SAFETY AND OPERATIONAL IMPACT OF TRUCK PLATOONING ON GEOMETRIC DESIGN PARAMETERS

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ABSTRACT

The most well-known benefits of heavy commercial vehicle (HCV) platooning are fuel savings and emission reductions. HCV platooning under SAE automation level 4 or 5 would also address the truck driver shortage by eliminating the driver from one or more HCVs in a platoon. This dissertation investigates the safety and operational implications of SAE level 4 HCV platooning on North American roadways. The research develops modified analytical models and micro-simulation models (PTV VISSIM) for analyzing impacts on two-lane rural highways, urban arterial roadways, and freeways. The study considers different time headways (0.6 sec and 1.2 sec) between the platooning vehicles, and three market penetration rates (0%, 5%, and 10%). The two-lane rural highways chapter investigates the passing sight distance (PSD) required to overtake an HCV platoon. The urban arterial roadways chapter compares existing traffic controls with traffic signal priority (TSP) for HCV platoons. The freeways chapter investigates freeway acceleration lane length on merging segments for HCV platooning operations. The findings suggest that two-HCV platooning with 0.6 sec time headway and a 5% market penetration rate can be allowed on designated North American roadways. With proper passing lanes, two-HCV platoons can be operated on two-lane rural highways that already permit long combination vehicle operations. Even with TSP, HCV platooning on urban arterial roadways at penetration rates higher than 5% at our selected intersection may, however, cause significant delays and overwhelm the traffic system. On freeways, two-HCV platooning at a 5% market penetration rate where the freeway acceleration lane is at least 600m long appear to be feasible. The study will assist transportation professionals and policymakers in

understanding the consequences of HCV platoons and deciding whether to allow HCV platooning on North American roadways.

DECLARATION OF CO-AUTHORSHIP / PREVIOUS PUBLICATIONS

I. Co-Authorship

I hereby declare that this dissertation includes material that was submitted for publication as a result of the collaborative research, as follows:

Chapter 2 of the dissertation co-authored with Peter Y. Park and Kevin Gingerich was submitted to the Journal of Intelligent Transportation Systems: Technology, Planning, and Operations for publication, which is currently in the review stage. Part of Chapter 2 was presented at 100th Annual Transportation Research Board (TRB) Conference and the 29th Canadian Association of Road Safety Professionals (CARSP) Conference. Chapter 3 of the dissertation, co-authored with Peter Y. Park and Kevin Gingerich, was published in Transportation Research Record (TRR) Journal, special issue Freight Transportation Automation, Logistics, and Supply Chains. Chapter 4 was also published in Sustainability Journal, and the co-author of this publication is Peter Y. Park and Kevin Gingerich.

In each of the above-mentioned research, the primary data analysis, result interpretation and writing were performed by the author. The co-authors, namely Dr. Peter Y. Park provided frequent supervisory input on the overall direction of the papers. Both Dr. Peter Y. Park and Dr. Kevin Gingerich provided editing support for the text and revisions before final acceptance for publication. They have also taken part in the conversation about the research questions and how to move forward.

I am aware of the York University Senate Policy on Authorship, and I certify that I have properly acknowledged the contribution of other researchers to my dissertation and have obtained permission from each of the co-author(s) to include the above material(s) in my dissertation.

I certify that, with the above qualification, this dissertation, and the research to which it refers, is the product of my own work.

II. Previous Publication

This dissertation includes three original papers that have been previously submitted / in the process of submission for publication in peer-reviewed journals, as follows:

Dissertation Chapter	Publication title/full citation	Publication status
Chapter 2	Chowdhury, T., Park, P., Gingerich, K. (2022) Estimation of Passing Sight Distance Required for Operation of Truck Platooning on Two-Lane Highways in North America, Journal of Intelligent Transportation System.	Under Review
Chapter 3	Chowdhury, T., Park, P., Gingerich, K. (2022) Operational Impact of Heavy Commercial Vehicle Platooning on Traffic Mobility Along Urban Arterials, Transportation Research Record.	Published
Chapter 4	Chowdhury, T., Park, P., Gingerich, K. (2022) Estimation of Appropriate Acceleration Lane Length for Safe and Efficient Truck Platooning Operation on Freeway Merge Areas, Sustainability.	Published

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LIST OF ACRONYMS AND ABBREVIATIONS

AADT	Average Annual Daily Traffic
AADTT	Average Annual Daily Truck Traffic
HCV	Heavy Commercial Vehicle
LCV	Long Combination Vehicle
GDP	Gross Domestic Product
FHWA	Federal Highway Administration
AASHTO	American Association of State Highway and Transportation Officials
TAC	Transportation Association of Canada
V2V	Vehicle-to-Vehicle
V2I	Vehicle-to-Infrastructure
V2X	Vehicle-to-Everything
AV	Autonomous Vehicle
CAV	Connected Autonomous Vehicle
SAE	Society of Automotive Engineers

ACC	Adaptive Cruise Control
CACC	Cooperative Adaptive Cruise Control
VISSIM	Verkehr In Städten - SIMulationsmodell
NHTSA	National Highway Traffic Safety Administration
MTO	Ministry of Transportation, Ontario

LIST OF APPENDICES

CHAPTER 1: INTRODUCTION

Goods movements serve as a fuel for economic development. Heavy commercial vehicles (HCVs) have long played an important role in the development of a modern economy, and continue to play a vital role in meeting the daily necessities of supply and demand.

