristics of an existing freeway segment with an on-ramp were considered for simulation strategies. The measures of performance used in this study were the average travel time for both freeway and ramp vehicles, unaccommodated demand on the freeway mainline and ramp (referred to as capacity drop), the percentage of ramp vehicles that merge below a specific speed threshold (VLMS), and PNC.

When the vehicle fleet transitions to all CAVs (100% penetration rate), the advantages of the strategies analyzed in this study almost vanished, and the do-nothing option was remarkably close to the best management strategy, outperforming others for all combinations of mainline and ramp traffic volumes. Thus, the current design guidelines for merging ramp terminals will be sufficient in the future when the vehicle fleet has fully transitioned to all CAVs. However, the results of this study confirm that during the vehicle fleet transition from all DVs to all CAVs, traffic operation and safety performance would deteriorate at these ramp terminals if no engineering intervention were implemented. The results also show that special traffic management in these areas can address these issues effectively.

The results for traffic performance indicated that travel time and capacity drop are affected by the CAV penetration rate and applied strategies. In general, at LOS D, strategy S0 (do-nothing) has a good performance for all presented traffic measures. However, when traffic volumes reach LOS E and over that, most proposed strategies show better results than base conditions for CAV penetration rate of between 25% and 100%.

Regarding capacity drop, it should be noted that this study did not look at the maximum throughput or volume travelling through the section, which is technically called capacity. Therefore, future research can find which strategy can maximize the capacity of the section based on the different road conditions, such as weather or traffic collision.

At low traffic volumes dissolving CAV platoons' strategies can improve traffic performance. S8, which uses the connectivity system to provide an appropriate gap for merging vehicles, has better traffic performance than other strategies at LOS D and E, which is in line with the results of previous studies (Sun et al. 2020; Karimi et al. 2020; Omidvar et al. 2020). Ramp metering in terms of travel time on the mainline outperforms other strategies at high traffic volumes; however, this strategy can create a traffic jam behind ramp traffic signal at high ramp traffic volumes.

For safety evaluation, two parameters were used in this study, VLMS and PNC. The percentage of VLMS introduced as a safety measure because slowing to a speed below the operating speed can cause a large speed differential between merging and freeway vehicles, increasing the potential of safety problems. The results of VLMS show that at LOS D and E, with increasing CAV penetration rate, the VLMS decrease. In addition, at the high traffic volumes S2, S6, and S7 show better results than others.

PNC was presented as another safety measure that shows the percentage of ramp vehicles that could not comfortably merge into the freeway, which increased the probability of collisions (Kanteti, 2019; Fatema and Hassan, 2013; Fatema et al., 2014). The evaluation of strategies based on PNC revealed that the ramp metering strategy outperforms other strategies because of reducing conflict between the ramp and mainline vehicles. S8, in which CAVs can coordinate with each other, showed better results than other strategies at LOS D and E when the CAV penetration rate is more than 50%. In general, all strategies except for S3 showed better results than the base condition. Furthermore, increasing the CAV penetration rate reduces PNC.

Finally, to show the relationship between PNC and collision frequency, the traffic characteristics and collisions history of 15 merging ramps in Ottawa, Ontario, were examined using negative binomial regression analysis. The results confirmed that PNC is correlated with collision frequency.

## 5.2 Future Research Recommendations

In this study, DVs and CAVs were the only types of vehicles considered, which include connectivity systems. However, a proper connectivity system may face challenges and take time to come to the market. Meanwhile, AVs without a connectivity system can transition faster to higher automation levels such as L4 and L5. However, these AVs will travel in the road network with different headways depending on their operators' settings.

Thus, it is suggested a staging plan with different transitions from DVs to L3-L5 with different settings of headway for AVs based on the different comfort levels of the AV operators. Also, in this study, the merging area considered for evaluation strategies was not adjacent to other merging or diverging areas. It is assumed that close merging and diverging areas can affect traffic operation because of changing traffic patterns and breaking CAV platoons. Thus, it is suggested that a long section of freeway that covers different merging and diverging areas should be considered for strategies evaluation. For other urban interchanges, the high ramp density may deem some management strategies impractical. Therefore, further analysis using a segment with ramps at relatively short spacings is recommended.

Regarding the measures of traffic performance, it is suggested that total time spent (TTS) in the system is also considered for future studies. TTS in the roadway network is an important measure for evaluating traffic efficiency, which is calculated by gathering the time spent for all generated vehicles in the network during the simulation period (Wang et al., 2016). The average travel time used in this study as an efficiency measure only considers the vehicles that could pass through a defined merging segment. Therefore, compared to travel time, TTS would consider the impact of each strategy on the total traffic demand represented by all vehicles generated in the network and whether they can pass through the merging segment or not.

Another issue that might be good to consider for evaluating strategies in the future is equity. In traffic management, efficiency is usually nominated as the most important measure to evaluate traffic performance, which does not include other measures such as environment and social equity (Kesten et al., 2013). Equity is a complex concept that is influenced by cultural and societal values, and therefore it is hard to find a comprehensive definition for that. However, equity could be defined as justice and fairness in the ubiquitous distribution of goods or rights as a simple definition (Kesten et al., 2013). In the context of this research, a strategy may be selected as the most efficient from a system perspective even though it may introduce considerably higher delay to the lower ramp volume. Thus, future studies should consider equity issues in traffic management strategies. One of the solutions to take equity into account when evaluating the proposed strategies is using the relative delay rate of freeway and ramp. Relative delay rate is calculated as delay rate divided by travel time on free-flow speed condition (Lomax et al, 1997). In this method, weighting delay can be used to compare the relative congestion on different roadway elements such as freeways and ramps (Lomax et al, 1997).

## References


Ahammed, M. A., Hassan, Y., and Sayed, T. A. 2008. Modeling driver behaviour and safety on freeway merging areas. *Journal of Transportation Engineering*, *134*(9), pp. 370–377.

Alyamani, M. and Y. Hassan. 2021. Driver behaviour on freeway entrance ramp terminals. *Journal of Transportation Engineering*, *Part A: Systems*, 147(12)

Arbib, J., and Seba, T. 2017. Rethinking transportation 2020-2030. Retrieved from: https://static1.squarespace.com/static/585c3439be65942f022bbf9b/t/591a2e4be6f2e1c13df930c5/1494888038959/RethinkX+Report_051517.pdf%0Ahttps://static1.squarespace.com/static/585c3439be65942f022bbf9b/t/59f279b3652deaab9520fba6/1509063126843/RethinkX+Report. (Accessed November 25, 2019).

Arem, B. V., Van Driel, C. J. G., and Visser, R. 2006. The impact of cooperative adaptive cruise control on traffic-flow characteristics. *IEEE Transactions on Intelligent Transportation Systems*, *7*(4), pp. 429–436.

Ayres, T. J., Li, L., Schleuning, D., and Young, D. 2001. Preferred time-headway of highway drivers. *ITSC 2001. 2001 IEEE Intelligent Transportation Systems*, pp. 826–829.

AASHTO .2018. *A policy on geometric design o f highways and streets*. American Association of State Highway and Transportation Officials. 7th Edition Washington, D.C.

BBC News. March 2018, Tesla in fatal California crash was on autopilot. Retrieved from: https://www.bbc.com/news/world-us-canada-43604440. (9Accessed April 21, 2020).

Brackstone, M., and McDonald, M. 1999. Car-following: A historical review. *Transportation Research Part F: Traffic Psychology and Behaviour*, *2*(4), pp. 181-196.

Boudette, Neal. 2017. Tesla's self-driving system cleared in deadly crash. *The New York Times.* Retrieved from*:* https://www.nytimes.com/2017/01/19/business/tesla-model-s-autopilot-fatal-crash.html. (Accessed November 25, 2019).

Bansal, P., and Kockelman, K. M. 2017. Forecasting americans' long-term adoption of connected and autonomous vehicle technologies. *Transportation Research Part A: Policy and Practice*, *95*, pp. 49–63.

Chong, J. 2016. Automated and connected vehicles: status of the technology and key policy issues for Canadian governments. Library of Parliament Research Publication, Publication No. 2016-98-E.

Cordera, R., Nogués, S., González-González, E., and Moura, J. L. 2021. Modeling the impacts of autonomous vehicles on land use using a LUTI model. *Sustainability*, *13*(4), 1608.

Daamen, W., Loot, M., and Hoogendoorn, S. 2010. Empirical analysis of merging behavior at freeway on-ramp. *Transportation Research Record: Journal of the Transportation Research Board*, *2188*, pp. 108–118.

El-Basyouny, K., and Sayed, T. 2006. Comparison of two negative binomial regression techniques in developing accident prediction models. *Transportation Research Record*, *1950*(1), pp. 9-16.

Fagnant, D.J. and Kockelman, K. 2015. Preparing a nation for autonomous vehicles: opportunities, barriers and policy recommendations. *Transportation Research Part A*, 77, pp. 167-181.

Fatema, T., Ismail, K., and Hassan, Y. 2015. Development and evaluation of generalized model specification for probabilistic design of acceleration speed change lanes. *Presented at 94th Annual Meeting of the Transportation Research Board*, Washington, D.C.

Fatema, T., K. Ismail, and Y. Hassan. 2014. Validation of probabilistic model for design of freeway entrance speed change lanes. *Transportation Research Record*, 2460(1), pp. 97-106.

Fatema, T., and Hassan, Y. 2013. Probabilistic design of freeway entrance speed-change lanes considering acceleration and gap acceptance behavior. *Transportation research record*, 2348, pp. 30-37.

Fuller, R. and Santo, J. 2002. *Human factors for highway engineers*. Elsevier Science Ltd., Kiklington, Oxford, UK.

General Motors. 1939. *Futurama 1939 New York world's fair "to new horizons"*. Retrieved from: https://youtu.be/sClZqfnWqmc, (Accessed October 15, 2019).

Ghiasi, A., O. Hussain, Z. S. Qian, and X. Li. 2017. A mixed traffic capacity analysis and lane management model for connected automated vehicles: a Markov chain method. *Transportation Research Part B: Methodological*, 106, pp. 266-292.

Gipps, P. G. 1981. A behavioural car-following model for computer simulation. *Transportation Research Part B: Methodological*, *15*(2), pp. 105-111.

Glancy, D. J. 2015. Autonomous and automated and connected cars - Oh my ! first generation autonomous cars in the legal ecosystem. *Minnesota Journal of Law, Science and Technology*, *16*(2), pp. 619–691

Goodall, N. 2014. Ethical decision making during automated vehicle crashes. *Transportation Research Record*, *2424*(1), pp. 58–65.

Goodcarbadcar. 2019. Auto sales data and stats. Accessed June 03, 2019. http://www.goodcarbadcar.net/2019/03/february-2019-the-best-selling-vehicles-in-canada-every-vehicle-ranked/.

Guizzo, E. 2011. How Google's self  driving car works. *IEEE Spectrum Automaton Blog*, pp. 1–9. Retrieved from: http://spectrum.ieee.org/automaton/robotics/artificial-intelligence/how-google-self-driving-car-works. (Accessed November 30, 2019).

Hayat, M.T., H. Park, and B.L. Smith. 2014. Connected vehicle enabled freeway merge assistance system-field test: preliminary results of driver compliance to advisory". *In 2014 IEEE Intelligent Vehicles Symposium Proceedings,* June 8-11, 2014, Dearborn, MI, USA, pp.1017-1022.

Hilbe, J. M. 2011. *Negative binomial regression*. Cambridge University Press, New York, USA.

Hooper, A. and Murray, D. 2018. An analysis of the operational costs of trucking. *American Transportation Research Institute*, (703), 17. Retrieved from: https://pdfs.semanticscholar.org/666b/e5a47215d29d17ef20924659fd29a0a7d11b.pdf . (Accessed 30, November 2019).

International organization for standardization (ISO). 2010. ISO15622, intelligent transport Systems adaptive cruise control systems - performance requirements and test procedures. Second edition, Switzerland.

Karbalaieali, S., Osman, O. A., and Ishak, S. 2019. A dynamic adaptive algorithm for merging into platoons in connected automated environments. IEEE Transactions on Intelligent Transportation Systems, 21(10), pp. 4111-4122.

Karimi, M., Roncoli, C., Alecsandru, C., and Papageorgiou, M. 2020. Cooperative merging control via trajectory optimization in mixed vehicular traffic. *Transportation Research Part C: Emerging Technologies*, *116*, 102663

Kanteti, N. H. 2019. *Effect of vehicles connectivity on the safety performance of freeway acceleration speed change lanes*. Master thesis, Department of Civil and Environmental Engineering, Carleton University, Ottawa, Canada.

Kesten, A. S., Ergün, M., and Yai, T. 2013. An analysis on efficiency and equity of fixed-time ramp metering. *Journal of Transportation Technologies, 3(2A),* PP. 48-56.

Kiran, J. S., and Jakkala, P. R. 2020. Cyber security and risk analysis on connected autonomous vehicles. *Solid State Technology*, *63*(2s).

Kondyli, A. and Elefteriadou, L. 2012. Driver behavior at freeway-ramp merging areas based on instrumented vehicle observations. *Transportation Letters*, *4*(3), pp. 129–142.

Larburu, M., Sanchez, J., and Rodriguez, D. 2010. Safe road trains for environment: human factors aspects in dual mode transport systems. *ITS World Congress, Busan,* pp. 1–12. Retrieved from:

https://pdfs.semanticscholar.org/8925/6fc292d8e77c82721f802529162c013a1471.pdf. (Accessed November 30, 2019).

Letter, C., and Elefteriadou, L. 2017. Efficient control of fully automated connected vehicles at freeway merge segments. *Transportation Research Part C: Emerging Technologies*, *80*, pp. 190-205.

Litman, T. 2015. Autonomous vehicle implementation predictions: implications for transport planning. *Transportation Research Board 94th Annual Meeting, 2015.*

Lomax, T., Turner, S., Shunk, G., Levinson, H. S., Pratt, R. H., Bay, P. N., and Douglas, G. B. 1997. *Quantifying congestion. Volume 2: User's guide* (No. Project 7-13 FY'92).

MacFarland, Matt. 2016. For the first time, Google's self-driving car takes some blame for a crash. *The Washington Post.* Retrieved from: https://www.washingtonpost.com/news/innovations/wp/2016/02/29/for-the-first-time-googles-self-driving-car-takes-some-blame-for-a-crash/?noredirect=on&utm_term=.a6f0e0d1fc5e. (Accessed November 30, 2019).

Marczak, F., Daamen, W., and Buisson, C. 2013. Merging behaviour: empirical comparison between two sites and new theory development. *Transportation Research Part C: Emerging Technologies*, *36*, pp. 530–546.

Matcha, B. N., Namasivayam, S. N., Ng, K. C., Sivanesan, S., and EhNoum, S. Y. 2021. Mixed-traffic vehicle dynamics: analysis and comparison of microscopic Gipp's car-following model and intelligent driver model. *Advances in Transportation Studies*, *55*.

Maurer, M., Gerdes, J. C., Lenz, B., and Winner, H. 2016. *Autonomous driving: technical, legal and social aspects*. Springer Nature.

Michaels, R. M., and Fazio, J. 1989. Driver behavior model of merging. *Transportation Research Record*, (1213), pp. 4–10.

Milakis, D., Snelder, M., Arem, B. van, Wee, B. van, and Homem de Almeida Correia, G. 2017. Development and transport implications of automated vehicles in the netherlands: scenarios for 2030 and 2050. *European Journal of Transport and Infrastructure Research*, 17(1).

Mitroi, I. S., Ciobica, A. M., and Popa, M. 2016. Car-following models. Comparison between models used by Vissim and AIMSUN. U.P.B. Sci. Bull., Series D, 78(4).

Nakka, S. K. S., Chalaki, B., and Malikopoulos, A. 2021. A multi-agent deep reinforcement learning coordination framework for connected and automated vehicles at merging roadways. *arXiv preprint arXiv:2109.11672*.

National Highway Traffic Safety Administration (NHTSA). 2016. *U.S. DOT Issues federal policy for safe testing and deployment of automated vehicles*. NHTSA Press Release, Sept 20, 2016. Retrieved from: http://www.nhtsa.gov/Press-Releases (Accessed September 25, 2016).

National Highway Traffic Safety Administration (NHTSA). 2017. *Automated driving systems 2.0: A vision for safety*. Report DOT HS 812 442.

Nowakowski, C., O'Connell, J., Shladover, S. E., and Cody, D. 2010. Cooperative adaptive cruise control: driver acceptance of following gap settings less than one second. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, *54*(24), pp. 2033–2037.

Omidvar, A., Elefteriadou, L., Pourmehrab, M., and Letter, C. 2020. Optimizing freeway merge operations under conventional and automated vehicle traffic. *Journal of Transportation Engineering, Part A: Systems*, *146*(7), 04020059.

Oregon Department of Transportation, ODOT .2011. *Protocol for VISSIM simulation*.

Ottawa open -data. 2021. Open data, maps, apps and stories from the City of Ottawa. Retrieved from: https://open.ottawa.ca/search?tags=transportation (Accessed March 15, 2021).

Pakzadnia, A., S. Roustom, and Y. Hassan. 2021. Accommodation of freeway merging in a mixed traffic environment including connected autonomous vehicles. *Canadian Journal of Civil Engineering.* 2021 (May):6. https://doi.org/10.1139/cjce-2020-0815

Panwai, S., and Dia, H. 2005. Comparative evaluation of microscopic car-following behavior. *IEEE Transactions on Intelligent Transportation Systems*, *6*(3), pp. 314-325.

Park, H., Bhamidipati, S. C., and Smith, B. L. 2011. Development and evaluation of enhanced intellidrive-enabled lane changing advisory algorithm to address freeway Merge Conflict. *Transportation research record*, 2243, pp. 146-157

Ploeg, J., Scheepers, B. T. M., Nunen, E. Van, Wouw, N. Van De, and Nijmeijer, H. 2011a. Design and experimental evaluation of cooperative adaptive cruise control. *Conference on Intelligent Transportation Systems (ITSC)*,October 5-7, 2011, Washington, DC, USA, pp. 260–265.

Ploeg, J., Serrarens, A. F. A., and Heijenk, G. J. 2011b. Connect & drive: design and evaluation of cooperative adaptive cruise control for congestion reduction. *Journal of Modern Transportation*, *19*(3), pp. 207–213.

Policy and Planning Support Committee (PPSC). 2018. The future of automated vehicles in Canada report of the PPSC working group on connected and automated vehicles, pp. 1–36.

Polus, A., M. Livneh, and J. Factor. 1985. Vehicle flow characteristics on acceleration lanes. *Journal of Transportation Engineering*. 111(6), pp. 595–606.

SAE. 2016. Taxonomy and definitions for terms related to on-road motor vehicle automated driving systems. Society of Automotive Engineering International Standard J3016.

Scarinci, R., Hegyi, A. and Heydecker, B. 2017. Definition of a merging assistant strategy using intelligent vehicles. *Transportation research part C: Emerging Technologies*, 82, pp. 161-179.

Shladover S. 1997. AHS Demo'97 "Complete success." *Intellimotion, Research Updates in Intelligent Transportation Systems.* 6(3), pp. 1. Retrieved from: https://merritt.cdlib.org/d/ark%3A%2F13030%2Fm5b58007/1/producer%2FIntellimotion v7n2.pdf. (Accessed November 30, 2019)

Shladover S.E. 1997. The GM-PATH Platoon. *Intellimotion, Research Updates in Intelligent Transportation Systems,* 6(3), pp. 2-3. Retrieved from: https://merritt.cdlib.org/d/ark%3A%2F13030%2Fm5b58007/1/producer%2FIntellimotion v7n2.pdf. (Accessed November 30, 2019)

Shladover, S. E., Lu, X., Song, B., Dickey, S., Nowakowski, C., Howell, A., Bu, F., Marco, D., Han-Shue, T., Nelson, D. 2005. Demonstration of automated heavy-duty vehicles. *California PATH Research Report Ucb-Its-Prr-2005-23*, (June), 459.

Singh, V. P., Jain, S. K., and Tyagi, A. 2007. *Risk and reliability analysis: a handbook for civil and environmental engineers*. American Society of Civil Engineers.

Society of Automotive Engineers, SAE international's new standard J3016. 2016. Taxonomy and definitions for terms related to on-road motor vehicle automated driving systems.

Storck, C. R., and Duarte-Figueiredo, F. 2020. A survey of 5G technology evolution, standards, and infrastructure associated with vehicle-to-everything communications by internet of vehicles. *IEEE Access*, *8*, pp. 117593-117614.

Sun, Z., Huang, T., and Zhang, P. 2020. Cooperative decision-making for mixed traffic: A ramp merging example. *Transportation research part C: emerging technologies*, *120*, 102764.

TAC, 2017. *Geometric design guide for Canadian roads*. Transportation Association of Canada, Ottawa, Ontario.

Taieb-Maimon, M., and Shinar, D. 2001. Minimum and comfortable driving headways: reality versus perception. h*uman factors*, *43*(1), pp. 159–172.

Talebpour, A., and Mahmassani, H. S. 2016. Influence of connected and autonomous vehicles on traffic flow stability and throughput. *Transportation Research Part C: Emerging Technologies*, *71*(October), pp. 143–163.

Tesla. 2021. Model S owner's manual.

Transport Canada. 2019. *Canadian motor vehicle traffic collision statistics: 2019.* Retrieved from: https://tc.canada.ca/en/road-transportation/statistics-data/canadian-motor-vehicle-traffic-collision-statistics-2019. (Accessed September 04, 2021).

Transport Canada. 2018. *Transportation in Canada 2018 – Overview report*. Report T1-21E-PDF, Ottawa, ON.

Transport Canada. 2020. *Transportation in Canada 2020 – Overview report*. Report T1-21E-PDF, Ottawa, ON.

TRB. 2016. *Highway capacity manual. 6th ed*. Transportation Research Board (TRB), Washington, DC.

Treiber, M., and Kesting, A. 2013. *Traffic flow dynamics data, models and simulation,* Springer-Verlag Berlin, Heidelberg.

Udeshi, S., Uko, M., Zafar, M., Altaf, A., Adebisi, B., and Ekpo, S. 2019. Integrated space-enabled hybrid 5G-V2X communications link modeling. *37th International communications satellite systems conference*, October 29- November 1,2019, Okinawa, Japan.

Van Arem, B., Van Driel, C. J. and Visser, R. 2006. The impact of cooperative adaptive cruise control on traffic-flow characteristics. *IEEE Transactions on Intelligent Transportation Systems*, 7(4), pp. 429–436.

Vander Werf, J., Shladover, S., Miller, M., and Kourjanskaia, N. 2002. Effects of adaptive cruise control systems on highway traffic flow capacity. *Transportation Research Record: Journal of the Transportation Research Board*, 1800(02), pp. 78–84.

Virginia Department of Transportation, VDOT .2020. *Traffic operations and safety Analysis Manual*, *(TOSAM)*.

Wang, B., and Gu, J. 2019. Calibration method for a microscopic simulation model of urban expressway using internet traffic operation data. *In IOP Conference Series: Materials Science and Engineering*, 688(2).