Recent advancements in intelligent transport systems (ITS), especially Vehicle-to-Vehicle (V2V) technology associated with HCVs travelling in intelligently connected convoys, are expected to provide substantial economic benefits. This study explores the safety and operational impact of heavy commercial vehicle (HCV) platooning (also known as truck platooning) on rural highways, urban arterials, and freeways in North America.

1.1 Importance of Goods Movement

Goods movement is often used as an indicator of the productivity and annual growth of a country. In 2018, the goods movement sector contributed 3.5% and 4.5% of the Gross Domestic Products (GDP) of the United States and Canada respectively (Bureau of Economic Analysis, 2019; Statistics Canada, 2020a). There are currently 149,236 and 122,048 trucking companies in the United States and Canada respectively (Statistics Canada, 2020b; USDOT, 2020). From 1999 to 2018, there was very substantial growth in HCV traffic in the United States (69.9%) and in Canada (65.4%) (Statistics Canada, 2020c; USDOT, 2020).

On-demand deliveries are increasingly becoming industry standard, partly due to the rapid growth in e-commerce. From 2018 to 2019, e-commerce sales increased by 15.9% in the United States and 8.1% in Canada (Clement, 2020). One of the most popular e-commerce platforms, Amazon, had 6.33 billion U.S. dollars in revenue in the third quarter of 2020 compared to 2.13 billion U.S. dollars during same period of 2019 (Davis, 2020). This rising trend in e-commerce is an important factor in the increase in HCV traffic.

According to the United States Federal Motor Carrier Safety Administration, 68.1% of all goods movement in 2017 was by road and 8.8% by rail in the United States. The remaining 23.1% of goods used other modes of transportation such as air, sea and pipelines (FMCSA, 2020). Commercial vehicles in Canada comprised 25.2% of total registered motor vehicles in 2018 (Statistics Canada, 2020c). It is clear that ground transportation, which relies on HCVs, is the most dominant mode for goods movement across North America.

HCVs are involved in transporting essential products such as groceries, medicine, gas etc. During the COVID-19 pandemic, non-essential cross-border movements between the United States and Canada were restricted. Although the restrictions caused a 90% drop in passenger movement (Canadian Trucking Alliance, 2020), logistic facilities remained operational and continued to meet daily necessities. HCV movement was reduced by 33% only during the travel restrictions (Canadian Trucking Alliance, 2020).

1.2 Goods Movement Impact on the Roadway Infrastructure

In 2018, approximately 490,630 million kilometers of HCV travel were completed in the United States, and about 37,991 million HCV kilometers were observed in Canada. HCV travel statistics for the United States show that, in 2018, 46.1 % of HCV travel occurred along rural highways and 53.9 % on urban roadways (USDOT, 2020).

In Canada, HCVs travelled 37,990 million kilometers: 37,864 million kilometers were for trips 25km or longer, and only 126 million kilometers were for trips of less than 25km (Statistics Canada, 2020d).

It is clear from these statistics that HCVs travel not only along freeways, but also along two-lane highways and urban arterial roadways.

Two-lane highways are the most extensive type of road infrastructure in North America. According to the Federal Highway Administration (FHWA), two-lane rural roads comprise 9.7 million kilometers (about 68.3%) of the 14.2 million kilometers of total road network in the United States (FHWA, 2019). Canada has more than one million kilometers of two-lane highway network, with 75.8% of these roadways located in Ontario, Quebec, Saskatchewan and Alberta (Transport Canada, 2020).

Traffic congestion is a major concern on urban roadways (Schrank et al., 2012). Traffic congestion deters economic development, and reduces competitiveness, livability, safety, and long-term environmental sustainability. In 2018, due to traffic congestion, people of the United States lost an average of 97 hours per year, costing about $87 billion USD in lost productivity (INRIX, 2020a). McCarthy (2020) reported that HCVs annually bear $66.1 billion USD of losses due to traffic congestion on urban roadways in the United States. Similar problems have been observed in different cities of Canada. In Canada, people lost an average of 27 hours in 2017 to traffic congestion (Dally Hive Staff, 2018). In Canada, traffic congestion is most severe in Montreal, Toronto, and Vancouver. In Toronto, for example, people lost an average of 135 hours to traffic congestion in 2018 (INRIX, 2020b). HCVs contribute to traffic congestion on arterial roadways because of their slow acceleration and deceleration (ITE, 2000). This causes queues and subsequently increases delays for all following vehicles at intersections. The literature shows that HCVs idling in congested traffic also have adverse effects on greenhouse gas emissions (Steenhof et al., 2006).