Wang, H. M., Molnár, T. G., Avedisov, S. S., Sakr, A. H., Altintas, O., and Orosz, G. 2020. Conflict analysis for cooperative merging using V2X communication. *In 2020 IEEE Intelligent Vehicles Symposium (IV),* October 20-23,2020, Las Vegas, USA, pp. 1538-1543.

Wang, M., Daamen, W., Hoogendoorn, S. P., & van Arem, B. 2016. Connected variable speed limits control and car-following control with vehicle-infrastructure communication to resolve stop-and-go waves. *Journal of Intelligent Transportation Systems*, 20(6), pp. 559-572.

Waymo .2018. *Google self-driving car project, millions of miles driven*. Retrieved from: https://waymo.com/ontheroad/. (Accessed June 25, 2019).

Wei, H., Meyer, E., Lee, J., and Feng, C. 2000. Characterizing and modeling observed lane-changing behavior: lane-vehicle-based microscopic simulation on urban street network. *Transportation Research Record: Journal of the Transportation Research Board*, (1710), pp. 104-113.

World Health Organization (WHO). 2018. *Global status report on road safety 2018*. Retrieved from: https://www.who.int/health-topics/road-safety#tab=tab_1. (Accessed August 25, 2021).

Xie, Y., Zhang, H., Gartner, N. H., and Arsava, T. 2017. Collaborative merging strategy for freeway ramp operations in a connected and autonomous vehicles environment. *Journal of Intelligent Transportation Systems*, *21*(2), pp.136-147.

Yastrebova, A., Ojanperä, T., Mäkelä, J., and Höyhtyä, M. 2021. Hybrid connectivity for autonomous vehicles: conceptual view and initial results. *In 2021 IEEE 93rd Vehicular Technology Conference (VTC2021-Spring).* April 25-28, 2021, Helsinki, Finland, pp. 1-6.

Zhu, J., Tasic, I., and Qu, X. 2021. Improving freeway merging efficiency via flow-level coordination of connected and autonomous vehicles. *arXiv preprint arXiv:2108.01875*.

Zhu, J. and I. Tasic. 2021. Safety analysis of freeway on-ramp merging with the presence of autonomous vehicles. *Accident Analysis & Prevention*, 152, 105966.

Zmud, J., Sener, I. N., and Wagner, J. 2016. Self-driving vehicles. *Transportation Research Record: Journal of the Transportation Research Board*, *2565*, pp. 57–64.

# Appendix A – Chapter 3 Supplemental Information

## A.1 Calculation of Maximum Traffic Volumes of LOS D and E

Maximum traffic volumes for LOS D and E were estimated based on the Highway Capacity Manual (2016).

**Maximum flow rate at LOS E:**

Maximum flow rates at LOS E for freeways are equal to capacity and can be calculated using the following equations:

$$Basic\ freeway\ capacity\ (pc/h/ln) = 2{,}200 + 10\ (FFS - 50), if\ capacity \leq 2{,}400 \quad \text{(A.1)}$$

where,

$FFS$ = free-flow speed (mi/h).

The free-flow speed of Highway 417 is assumed 110 km/h or 70 mi/h; thus, the Capacity would be:

$$Basic\ freeway\ capacity = 2{,}200 + 10\ (70 - 50) = 2{,}400\ pc/h/ln$$

**Maximum flow rate at LOS D:**

Maximum traffic volume at LOS D can be determined as:

$$\text{Breakpoint (BP)} = [1{,}000 + 40 \times (75 - (\text{FFS} \times \text{SAF}))] \times CAF^2 \quad \text{(A.2)}$$

where,

SAF = the speed adjustment factor, and CAF = the capacity adjustment factor.

Capacity adjustment and speed adjustment factors are assumed 1.0; thus, the breakpoint would be:

$\mathrm{BP} = (1{,}000 + 40\,(75 - 70) = 1{,}200\ \mathrm{pc/ln/h}$

The mean speed of traffic stream (mi/h) can be calculated as follows:

$$S = FFS - \frac{(FFS - \frac{Capacity}{Density\ at\ Capacity})(v_p - BP)^2}{(Capacity - BP)^2} \tag{A.3}$$

where,

$v_p$ = the demand flow rate (pc/h/ln), and it is equal to:

$$vp = \text{Density x mean speed of traffic stream} \tag{A.4}$$

Maximum density at LOS E and D equals 45 and 35 pc/mi/ln, respectively (TRB, 2016). The first trial of $v_p$ can be calculated via multiple of FFS and density at LOS D:

$vp = 70 \text{ x } 35 = 2450\ \mathrm{pc/h/ln}$

Then the mean speed would be $S = 51.9$ mi/h

Then a new $v_p$ can be estimated with the calculated mean speed. After using the trial-and-error method, the maximum flow rate at LOS D would be estimated at approximately 2100 pc/h/ln.

### A.2 Traffic Volumes Assigned in Simulation and Simulation Runs Tables

**Table A.1 Traffic volumes assigned in simulations on freeway lanes.**

| LOS | Assigned volume upstream the merge area (pc/h) | Expected volume and LOS downstream the merge area (pc/h) | | | |
|---|---|---|---|---|---|
| | | Ramp volume 400 pc/h | | Ramp volume 1,300 pc/h | |
| D | 6,300 | 6,700 | LOS E | 7,600 | 5.6% > LOS E |
| E | 7,200 | 7,600 | 5.6% > LOS E | 8,500 | 18% > LOS E |
| E* | 8,640 | 9,040 | 25.6%> LOS E | 9,940 | 38% > LOS E |

**Table A.2 Parameters and numbers of the different simulation runs.**

| Strategy | CAV% | Freeway Traffic volume (pc/ln/h) | Ramp traffic volume (pc/h) | Ramp Speeds (km/h) | Number of scenarios | Traffic Arrival Types | Total number of runs |
|---|---|---|---|---|---|---|---|
| S0 | 0, 25, 50, 75, 100 | 2,100, 2400, 2,880 | 400, 1,300 | 40, 80 | 60 | 3 | 60 × 3 |
| S1, S2, S6, S7, & S8 | 25, 50, 75, 100 | | | | 48 per strategy | | 48 × 3 ×5 |
| S3, S4, & S5 | 25, 50, 75 | | | | 36 per strategy | | 36 × 3 ×3 |
| Total | | | | | 408 | | 1,224 |

### A.3 Calibration of the Simulation Software

Vissim software was calibrated based on a traffic database collected from UAV videos provided for another ongoing study. The videos were recorded at Highway 417 and O'Connor Street Interchange, which is in the vicinity of the study area, during an off-peak period on September 04, 2020. Eleven videos with a total duration of 56 minutes were used to extract traffic data of a 405 m segment of the freeway, including an on-ram terminal. Traffic volume on the freeway and ramp was observed at 4,066 and 600 pc/h, respectively. A sample of 100 freeway passenger cars was selected and found that the average travel time and space mean speed were 13.96 and 104.45 km/h, respectively, for the 405 m segment. The cumulative speed distribution of the freeway is illustrated in Figure A.1 for this sample.

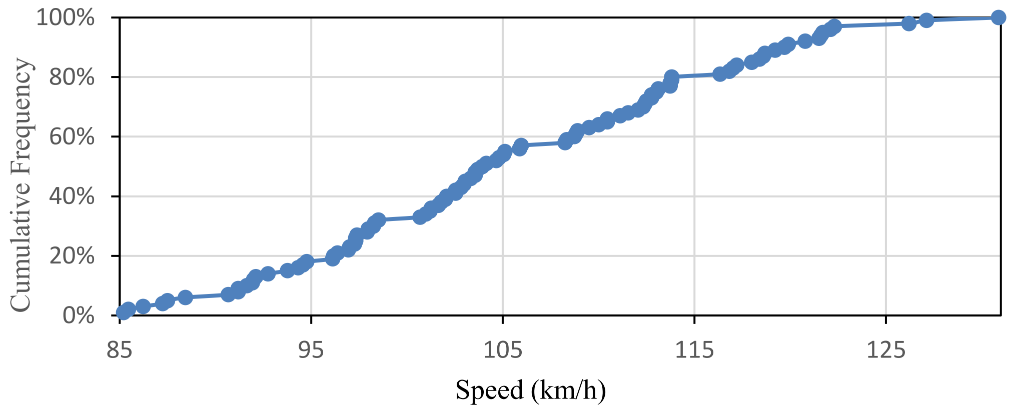



**Figure A.1 Cumulative speed distribution of mainline vehicles on a Highway 417.**

To calibrate Vissim, a practical calibration system was selected. The procedure of this calibration system includes piking performance measures, collecting required traffic data, setting the calibration parameters, determining primary values of parameters, simulating collected traffic data, evaluating the results and adjusting the values of parameters Wang and Gu (2019).

The performance measures for calibration were selected travel time and traffic volumes (TOSAM 2020). The parameters used for calibration of Vissim DVs car-following model were determined based on ODOT (2011) protocol as shown in Table A.3. In addition, the *GEH* equation ODOT (2011) was used to compare average travel times and traffic volumes between observed and simulated values to evaluate the accuracy of the results.

$$GEH = \sqrt{\frac{2(m-c)^2}{(m+c)}} \tag{A.5}$$

where,

$m$ = simulated value and $c$ observed value.

For acceptable results, *GEH* value should be less than 5%. Table A.3 presents the calibrated values for selected car-following model parameters and performance measures. The results show that the *GEH* values for freeway traffic volume and average travel time are 0.85% and 0.12%, which are acceptable.

**Table A.3 Default and calibrated car following model parameters.**

| Parameters | Default | Calibrated |
|---|---|---|
| CC0 (Standstill distance) | 1.5 m | 1.0 m |
| CC1 (following distance drivers must maintain at specific speed) (s) | 0.9 s | 0.75 s |
| CC2 (‘Following’ variation) | 4.0 m | 3.0 m |
| CC4 (Negative ‘Following’ threshold) | -0.35 | -0.3 |
| CC5 (Positive ‘Following’ threshold) | 0.35 | 0.3 |
| Average travel time (s) | 13.96 | 14.43 |
| Traffic volume on mainline (pc/h) | 4,066 | 4,012 |

### A.4 Freeway and Ramp Speed Distributions for Vissim Simulation

The desired speed on the mainline lanes of this study area for DVs was chosen based on the speed distribution of the sample collected from UAV videos (Figure A.1). Normal speed distributions for the design speeds of 40 and 80 km/h were assumed for ramp vehicles, with the mean and standard deviation estimated based on a previous study on Highway 417 using the following equations (Fatema and Hassan 2013):

$$\mu_v = -0.287 + 0.922\, V_{85}, \quad R^2 = .99 \tag{A.6}$$

$$\sigma_v = 0.446 + 0.069\, V_{85}\,, \quad R^2 = .65 \tag{A.7}$$

where,

$\mu_v$ = mean speed (m/s), $\sigma_v$ = standard deviation of speed distribution (m/s), $V_{85}$ = 85th percentile speed (m/s), and $R^2$ = coefficient of determination.

In applying these equations, the design speed was assumed as $V_{85}$ (Fatema and Hassan 2013). For CAVs, the posted speed is applied as the mean speed, and a reasonably limited speed variation of 5% of the posted speed is assumed for the standard deviation. The resulting mean and standard deviation values for ramp and mainline vehicles are presented in Table A.4

**Table A.4 Normal distribution parameters for ramp and freeway vehicles' speed.**

| Segment and design speed | Design speed | Posted speed limit | DVs | | CAVs | |
|---|---|---|---|---|---|---|
| | | | $\mu_v$ | $\sigma_v$ | $\mu_v$ | $\sigma_v$ |
| Ramp (40) | 40 | 30 | 36.593 | 3.206 | 30.0 | 1.5 |
| Ramp (80) | 80 | 70 | 73.473 | 5.966 | 70.0 | 3.5 |
| Freeway (110) | 110 | 100 | 105.49 | 10.573 | 100 | 5.0 |

All speeds are in km/h.

### A.5 The Distribution of Canadian Vehicles' lengths

The distribution of vehicles' lengths was selected based on vehicles' models representing the top 31 selling vehicles in Canada for one year between February 2018 and 2019 (Goodcarbadcar, 2019). Together, these vehicles include 56% of total Canadian vehicle sales in these 12 months, while each of the remaining 240 cars reported for less than 1% of sales. The length of simulation vehicles was selected based on the length of these sold vehicles in Canada. These lengths were categorized into seven groups, as represented in Table A. 5.

**Table A. 5 Lengths of top-selling vehicles in Canada categorized in seven-length Groups.**

| Vehicle length (mm) | %Market share | %Group share | Group's vehicle lengths (mm) |
|---|---|---|---|
| 4165 | 1.26% | 5.04% | 4275 |
| 4258 | 2.09% | | |
| 4380 | 1.69% | | |
| 4459 | 2.09% | 15.97% | 4535 |
| 4480 | 2.17% | | |
| 4524 | 3.81% | | |
| 4550 | 2.52% | | |
| 4586 | 5.38% | | |
| 4620 | 2.97% | 25.34% | 4641 |
| 4623 | 2.00% | | |
| 4630 | 5.01% | | |
| 4630 | 3.96% | | |
| 4640 | 5.90% | | |
| 4651 | 1.98% | | |
| 4686 | 3.52% | | |
| 4694 | 1.59% | 11.73% | 4750 |
| 4701 | 1.78% | | |
| 4702 | 1.08% | | |
| 4770 | 1.82% | | |
| 4779 | 1.47% | | |
| 4785 | 3.99% | | |
| 4801 | 1.47% | 6.36% | 4899 |
| 4821 | 1.98% | | |
| 4880 | 1.27% | | |
| 5095 | 1.64% | | |
| 5759 | 8.95% | 21.61% | 5815 |
| 5856 | 12.66% | | |
| 5967 | 1.60% | 13.95% | 6096 |
| 6007 | 3.44% | | |
| 6137 | 4.79% | | |
| 6174 | 4.12% | | |
| Total | 55.94% | 100.00% | --- |

## A.6 Ramp Metering Traffic Management in S7

Ramp metering in S7 allows ramp vehicles to merge onto the freeway when FRL's detectors find a large enough gap on FRL. A vehicle actuated programming (VAP) in Vissim was used to define the signal control logic of this strategy for the simulation.

This program is part of a user-friendly tool in the Vissim software named VisVap. The logic program flowchart created for S7 in the VisVap is shown in Figure A.2.

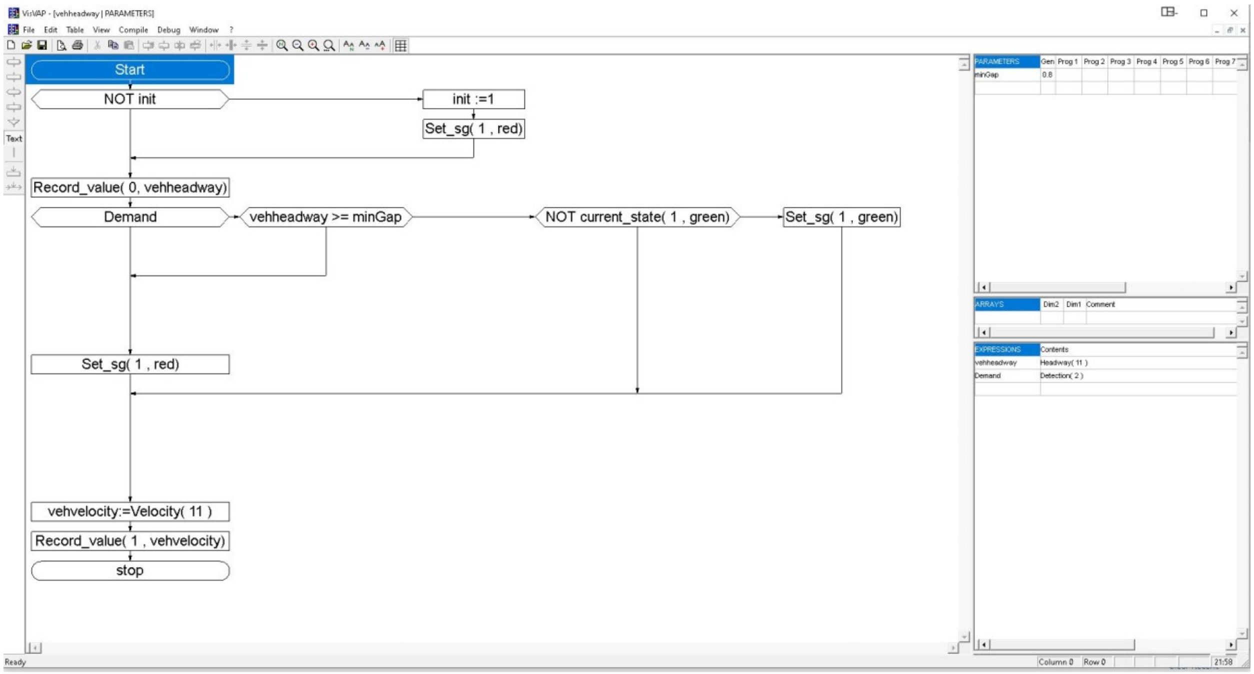



**Figure A.2 Flowchart of ramp metering in VisVAP.**

### A.7 Collaborative Merging Model in S8

A merging procedure model for a mixed traffic environment that includes DVs and CAVs using a connectivity system was developed for S8 (Figure A.3). The procedure for merging manoeuvres considers the type of vehicles and the FRL lead and lag vehicles on the freeway. It also assumed that a controller could detect merging vehicles on the ramp. If the detected gaps on the FRL are not acceptable, the controller requests upstream FRL CAVs to provide an acceptable gap for the merging vehicle. After the request, CAVs on FRL, based on the traffic conditions, will provide an acceptable gap via acceleration, deceleration, or a lane-changing manoeuvre.

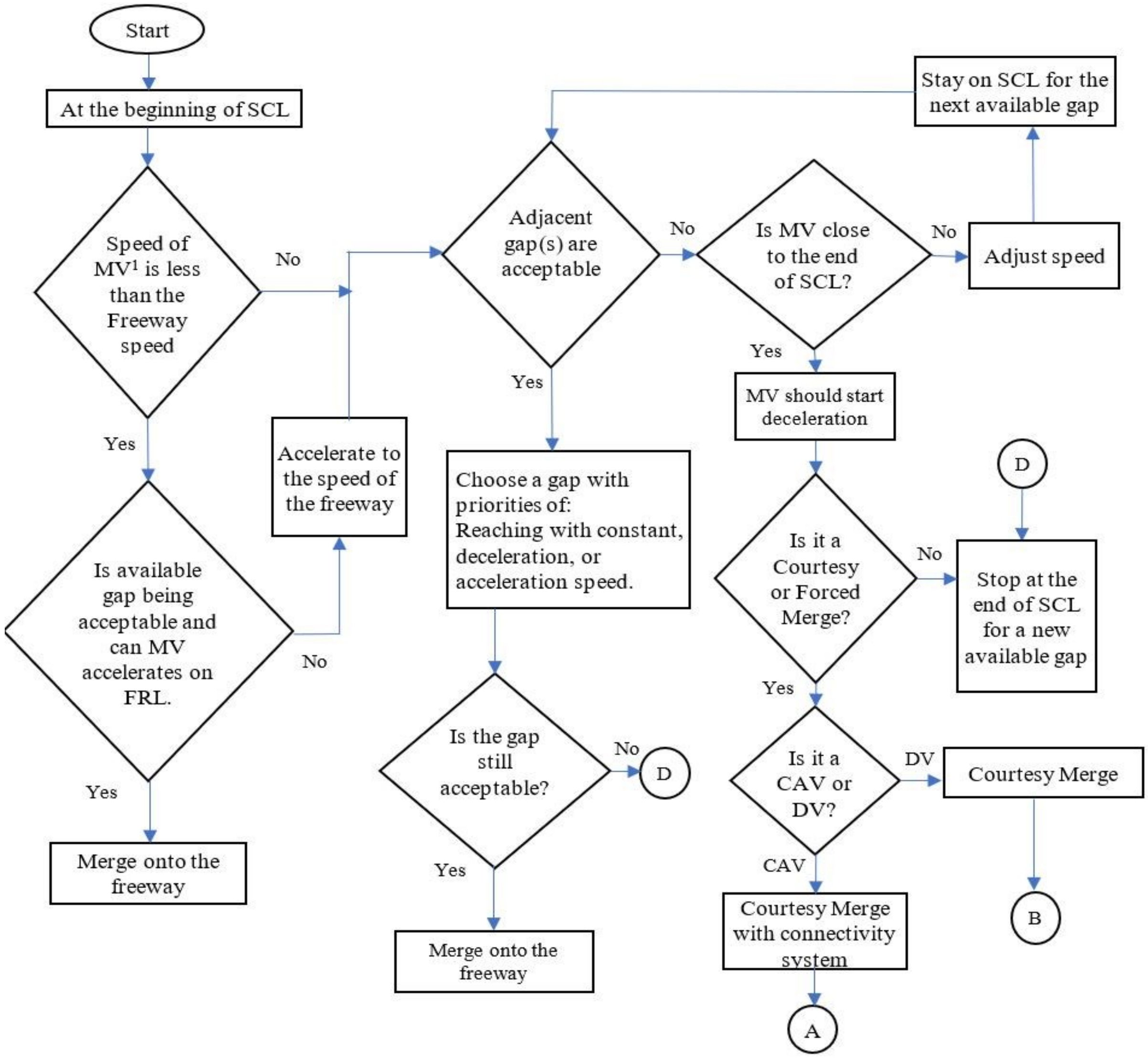



**Figure A.3 Flowchart of collaborative merging model utilizing vehicles' connectivity (Part 1).**

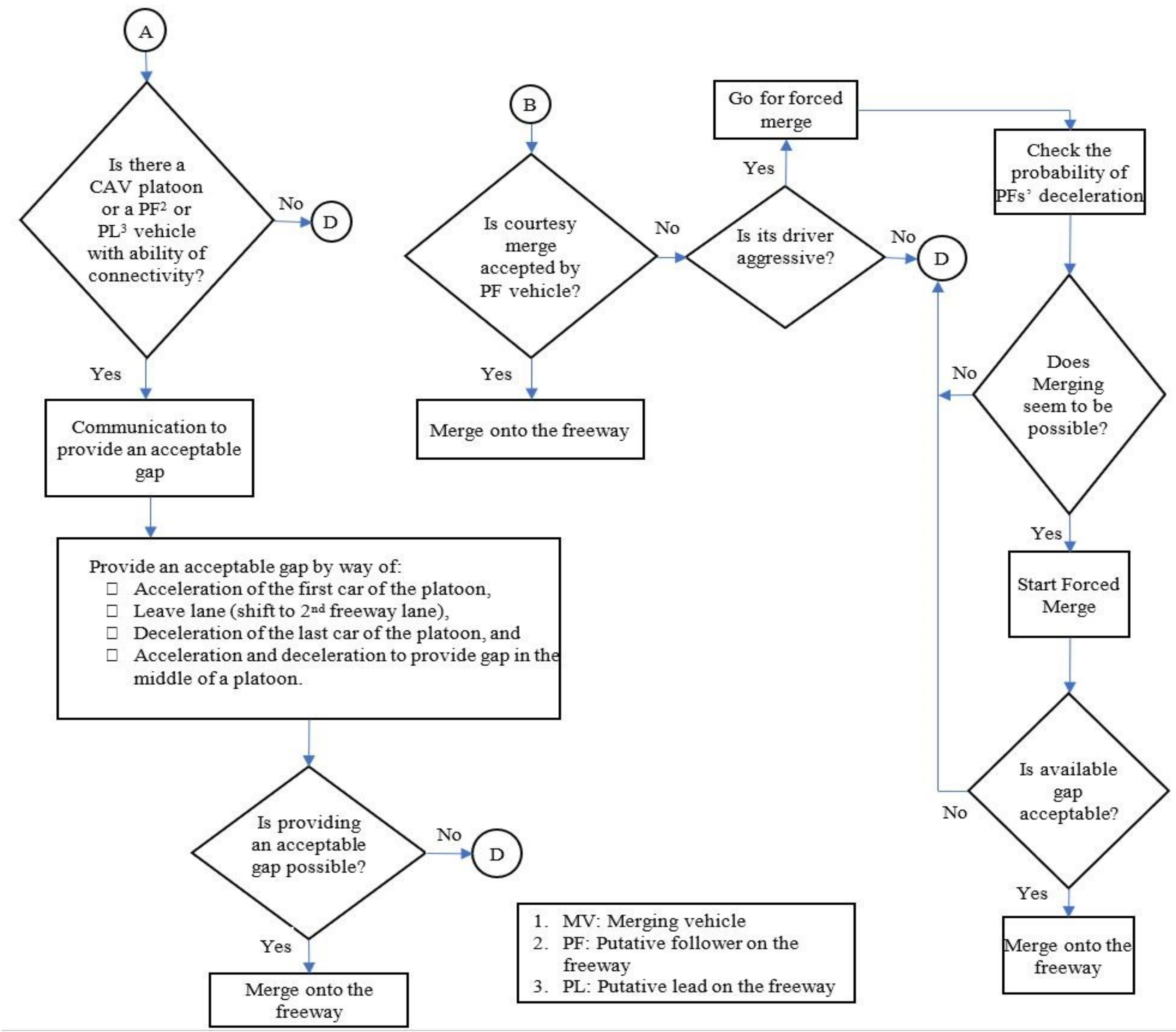
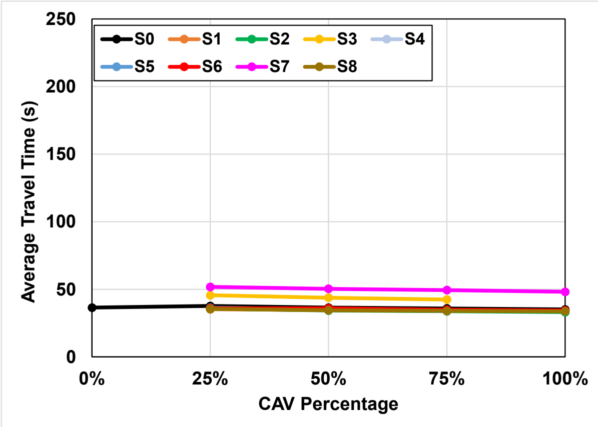