1.3 Goods Movement and V2V Technology

HCV manufacturers and stakeholders have been focused on finding effective and sustainable benefits for the road freight transport industry. A promising approach in the goods movement industry appears to be semi or fully automated HCV platooning, also known as truck platooning (hereafter HCV platooning), connected based on V2V technology and electronic data communication. HCV platooning refers to connecting two or more HCVs wirelessly to allow them to travel as a convoy.

The Society of Automotive Engineers (SAE) has proposed six different levels of driving automation ranging from level 0 (no automation) to level 5 (full automation) (SAE International Standard, 2016). The level of HCV platooning depends on the level of human-control required. For instance, level 1 HCV platooning requires human drivers on every HCV in a platooned convoy to control all HCVs. At this level, HCV platooning technology is nothing more than a driver assistance tool, similar to a forward braking system that may help to reduce drivers' workload and increase traffic safety. In SAE level 4 or 5 automation, HCV platooning would involve possibly removing the human driver from one to all of the HCVs in the platoon by maintaining a partially- or fully-connected V2V environment (USDOT, 2018a).

HCV platooning leads to reduced air resistance and energy consumption (Ellwanger and Wohlfarth, 2017). It is also expected to decrease fuel consumption. When HCVs are platooned, the vehicles maintain short longitudinal distances between platooning vehicles. Earlier researchers have anticipated approximately 6-10% fuel consumption reduction benefits from headways of 0.6 sec ~ 1.2 sec (10 ~15m) between two subsequent HCVs (Alam et al., 2015; Browand et al., 2004; Janssen et al., 2015). Different countries allow different time headway gaps. The time headway gap is a crucial parameter, as air drag and fuel consumption reduction can be higher for HCV platoons with low time headway gaps (Alam et al., 2015; Browand et al., 2004; Janssen et al., 2015; Kuhn et al., 2017).

The time headway gaps have safety implications. When vehicles are travelling with a 0.3 sec time headway gap, the following distance becomes 6m ~ 7m (Janssen et al., 2015). Although autonomous vehicles (AVs) can travel with a 0.3 sec time headway gap, safety standards require HCV platoons to travel with a headway of at least 0.6 seconds on North American roadways (Alkim et al., 2016; Kuhn et al., 2017). To maintain tight time headways, platooned HCVs are required to communicate wirelessly under longitudinal controlled conditions. These conditions can be established through cooperative adaptive cruise control (CACC) communication. This communication strategy allows following vehicles not only to know about the acceleration and speed of preceding HCVs, but also to share information regarding the roadway infrastructure and traffic conditions ahead via V2V communication (Kuijpers, 2017; Ploeg, 2014).

The HCV driver shortage is another major concern in the logistics industry. HCV platooning could reduce the number of human drivers required, an important potential benefit for the logistics industry, particularly in North America. Costello (2019) estimated that by 2028, the United States might face an additional shortage of 160,000 HCV drivers. Similarly, Butler (2019) reported that the HCV driver shortage may be around 34,000 in Canada by 2024.

The anticipated financial benefits of HCV platooning require at least SAE level 4 automation, i.e., the elimination of human drivers in the second or third HCV in a platoon (i.e., following HCVs). Eventually, the potential includes the elimination of human drivers in all the HCVs in a platoon including the leading HCV.

Peloton Technology in the United States has recently investigated fuel efficiency and productivity by conducting a trial of two-HCV platoons. The results demonstrate that HCV platooning could double driver productivity (Fisher, 2020). Similarly, in La Tuque, Quebec, Canada, FPInnovations has been testing HCV platooning operations to transport timber from forests to ports since 2018 (Proust et al., 2019). In Quebec, the emphasis was reducing reliance on human drivers due to the shortage of human drivers willing to work in distant forests or areas away from major urban centres (Proust et al., 2019).

Forestry is eager eagerness to adopt the HCV platooning technique to counter driver shortage, it is important to evaluate the performance of the road infrastructure for HCV platooning. Two-vehicle HCV platooning and long combination vehicles (LCVs) are fairly similar, HCV platooning can be tested on North American highways where LCVs are permitted.

Figure 1-1 shows the three different configurations of LCV presented in the North American Geometric design guidelines: 1) B-Train Double LCV (25m), 2) Rocky Mountain (29.67m) and 3) Turnpike Double (34.75m). The length of LCVs differs according to the size of different trailers. LCVs are known to require special treatment for safe operation due to their longer length and heavier weight compared to traditional HCVs, which can make them more difficult to control and maneuver and increase the risk of collisions (Barton and Morrall, 1998; Harkey et al., 1996; Kenny et al., 2000; McCutchon et al., 2006; Montufar et al., 2007; Robertson et al., 1987).