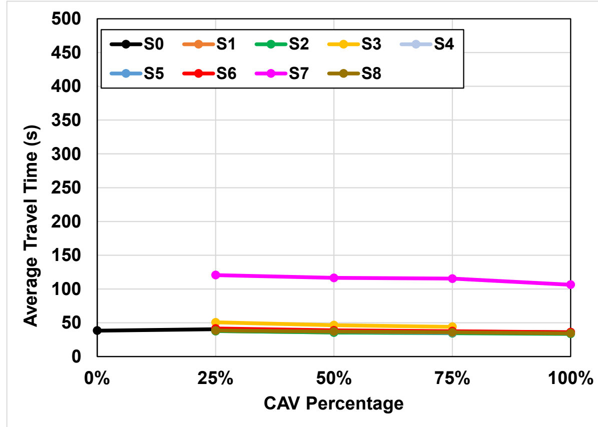

**Figure A.3 Flowchart of collaborative merging model utilizing vehicles' connectivity (Part 2).**

### A.8 Simulation Results for 80km/h Ramp Design Speed

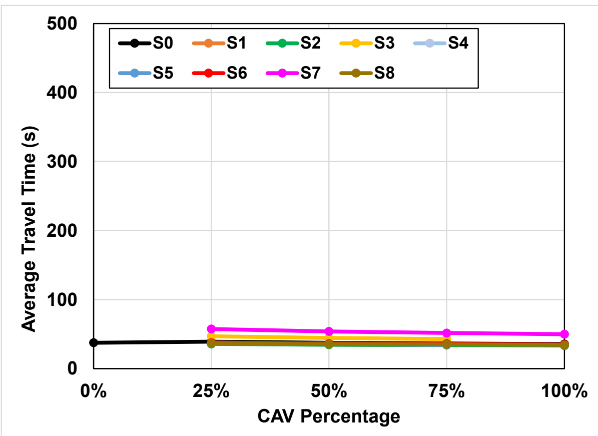
Figure A.4 and A.5 illustrate the average travel times for ramp and freeway respectively for 80 km/h ramp design speed, and Figure A.3 illustrates VLMS percentage for 80km/h ramp design speed.



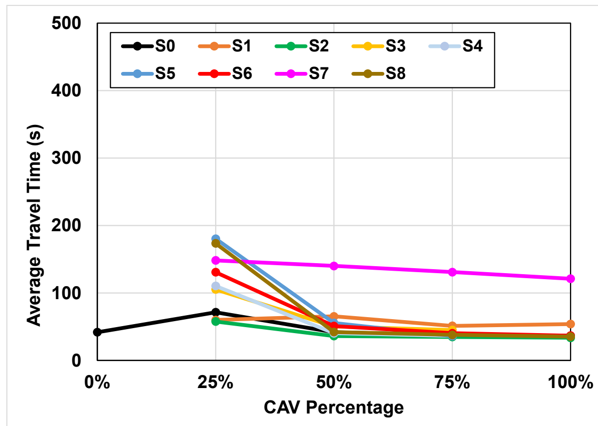

(a) LOS D, ramp volume = 400 pc/h.



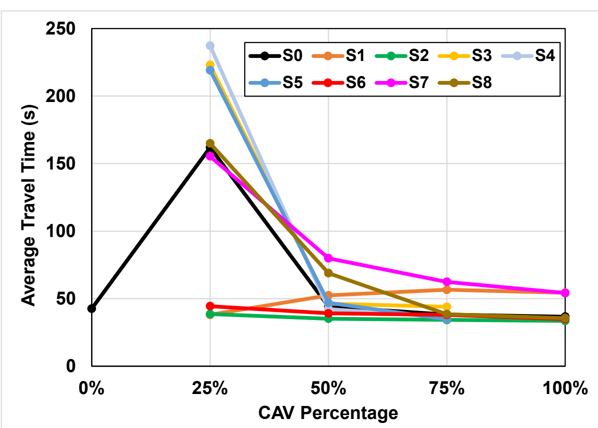

(b) LOS D, ramp volume = 1,300 pc/h.



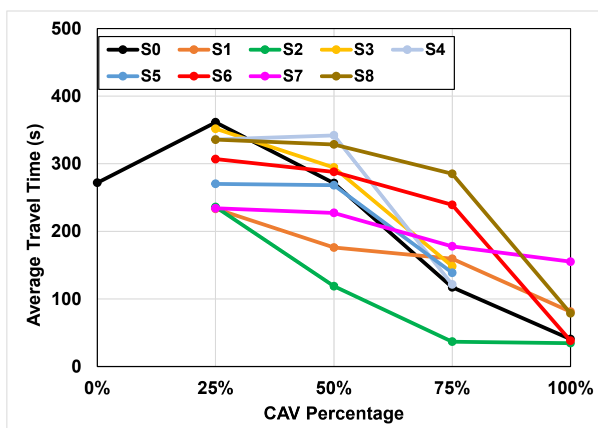

(c) LOS E, ramp volume = 400 pc/h.




(d) LOS E, ramp volume = 1,300 pc/h.

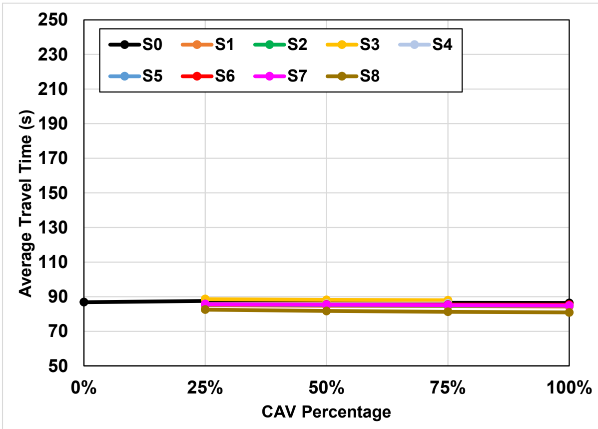


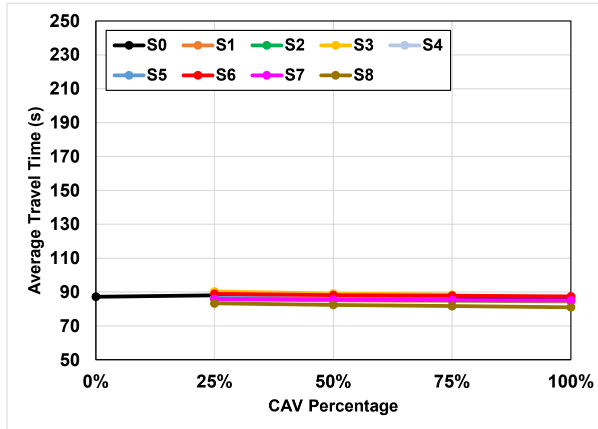

(e) LOS E*, ramp volume = 400 pc/h.




(f) LOS E*, ramp volume = 1,300 pc/h.

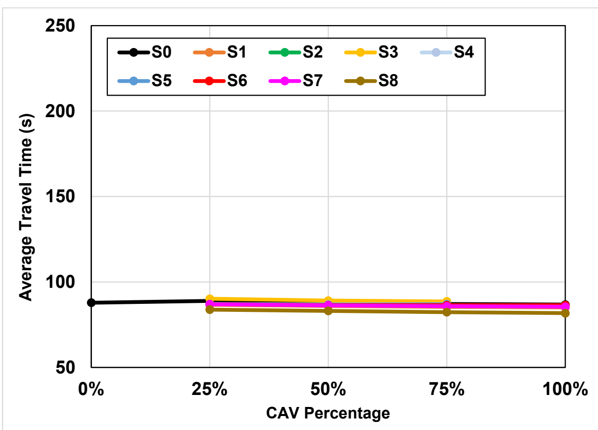
**Figure A.4 Average travel time for ramp vehicles (80 km/h ramp design speed).**

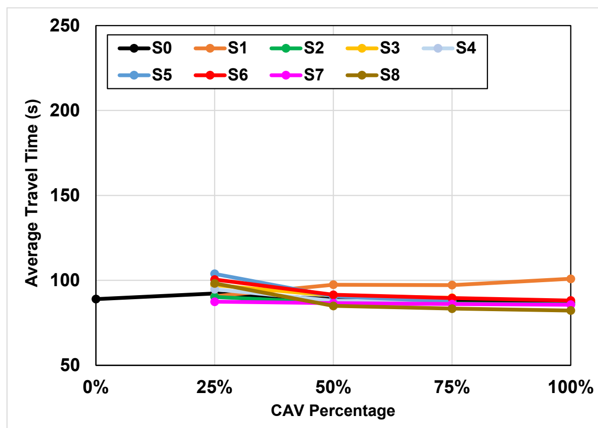



(a) LOS D, ramp volume 400 pc/h.

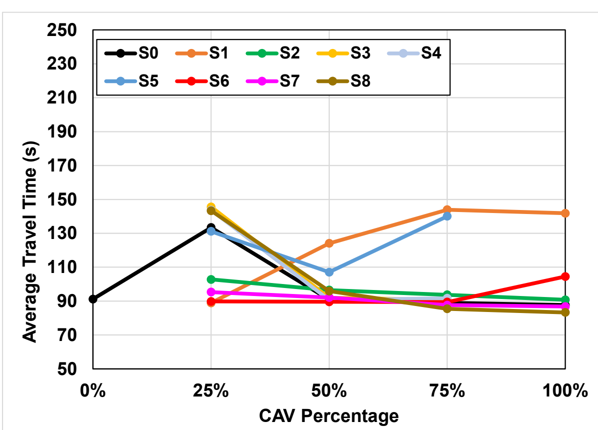
(b) LOS D, ramp volume 1,300 pc/h.

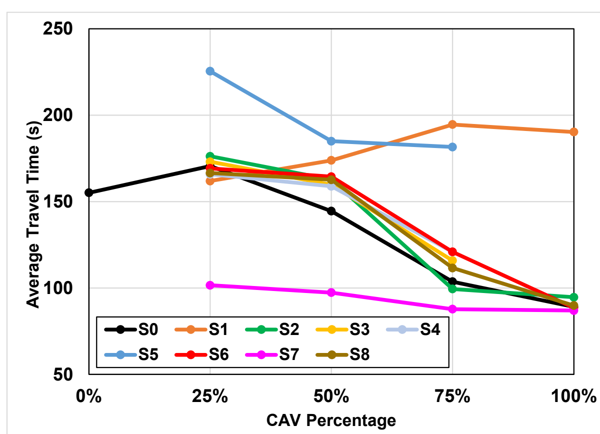



(c) LOS E, ramp volume 400 pc/h.

(d) LOS E, ramp volume 1,300 pc/h.

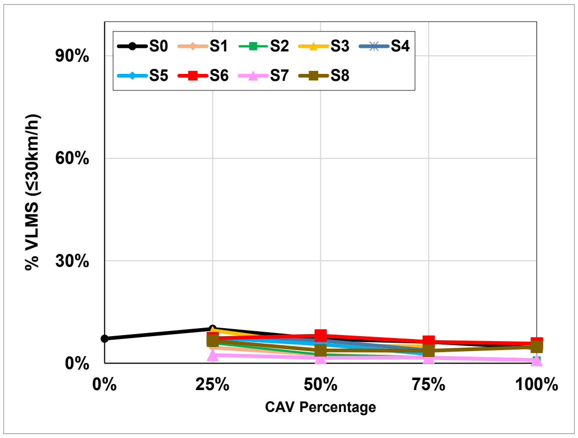


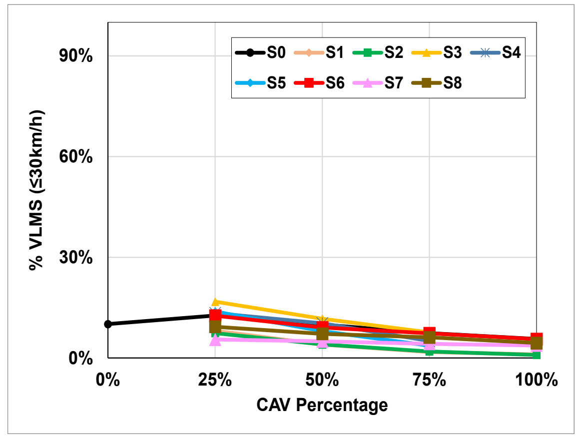

(e) LOS E*, ramp volume 400 pc/h.

(f) LOS E*, ramp volume 1,300 pc/h.

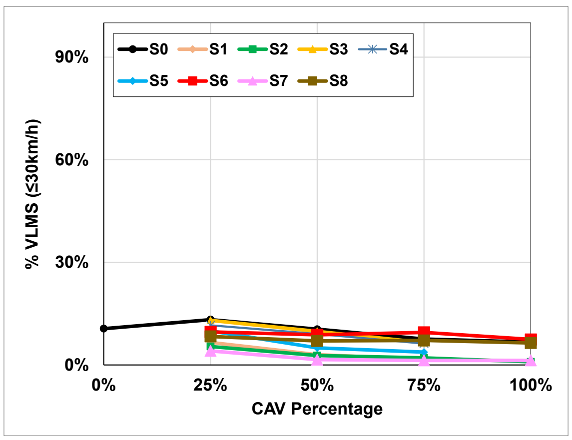
**Figure A.5 Average travel time for freeway vehicles (80 km/h ramp design speed).**



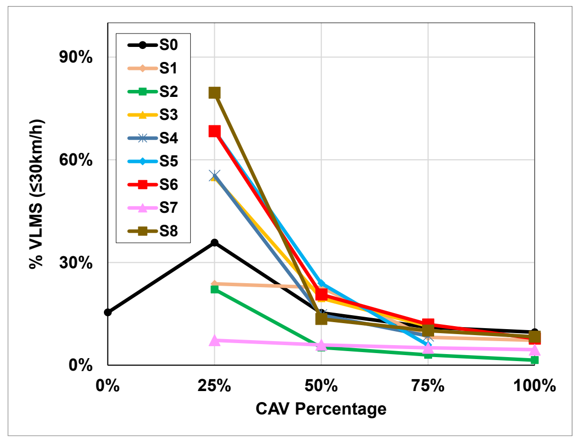

(a) LOS D, ramp volume 400 pc/h.



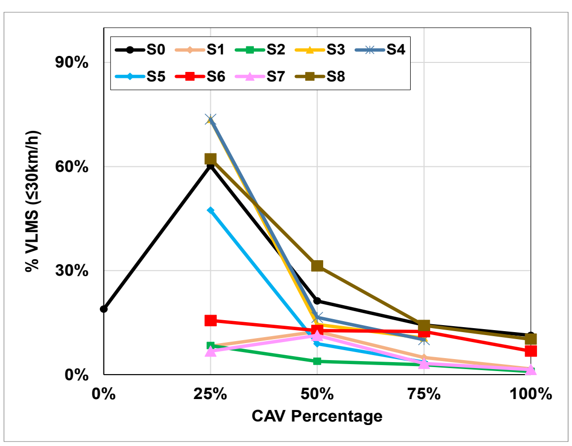

(b) LOS D, ramp volume 1,300 pc/h.



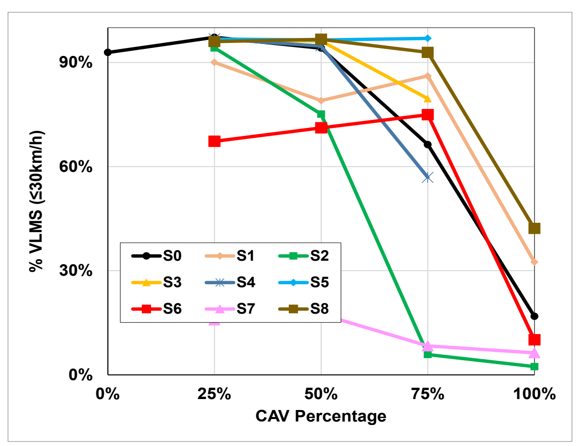

(c) LOS E, ramp volume 400 pc/h.




(d) LOS D, ramp volume 1,300 pc/h.




(e) LOS E*, ramp volume 400 pc/h.




(f) LOS E*, ramp volume 1,300 pc/h.

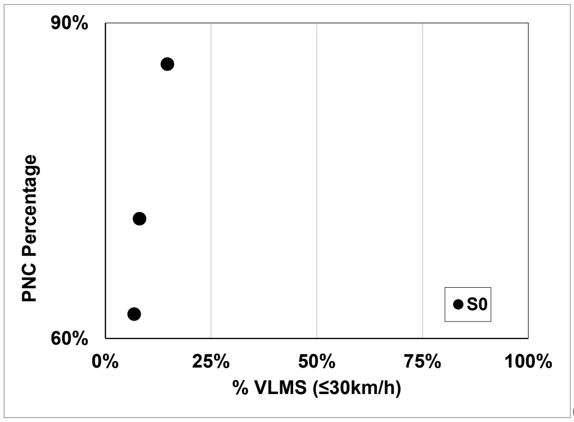
**Figure A.6 Percentage VLMS, speed threshold of 30 km/h (80 km/h ramp design speed).**

## A.9 Relationship Between the Percentage of PNC and Percentage of VLMS

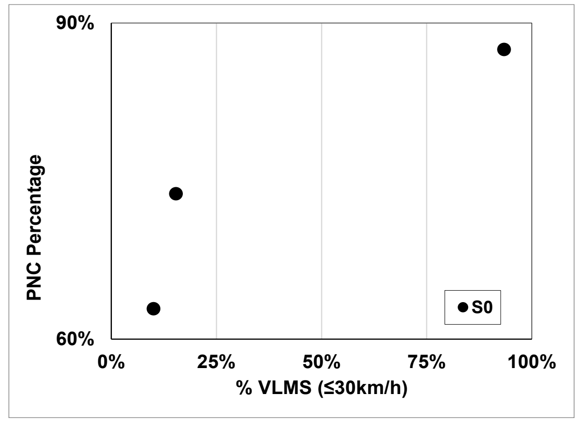
Figures A. and A.8 illustrate the relationship between VLMS and PNC for different traffic conditions and merging strategies. Each graph represents a specific CAV% and ramp volume, and in the graphs, each strategy demonstrates three points associated with the relationship between PNC and VLMS based on three mainline traffic volumes (for LOS D, E, and E*). The observations on the graphs reveal that:

- In S0, S3, S4, S5, and S8 (especially S0), with increasing VLMS, the PNC is increased.
- S2, S3, and S6 are using increasing the minimum headways between FRL CAV vehicles or platoons, and for these reasons, PNC values are not necessarily rising with increasing VLMS, especially when the CAV% goes up. Because in the FRL traffic, these strategies provide enough gaps for merging vehicles.
- S7 uses ramp metering, indicating that the merging vehicles wait at the traffic signal until there is an available gap on the FRL. Therefore, the graphs show that the PNC and VLMS on this strategy slightly changed with increasing traffic volumes.

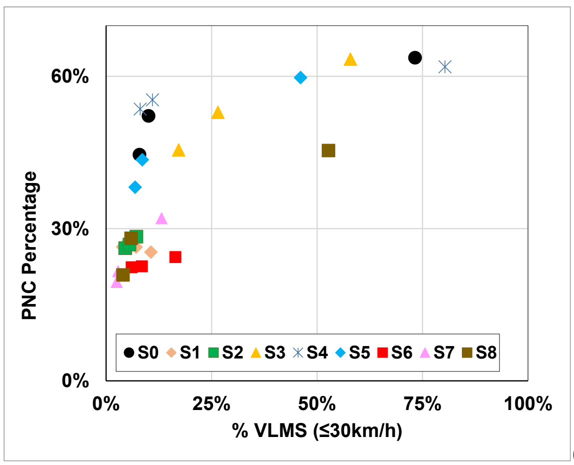
In general, it can be found that with rising VLMS, the PNC will increase in most scenarios, especially when there is 0% CAV or not using a specific strategy. Therefore, VLMS could be used as a safety measure. However, VLMS and PNC may not show a strong relationship with high CAV% in different strategies because each VLMS or PNC may represent different parts of a safety measure. For example, a high VLMS shows a low merging speed that can interrupt the freeway. In addition, a high PNC shows the waiting vehicles at the end of SCL, after finding an available gap, may merge together and provide an unsafe situation. It can also be argued that VLMS is less sensitive to safety performance than PNC; hence, PNC would need a safety measure.