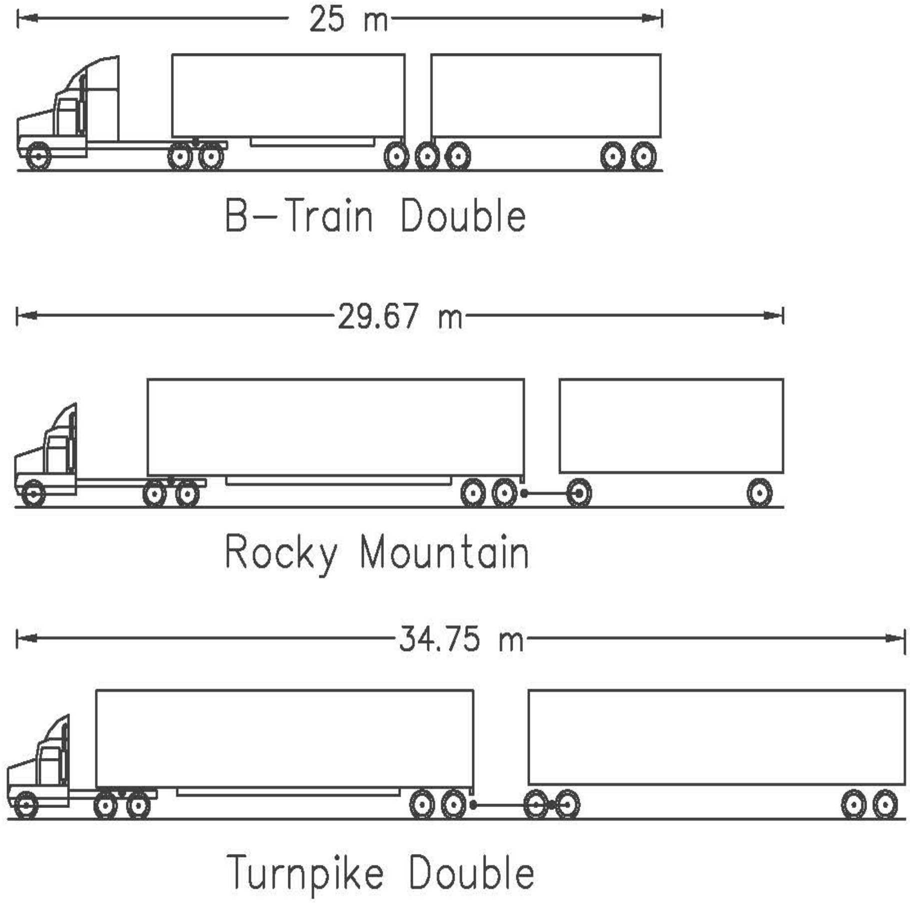


Figure 1-1: Different Configurations of LCVs (AASHTO, 2018; TAC, 2017)

Regulations for LCVs vary by province and state in Canada and the United States. Each jurisdiction has its own set of rules and regulations for the operation of LCVs on their highways, and permits are generally required for their use. Permits are typically issued for specific types of LCVs (Regehr et al., 2009). In Canada, provinces such as Ontario, allow LCVs to use the right-most (shoulder-side) lane of multi-lane freeways (400 series) and prohibit them from using rural two-lane roads due to concerns about maneuverability and increased collision risks. Similarly, in British Columbia, New Brunswick, and Nova Scotia, LCVs are limited to the right-most lane of multi-lane highways and restricted on rural two-lane roads. In contrast, provinces like Alberta, Saskatchewan, Quebec, and the Northwest Territories have no lane restrictions for LCV operations on multi-lane highways. Alberta, Saskatchewan and Manitoba allow LCVs on two-lane rural highways with certain restrictions, such as during weekend peak recreation hours or on holidays. The LCV restrictions are intended to ensure safe operation and to minimize collision risks (Wood and Regehr, 2017). It is important to note that Rocky Mountain LCVs are only permitted in western Canadian provinces such as British Columbia, Alberta, Saskatchewan, Manitoba, while Turnpike Double LCVs can travel throughout Canada with the exception of the Northwest Territories.

In the United States, states such as Wyoming, Utah, and New Mexico allow LCVs on two-lane rural highways but with certain restrictions such as selected roads and only at certain times of day (FHWA, 2018). On the other hand, states such as Texas, Arkansas and Oklahoma do not allow LCVs on two-lane rural highways due to safety concerns and the increased risk of accidents on these types of roadways (FHWA, 2018).

In western Canada, the LCVs of up to a maximum of length of 41m are allowed to travel, whereas in Ontario, New Brunswick, Nova Scotia, and Northwest Territories the maximum length allowed is 40m (Wood and Regehr, 2017). According to TAC, the maximum LCV length permitted is 25m (B-Train Double). AASHTO suggests a maximum length of 34.75m for LCVs (Turnpike -Double Combination) (AASHTO, 2018; TAC, 2017). B-Train LCVs do not need a special permit to run in most provinces, and were previously restricted to 25m in length but are now permitted to be as long as 28m in Manitoba and Saskatchewan (Manitoba Transportation and Infrastructure Department, 2022; Ministry of Highways -

Government of Saskatchewan, 2022). This study, focuses on the B-Train double, i.e., LCVs with a length of 25m.

Several North American jurisdictions (e.g., California, Texas, Florida, Alberta, and Ontario) have started allowing the operation and testing of HCV platooning techniques on freeways to minimize potential negative impacts of HCV platooning and maximize anticipated benefits (CCMTA, 2016; Kuhn et al., 2017). Figure 1-2 shows the seven highway sections that have been authorized for a pilot study of HCV platooning in Ontario. All the sections are multi-lane divided and limited access highways (i.e., freeways).

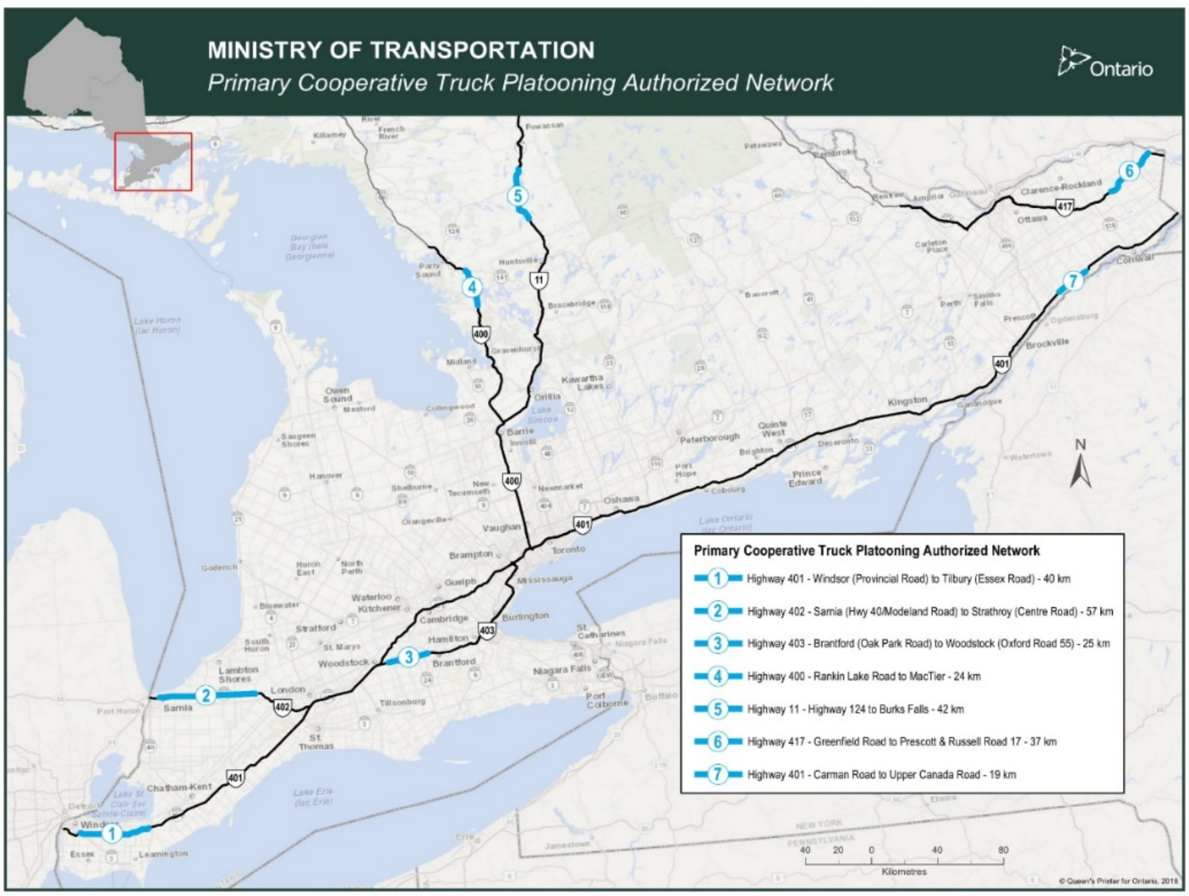


Figure 1-2: Ontario HCV Platooning Sites (MTO, 2018)

The National Highway Traffic Safety Administration (NHTSA) suggests that, under V2V technology, vehicles can communicate with each other over a range of approximately 300m (NHTSA, 2020). An HCV platoon may also communicate with the infrastructure and with other AV vehicles. Such communication may help to improve operations and safety on the roadway network. For example, communication with infrastructure, may reduce the number of stops and help to reduce CO_2 emissions and vehicle delays.

1.4 Existing HCV Platooning Pilot Projects

The application of V2V and vehicle-to-infrastructure (V2I) allow AVs and connected autonomous vehicles (CAVs) to make significant safety and operational improvements to the transportation system. About 3,700 road accident-related deaths per day around the world were reported for 2018 (WHO, 2018). Several studies have reported that by introducing AVs, the number of accidents could be reduced by 90% (Arbib and Seba, 2017; Fagnant and Kockelman, 2015; Gao et al., 2016). AVs could increase highway capacity from 2,100 vehicles per hour per lane to 3,970 vehicles per hour per lane when all vehicles are in CACC (Kockelman et al., 2017). Pilot projects have been conducted to improve autonomous and cooperative driving technology for HCV platooning, and to investigate the effects of cooperative and autonomous driving. The outcomes have indicated significant benefits in terms of fuel consumption reduction and an increase in road capacity, but a number of challenges have been reported due to the complexity of interactions between vehicles and infrastructure (Deng, 2016a, 2016b; Deng and Boughout, 2016; Mcauliffe et al., 2017; Transport Canada, 2019a).