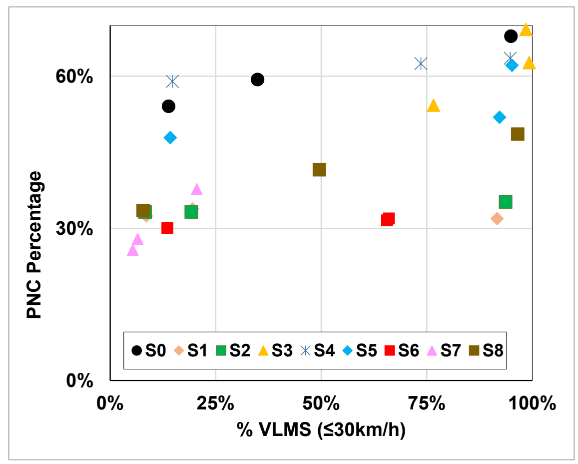

(a) CAV 0%, ramp volume 400 pc/h.



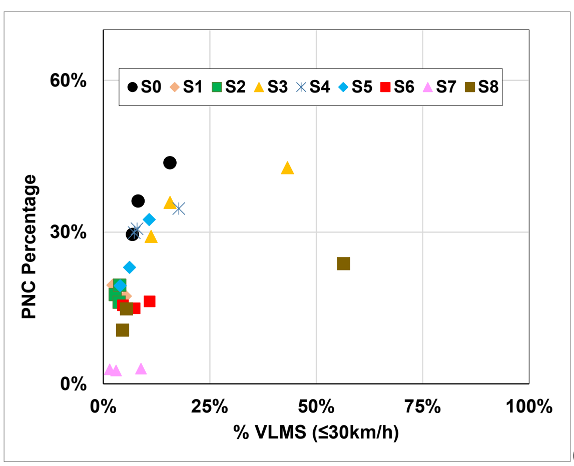

(b) CAV 0%, ramp volume 1,300 pc/h.



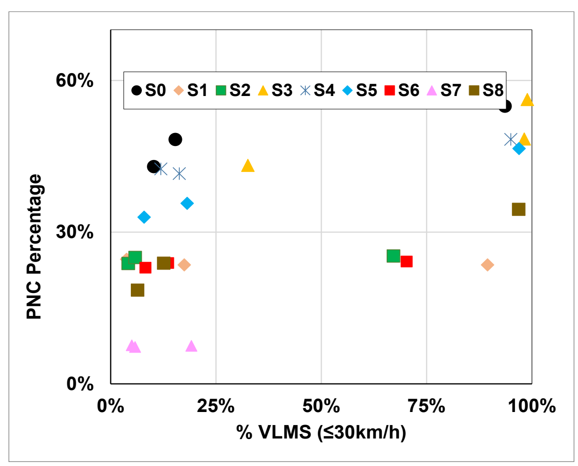

(c) CAV 25%, ramp volume 400 pc/h.




(d) CAV 25%, ramp volume 1,300 pc/h.

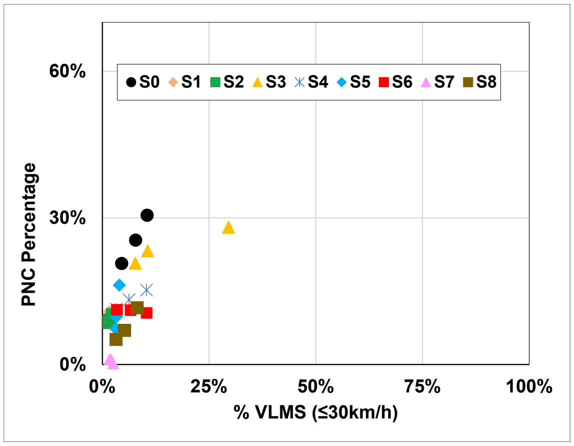



(e) CAV 50%, ramp volume 400 pc/h.

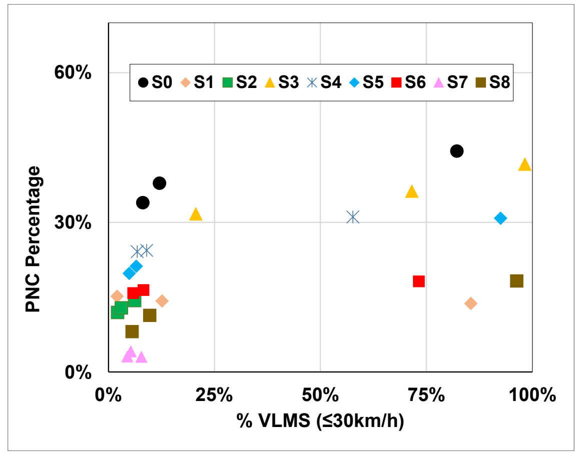



(f) CAV 50%, ramp volume 1,300 pc/h.

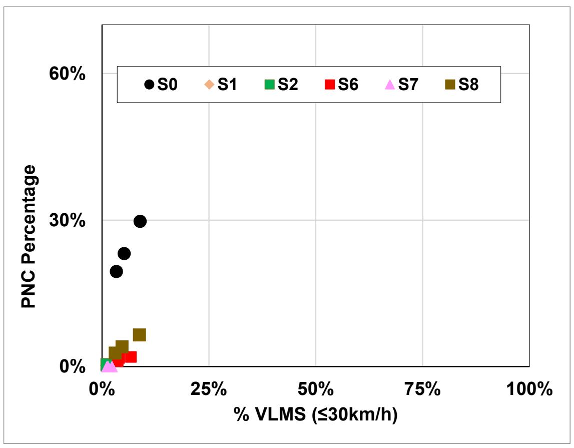
**Figure A.7 PNC versus VLMS, speed threshold of 30 km/h (40 km/h ramp design speed).**



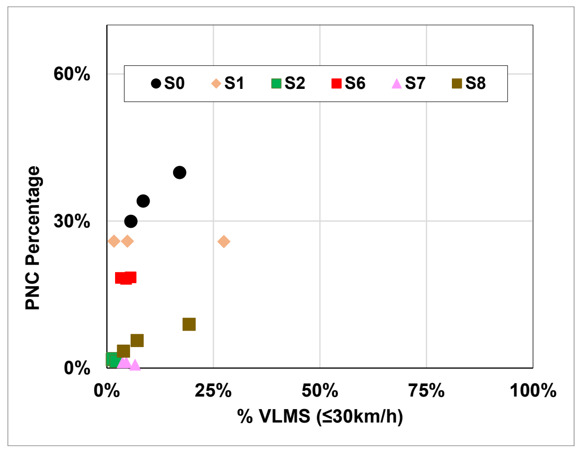

(g) CAV 75%, ramp volume 400 pc/h.




(h) CAV 75%, ramp volume 1,300 pc/h.

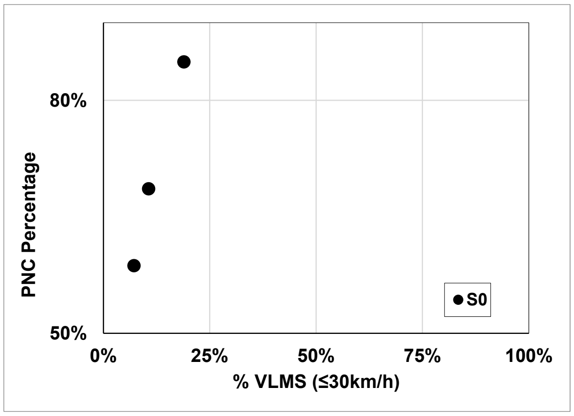



(i) CAV 100, ramp volume 400 pc/h.

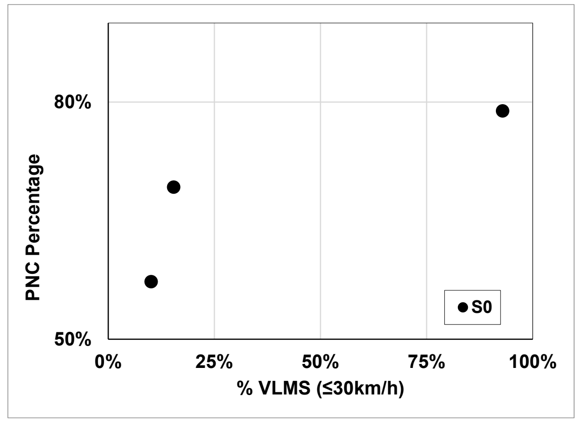



(j) CAV 100, ramp volume 1,300 pc/h.

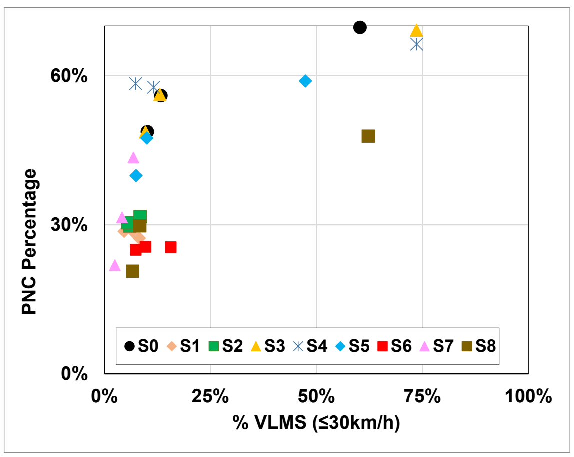
**Figure A.7 PNC versus VLMS, speed threshold of 30 km/h (40 km/h ramp design speed) (Continued).**



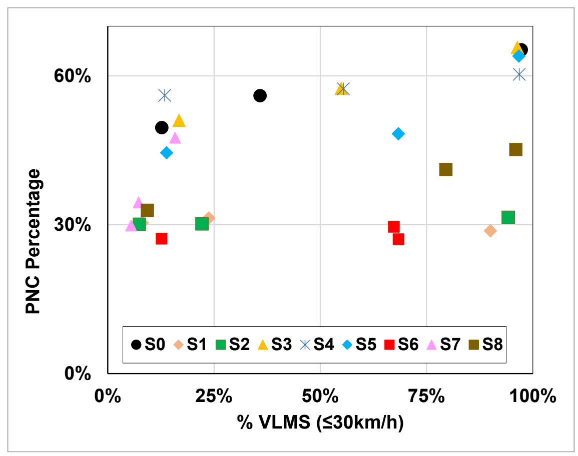

(a) CAV 0%, ramp volume 400 pc/h.



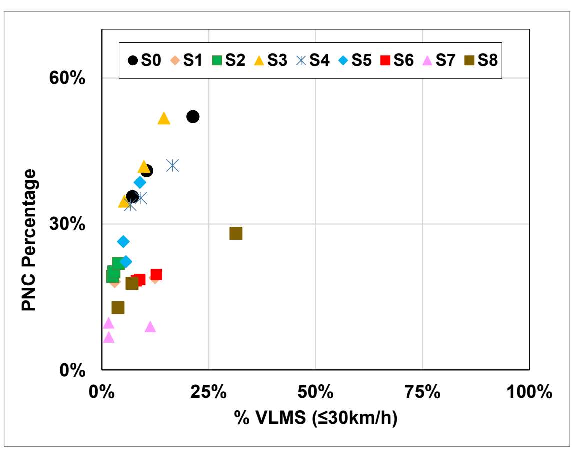

(b) CAV 0%, ramp volume 1,300 pc/h.



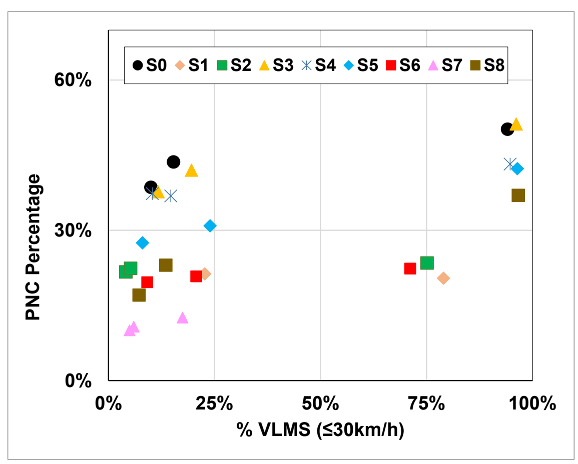

(c) CAV 25%, ramp volume 400 pc/h.




(d) CAV 25%, ramp volume 1,300 pc/h.

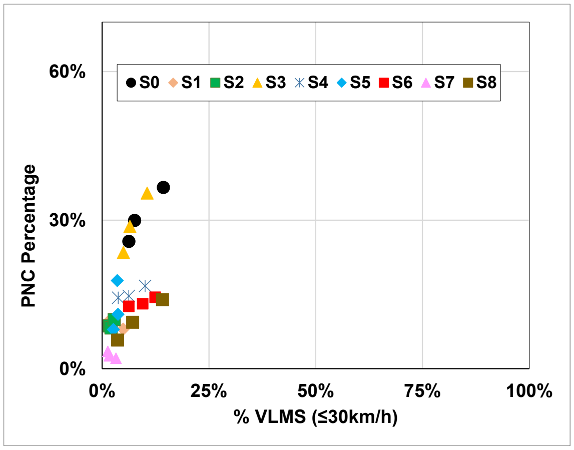



(e) CAV 50%, ramp volume 400 pc/h.

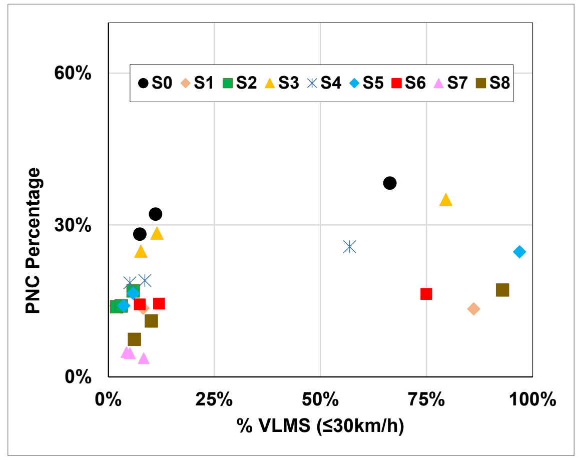



(f) CAV 50%, ramp volume 1,300 pc/h.

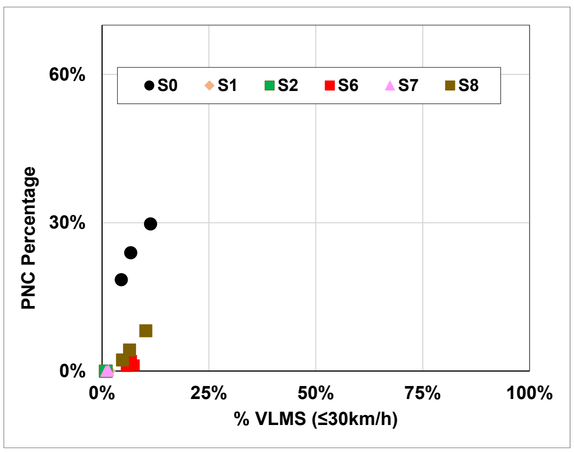
**Figure A.8 PNC versus VLMS, speed threshold of 30 km/h (80 km/h ramp design speed).**



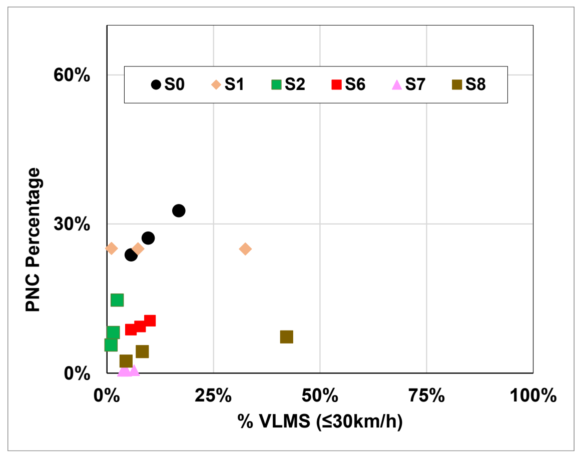

(g) CAV 75%, ramp volume 400 pc/h.




(h) CAV 75%, ramp volume 1,300 pc/h.




(i) CAV 100, ramp volume 400 pc/h.




(j) CAV 100, ramp volume 1,300 pc/h.

**Figure A.8 PNC versus VLMS, speed threshold of 30 km/h (80 km/h ramp design speed) (Continued).**

# Appendix B – Chapter 4 Supplemental Information

## B.1 Negative binominal Regression

Different methods such as normal linear, Poisson, and negative binomial (NB) regressions have been presented to develop a prediction collisions model. However, NB regression has generally showed better results than other regression to predict collisions (El-Basyouny and Sayed, 2006). The NB model is based on a basic probability distribution function and results from a generalization of Poisson regression, which releases the restrictive assumption of the Poisson model that the variance is equal to the mean (Hilbe, 2011). Therefore, NB distribution, in which the variance is greater than the mean, shows more realistic results for prediction collision than Poisson due to collisions data likely to be over scattered (El-Basyouny and Sayed 2006). One of the NB regression models that are used for road segments is shown in Equation A.1 (El-Basyouny and Sayed, 2006)

$$N = n_0 \times L^{n_1} \times V^{n_2} \times exp^{\sum_{i=1}^{z} m_i x_i} \quad \text{(B.1)}$$

where

$N$ = expected collision frequency; $L$ = road segment length; $V$ = annual average daily traffic (AADV) for the road segment; $x_i$ = additional variables than roadway length and AADT; $n_0, n_0, n_0, m_i$= model parameters.

## B.2 Supplemental figure and tables

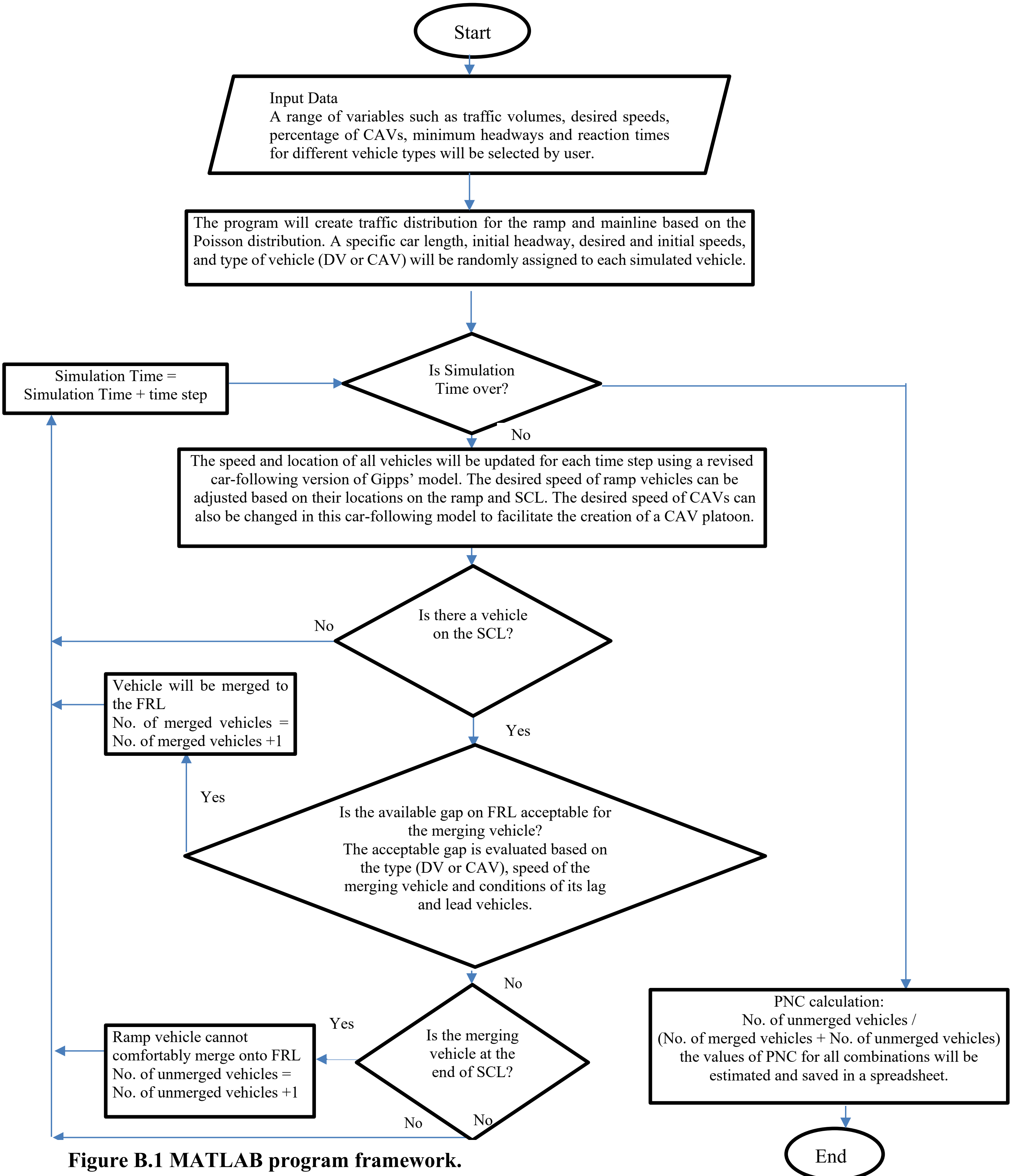
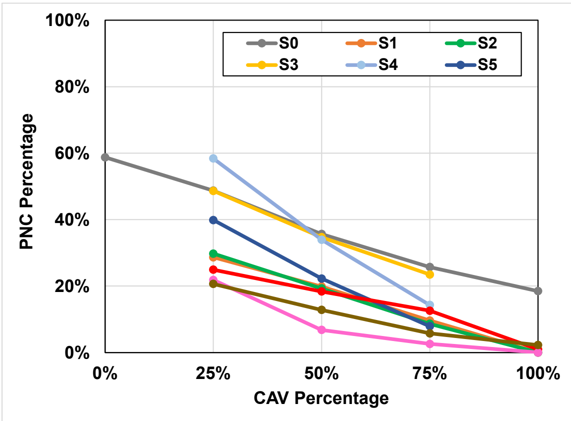
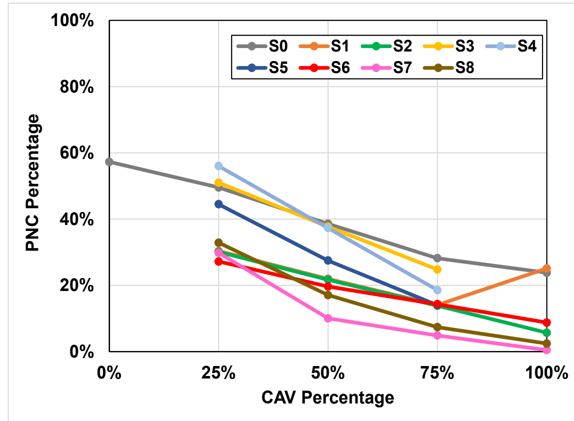


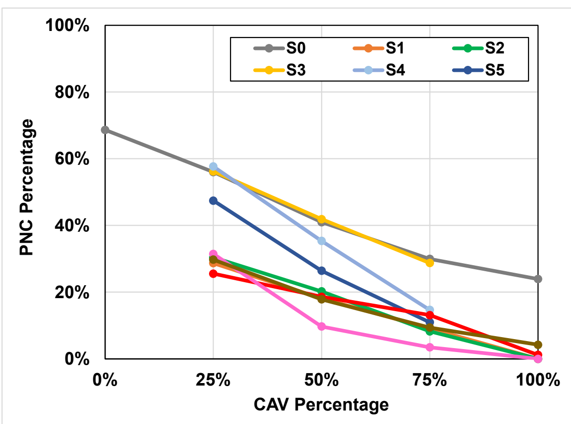

**Figure B.1 MATLAB program framework.**



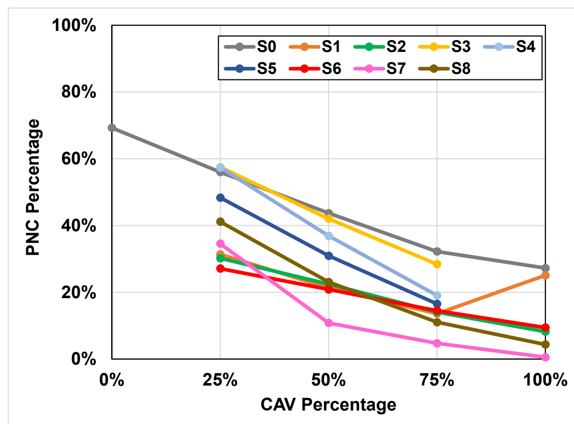

(a) LOS D, Ramp volume = 400 veh/h.