1.4.1 European Truck Platoon Challenge

In the European Truck Platoon Challenge (2016), HCVs from six different manufacturers (Scania, Volvo, Man, Daimler etc.), travelled from several European City centres to the Port of Rotterdam highways in the Netherlands (Alkim et al., 2016). Throughout the testing, the HCVs journeyed on conventional public roadways and communicated with each other via V2V technology. The study found that HCVs travelling as an HCV platoon, i.e., like a single vehicle, might interrupt existing traffic flow conditions, and that might be problems when an HCV platoon had to negotiate complex traffic environments such as ramps, tunnels, and curvatures (Alkim et al., 2016).

1.4.2 PATH Research Project

The University of California-Berkeley's PATH research project started testing CACC control systems for HCV platooning in 2015 with support from the FHWA (Ramezani et al., 2018a). Transport Canada has also participated in an SAE level 2 HCV platooning energy evaluation study with PATH and other stakeholders. PATH measured the impact of three HCV platoons travelling along a multilane freeway corridor under mixed traffic conditions to assess the impact on traffic flow and fuel consumption. Transport Canada conducted several tests on a 25 km test track in Blainville, Quebec. An HCV platoon travelled on the test track at 89 km/hr and at 105 km/hr speeds while maintaining a tight time headway gap. The field test results showed that aerodynamic drag was significantly reduced (14.2%) for HCVs following each other with a time headway gap of 0.6 sec (Mcauliffe et al., 2017; Transport Canada, 2019a). The PATH research team used microsimulation to assess the impact of HCV platooning on aerodynamic drag. The results showed a 15.72% aerodynamic drag reduction for the following HCVs, and an improvement in the average travel speed of HCVs travelling in CACC (Ramezani et al., 2018a).

The above discussion suggests that the logistics industry is moving towards using fully automated HCVs. The industry is anticipating that SAE level 3 or level 4 HCVs will travel as convoys on our roadway system and will provide safety and operational benefits, i.e., fewer collisions and reduced fuel consumption.

1.5 HCV Platooning Impact on Roadway Infrastructure

According to the American Association of State Highway and Transportation Officials (AASHTO) and Transportation Association of Canada (TAC) geometric design guidelines, roadway infrastructure is classified into multilane freeways, two-lane highways, arterial roadways, local roadways (AASHTO, 2018; TAC, 2017). Factors such as human behaviour, perception reaction time, vehicle length and deceleration rate affect parameters such as passing sight distance and acceleration lane length both of which are used to design two-lane roadways and freeways. In addition, parameters such as time headway dictate signal timing design and govern the operational performance (i.e., average travel time) on urban arterial roadways. This section examines these factors and how they affect the design of two-lane highways, freeways and signal timings of arterial roads.

The AASHTO and TAC guidelines provide geometric design guidelines for North American roads. The guidelines provide direction for planners and designers developing sustainable design solutions for a very wide range of situations and local environmental conditions. As the guidelines were developed for the operation of human-driven vehicles and do not consider next generation transportation including HCV platooning, it is important to investigate the impact of HCV platooning on geometric design parameters.

All HCVs are currently operated by human drivers and roadway infrastructure has been designed and built with consideration of possible human drivers' errors. Initially, HCV platooning will be operated in partially automated conditions, but HCV platooning is expected to become fully automated. In Section 1.3, we noted that HCVs will have communication capabilities and behave cooperatively via CACC and V2V technology which will help HCVs to travel in convoys. The involvement of CACC and V2V requires changes in primary roadway geometric design parameters such as driver perception-reaction time and deceleration rate (Kuhn et al., 2017; Ramezani et al., 2018a; Shladover et al., 2018). While HCV platooning will be operated on any category of roadway, the platoons will look and behave like a single vehicle, i.e., like a road freight train (Zhang et al., 2020). The overall length of the HCV platooning will be longer than the human driven single unit HCV. Vehicle length is also an important factor in roadway design (AASHTO, 2018; TAC, 2017).

The AASHTO and TAC design standards use 2.5 sec for driver perception-reaction time (AASHTO, 2018; TAC, 2017). This reaction time defines the time required for an incident to be avoided by 85th percentile drivers. Vehicles equipped with CACC can react quickly (Khoury and Amine, 2019). CACC will allow the time headway gap to be reduced by 0.6 sec to 1.2 sec, which will impact roadway capacity (Kuhn et al., 2017; Ramezani et al., 2018a; Shladover et al., 2018).

According to AASHTO and TAC, the deceleration rate is 3.4 m/s^2 for all categories of vehicle (AASHTO, 2018; TAC, 2017). Ramezani et al. (2018a) reported a comfortable deceleration rate of 1.62 m/s^2 for a platoon of HCVs connected via CACC and V2V, but the study reported a maximum deceleration rate of 3 m/s^2. In HCV platoons, multiple HCVs will maintain tight time headway gaps and will be able to decelerate faster than an individual HCV under current conditions. A reduced perception-reaction time and deceleration rate will impact the stopping distance calculation (AASHTO, 2018; TAC, 2017).

The literature does not report on how HCV platooning affects the safety and operations of other vehicles sharing the same roadways (AASHTO, 2018; TAC, 2017). This omission indicates a need to explore the safety and operational impacts of platooned HCV's and to consider the safety and operational issues on different classifications of roadway. This research focuses on two-lane rural highways, urban arterial roadways and freeways only.

1.5.1 Two-lane rural highways

On two-lane highways, overtaking maneuvers are permitted to pass slow-moving vehicles, or else faster vehicles get stuck behind slow-moving vehicles and tend to perform risky overtaking (Hostetter and Seguin, 1969; Koorey, 2007). A conservative approach is preferred when developing design guidelines. Passing sight distance (PSD) is used to define the space required for safe passing maneuvers, and a longer vehicle requires a greater PSD.

In the AASHTO guidelines (2018) HCV length can range from 9.14 m to 22.4 m. In the TAC guidelines (2017), HCV length can range from 6.4 m to 22.7 m. LCVs are much longer than HCVs, and HCV platoons are even longer.

The most recent AASHTO guidelines (2018) acknowledge the importance of the length of an impeding vehicle, but the recommended PSD is based on the estimated overtaking distance required to pass a slow-moving passenger vehicles rather than a slow-moving LCV or

HCV (AASHTO, 2018, 2011; Harwood et al., 2008) and there is very little research into this issue. Since HCV platoons may travel on two-lane highways, existing PSD requirements may be inadequate for fast-moving passenger cars wanting to overtake a platoon.

When estimating the minimum PSD required for HCV platooning, two additional factors must be considered: the number of HCVs in a platoon, and the physical gap between the platooned HCVs. In this study, we considered two and three HCVs in a platoon, and we considered 0.6 sec and 1.2 sec time headways between the platooned HCVs.

By considering the length of an HCV, the number of HCVs in a platoon, and the time headways between the platooned HCVs, this study develops a modified 2018 AASHTO analytical PSD model and estimates PSDs required by a passenger car for overtaking HCV platooning and LCVs for design speeds of 50-130 km/h roads.

HCV platooning may also have a negative impact on the operational performance of two-lane rural highways. For example, the level of service (LOS) of two-lane highways may be degraded due to a reduction in passing opportunities due to the lack of adequate PSD. Highway designers (based on existing standards) cannot provide a sufficient number of passing lanes/climbing lanes even if they have considered the above-omitted factors. This shortage of passing lanes/climbing lanes along two-lane highways can lead to head-on collisions. If the number of passing opportunities reduces, fast-moving vehicles have to stay behind the slow-moving HCV for long periods. This staying behind the slow-moving HCV can make the fast-moving passenger vehicle impatient and force them to violate the law (Hostetter and Seguin, 1969; Koorey, 2007). The reduction in the number of passing opportunities may also lead to an increased number of conflicts (Kaub and Berg, 1988).

Although an evaluation conducted by Paulsen (2018) in Norway suggested that an additional 300% PSD is desired compared to the current Norwegian geometric design standard for three-HCV platoon operations, North America may acquire significant benefits by operating HCV platoons along two-lane highways due to geographic conditions, infrastructure, and current roadway developments.

Chapter 2 investigates the effect of HCV platooning on two-lane highway operations. The research recognizes that PSD is affected by vehicle length, and explores the effects of HCV platooning on two-lane freeways in order to make overtaking maneuvers as safe as possible and to increase the potential benefits HCV platooning (AASHTO, 2018; Forbes, 1990; Hanley and Forkenbrock, 2005; Harwood et al., 2008; Harwood and Glennon, 1989, 1976; Hassan et al., 1996; Jenkins, 2004; Lieberman, 1982; Ohene and Ardekani, 1988; Rilett et al., 1990; Saito, 1984; TAC, 2017; Van Valkenburg and Michael, 1971; Wang and Cartmell, 1998; Weaver and Glennon, 1972).

1.5.2 Arterial Roadways

The arterial roadway infrastructure in urban settings is another essential component for delivering goods to warehouses, businesses and households. As LCVs face difficulties travelling along arterial roads due to their increased horizontal clearance and turning radius requirements, LCVs are restricted from travelling on several arterial roadways. Where turning radius is limited, HCV platooning can be used to perform delivery services along arterial roadways where LCV operations are prohibited. Research conducted by Lioris et al., (2017) observed that platooning technology for passenger cars can increase roadway capacity by doubling the throughput. No research has examined the effects of HCV platooning on urban arterial roadways, but some studies have stated that platooning technology can improve the operational performance of the urban arterial road network in terms of reducing travel time delays (Lazar et al., 2018; Tiaprasert et al., 2019; Wang et al., 2020). Research has also shown significant operational improvements (reduced travel times) by introducing truck signal priority (TSP) (Kaisar et al., 2020; Rampure et al., 2019). Providing signal priority for HCV platooning may enhance the operational benefits (i.e., reduce travel time and reduce the number of stops) on urban arterial roadways. A study designed to evaluate urban arterial roadway performance under HCV platoon operation with conventional signal control conditions and with TSP would be useful.