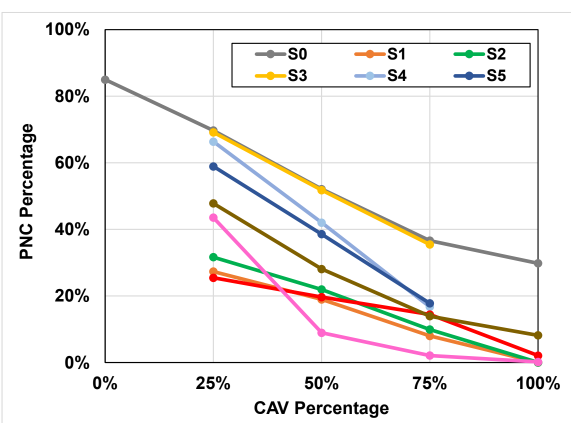

(b) LOS D, Ramp volume = 1,300 veh/h.



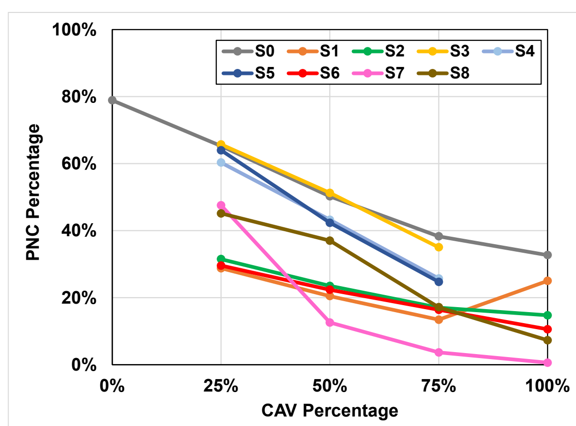

(c) LOS E, Ramp volume = 400 veh/h.




(d) LOS E, Ramp volume = 1300 veh/h.




(e) LOS E*, Ramp volume = 400 veh/h.




(f) LOS E*, Ramp volume = 1,300 veh/h.

**Figure B.2 PNC results (80 km/h ramp design speed).**

**Table B.1. Mean PNC value for the different numbers of the simulation runs.**

| Number of runs | Number of ramp vehicles | Mean PNC | Change in mean PNC (%) |
|---|---|---|---|
| 3 | 2,550 | 0.4427 | - |
| 5 | 4,250 | 0.4371 | -1.26% |
| 7 | 5,950 | 0.4401 | 0.69% |
| 10 | 8,500 | 0.4388 | -0.3% |

**Table B.2. Summary of collisions regression models - total collisions.**

| No. | Constant | Variable 1 | | Variable 2 | | Variable 3 (PNC) | | AIC |
|---|---|---|---|---|---|---|---|---|
| | Coefficient | Coefficient | Name | Coefficient | Name | Coefficient | Name | |
| 1 | 2.1114† | -0.0008 | L_SCL | $2.45\times10^{-5}$** | Q_FWY | | | 122.240 |
| 2 | 2.3393† | -0.0015 | L_SCL | $3.42\times10^{-5}$ | Q_FWY | -1.6220 | PNC | 124.083 |
| 3 | 2.1113† | -0.0008 | L_SCL | $2.34\times10^{-5}$** | Q_FRL | | | 122.240 |
| 4 | 2.3392† | -0.0015 | L_SCL | $7.35\times10^{-5}$ | Q_FRL | -1.6221 | PNC | 124.083 |
| 5 | 5.1155** | -0.0043* | L_SCL | $-3.34\times10^{-5}$ | Q_En | | | 128.460 |
| 6 | 2.1597* | 0.0002 | L_SCL | $-8.29\times10^{-5}$ | Q_En | 4.1072** | PNC | 123.536 |
| 7 | 2.4986* | -0.0013 | L_SCL | $5.33\times10^{-5}$* | Q_FRL_EN | | | 124.910 |
| 8 | 1.7732 | 0.0030 | L_SCL | $-1.675\times10^{-4}$ | Q_FRL_EN | 13.0918* | PNC | 124.062 |
| 9 | 2.1080* | -0.0009 | L_SCL | $2.31\times10^{-5}$** | Q_Tot | | | 122.990 |
| 10 | 2.3800* | -0.0021 | L_SCL | $4.50\times10^{-5}$ | Q_Tot | -3.5716 | PNC | 128.286 |
| 11 | -4.9260 | -1.2753 | Log(L_SCL) | 2.6820** | Log(Q_FRL) | | | 121.620 |
| 12 | -7.3539 | -2.0739 | Log(L_SCL) | 3.8738 | Log(Q_FRL) | -1.8118 | PNC | 123.349 |
| 13 | 13.6679** | -3.8294* | Log(L_SCL) | -0.1410 | Log(Q_En) | | | 130.830 |
| 14 | 4.5662 | -0.4161 | Log(L_SCL) | -0.3948 | Log(Q_En) | 3.4652* | PNC | 125.008 |
| 15 | -3.9707 | -1.5492 | Log(L_SCL) | 2.5732* | Log(Q_FRL_En) | | | 123.850 |
| 16 | 1.4974 | -0.6230 | Log(L_SCL) | 0.5773 | Log(Q_FRL_En) | 2.5371 | PNC | 125.677 |
| 17 | -6.4962 | -1.2980 | Log(L_SCL) | 2.7377** | Log(Q_Tot) | | | 125.130 |
| 18 | -11.9336 | -2.3098 | Log(L_SCL) | 4.5996 | Log(Q_Tot) | -2.5688 | PNC | 123.972 |
| 19 | 2.1748** | 0.0276† | Exp_FWY | | | | | 127.710 |
| 20 | 1.9349** | 0.0067 | Exp_FWY | | | 3.1341** | PNC | 123.489 |
| 21 | 2.1747** | 0.0828† | Exp_FRL | | | | | 127.710 |
| 22 | 4.2673** | 0.0042 | Exp_FRL | | | 2.0454** | Log(PNC) | 123.411 |
| 23 | 3.5120** | -0.0648 | Exp_En | | | | | 132.450 |
| 24 | 4.7105** | -0.1073 | Exp_En | | | 2.1988** | Log(PNC) | 121.609 |
| 25 | 4.7770** | -0.0713 | Exp_En | -0.0251* | Ramp-DS | | | 128.831 |
| 26 | 5.4899** | -0.1016 | Exp_En | -0.0179† | Ramp-DS | 2.0046** | Log(PNC) | 120.656 |
| 27 | 8.9323** | -0.0615 | Exp_En | -3.2208* | Log(Ramp-DS) | | | 128.756 |
| 28 | 8.1489** | -0.0952 | Exp_En | -2.1241† | Log(Ramp-DS) | 1.9757** | Log(PNC) | 121.143 |
| 29 | 2.3787** | 0.0564 | Exp_FRL_En | | | | | 129.090 |
| 30 | 4.8769** | -0.0235 | Exp_FRL_En | | | 2.3600** | Log(PNC) | 123.092 |
| 31 | 2.1928** | 0.0254† | Exp_Tot | | | | | 130.270 |
| 32 | 4.4755** | -0.0021 | Exp_Tot | | | 2.1576** | Log(PNC) | 123.400 |
| 33 | -1.1881 | 2.8132* | Log (Exp_FWY) | | | | | 126.550 |
| 34 | 1.0826 | 0.7327 | Log (Exp_FWY) | | | 3.0067* | PNC | 123.408 |
| 35 | 0.1529 | 2.8130* | Log(Exp_FRL) | | | | | 128.670 |
| 36 | 4.1485† | 0.1494 | Log(Exp_FRL) | | | 2.0285* | Log(PNC) | 123.410 |
| 37 | 3.4151** | -0.2387 | Log(Exp_En) | | | | | 132.670 |
| 38 | 4.4884** | -0.3466 | Log(Exp_En) | | | 2.1109** | Log(PNC) | 122.860 |

**Table B.2. Summary of collisions regression models - total collisions (Continued).**

| No. | Constant | Variable 1 | | Variable 2 | | Variable 3 (PNC) | | AIC |
|---|---|---|---|---|---|---|---|---|
| | Coefficient | Coefficient | Name | Coefficient | Name | Coefficient | Name | |
| 39 | 0.4810 | 2.3451 | Log(Exp_FRL_En) | | | | | 130.700 |
| 40 | 5.8489** | -1.0819 | Log(Exp_FRL_En) | | | 2.4706** | Log(PNC) | 122.970 |
| 41 | -1.1967 | 2.7649* | Log(Exp_Tot) | | | | | 129.370 |
| 42 | 4.8777* | -0.2906† | Log(Exp_Tot) | | | 2.2008** | Log(PNC) | 123.385 |
| 43 | -10.0677* | 3.1156** | Log(Q_FRL) | | | | | 120.199 |
| 44 | -9.0859 | 2.8611 | Log(Q_FRL) | | | 0.3154 | PNC | 122.185 |
| 45 | -10.6320* | 3.1844** | Log(Q_FRL_En) | | | | | 122.578 |
| 46 | 2.6720 | -0.1397 | Log(Q_FRL_En) | | | 3.5718 | PNC | 123.725 |
| 47 | -7.9897* | 2.8403** | Log(Q_FRL) | -0.0180† | Ramp-DS | | | 119.273 |
| 48 | -10.6822 | 3.5543† | Log(Q_FRL) | -0.0191† | Ramp-DS | -0.9084 | PNC | 121.138 |
| 49 | -8.4732* | 2.9032** | Log(Q_FRL_En) | -0.0186† | Ramp-DS | | | 121.714 |
| 50 | -4.0238 | 1.7722 | Log(Q_FRL_En) | -0.0172 | Ramp-DS | 1.2344 | PNC | 123.618 |
| 51 | -9.8805* | 2.9364** | Log(Q_Tot) | -0.0182† | Ramp-DS | | | 119.905 |
| 52 | -15.5591 | 4.2513 | Log(Q_Tot) | -0.0201† | Ramp-DS | -1.5464 | PNC | 121.668 |
| 53 | -4.9740 | 2.7892** | Log(Q_FRL) | -2.1885† | Log(Ramp-DS) | | | 119.611 |
| 54 | -7.0489 | 3.3763 | Log(Q_FRL) | -2.2972† | Log(Ramp-DS) | -0.7500 | PNC | 121.520 |
| 55 | -5.1843 | 2.8487** | Log(Q_FRL_En) | -2.3575† | Log(Ramp-DS) | | | 121.797 |
| 56 | 24.7002 | -3.6024 | Log(Q_FRL_En) | -2.1119 | Log(Ramp-DS) | 4.1318 | Log(PNC) | 122.425 |
| 57 | -6.7355 | 2.8824** | Log(Q_Tot) | -2.2487† | Log(Ramp-DS) | | | 120.161 |
| 58 | -11.5721 | 4.0658 | Log(Q_Tot) | -2.4594† | Log(Ramp-DS) | -1.3982 | PNC | 121.967 |

Note: † $p$-value ≤ 0.1; * $p$-value ≤ 0.05; ** $p$-value ≤ 0.01.

$Log(x)$ = logarithm $(x)$; $Exp\_x$= exposure in a million vehicle kilometres for five years = $Q\_x \times 365 \times Length\ of\ SCL \times 5 \times 10^{-9}$; $L\_SCL$ = length of SCL; $Q\_FWY$= the AADT of the mainline along with SCL of ramps; $Q\_FRL$ = the AADT of the FRL along with SCL of ramps; $Q\_EN$ = the AADT of ramps; $Q\_FRL\_EN$ = AADT of ramp and FRL at each merging area; $Q\_Tot$ = AADT of mainline and ramp at each merging area; $Ramp\_DS$ = ramp design speeds; $p$-value = the significance of the model parameters; AIC= Akaike information criterion. In general, a lower AIC value indicates a better model (Polus et al. 1985).

**Table B.3. Summary of collisions regression models - only ramp collisions.**

| No. | Constant | Variable 1 | | Variable 2 | | Variable 3 (PNC) | | AIC |
|---|---|---|---|---|---|---|---|---|
| | Coefficient | Coefficient | Name | Coefficient | Name | Coefficient | Name | |
| 1 | 4.6737* | -0.00005 | Q_FRL | -0.0067† | L_SCL | | | 68.36 |
| 2 | 3.1809 | -0.0002* | Q_FRL | -0.0025 | L_SCL | 9.1554† | PNC | 67.49 |
| 3 | 1.3503 | 0.0001* | Q_En | -0.0020 | L_SCL | | | 66.34 |
| 4 | 1.6513 | 0.0002* | Q_En | -0.0052 | L_SCL | -1.4786 | Log(PNC) | 66.23 |
| 5 | 3.0538 | -0.00001 | Q_FRL_EN | -0.0043 | L_SCL | | | 69.85 |
| 6 | 3.5783† | 0.00028† | Q_FRL_EN | -0.0092* | L_SCL | -16.9127† | PNC | 68.70 |
| 7 | 4.2197* | -0.00001 | Q_Tot | -0.0060† | L_SCL | | | 69.08 |
| 8 | 3.1847 | -0.00010† | Q_Tot | -0.0012 | L_SCL | 14.3655 | PNC | 68.79 |
| 9 | 17.0309* | -0.00005 | Q_FRL | -5.7855† | Log(L_SCL) | | | 68.20 |
| 10 | 8.2291 | -0.0002* | Q_FRL | -2.3196 | Log(L_SCL) | 9.0035† | PNC | 67.39 |
| 11 | 5.2120 | 0.0001* | Q_En | -1.7928 | Log(L_SCL) | | | 66.25 |
| 12 | 11.2964† | 0.0002* | Q_En | -4.5219† | Log(L_SCL) | -1.4885 | Log(PNC) | 66.04 |
| 13 | 12.5900† | -2.0443 | Log(Q_FRL) | -0.0070* | L_SCL | | | 67.95 |
| 14 | 32.3417* | -7.6806* | Log(Q_FRL) | -0.0031 | L_SCL | 8.2761† | PNC | 66.68 |
| 15 | 7.0893 | -0.9122 | Log(Q_FRL_En) | -0.0050 | L_SCL | | | 69.62 |
| 16 | -47.2994 | 10.7682 | Log(Q_FRL_En) | -0.0069* | L_SCL | -7.8919 | Log(PNC) | 69.46 |
| 17 | -0.9776 | 0.8866 | Log(Q_En) | -0.0026 | L_SCL | | | 67.54 |
| 18 | -1.0635 | 1.0255† | Log(Q_En) | -0.0053 | L_SCL | -1.1718 | Log(PNC) | 68.31 |
| 19 | 25.4072* | -2.0434 | Log(Q_FRL) | -6.0180* | Log(L_SCL) | | | 67.80 |
| 20 | 37.9969** | -7.6277 | Log(Q_FRL) | -2.7317 | Log(L_SCL) | 8.1917† | PNC | 66.61 |
| 21 | 3.9787 | 0.8817 | Log(Q_En) | -2.3068 | Log(L_SCL) | | | 67.46 |
| 22 | 8.7211 | 1.0266† | Log(Q_En) | -4.5921 | Log(L_SCL) | -1.1730 | Log(PNC) | 68.19 |
| 23 | 1.9558** | -0.0576† | Exp_FRL | | | | | 68.63 |
| 24 | 2.0764** | -0.1660* | Exp_FRL | | | 3.8378* | PNC | 65.02 |
| 25 | 1.6900† | -0.0578 | Exp_FRL | 0.0052 | Ramp-DS | | | 70.51 |
| 26 | 0.9470 | -0.2024** | Exp_FRL | 0.0231† | Ramp-DS | 5.0377** | PNC | 64.47 |
| 27 | 0.6508 | -0.0569 | Exp_FRL | 0.7614 | Log(Ramp-DS) | | | 70.47 |
| 28 | -3.1251 | -0.1978** | Exp_FRL | 3.0558† | Log(Ramp-DS) | 5.0544** | PNC | 64.23 |
| 29 | 0.6350† | 0.1777† | Exp_En | | | | | 69.33 |
| 30 | 0.4517 | 0.1677 | Exp_En | | | 0.6404 | PNC | 68.92 |
| 31 | -0.7470 | 0.1766† | Exp_En | 0.8139 | Log(Ramp-DS) | | | 69.01 |
| 32 | -1.8661 | 0.1639† | Exp_En | 1.3067 | Log(Ramp-DS) | 0.9523 | PNC | 70.44 |
| 33 | 1.5109† | -0.0189 | Exp_FRL_En | | | | | 69.85 |
| 34 | 1.7811* | -0.0920 | Exp_FRL_En | | | 2.7353 | PNC | 69.41 |
| 35 | 0.1596 | -0.0186 | Exp_FRL_En | 0.7906 | Log(Ramp-DS) | | | 71.68 |
| 36 | -2.1063 | -0.1182† | Exp_FRL_En | 2.3467 | Log(Ramp-DS) | 3.6726† | PNC | 69.97 |
| 37 | 2.6504† | -1.3158 | Log(Exp_FRL) | | | | | 69.16 |
| 38 | 5.3318** | -5.0655* | Log(Exp_FRL) | | | 4.2693* | PNC | 65.54 |

**Table B.3. Summary of collisions regression models - only ramp collisions (Continued).**

| No. | Constant | Variable 1 | | Variable 2 | | Variable 3 (PNC) | | AIC |
|---|---|---|---|---|---|---|---|---|
| | Coefficient | Coefficient | Name | Coefficient | Name | Coefficient | Name | |
| 39 | 2.4001 | -1.3143 | Log(Exp_FRL) | 0.0048 | Ramp-DS | | | 71.06 |
| 40 | 5.0282** | -6.3348** | Log(Exp_FRL) | 0.0236† | Ramp-DS | 5.6787** | PNC | 64.94 |
| 41 | 0.8340** | 0.8696 | Log(Exp_En) | | | | | 67.97 |
| 42 | 0.5876 | 0.8195 | Log(Exp_En) | | | 0.7986 | PNC | 69.53 |
| 43 | 1.6697 | -0.3886 | Log(Exp_FRL_En) | | | | | 69.95 |
| 44 | 3.9344 | -3.0293 | Log(Exp_FRL_En) | | | 2.6806 | PNC | 69.85 |
| 45 | -1.4951 | 0.9308 | Log(Exp_En) | 1.3530 | Log(Ramp-DS) | | | 69.46 |
| 46 | -3.0238 | 0.9115 | Log(Exp_En) | 2.0102 | Log(Ramp-DS) | 1.2431 | PNC | 70.49 |
| 47 | 0.2611 | 0.9511 | Log(Exp_En) | 0.0104 | Ramp-DS | | | 69.49 |
| 48 | -0.3514 | 0.9379 | Log(Exp_En) | 0.0148 | Ramp-DS | 1.1651 | PNC | 70.62 |
| 49 | 1.3711 | -1.2881 | Log(Exp_FRL) | 0.7333 | Log(Ramp-DS) | | | 71.02 |
| 50 | 0.7721 | -6.1870** | Log(Exp_FRL) | 3.1208† | Log(Ramp-DS) | 5.6801** | PNC | 64.69 |
| 51 | -0.8483 | 0.1388 | Log(Q_FRL) | 0.8575 | Log(Ramp-DS) | | | 71.82 |
| 52 | 31.6105** | -9.1419** | Log(Q_FRL) | 2.7092 | Log(Ramp-DS) | 11.756** | PNC | 65.14 |

Note: † $p$-value ≤ 0.1; * $p$-value ≤ 0.05; ** $p$-value ≤ 0.01.

$Log(x)$ = logarithm $(x)$; $Exp\_x$= exposure in a million vehicle kilometres for five years = $Q\_x \times 365 \times Length\ of\ SCL \times 5 \times 10^{-9}$; $L\_SCL$ = length of SCL; $Q\_FWY$= the AADT of the mainline along with SCL of ramps; $Q\_FRL$ = the AADT of the FRL along with SCL of ramps; $Q\_EN$ = the AADT of ramps; $Q\_FRL\_EN$ = AADT of ramp and FRL at each merging area; $Q\_Tot$ = AADT of mainline and ramp at each merging area; $Ramp\_DS$ = ramp design speeds; $p$-value = the significance of the model parameters; AIC= Akaike information criterion. In general, a lower AIC value indicates a better model (Polus et al. 1985).

### B.2 MATLAB Program

| |
|---|
| Pnc_control.m (Start Page. the major parameters such as number of iterations, merging strategy method, traffic volumes, Ramp design speed, CAV penetration rates, and output file will be defined here.) |

```
clear
clc
codeVer = 01; %version of code used
nRuns = 7;    %all number of runs; can be one value or a vector
outputOption = 10; %option to write output in Excel file: 0 or -ve do not
                %write; +ve value write it

%    **************    INPUT    *********    INPUT    ****************    INPUT
*************
strgyi="S2"; % S0-S8
% ************* (1) Traffic Volumes--------------------------------------

hrVolFRLi = [ 2100 2400 2880];      % Freeway Traffic Volume
hrVolRampi = [ 400 1300];           % Ramp Traffic Volume

% ************** (2) Percentage of Vehicles-------------------------------
percentCAVi = [25 50 75 100];      % Determine the percentage of CAVs

% ************** (3) Speeds ---------------------------------------------
rampDesSpeedKMHi = [40 80];        % ramp design speed  km/h

%
**********************************************************************
*
if outputOption
   outputFile = '2021-07-15-S2.xlsx';
   summarySheet = 'Summary';
   detailSheet = 'Detailed';
   %suppress warning of creating sheet
   warning('off','MATLAB:xlswrite:AddSheet');

   heading = {'Code Version',num2str(codeVer),'', '', '', '', ''; ...
      'Number of Runs',num2str(nRuns),'', '', '', '', ''; ...
      'Index', 'FRL Vol', 'RMP Vol', '% CAV', 'RAMP DesSpeed(km/h)', ...
      'meanPNC', 'sdPNC'};
   xlswrite(outputFile, heading, summarySheet, 'A1');
end
```

```
iScen = 0;
nScenarios = length(hrVolFRLi)*length(hrVolRampi)*length(percentCAVi)*...
    length(rampDesSpeedKMHi);
Pnc=zeros(nScenarios,nRuns);
AllData = NaN((nRuns+1), nScenarios);
AllData(1,:) = 1:nScenarios;

fprintf('Total number of analysis scenarios: %d \n', nScenarios);

  for irs = 1:length(rampDesSpeedKMHi)
     for ivf = 1:length(hrVolFRLi)

       for ivr = 1:length(hrVolRampi)

         for icv = 1:length(percentCAVi)

            iScen = iScen+1;
            for ir = 1:nRuns

              fprintf('\nScenario %d: & Number of Run %d\n',...
               iScen, ir);
              rng(ir)
              Pnc(iScen,ir) = PNC_MixedFleet3 (strgyi,...
                 hrVolFRLi(ivf),hrVolRampi(ivr), percentCAVi(icv),...
                 rampDesSpeedKMHi(irs));

              AllData(ir+1,iScen) = Pnc(iScen,ir);
            end

            if outputOption
               meanPNC = mean(Pnc(iScen,:));
               sdPNC = std(Pnc(iScen,:));
               cellIdx = ['A', num2str(3+iScen)];
               sumData = {iScen, hrVolFRLi(ivf), hrVolRampi(ivr),...
                 percentCAVi(icv), rampDesSpeedKMHi(irs),  meanPNC,...
                 sdPNC};
               xlswrite(outputFile, sumData, summarySheet, cellIdx);
            end
         end
       end
     end
  end

if outputOption
    xlswrite(outputFile, AllData, detailSheet, 'A1');
```

```
end

fprintf ('end of script \n')
end
       end
   end

if outputOption
    xlswrite(outputFile, AllData, detailSheet, 'A1');
end

fprintf ('end of script \n')
```

**PNC_MixedFleet3.m** (Define other parameters such as minimum headways, reaction times, maximum acceleration rates, maximum CAV platoon size, SCL length, start and end of

```
function  Pnc = PNC_MixedFleet3 (strgyi, hrVolFRLi, hrVolRampi,...
   percentCAVi, rampDesSpeedKMHi)
% clear
% clc
%update Apr 21, 2021
%update March 08, 2020:AP, adding strategies
%update Jan 25, 2020:AP
%update Dec 17, 2019: all vehicles are generated in the beginning
%update Dec 4, 2019
%update Dec 3, 2019
%update Nov 26, 2019
%update Nov 19, 2019: : add variables speedStdRV speedPost2MaxRV
%speedPost2MinRV speedPost2AvgRV instead of constants
%update Nove 12, 2019: define variables timeLastDecFwy & timeLastDecRamp

global fwyDesSpeed rampDesSpeed
global fwyDesSpeedKMH rampDesSpeedKMH
global maxAccRate maxDecRate
global strgy desiredAccRamp
global reactTimeRV reactTimeCAV largHdway
global minHeadwayCAV  minHeadwayRV
global startLocationSCL sclMergeLength  sclAccLength
global timeStep timeWarmUp speedPost2AvgRV_Fw
global speedPost2MinRV speedPost2MinRV_Fwy speedPost2AvgRV_Rmp
global vehLocFwy vehTypeFwy vehSpeedFwy vehLengthFwy
global vehLocFwy2 vehTypeFwy2 vehSpeedFwy2 vehLengthFwy2
global percentAV percentTrucks percentBuses percentCAV
global hdCumFwy hdCumRamp hrVolRamp platoonHeadway platoonSize
global timeLastDecFwy  timeLastDecFwy2 vehDesiredSpeedFwy
global avgAccFwy avgAccFwy2 minGapRV minGapCAV largGap
global timeLastDecRamp vehDesiredSpeedRamp vehLocRamp
global vehTypeRamp vehSpeedRamp vehLengthRamp avgAccRamp
global segment_1  segment_2 segment_3 vehDesiredSpeedFwy2 hdCumFwy2
global diff_desrd_spd_segment_1 diff_desrd_spd_segment_2
global rampStopLoc detectorLoc endLocationSCL diff_desrd_spd_segment_3

rng('default')

%    **************    INPUT    *********    INPUT    ****************    INPUT
*************
```

```
% ************** (0) Select Strategy ------------------------------------
strgy=strgyi;  % Strategies S0, S1, S2, S3, S4, S5, S6, S7, S8

% ************** (1) Traffic Volumes--------------------------------------
hrVolFRL = hrVolFRLi;              % Traffic volume of FRL
hrVolRamp = hrVolRampi;            % Traffic volume of Ramp

% ************** (2) Percentage of Vehicles-------------------------------
percentCAV=percentCAVi ;           % Determine the percentage of CAVs
percentAV = 0;                     % Determine the percentage of AVs
percentTrucks = 0;                 % percentage of Truck
percentBuses = 0;                  % percentage of Bus

% ************** (3) Speeds ---------------------------------------------
% Vehicles on Freeway
% freeway design speed
   fwyDesSpeedKMH = 110; fwyDesSpeed = fwyDesSpeedKMH/3.6;
   % diff between fwy design speed and posted speed
   fwySpeedDiffKMH = 10; fwySpeedDiff = fwySpeedDiffKMH/3.6;
   fwyPostSpeed = fwyDesSpeed-fwySpeedDiff; % posted speed of freeway  m/s
   meanSpeedFw = 105.5;                % Freeway mean speed km/h
   % standard deviation of desired speed for DVs on fwy
   speedStdRVFwy = 10.57/3.6;
   % Max speed for DVs on fwy = posted speed + speedPost2MaxRVFwy
   speedPost2MaxRV_Fwy = speedStdRVFwy*2;   % Or 2*speedStdRVFwy;
   % Max speed for DVs on fwy = posted speed - speedPost2MinRVFwy
   speedPost2MinRV_Fwy = speedStdRVFwy*2;   % Or 2*speedStdRVFwy;
   speedPost2AvgRV_Fw =meanSpeedFw/3.6 - fwyPostSpeed;
% Vehicles on Ramp
   % Ramp design speed  m/s
   rampDesSpeedKMH=rampDesSpeedKMHi;                  rampDesSpeed                  =
rampDesSpeedKMH/3.6;
   % diff between ramp design speed and posted speed
   rampSpeedDiffKMH = 10; rampSpeedDiff = rampSpeedDiffKMH/3.6;
   rampPostSpeed = rampDesSpeed-rampSpeedDiff;  % posted speed of ramp,m/s
      if rampPostSpeed==(30/3.6) || rampPostSpeed <= (40/3.6)
         % standard deviation of desired speed for DVs on ramp is as
         speedStdRVRamp = 3.21/3.6;    sumed
         % Average speed of DV = posted speed + speedPost2AvgRV
         speedPost2AvgRV_Rmp = 6.6/3.6;
         % Or meanSpeedRmp/3.6 -rampPostSpeed;
      elseif rampPostSpeed >(40/3.6)
         speedStdRVRamp = 6.0/3.6;
         speedPost2AvgRV_Rmp =3.5/3.6; %meanSpeedRmp/3.6-rampPostSpeed;
      end
   % Max speed for DVs on ramp = posted speed + speedPost2MaxRVRamp
```

```
   speedPost2MaxRVRamp = 2*speedStdRVRamp;
   % Min speed for DVs = posted spedd - speedPost2MinRV
   speedPost2MinRV = 2*speedStdRVRamp;
% Strategy 3
% different desired speed for segment 1 of S3
diff_desrd_spd_segment_1=-3/3.6;
% different desired speed for segment 2 of S3
diff_desrd_spd_segment_2=-6/3.6;
% different desired speed for segment 3 of S3
diff_desrd_spd_segment_3=-9/3.6;

% ************** (4) Traffic Parameters ----------------------------------
% Minimum headway and gap for Regular Veh (veh length =6m)
minHeadwayRV=1.0;  minGapRV=0.8;
% Minimum headway and Gap for CAVs
minHeadwayCAV=0.5; minGapCAV=0.3;
% Large enough headway & Gap, which create a wide gap for merging vehicles
largHdway=2.0; largGap=1.8;
reactTimeRV=0.6;          % Reaction time for Regular vehicles
reactTimeCAV=0.2;          % Reaction Time for CAV Vehicles
maxAccRate = 2;            % Max Acceleration rate (m/s2)
maxDecRate = -3;           % Max Deceleration rate (m/s2)
platoonHeadway = minHeadwayCAV;  %Strategy 5 (S5 old and S6 new)
   if hrVolRamp ==400
   %Strategy 6 Platoon size for 400 and 1300 ramp vehicles are 14 and 2
      platoonSize = 14;
   elseif hrVolRamp ==1300
      platoonSize = 2;
   end

% ************** (5) Locations -------------------------------------------
% Start point of generating freeway vehicles relative to gore
startLocationFwy = -5200;
% Start point of generating ramp vehicles relative to gore
startLocationRamp = -250;
% Start point of SCL relative to gore within this distance,
startLocationSCL = -50;
                  %the SCL vehicle can accelerate but cannot merge
segment_1=-900;      % Location on FRL (m), change speed/headway for S2/3
segment_2=-600;      % Location on FRL (m), change speed/headway for S2/3
segment_3=-300;      % Location on FRL (m), change speed/headway for S2/3
rampStopLoc=-25;      % Location of ramp stop for before merging gore,m(S7)
detectorLoc=-190;  % Location of headway detector before merging gore,m S7)
sclAccLength =345;    % length of acceleration lane.
   %If put zero it is automatically calculated based on AASHTO table
   if sclAccLength == 0
```

```
        % Finding acceleration length based on AASHTO 2011
        sclAccLength = accelerationSclAashtoLength;
    end
% End point of SCL relative to gore
endLocationSCL = sclAccLength;
% ramp vehicle can merge only between gore and end of SCL
sclMergeLength = sclAccLength + startLocationSCL;
 % vehicles beyond this point are not considered in the simulation
endLocationFwy = sclAccLength + 1000;

% ************* (6) Time -----------------------------------------------
% time of simulation in seconds - in this case = 60 min
timeTotalSim = 60*60;
timeStep=0.1;          % time step in seconds
timeWarmUp = 15*60;    % warm up time (Sec) - in this case = 15 min
% the end of time for checking for posiblility of merging
timeEndCalculate = timeTotalSim + timeWarmUp;
noTimSteps= timeEndCalculate /timeStep;

rampStop=zeros (noTimSteps,1);

simTime = 0;

%*************************************************************
%///////Generate vehicles on the ramp and freeway right lane \\\\\\\
%vehTimeLastDecFwy(iVehFwy) = simTime;

    [vehDesiredSpeedRamp,vehTypeRamp,hdCumRamp,vehSpeedRamp,...
        vehLengthRamp,desiredAccRamp] = generateCars(...
        rampPostSpeed,hrVolRamp, minHeadwayRV, speedStdRVRamp,...
        speedPost2MaxRVRamp);

    [vehDesiredSpeedFwy,vehTypeFwy,hdCumFwy,vehSpeedFwy,vehLengthFwy,...
        accNotUsed] = generateCarsFwy(...
        fwyPostSpeed,hrVolFRL, minHeadwayRV,speedStdRVFwy,...
        speedPost2MaxRV_Fwy);
    %accNotUsed is a desired acc rate relevant only to ramp vehicles

    if strgy=="S8"
        [vehDesiredSpeedFwy2,vehTypeFwy2,hdCumFwy2,vehSpeedFwy2,...
            vehLengthFwy2,accNotUsed] = generateCarsFwy2(...
            fwyPostSpeed,hrVolFRL, minHeadwayRV,speedStdRVFwy,...
            speedPost2MaxRV_Fwy);
    end

    % all fwy and ramp vehicles get in the simulation when
```

```
    % they reach their start location
    % number of vehs to be created is increased to account for the warmup
    % time; number is rounded up to the nearest integer
    vehLocFwy = ones(ceil(hrVolFRL *(1+timeWarmUp/3600)+hrVolRamp*1.5)...
        ,1)*startLocationFwy;
    vehLocFwy2 = ones(ceil(hrVolFRL *(1+timeWarmUp/3600)+hrVolRamp*1.5)...
        ,1)*startLocationFwy;
    vehLocRamp = ones(ceil(hrVolRamp*(1+timeWarmUp/3600))+hrVolRamp,1)...
        *startLocationRamp;

   % additional vector for average vehicle acceleration
   avgAccFwy =  zeros(ceil(hrVolFRL *(1+timeWarmUp/3600)+hrVolRamp*1.5),1);
   avgAccFwy2 =  zeros(ceil(hrVolFRL *(1+timeWarmUp/3600)+hrVolRamp*1.5),1);
   avgAccRamp = zeros(ceil(hrVolRamp*(1+timeWarmUp/3600)+hrVolRamp),1);

   % additional vector for the time of last decision
   timeLastDecFwy =  zeros(ceil(hrVolFRL *(1+timeWarmUp/3600)+hrVolRamp*...
       1.5),1);
   timeLastDecFwy2 = zeros(ceil(hrVolFRL *(1+timeWarmUp/3600)+hrVolRamp*...
       1.5),1);
   timeLastDecRamp = zeros(ceil(hrVolRamp*(1+timeWarmUp/3600)+hrVolRamp),1);

%initiate variables to count the number of vehicles that merged and did not
%merge
    nVehMerged = 0;
    nVehNotMerged = 0;

    firstVehRamp = 1;      % First car in the simulation on ramp
    lastVehRamp = 1;       % Last car in the simulation on ramp
    lvRamp = 1;

    firstVehFwy = 1;       % First car in the simulation on FRL
    lastVehFwy = 1;        % Last car in the simulation on FRL
    lvFwy = 1;

    if strgy=="S8"
        firstVehFwy2 = 1;   % First car in the simulation on FML
        lastVehFwy2 = 1;    % Last car in the simulation on FML
        lvFwy2 = 1;
    end

jt=1;  % A counter for S7

% simulate vehicles and create other vehicles based on simulation time &
% their gaps
```

```
for simTime = timeStep:timeStep:timeEndCalculate

%^^^^^^ Adjust indices of vehicle considered in simulation ^^^^^^^

  if simTime>=hdCumRamp(lvRamp)
    %time to release the next vehicle on ramp
    lastVehRamp = lastVehRamp + 1;
    lvRamp =lvRamp+1;
  end

  if simTime>=hdCumFwy(lvFwy)
    %time to release the next vehicle on freeway
    lastVehFwy = lastVehFwy + 1;
    lvFwy =lvFwy+1;
  end

  if lastVehFwy>firstVehFwy && vehLocFwy(firstVehFwy)>=endLocationFwy
    %there are more than one vehicle on the fwy in simulation
    %the second vehicle reached the limits of simulation
    %do not consider the first vehicle anymore and keep the second to
    %allow Gibbs model for the following vehicles
    firstVehFwy = firstVehFwy + 1;
  end

  if strgy=="S8"
    if simTime>=hdCumFwy2(lvFwy2)
      %time to release the next vehicle on freeway
      lastVehFwy2 = lastVehFwy2 + 1;
      lvFwy2 =lvFwy2+1;
    end

    if lastVehFwy2>firstVehFwy2 && vehLocFwy2(firstVehFwy2)>=...
        endLocationFwy
      %there are more than one vehicle on the fwy in simulation
      %the second vehicle reached the limits of simulation
      %do not consider the first vehicle anymore and keep
      %the second to allow Gibbs model for the following vehicles
      firstVehFwy2 = firstVehFwy2 + 1;
    end
  end

%^^^^^^^^^^^ Update Vehicle Speed and Location (Gipps Model) ^^^^^^^^

   [vehSpeedFwy,vehDesiredSpeedFwy,vehLocFwy,timeLastDecFwy,...
     avgAccFwy, rsex]= updateSpeedAndLoc(0,firstVehFwy,lastVehFwy,...
     vehSpeedFwy,vehDesiredSpeedFwy,vehLocFwy,vehTypeFwy,...
```

```
        vehLengthFwy,timeLastDecFwy,avgAccFwy,simTime, 0);

    if strgy=="S8"
        [vehSpeedFwy2,vehDesiredSpeedFwy2,vehLocFwy2,timeLastDecFwy2,...
          avgAccFwy2, rsex]= updateSpeedAndLoc(0,firstVehFwy2,...
          lastVehFwy2,vehSpeedFwy2,vehDesiredSpeedFwy2,vehLocFwy2,...
          vehTypeFwy2,vehLengthFwy2,timeLastDecFwy2,avgAccFwy2,...
          simTime, 0);
    end

    [vehSpeedRamp,vehDesiredSpeedRamp,vehLocRamp,timeLastDecRamp,...
      avgAccRamp,rampStop(jt,1)]= updateSpeedAndLoc(1,firstVehRamp,...
      lastVehRamp,vehSpeedRamp,vehDesiredSpeedRamp,vehLocRamp,...
      vehTypeRamp,vehLengthRamp,timeLastDecRamp,avgAccRamp,simTime,...
      rsex);

jt=jt+1;

%^^^^^^^^^^^^^^ Check status of ramp vehicles ^^^^^^^^^^^^^^
    for ir = firstVehRamp:lastVehRamp

      %check for 3 conditions: ramp vehicle is after the gore, before
      %end SCL, and did not merge yet

      if vehLocRamp(ir)>0
        if vehLocRamp(ir) <= sclAccLength && simTime >= timeWarmUp
          %check if the ramp vehicle can merge or not
          [mergeORnot,leadVehFwy]=AvAndAccGaps(vehSpeedRamp(ir),...
            vehTypeRamp(ir),vehLocRamp(ir),vehLengthRamp(ir));
          if mergeORnot == 1  && isempty(leadVehFwy)==0

              %ramp vehicle merged onto the FRL
              %count of merged vehicles after the warm-up time
              nVehMerged = nVehMerged + 1;

              %remove the vehicle from the ramp and re-assign to the
              %fwy
              reassignVeh(mergeORnot, ir, leadVehFwy);

              %the index of first ramp vehicle is always 1
              %the index of last ramp vehicle is reduced to
              %account for the removal of one ramp vehicle

              lastVehRamp = lastVehRamp - 1;
              %the index of first fwy vehicle is not affected
              %the index of last fwy vehicle is increased to
```

```
            %account for the merging of one ramp vehicle
            lastVehFwy = lastVehFwy + 1;
          end
        elseif vehLocRamp(ir) > sclAccLength
            %ramp vehicle reaches end of SCL without merging
            %add the count of non-merged vehicles and remove it
            %from the ramp vectors
            %count of non-merged vehicles after the warm-up time

            if simTime >= timeWarmUp
              nVehNotMerged = nVehNotMerged + 1;
            end
            mergeORnot = 0;
            reassignVeh(mergeORnot, ir, 0);
            %the index of first ramp vehicle is always 1
            %the index of last ramp vehicle is reduced to
            %account for the removal of one ramp vehicle
            lastVehRamp = lastVehRamp - 1;
        end

      end
    end

end

Pnc=nVehNotMerged/(nVehNotMerged+nVehMerged);
```

**UpdateSpeedAndLoc.m** (a function that uses for updating vehicle speed and location on the ramp and freeway lanes)

```
function [vehSpeed,vehDesiredSpeed,vehLoc,timeLastDec,avgAccSubject,...
   rampStp]= updateSpeedAndLoc(onRampVeh,firstVeh,lastVeh,vehSpeed,...
   vehDesiredSpeed,vehLoc,vehType,vehLen,timeLastDec,avgAccSubject,...
   simTime, rampStp)

%update Apr 21, 2021
%update March 08, 2020, adding strategies
%update Dec 17, 2019
%update Dec 3, 2019
%ramp vehicle would accelerate at desired acc rate if there is no lead
%vehicle until it reaches the desired speed
%update Nove 12, 2019:
%correcting some lines for missing brackets
%added condition for first vehicle; still need to account for 1st
%ramp acceleration

global timeStep  strgy endLocationSCL
global fwyDesSpeed rampDesSpeed
global maxAccRate desiredAccRamp
global maxDecRate  largGap minGapCAV
global reactTimeRV reactTimeCAV
global startLocationSCL
global segment_1  segment_2 segment_3
global diff_desrd_spd_segment_1 diff_desrd_spd_segment_2
global diff_desrd_spd_segment_3 rampStopLoc detectorLoc gthetaS6

galpha = 2.5; gbeta = 0.025; gdelta = 0.5; %Gipps Model parameters
speedDiff = fwyDesSpeed - rampDesSpeed;    %difference between fwy & ramp

% Define minimum and maximum time headway to the lead vehicle within which
% an CAV follower will increase speed to close the gap and build a platoon
%equivalent to min headway between subject and lead vehicles
minTime = 2*reactTimeCAV;
%time required to close the gap if the subject vehicle travels at D. Speed
maxTime = 20;

toler = timeStep/10; %time tolerance for equality check
if lastVeh > 0

for i = lastVeh:-1:firstVeh
```

```
% ^^SET DESIRED and DESIGN SPEED based on Veh Location on Ramp,SCL,or Fwy
^
   if onRampVeh==1
      %this is the case of a ramp vehicle
      %need to check if the vehicle is on SCL or still on ramp
      if vehLoc(i)<startLocationSCL
         %vehicle is till on ramp
         desiredSpeed = vehDesiredSpeed(i);
         designSpeed = rampDesSpeed;

      %Strateg 7: if there is no a acceptable gap on FW,
      % Vehicle is going to stop
      else
         if strgy =="S7" && rampStp ==1 && vehLoc(i)< 0
            desiredSpeed = 0;
            designSpeed = 0;
         else
            %vehicle is on SCL; change desired and design speeds
            desiredSpeed = vehDesiredSpeed(i)+ speedDiff;
            designSpeed = fwyDesSpeed;
         end
      end
   else
      %this is the case of a freeway vehicle
      desiredSpeed = vehDesiredSpeed(i);
       if strgy=="S3" && (vehType(i)==2||vehType(i)==3)
            if vehLoc(i)>segment_1 && vehLoc(i)<segment_2
               desiredSpeed=desiredSpeed + diff_desrd_spd_segment_1 ;
            elseif vehLoc(i)>= segment_2 && vehLoc(i)<segment_3
               desiredSpeed=desiredSpeed + diff_desrd_spd_segment_2 ;
            elseif vehLoc(i)>= segment_3 && vehLoc(i)< 0
               desiredSpeed=desiredSpeed + diff_desrd_spd_segment_3 ;
            end
       end
      designSpeed = fwyDesSpeed;
   end

%   ^^^^^^^^^^^^^^^^  Update Speed of FIRST VEHICLE   ^^^^^^^^^^^^^^^^^^^^^

   if i == firstVeh
      %for the first vehicle, there is no lead vehicle
      %so for first vehicle Gipps model will not work
      if onRampVeh==1 && vehSpeed(i)<desiredSpeed
         %ramp vehicle with no lead vehicle
         %accelerate at desired acceleration rate
```

```
        %vehicle does not acclerate beyond the desired speed
        newSpeed = vehSpeed(i)+desiredAccRamp(i)*timeStep;
          if newSpeed>desiredSpeed
            actualAccTime = (desiredSpeed - vehSpeed(i))/...
              desiredAccRamp(i);
            vehLoc(i) = vehLoc(i) + (vehSpeed(i)*actualAccTime +...
              0.5*desiredAccRamp(i)*actualAccTime^2) +...
              desiredSpeed*(timeStep-actualAccTime);
            vehSpeed(i) = desiredSpeed;
          else
            vehLoc(i) = vehLoc(i) + vehSpeed(i) * timeStep +...
              0.5*desiredAccRamp(i)*timeStep^2;
            vehSpeed(i) = newSpeed;
          end
        timeLastDec(i)=simTime;
      else
      %vehicle is a fwy/ramp vehicle that reached desired speed
      %need to only change location; speed remains the same
          if vehSpeed(i)< desiredSpeed
              vehSpeed(i)= desiredSpeed;
          end
        vehLoc(i) = vehLoc(i) + vehSpeed(i) * timeStep;
        timeLastDec(i)=simTime;
      end

% ^^^^^^^^^^^^^^^^^^^^^^^^^^  OTHER VEHICLES  ^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^
    else
      %this is a following vehicle; Gipps model applies
      %Exctract speed and location of lead and subject vehicles
      %Lead is the vehicle in front of the one being updated
      %Subject is the vehicle being updated

      spdLead = vehSpeed(i-1);
      spdSubject = vehSpeed(i);
      locLead = vehLoc(i-1);
      locSubject = vehLoc(i);
      lengthLead = vehLen(i-1);

% SETTING STRATEGY 7 BASED on LOC OF FWY VEHICLES
       if strgy=="S7" && locSubject > detectorLoc && locSubject <...
           rampStopLoc && onRampVeh==0
        % check with Vissim Analysis
         if (vehLoc(i-1)- vehLoc(i)-vehLen(i-1))/vehSpeed(i) <= .8
          rampStp=1;
        end
       end
```

```
% END STRATEGY 7

% ^^^^^^^^^^^^^^^^^^^^^^^ GIPPS MODEL ^^^^^^^^^^^^^^^^^^^^^^^

    if vehType(i)==1
      RT=reactTimeRV;
      % for DVs, delay in speed adjustment almost equal to RT/2
      gtheta=RT/2;
    else
      RT=reactTimeCAV;
        if strgy=="S1" && (locSubject>(endLocationSCL+450)...
              || locSubject< 0)
          gtheta=largGap-RT;
        elseif strgy=="S2" && locSubject>segment_1 &&...
              locSubject< segment_2
          gtheta=largGap/3-RT;
        elseif strgy=="S2" && locSubject >= segment_2 &&...
              locSubject< segment_3
          gtheta=largGap*2/3-RT ;
        elseif strgy=="S2" && locSubject >= segment_3 &&...
              locSubject< 0
          gtheta=largGap-RT  ;
        elseif strgy=="S6"  && onRampVeh==0
          gtheta=gthetaS6(i);
        else
          gtheta=minGapCAV-RT;
        end
    end
       if gtheta<0
         gtheta=0;
      end
    %total gap between front of subject vehicle and rear of lead veh
    totGap = locLead - locSubject - lengthLead;

    if (abs(simTime-timeLastDec(i)-RT)<=toler && abs(simTime-...
         timeLastDec(i)-RT)>=(-1*toler)) || timeLastDec (i)==0
      % the codition abs(simTime-timeStep)<=toler [equivalen to
      % simTime=timeStep] is for use in the first iteration only
    if totGap <= 0
      vehSpeed(i)=0;
    else
      Va = spdSubject + galpha*maxAccRate*RT*(1-spdSubject/...
         desiredSpeed)*(gbeta+spdSubject/desiredSpeed)^gdelta;
      Vb = maxDecRate*(RT/2+gtheta)+((maxDecRate*(RT/2+gtheta))^2....
      -maxDecRate*(2*totGap-spdSubject*RT-(spdLead^2/...
      maxDecRate)))^.5;
```

```
      vehSpeed(i) = min(Va,Vb);
    end
      %calculate average acceleration rate of subject vehicle over
      %the duration of reaction time to calculate distance travelled
      %[need to initiate this variable]
      avgAccSubject(i)=(vehSpeed(i)-spdSubject)/RT;

      %save initial subject vehicle speed for distance calculations
      initialSpdSubject = spdSubject;

      %save time of last vehicle decision
      timeLastDec(i)=simTime;

      if (vehType(i-1)==2||vehType(i-1)==3) && (totGap/spdSubject)...
          >minTime && (totGap/(designSpeed-spdLead))<maxTime
        % condition compares minTime to actual headway but compares
        % maxTime to gap divided over max possible speed increase

        % the subject vehicle will accelerate to designSpeed
        % if it is at maxTime from the lead vehicle
        vehDesiredSpeed(i) = designSpeed;

        % an alternative scenario is to set a maximum speed based
        % on a ratio of time gap between the subject and lead
        % vehicles {disable this option for now)

      end
    else
      %calculate the initial subject vehicle speed for this time step
      %(required for distance calculations)
      initialSpdSubject = spdSubject + avgAccSubject(i)*(simTime-...
        timeLastDec(i));
    end

    %update vehicle location within the time step
    diffLoc_vehi=initialSpdSubject*timeStep+0.5*avgAccSubject(i)*...
      timeStep^2;

    vehLoc(i)=vehLoc(i)+diffLoc_vehi;
  end
end
end
```

**AvAndACCGaps.m** (check gap acceptance for different merging situations, such as merge a DV between CAVs, a CAV between CAVs, …)

```
function [mergeORnot, leadVehFwy] = AvAndAccGaps(vehSpeedRamp,...
    vehTypeRamp,vehLocRamp,vehLength)
%Jan 24, 2021
%Oct 28, 2020
%Dec 3, 2019
%Nov 26, 2019
%   Output is a binary variable whether the vehicle will merge or not
%   mergeORnot = 1: vehicle will merge
%   mergeORnot = 0: vehicle will not merge
%Nov 20, 2019
%   Added functionality to get acceptable and available gaps
%   Use actual FRL vehicle speed instead of an arbitrary avg speed
%Nov 19, 2019:
%   added funcationality to find lead and lag vehicle and calculate lead
%   and lag gap accordingly; still need to change freeway speed with the
%   actual speed of the lead and lag vehicles

global maxAccRate
global maxDecRate
global reactTimeRV reactTimeCAV
global sclMergeLength speedMaxCAV
global vehLocFwy vehTypeFwy vehSpeedFwy vehLengthFwy
global  endLocationSCL
global vehLocFwy2 vehTypeFwy2 vehSpeedFwy2 vehLengthFwy2
global strgy
mergeORnot = 1; %default value is that the ramp vehicle merges

%%%%%%%%%%%%%%%%%%%%%%%%% lead and lag gaps %%%%%%%%%%%%%%%%%%%%%%%%%
%find the first vehicle ahead or first vehicle behind of the ramp
%vehicle which is last vehicle in the vector ahead of ramp vehicle
%find the first vehicle behind the ramp vehicle which is first
%vehicle in the vector ahead of ramp vehicle
leadVehFwy = find(vehLocFwy>=vehLocRamp, 1, 'last' );
lagVehFwy = find(vehLocFwy<=vehLocRamp, 1, 'first' );

if isempty(leadVehFwy)||isempty(lagVehFwy)
    %no lag vehicle behind on the freeway
    %no lead vehicle on the freeway
    %in this scenario, there is no vehicle on the FRL behind the ramp
    %vehicle; the vehicle can merge and no need to continue the function
    mergeORnot = 1;
```

```
    return;

else
    %calaculate available gap rear to front

    GapAv= vehLocFwy(leadVehFwy)-vehLocFwy(lagVehFwy);
    %again, this gap is rear to front;

    if vehTypeRamp == 1
        %Ramp vehicle is DV; accepted gaps are based on Fatema et al equ.
        %relative distance, required to estimate acceptable gap
        RelDist = vehLocRamp/sclMergeLength;
        totalGapAcc = (9.563 - 0.216 * vehSpeedRamp - 1.322*RelDist)...
            * vehSpeedRamp;
    else
    %ramp vehicle is CAV; acceptable gaps are claculated based on speeds of
    %vehicles in FRL
    %reaction time used in calculating lead/lag gap depends on the type of
    %lead/lag vehicle
        leadVehSpd = vehSpeedFwy(leadVehFwy);
        lagVehSpd = vehSpeedFwy(lagVehFwy);
%%%%%%%%%%%%%% lead gap for CAV %%%%%%%%%%%%%%
            if vehTypeFwy(leadVehFwy) == 1
                %lead vehicle on freeway is DV, use reaction time DV
                Fwy1VehLagRT = reactTimeRV;
            else
                %lead vehicle on freeway is CAV, use reaction time CAV
                Fwy1VehLagRT = reactTimeCAV;
            end
                %apply the equation for lead gap
            if leadVehSpd >= vehSpeedRamp
                leadGapAcc = Fwy1VehLagRT * vehSpeedRamp;
            else
                leadGapAcc = leadVehSpd * ((leadVehSpd-vehSpeedRamp)/...
                    maxDecRate)+Fwy1VehLagRT*leadVehSpd+vehLength-0.5*...
                    maxDecRate*((leadVehSpd-vehSpeedRamp)/maxDecRate)^2....
                    +vehSpeedRamp*(leadVehSpd-vehSpeedRamp)/maxDecRate;
            end
%%%%%%%%%%%%%% lag gap for CAV %%%%%%%%%%%%%%
            if vehTypeFwy(lagVehFwy) == 1
                %lag vehicle on freeway is DV, use reaction time DV
                rampVehLagRT = reactTimeRV;
            else
                %lag vehicle on freeway is CAV, use reaction time CAV
                rampVehLagRT = reactTimeCAV;
            end
```

```
            %apply the equation for lag gap
          if lagVehSpd > vehSpeedRamp
            lagGapAcc = lagVehSpd*((lagVehSpd-vehSpeedRamp)/...
               maxAccRate)+rampVehLagRT*lagVehSpd+vehLength-0.5*...
               maxAccRate*((lagVehSpd-vehSpeedRamp)/maxAccRate)^2....
            +vehSpeedRamp*(lagVehSpd-vehSpeedRamp)/maxAccRate;
          else
           lagGapAcc = rampVehLagRT * lagVehSpd;
          end
          totalGapAcc = leadGapAcc+lagGapAcc;
   end

%check if the ramp vehicle can merge based on the total lead and lag gaps
   if GapAv < totalGapAcc
      mergeORnot = 0;
   else
      return;
   end
end

if strgy=="S8"

% ************************************ TOTAL ACCEPTED GAP FOR DVs
*******
   if vehTypeRamp == 1 % 1 means DVs
      RelDist = vehLocRamp/sclMergeLength;
      totalGapAcc = (9.563 - 0.216 * vehSpeedRamp - 1.322*RelDist) *...
         vehSpeedRamp;
   else
%   ******************************* TOTAL ACCEPTED GAP FOR CAVs
*******
      if isempty(leadVehFwy)
         %no lead vehicle on the freeway
         leadGapAcc = 0;
      else
         leadVehSpdFw2 = vehSpeedFwy(leadVehFwy);

         if vehTypeFwy(leadVehFwy) == 1
            %lead vehicle on freeway is DV, use reaction time DV
            %Driver-operated vehicle= Regular vehicles)
            Fwy1VehLagRT = reactTimeRV;
         else
            %lead vehicle on freeway is CAV, use reaction time CAV
            Fwy1VehLagRT = reactTimeCAV;
         end
```

```
            if leadVehSpdFw2 >= vehSpeedRamp
               leadGapAcc = Fwy1VehLagRT * vehSpeedRamp;
            else
               leadGapAcc = leadVehSpdFw2 * ((leadVehSpdFw2-...
                  vehSpeedRamp)/maxDecRate)+(Fwy1VehLagRT*...
                  leadVehSpdFw2)+vehLength-0.5*maxDecRate*...
                  ((leadVehSpdFw2-vehSpeedRamp)/maxDecRate)^2....
               +vehSpeedRamp*(leadVehSpdFw2-vehSpeedRamp)/maxDecRate;
            end
         end

         if isempty(lagVehFwy)
            lagGapAcc=0;
         else
            lagVehSpd = vehSpeedFwy(lagVehFwy);
            if vehTypeFwy(lagVehFwy) == 1
               %lag vehicle on freeway is DV, use reaction time DV
               rampVehLagRT = reactTimeRV;
            else
               %lag vehicle on freeway is CAV, use reaction time CAV
               rampVehLagRT = reactTimeCAV;
            end

            if lagVehSpd > vehSpeedRamp
               lagGapAcc = lagVehSpd*((lagVehSpd-vehSpeedRamp)/...
                  maxAccRate)+rampVehLagRT*...
                  lagVehSpd+vehLength-0.5*maxAccRate*...
                  ((lagVehSpd-vehSpeedRamp)/maxAccRate)^2....
                  +vehSpeedRamp*(lagVehSpd-vehSpeedRamp)/maxAccRate;
            else
               lagGapAcc = rampVehLagRT * lagVehSpd;
            end
         end
         totalGapAcc= leadGapAcc + lagGapAcc; % total accepted gap for CAVs
      end
   % ******************* Acceleration Priority for S8 *********************
    if  vehTypeFwy(leadVehFwy) ~= 1
               % require additional distance for merging
               add_dis= totalGapAcc - GapAv;
               t=((endLocationSCL- vehLocRamp)/vehSpeedRamp);
               newLeadVehSpeed = vehSpeedFwy(leadVehFwy) + (maxAccRate*t);
                  if newLeadVehSpeed > speedMaxCAV
                     newLeadVehSpeed = speedMaxCAV;
                  end
               if ((((newLeadVehSpeed + vehSpeedFwy(leadVehFwy))/2) -...
                     (vehSpeedFwy(leadVehFwy+1)))*t)>= add_dis
```

```
            newLeadVehLoc=vehLocFwy(leadVehFwy)+((vehSpeedFwy(...
              leadVehFwy)+newLeadVehSpeed)/2) * t;
              if ((vehLocFwy(leadVehFwy-1)+ vehSpeedFwy(...
                  leadVehFwy-1)*t)-vehLengthFwy(...
                  leadVehFwy-1)-newLeadVehLoc) >= (...
                  reactTimeCAV * newLeadVehSpeed)
                mergeORnot=1;
                return;
              end
          end
    end
% ********************** Lane Change Priority for S8 ********************

%find the first vehicle ahead or first vehicle behind of the FRL lead veh
% on the the FML
    lead1VehFwy2 = find(vehLocFwy2>=vehLocFwy(leadVehFwy), 1, 'last' );
    lag1VehFwy2 = find(vehLocFwy2<=vehLocFwy(leadVehFwy), 1, 'first' );
    if isempty(lead1VehFwy2)|| isempty(lag1VehFwy2)
        %no lead or Lag vehicle on the freeway second lane
        %So the lead vehicle on the freeway first lane can merge to
        %second lane. Now with lane changing the FRL lead vehicle to
        % the second lane the avalable gap on FRL will change to:
        GapAv2= vehLocFwy(leadVehFwy-1)-vehLocFwy(lagVehFwy)-...
          vehLengthFwy(leadVehFwy-1) ;
        if GapAv2 > totalGapAcc
          mergeORnot = 1;
          return;
        end
    end
    %find the first vehicle ahead or first vehicle behind of the
    % FRL Lag vehilce on the the FML
    lead2VehFwy2 = find(vehLocFwy2>=vehLocFwy(lagVehFwy), 1, 'last' );
    lag2VehFwy2 = find(vehLocFwy2<=vehLocFwy(lagVehFwy), 1, 'first' );
    if isempty(lead2VehFwy2)|| isempty(lag2VehFwy2)
        %no lead or Lag vehicle on the freeway second lane
        %So the lag vehicle on the freeway first lane can merge to
        %second lane. Now with lane changing the FRL lag vehicle to
        % the second lane the avalable gap on FRL will change to:
        GapAv3= vehLocFwy(leadVehFwy)-vehLocFwy(lagVehFwy+1)-...
          vehLengthFwy(leadVehFwy) ;
        if GapAv3 > totalGapAcc
          mergeORnot = 1;
          return;
        end
    end
 %calaculate available gap rear to front for FML for FRL lead vehicle
```

```
        GapAv1Fwy2 = vehLocFwy2(lead1VehFwy2) - vehLengthFwy2(...
          lead1VehFwy2)- vehLocFwy2(lag1VehFwy2);
%apply the equation for lead gap
        leadVehSpdFw2 = vehSpeedFwy2(lead1VehFwy2);
            if vehTypeFwy2 (lead1VehFwy2)==1
                Fwy1VehLeadRT = reactTimeRV;
            else
                Fwy1VehLeadRT = reactTimeCAV;
            end
            if leadVehSpdFw2 >= vehSpeedFwy (leadVehFwy)
                lead1GapAccFwy2 = Fwy1VehLeadRT *...
                    vehSpeedFwy (leadVehFwy);
            else
                lead1GapAccFwy2 = leadVehSpdFw2 * ((leadVehSpdFw2-...
                    vehSpeedFwy(leadVehFwy))/maxDecRate)+...
                    Fwy1VehLeadRT*leadVehSpdFw2+vehLength-0.5*...
                    maxDecRate*((leadVehSpdFw2-vehSpeedFwy(...
                    leadVehFwy))/maxDecRate)^2+vehSpeedFwy(...
                    leadVehFwy)*(leadVehSpdFw2-vehSpeedFwy(...
                    leadVehFwy))/maxDecRate;
            end
%apply the equation for lag gap
         lagVehSpdFwy2 = vehSpeedFwy2(lag1VehFwy2);
            if vehTypeFwy2 (lag1VehFwy2)== 1
                Fwy1VehLagRT = reactTimeRV;
            else
                Fwy1VehLagRT = reactTimeCAV;
            end
            if lagVehSpdFwy2 > vehSpeedFwy(leadVehFwy)
                lag1GapAccFwy2 = lagVehSpdFwy2*((lagVehSpdFwy2-...
                    vehSpeedFwy(leadVehFwy))/maxAccRate)+...
                    Fwy1VehLagRT*lagVehSpdFwy2+vehLength-0.5*...
                    maxAccRate*((lagVehSpdFwy2-vehSpeedFwy(...
                    leadVehFwy))/maxAccRate)^2+vehSpeedFwy(...
                    leadVehFwy)*(lagVehSpdFwy2-vehSpeedFwy(...
                    leadVehFwy))/maxAccRate;
            else
                lag1GapAccFwy2 = Fwy1VehLagRT * lagVehSpdFwy2;
            end

   if (GapAv1Fwy2)>= (lead1GapAccFwy2+lag1GapAccFwy2) && (vehLocFwy(...
         leadVehFwy-1)-vehLocFwy(...
         lagVehFwy)-vehLengthFwy(leadVehFwy-1) < totalGapAcc)
          mergeORnot=1;
          return;
   end
```

```
%calaculate available gap rear to front for FML for FRL lag vehicle
      GapAv2Fwy2 = vehLocFwy2(lead2VehFwy2) - vehLengthFwy2(...
         lead2VehFwy2)- vehLocFwy2(lag2VehFwy2);
%apply the equation for lead gap
      leadVehSpdFw2 = vehSpeedFwy2(lead2VehFwy2);
         if vehTypeFwy2 (lead2VehFwy2)==1
            Fwy2VehLeadRT = reactTimeRV;
         else
            Fwy2VehLeadRT = reactTimeCAV;
         end
         if leadVehSpdFw2 >= vehSpeedFwy (leadVehFwy)
            lead2GapAccFwy2 = Fwy1VehLeadRT *...
               vehSpeedFwy (leadVehFwy);
         else
            lead2GapAccFwy2 = leadVehSpdFw2 * ((leadVehSpdFw2-...
               vehSpeedFwy(leadVehFwy))...
               /maxDecRate)+Fwy2VehLeadRT*leadVehSpdFw2+...
               vehLength-0.5*maxDecRate*((...
               leadVehSpdFw2-vehSpeedFwy(leadVehFwy))/...
               maxDecRate)^2+vehSpeedFwy(...
               leadVehFwy)*(leadVehSpdFw2-vehSpeedFwy(...
               leadVehFwy))/maxDecRate;
         end
%apply the equation for lag gap
       lagVehSpdFwy2 = vehSpeedFwy2(lag2VehFwy2);
         if vehTypeFwy2 (lag2VehFwy2)== 1
            Fwy2VehLagRT = reactTimeRV;
         else
            Fwy2VehLagRT = reactTimeCAV;
         end
         if lagVehSpdFwy2 > vehSpeedFwy(leadVehFwy)
            lag2GapAccFwy2 = lagVehSpdFwy2*((lagVehSpdFwy2-...
               vehSpeedFwy(leadVehFwy))...
               /maxAccRate)+Fwy2VehLagRT*lagVehSpdFwy2+...
               vehLength-0.5*maxAccRate*((...
               lagVehSpdFwy2-vehSpeedFwy(leadVehFwy))/...
               maxAccRate)^2+vehSpeedFwy(...
               leadVehFwy)*(lagVehSpdFwy2-vehSpeedFwy(...
               leadVehFwy))/maxAccRate;
         else
            lag2GapAccFwy2 = Fwy1VehLagRT * lagVehSpdFwy2;
         end

  if (GapAv2Fwy2)>= (lead2GapAccFwy2+lag2GapAccFwy2) && (...
       vehLocFwy(leadVehFwy-1)...
       -vehLocFwy(lagVehFwy)-vehLengthFwy(leadVehFwy-1) < totalGapAcc)
```

```
            mergeORnot=1;
            return;
      end
% ************************ Deaccleration Priority for S8 *****************

        if  vehTypeFwy(lagVehFwy) ~= 1
            add_dis=totalGapAcc - GapAv;
            t=((endLocationSCL- vehLocRamp)/vehSpeedRamp);
            newLagVehSpeed = vehSpeedFwy(lagVehFwy) + (maxDecRate*t);

             if (((vehSpeedFwy(lagVehFwy-1)-(newLagVehSpeed +...
                    vehSpeedFwy(lagVehFwy))/2))*t) >= add_dis
                  newLagVehLoc=vehLocFwy(lagVehFwy)+((vehSpeedFwy(...
                     lagVehFwy)+newLagVehSpeed)/2) * t;
                  if newLagVehLoc-vehLengthFwy(lagVehFwy)- (...
                     vehLocFwy(lagVehFwy+1)+(vehSpeedFwy(...
                     lagVehFwy+1)*t)) >= (reactTimeCAV *...
                     vehSpeedFwy(lagVehFwy))
                    mergeORnot =1;
                  else
                    mergeORnot =0;
                  end
             end
        end
end
% ************************  End of Strategy 8  *************************
end
```

**generateCars.m** (generate vehicles for on-ramp and assign vehicle characteristics to them such as vehicle type (CAV or DV), length, initial location, headway, and desired speed)

```
function [vehDesiredSpeed,vehType,vehHeadway,vehInitialSpeed,vehLength,...
   desiredAcc] = generateCars(postSpeed,hrVolume,minHeadwayRV,...
   speedStdRV,speedPost2MaxRV)

%update Dec 17, 2019:
%all vehicles are generated at the beginning of the simulation
%different speedStdRV and speedPost2MaxRV for ramp and freeway
%update Dec 3, 2019:
%add random desired acceleration if there is no lead vehicle
%removed need to call of function poisson1
%update Nov 19, 2019: add variables speedStdRV speedPost2MaxRV
%speedPost2MinRV speedPost2AvgRV instead of constants
%update Nove 12, 2019; no real change from previous version

global speedPost2MinRV speedPost2AvgRV_Rmp
global maxAccRate
global timeWarmUp hrVolRamp
global percentCAV percentAV percentTrucks percentBuses

 rng('shuffle')
% Speed is selected based on random numbers from a normal
% distribution with mean and standard deviation
% standard deviation of desired speed for CAVs, m/s
speedStdCAV = 0.05*postSpeed;
speedTolCAV = 0.05*postSpeed*2;          % speed tolerance for CAVs
speedAvgCAV = postSpeed;      % assume average speed of CAV = posted speed
speedMaxCAV = speedAvgCAV+speedTolCAV;    % Max speed for CAVs vehicles
speedMinCAV = speedAvgCAV-speedTolCAV;    % Min speed for CAVs vehicles

speedAvgRV = postSpeed+speedPost2AvgRV_Rmp; % Average speed of DVs
% Max speed for regular vehicles (DV)
speedMaxRV = speedAvgRV+speedPost2MaxRV;
% Min speed for regular vehicles (DV)
speedMinRV = speedAvgRV-speedPost2MinRV;
%min desired acceleration if there is no lead vehicle
maxDesiredAcc = 1*maxAccRate;
%max desired acceleration if there is no lead vehicle
minDesiredAcc = 0.5*maxAccRate;
%Set the vehicle length, PC=5.79m, Truck = 9.14, Bus = 12.36 (AASHTO 2011)
lengthPC = [4.27; 4.53; 4.53; 4.53; 4.64; 4.64; 4.64; 4.64; 4.64; 4.75;...
```

```
    4.75; 4.9; 5.81; 5.81; 5.81; 5.81; 6.1; 6.1; 6.1];
lengthT = 9.14;
lengthB = 12.36;

%number of vehicles to be created is increased to account for the warmup
%time; number is rounded up to the nearest integer
nVeh = ceil(hrVolume*(1+timeWarmUp/3600)+hrVolRamp);
%Assign vehicle types (1=DV, 2=CAV, 3=AV)
vehType = ones(nVeh,1);
randCavRv = randperm(nVeh); %random vector of vehicle index
%vehicle type is CAV
vehType(randCavRv<=percentCAV*nVeh/100) = 2;
%vehicle type is AV
vehType((randCavRv>percentCAV*nVeh/100)&(randCavRv<=(percentCAV+...
    percentAV)*nVeh/100)) = 3; V
vehType(1) = 1; % First vehicle is assumed DV (vehType = 1)

nVehRV = length(find(vehType==1));  %exact number of DVs
nVehCAV = length(find(vehType==2)); %exact number of CAVs
nVehAV = length(find(vehType==3));  %exact number of AVs

%Assign vehicle length based on PC, Bus, or truck
indexVehLength= randi(numel(lengthPC),[nVeh,1]);
vehLength =lengthPC(indexVehLength);
randVehLen = randperm(nVeh); %random vector of vehicle index
%length of trucks
vehLength(randVehLen<=percentTrucks*nVeh/100) = lengthT;
%length of buses
vehLength((randVehLen>percentTrucks*nVeh/100)&(randVehLen<=(...
    percentTrucks+percentBuses)*nVeh/100)) = lengthB;
vehLength(1) = lengthPC(1); % First vehicle is assumed PC

% Speed **************** Speed **************** Speed *****************
% Set initial speed value based on normal distribution knowing the
% average speed and standard deviation; speed cannot exceed a specific max
% or below a specific minimum
% There are two speed distributions: one for CAVs&AVs and one for AVs
randomSpeedCAV = normrnd(speedAvgCAV, speedStdCAV, [nVehCAV+nVehAV, 1]);
randomSpeedCAV(randomSpeedCAV>speedMaxCAV) = speedMaxCAV;
randomSpeedCAV(randomSpeedCAV<speedMinCAV) = speedMinCAV;
randomSpeedRV = normrnd (speedAvgRV, speedStdRV, [nVehRV, 1]);
randomSpeedRV(randomSpeedRV>speedMaxRV) = speedMaxRV;
randomSpeedRV(randomSpeedRV<speedMinRV) = speedMinRV;

vehDesiredSpeed = zeros(nVeh,1); %initialize sesired vehicle speed
vehDesiredSpeed((vehType==2)|(vehType==3))=randomSpeedCAV;
```

```
vehDesiredSpeed(vehType==1)=randomSpeedRV;

%Initially, the ranomly assigned speed is the instantaneous
%speed and also the desired speed
vehInitialSpeed = vehDesiredSpeed;

% For the first vehicle; maximum speed is equal to max DV speed and initial
% speed is equal to posted speed
vehDesiredSpeed(1) = speedMaxRV;
vehInitialSpeed(1) = postSpeed;

% assign random headway (Poisson distribution) for all vehicles
% headway cannot be less than a specific min headway
flowLambda=1/hrVolume*3600;
vehHeadway = (poissrnd(flowLambda*100,[nVeh,1]))/100;
vehHeadway(vehHeadway<minHeadwayRV) = minHeadwayRV;
vehHeadway = cumsum(vehHeadway); %this is vector of the cumulative headways

%generate random desired acceleration
%for now, use uniform distribution between a min and max value
%relevant only to ramp vehicles
```

**generateCarsFwy.m** (generate vehicles for FRL and assign vehicle characteristics to them such as vehicle type (CAV or DV), length, initial location, headway, and desired speed)

```
function [vehDesiredSpeed,vehType,vehHeadway,vehInitialSpeed,vehLength,...
   desiredAcc] = generateCarsFwy(postSpeed,hrVolume,minHeadwayRV,...
   speedStdRV,speedPost2MaxRV)

%update Dec 17, 2019:
%all vehicles are generated at the beginning of the simulation
%different speedStdRV and speedPost2MaxRV for ramp and freeway
%update Dec 3, 2019:
%add random desired acceleration if there is no lead vehicle
%removed need to call of function poisson1
%update Nov 19, 2019: add variables speedStdRV speedPost2MaxRV
%speedPost2MinRV speedPost2AvgRV instead of constants
%update Nove 12, 2019; no real change from previous version
%update June 16, 2020; CAV Reuction on FRL factor for startegy 4

global speedPost2AvgRV_Fw speedPost2MinRV_Fwy
global maxAccRate  lengthPC hrVolRamp
global timeWarmUp  speedMaxCAV reactTimeRV reactTimeCAV
global percentCAV percentAV percentTrucks percentBuses
global strgy gthetaS6 platoonSize  minGapCAV largGap
rng('shuffle')
% Speed is selected based on random numbers from a normal distribution
% with mean and standard deviation
speedStdCAV = 0.05*postSpeed;
% standard deviation of desired speed for CAVs, m/s
speedTolCAV = 0.05*postSpeed*2;
% speed tolerance CAVs
speedAvgCAV = postSpeed;
% assume average speed of CAV = posted speed
speedMaxCAV = speedAvgCAV+speedTolCAV;
% Max speed for AVs and CAVs vehicles
speedMinCAV = speedAvgCAV-speedTolCAV;
% Min speed for AVs and CAVs vehicles

speedAvgRV = postSpeed+speedPost2AvgRV_Fw;   % Average speed of DVs
speedMaxRV = speedAvgRV+speedPost2MaxRV;
% Max speed for regular vehicles
speedMinRV = speedAvgRV-speedPost2MinRV_Fwy;
% Min speed for regular vehicles
%min desired acceleration if there is no lead vehicle
maxDesiredAcc = 1*maxAccRate;
```

```
%max desired acceleration if there is no lead vehicle
minDesiredAcc = 0.5*maxAccRate;

%Set the vehicle length, PC=5.79m, Truck = 9.14, Bus = 12.36 (AASHTO 2011)
lengthPC = [4.27; 4.53; 4.53; 4.53; 4.64; 4.64; 4.64; 4.64; 4.64; 4.75;...
    4.75; 4.9; 5.81; 5.81; 5.81; 5.81; 6.1; 6.1; 6.1];
lengthT = 9.14;
lengthB = 12.36;

%number of vehicles to be created is increased to account for the warmup
%time; number is rounded up to the nearest integer
nVeh = ceil(hrVolume*(1+timeWarmUp/3600)+hrVolRamp*1.5);
% 50% more just incase

%Assign vehicle types (1=DV, 2=CAV, 3=AV)
vehType = ones(nVeh,1);
randCavRv = randperm(nVeh); %random vector of vehicle index
vehType(randCavRv<=percentCAV*nVeh/100) = 2; %vehicle type is CAV
vehType((randCavRv>percentCAV*nVeh/100)&(randCavRv<=(percentCAV+...
    percentAV)*nVeh/100)) = 3; %vehicle type is AV
vehType(1) = 1; % First vehicle is assumed RV (vehType = 1)

nVehRV = length(find(vehType==1));  %exact number of DVs
nVehCAV = length(find(vehType==2)); %exact number of CAVs
nVehAV = length(find(vehType==3));  %exact number of AVs

if strgy=="S6"
    pas=1;
    gthetaS6 = ones(nVeh,1);
    for i=1:nVeh
    if vehType(i)==1
        gthetaS6(i) =reactTimeRV/2;
    elseif  i >= pas && i+platoonSize-1 <= nVeh
          if   (vehType (i:i+platoonSize-1)>1)
                gthetaS6(i)=largGap-reactTimeCAV;
                pas= i+platoonSize;
          else
                gthetaS6(i)= minGapCAV-reactTimeCAV;
          end
    else
        gthetaS6(i)= minGapCAV-reactTimeCAV;
    end
    end
end

%Assign vehicle length based on PC, Bus, or truck
```

```
indexVehLength= randi(numel(lengthPC),[nVeh,1]);
vehLength =lengthPC(indexVehLength);
randVehLen = randperm(nVeh); %random vector of vehicle index

%length of trucks
vehLength(randVehLen<=percentTrucks*nVeh/100) = lengthT;
%length of buses
vehLength((randVehLen>percentTrucks*nVeh/100)&(randVehLen<=(...
   percentTrucks+percentBuses)*nVeh/100)) = lengthB;
vehLength(1) = lengthPC(1); % First vehicle is assumed a PC

% Speed **************** Speed **************** Speed *****************
% Set initial speed value based on normal distribution knowing the
% average speed and standard deviation; speed cannot exceed a specific max
% or below a specific minimum
% There are two speed distributions: one for CAV and one for AV
randomSpeedCAV = normrnd(speedAvgCAV, speedStdCAV, [nVehCAV+nVehAV, 1]);
randomSpeedCAV(randomSpeedCAV>speedMaxCAV) = speedMaxCAV;
randomSpeedCAV(randomSpeedCAV<speedMinCAV) = speedMinCAV;

randomSpeedRV = normrnd (speedAvgRV, speedStdRV, [nVehRV, 1]);
randomSpeedRV(randomSpeedRV>speedMaxRV) = speedMaxRV;
randomSpeedRV(randomSpeedRV<speedMinRV) = speedMinRV;

vehDesiredSpeed = zeros(nVeh,1); %initialize sesired vehicle speed
vehDesiredSpeed((vehType==2)|(vehType==3))=randomSpeedCAV;
vehDesiredSpeed(vehType==1)=randomSpeedRV;

%Initially, the ranomly assigned speed is the instantaneous
%speed and also the desired speed
vehInitialSpeed = vehDesiredSpeed;

% For the first vehicle; maximum speed is equal to max RV speed and initial
% speed is equal to posted speed
vehDesiredSpeed(1) = speedMaxRV;
vehInitialSpeed(1) = postSpeed;

% assign random headway (Poisson distribution) for all vehicles
% headway cannot be less than a specific min headway
flowLambda=1/hrVolume*3600;
vehHeadway = (poissrnd(flowLambda*100,[nVeh,1]))/100;
vehHeadway(vehHeadway<minHeadwayRV) = minHeadwayRV;
vehHeadway = cumsum(vehHeadway); %this is vector of the cumulative headways

%generate random desired acceleration
%for now, use uniform distribution between a min and max value
```

```
%relevant only to ramp vehicles
desiredAcc = (maxDesiredAcc - minDesiredAcc)*rand(nVeh,1) + minDesiredAcc;
end
```

| |
|---|
| **generateCarsFwy2.m** (generate vehicles for FSL and assign vehicle characteristics to them such as vehicle type (CAV or DV), length, initial location, headway, and desired speed) |

```
function [vehDesiredSpeed,vehType,vehHeadway,vehInitialSpeed,vehLength,...
    desiredAcc] = generateCarsFwy2(...
    postSpeed,hrVolume,minHeadwayRV,speedStdRV,speedPost2MaxRV)

%update Dec 17, 2019:
%all vehicles are generated at the beginning of the simulation
%different speedStdRV and speedPost2MaxRV for ramp and freeway
%update Dec 3, 2019:
%add random desired acceleration if there is no lead vehicle
%removed need to call of function poisson1
%update Nov 19, 2019: add variables speedStdRV speedPost2MaxRV
%speedPost2MinRV speedPost2AvgRV instead of constants
%update Nove 12, 2019; no real change from previous version
%update June 16, 2020; CAV Reuction on FRL factor for startegy 4

global speedPost2AvgRV_Fw speedPost2MinRV_Fwy
global maxAccRate  lengthPC
global timeWarmUp  hrVolRamp
global percentCAV percentAV percentTrucks percentBuses
rng('shuffle')
% Speed is selected based on random numbers from a normal distribution
%with mean and standard deviation
speedStdCAV = 0.05*postSpeed;
% standard deviation of desired speed for CAVs, m/s
speedTolCAV = 0.05*postSpeed*2;
% speed tolerance for CAVs
speedAvgCAV = postSpeed;
% assume average speed of CAV = posted speed
speedMaxCAV = speedAvgCAV+speedTolCAV;
% Max speed for AVs and CAVs vehicles
speedMinCAV = speedAvgCAV-speedTolCAV;
% Min speed for AVs and CAVs vehicles

speedAvgRV = postSpeed+speedPost2AvgRV_Fw;     % Average speed of DVs
speedMaxRV = speedAvgRV+speedPost2MaxRV;
% Max speed for regular vehicles
speedMinRV = speedAvgRV-speedPost2MinRV_Fwy;
% Min speed for regular vehicles

maxDesiredAcc = 1*maxAccRate;
```

```
%min desired acceleration if there is no lead vehicle
minDesiredAcc = 0.5*maxAccRate;
%max desired acceleration if there is no lead vehicle

%Set the vehicle length, PC=5.79m, Truck = 9.14, Bus = 12.36 (AASHTO 2011)
lengthPC = [4.27; 4.53; 4.53; 4.53; 4.64; 4.64; 4.64; 4.64; 4.64; 4.75;...
    4.75; 4.9; 5.81; 5.81; 5.81; 5.81; 6.1; 6.1; 6.1];
lengthT = 9.14;
lengthB = 12.36;

%number of vehicles to be created is increased to account for the warmup
%time; number is rounded up to the nearest integer
nVeh = ceil(hrVolume*(1+timeWarmUp/3600)+hrVolRamp*1.5);

%Assign vehicle types (1=DV, 2=CV, 3=AV)
vehType = ones(nVeh,1);
randCavRv = randperm(nVeh); %random vector of vehicle index
vehType(randCavRv<=percentCAV*nVeh/100) = 2; %vehicle type is CAV
%vehicle type is AV
vehType((randCavRv>percentCAV*nVeh/100)&(randCavRv<=(percentCAV+...
    percentAV)*nVeh/100)) = 3;
vehType(1) = 1; % First vehicle is assumed RV (vehType = 1)

nVehRV = length(find(vehType==1));  %exact number of DVs
nVehCAV = length(find(vehType==2)); %exact number of CAVs
nVehAV = length(find(vehType==3));  %exact number of AVs

%Assign vehicle length based on PC, Bus, or truck
indexVehLength= randi(numel(lengthPC),[nVeh,1]);
vehLength =lengthPC(indexVehLength);
% vehLength = ones(nVeh,1)*lengthPC;
randVehLen = randperm(nVeh); %random vector of vehicle index
%length of trucks
vehLength(randVehLen<=percentTrucks*nVeh/100) = lengthT;
%length of buses
vehLength((randVehLen>percentTrucks*nVeh/100)&(randVehLen<=(...
    percentTrucks+percentBuses)*nVeh/100)) = lengthB;
vehLength(1) = lengthPC(1); % First vehicle is assumed PC

% Speed **************** Speed **************** Speed *****************
% Set initial speed value based on normal distribution knowing the
% average speed and standard deviation; speed cannot exceed a specific max
% or below a specific minimum
% There are two speed distributions: one for CAVs and one for AVs
randomSpeedCAV = normrnd(speedAvgCAV, speedStdCAV, [nVehCAV+nVehAV, 1]);
randomSpeedCAV(randomSpeedCAV>speedMaxCAV) = speedMaxCAV;
```

```
randomSpeedCAV(randomSpeedCAV<speedMinCAV) = speedMinCAV;

randomSpeedRV = normrnd (speedAvgRV, speedStdRV, [nVehRV, 1]);
randomSpeedRV(randomSpeedRV>speedMaxRV) = speedMaxRV;
randomSpeedRV(randomSpeedRV<speedMinRV) = speedMinRV;
%initialize sesired vehicle speed
vehDesiredSpeed = zeros(nVeh,1);
vehDesiredSpeed((vehType==2)|(vehType==3))=randomSpeedCAV;
vehDesiredSpeed(vehType==1)=randomSpeedRV;

%Initially, the ranomly assigned speed is the instantaneous
%speed and also the desired speed
vehInitialSpeed = vehDesiredSpeed;
% For the first vehicle; maximum speed is equal to max RV speed and initial
% speed is equal to posted speed
vehDesiredSpeed(1) = speedMaxRV;
vehInitialSpeed(1) = postSpeed;

% assign random headway (Poisson distribution) for all vehicles
% headway cannot be less than a specific min headway
flowLambda=1/hrVolume*3600;
vehHeadway = (poissrnd(flowLambda*100,[nVeh,1]))/100;
vehHeadway(vehHeadway<minHeadwayRV) = minHeadwayRV;
vehHeadway = cumsum(vehHeadway); %this is vector of the cumulative headways

%generate random desired acceleration
%for now, use uniform distribution between a min and max value
%relevant only to ramp vehicles
desiredAcc = (maxDesiredAcc - minDesiredAcc)*rand(nVeh,1) + minDesiredAcc;
end
```

**accelerationSclAashtoLength.m** (Calculation SCL length based on AASHTO 2018 design guideline)

```
function sclLength = accelerationSclAashtoLength

% Jan 25 2020; Change from fwyDesignSpeed to fwyDeesignSpeedKMH, AP

global fwyDesSpeedKMH rampDesSpeedKMH

tableRows = 50:10:120;
tableCols = [0, 20:10:80];

aashtoTable =[60,50,30, 0, 0, 0, 0, 0;...
    95,80,65,45,0,0,0,0;...
    150,130,110,90,65,0,0,0;...
    200,180,165,145,115,65,0,0;...
    260,245,225,205,175,125,35,0;...
    345,325,305,285,255,205,110,40;...
    430,410,390,370,340,290,200,125;...
    545,530,515,490,460,410,325,245];

w = find(tableRows==fwyDesSpeedKMH);
z = find(tableCols==rampDesSpeedKMH);

%need to account for speeds that do not exactly match a row and/or column
sclLength=aashtoTable(w,z);
```

**reassignVeh.m** (reassign FRL vehicles characteristics after ramp vehicles merge into FRL

```
function reassignVeh(im, ir, ifwy)

%update Jan 27, 2020, AP
%update Dec 17, 2019
%   Vector of headway is now cumulative

%created Dec 4, 2019
%   remove a merged ramp vehicle from the ramp and assign to the fwy
%
%   if the ramp vehicle failed to merge, it is only removed from the ramp
%   and not assigned to the fwy
%   im = mergeORnot (1: vehicle merged; 0: vehicle did not merge)
%   ir: index of the ramp vehicle
%   ifwy: index of the lead fwy vehicle

global hdCumFwy timeLastDecFwy vehDesiredSpeedFwy vehLocFwy
global vehTypeFwy vehSpeedFwy vehLengthFwy avgAccFwy gthetaS6
global fwyDesSpeed  rampDesSpeed strgy
global timeLastDecRamp vehDesiredSpeedRamp vehLocRamp
global vehTypeRamp vehSpeedRamp vehLengthRamp avgAccRamp desiredAccRamp


if im == 1
   %ramp vehicle merged into the fwy; ramp vehilce is assigned to fwy
   %follow headway needs to be adjusted on both ramp and
   %fwy for the ramp vehicle changing lane
   %hdF1 = new cumulative headway of the ramp vehicle after merging
   hdF1 = 0 ;

   hdCumFwy = vertcat(hdCumFwy(1:ifwy), hdF1, hdCumFwy((ifwy+1):end));

   %for other vectors, simply remove from ramp and add to fwy
   timeLastDecFwy = vertcat(timeLastDecFwy(1:ifwy),...
      timeLastDecRamp(ir), timeLastDecFwy(ifwy+1:end));
   vehDesiredSpeedRamp(ir)=vehDesiredSpeedRamp(ir) +(fwyDesSpeed -...
      rampDesSpeed);
   vehDesiredSpeedFwy = vertcat(vehDesiredSpeedFwy(1:ifwy),...
      vehDesiredSpeedRamp(ir), vehDesiredSpeedFwy(ifwy+1:end));
   VehLoc= (vehLocFwy(ifwy)+ vehLocFwy(ifwy+1))/2;
   vehLocFwy = vertcat(vehLocFwy(1:ifwy), VehLoc, vehLocFwy(ifwy+1:end));
   vehTypeFwy = vertcat(vehTypeFwy(1:ifwy), vehTypeRamp(ir),...
```

```
        vehTypeFwy(ifwy+1:end));
    if strgy=="S6"
    gthetaS6 = vertcat(gthetaS6(1:ifwy), (gthetaS6(ifwy)), ...
        gthetaS6(ifwy+1:end));
    end
    vehSpeedFwy = vertcat(vehSpeedFwy(1:ifwy), vehSpeedRamp(ir),...
        vehSpeedFwy(ifwy+1:end));
    vehLengthFwy = vertcat(vehLengthFwy(1:ifwy), vehLengthRamp(ir),...
        vehLengthFwy(ifwy+1:end));
    avgAccFwy = vertcat(avgAccFwy(1:ifwy), avgAccRamp(ir),...
        avgAccFwy(ifwy+1:end));
end

%whether the ramp vehicle merged or reached end of SCL without merging, it
%is removed from the ramp
% hdCumRamp(ir) = [];
timeLastDecRamp(ir) = [];
vehDesiredSpeedRamp(ir) = [];
vehLocRamp(ir) = [];
vehTypeRamp(ir) = [];
vehSpeedRamp(ir) = [];
vehLengthRamp(ir) = [];
avgAccRamp(ir) = [];
desiredAccRamp(ir) = [];

end
```