1.5.3 Freeways

To analyze the impact of HCV platooning on freeway traffic flow, Deng et al. conducted a simulation-based study on 3.5 km (2.2 miles) segment under mixed traffic conditions. The research showed an increase in hourly traffic flow rate for the operation of two-HCV platoons (Deng, 2016a, 2016b; Deng and Boughout, 2016). Ramezani et al. (2018a) also analyzed HCV platooning under mixed traffic conditions. Their study area was a 24.1 km (15 miles) segment of the I-710 NB freeway corridor in Southern California. The study showed an increase in roadway capacity under HCV platooning operations, but the analysis did not evaluate the impact of HCV platooning on exit and entrance ramps at interchanges.

Wang et al., (2019) found that HCV platooning might have a negative influence on the merging segment of a freeway due to the number of vehicles in the platoon. The majority of the HCV platoon merged onto the freeway in the last 50 m of the acceleration lane and faced difficulty in merging immediately onto the freeway. Merging was easier for single-unit HCVs.

Arnold and Roorda (2020) conducted a simulation-based analysis of HCV platooning operations on a merging ramp of Dixon Road along Highway 401 in the Greater Toronto and Hamilton Area (GTHA). The evaluation was conducted on an extended merging ramp and ramp metering segment. The study reported an insignificant operational impact in terms of average travel time delays and highway speeds along the road network.

Some studies have shown an improvement in freeway traffic operations without investigating the impact on on/off ramp geometric design parameters such as acceleration/deceleration lane length. The length of acceleration/deceleration lane is limited by topography and ramp configurations. In some cases, HCV platoons may occupy a significant length of acceleration lane on a merging segment and experience challenges in finding an adequate gap for merging safely. These circumstances may create delays and conflicting situations on ramps. As existing research provides no direction regarding minimum acceleration lane length requirements for HCV platooning merging maneuvers, our this study investigates the impact of HCV platooning on the acceleration lane length required for a merge section of a ramp from a safety and operational perspective.

HCV platooning has numerous prospects for traffic operations and road safety. However, limited research has explained the consequences of HCV platooning on road infrastructure. Moreover, we also need to examine if the deployment of HCV platooning would require any changes in North American highway geometric design guidelines. Through this research, we have performed an extensive investigation on the safety and operational impacts of all categories of road facilities for the deployment of HCV platooning, which may help policymakers to decide how HCV platooning can be allowed along North American roadways.

1.6 Market Penetration Rate

The operational performance of a roadway under HCV platooning is also affected by the market penetration rate of HCV platooning. For example, a study on an 8.5km (5.3 miles) segment of Alabama's I-85 interstate freeway showed that a 0% to 20% increase in the market penetration rate of HCV platooning decreased travel time delay for passenger vehicles and HCVs by 7.7 sec (40%) from 19.1 seconds per vehicle, and that a 100% HCV platooning market penetration rate reduced travel time delay by 13.3 sec (69%) (Gordon and Turochy, 2016).

The impact of passenger vehicle platooning on arterial roadways was studied by Lioris et al. (2017) and Smith et al. (2020). Both studies observed that a 100% market penetration rate for passenger vehicles could double the number of passenger vehicles.

It is not clear when or whether platooned HCVs could reach a 100% market penetration rate on a roadway especially as SAE level 4 HCV platooning requires V2I communications. Although numerous studies have discussed relatively high levels of market penetration for HCV platooning, SAE level 4 HCV platooning is unlikely to be widely used in the near future as it requires significant capital investment in wireless communication technologies such as 5G (or even 6G) to enable seamless communication between HCVs in V2V setting (Chowdhury et al., 2022; Chowdhury et al., 2022). Some level of platooning can be reasonably expected as autonomous vehicle technology continues to develop. If SAE level 4 HCV platooning is achieved, we may find that the logistics industry will begin using HCV platooning technology at a low market penetration rate and increase HCV platooning until the desired benefits of reduced labour and fuel costs are realized. Previous research has not provided guidance regarding low penetration rates, i.e., 5% and 10% of HCV platooning operations. The market penetration rate of 5% refers to the percentage of HCVs that are operated as platoons during the specific study period. However, in reality, the number of platooned HCVs can vary depending on various factors such as hourly traffic flow and the availability of HCV platooning. This gap in our knowledge suggests a need for analyzing how relatively low percentages of HCV platooning operations affect the safety and mobility on the different types of roadway in the near future.

1.7 Research Methodology

1.7.1 Analytical Method

The analytical method refers to a set of deterministic techniques used to estimate and analyze a particular given situation. The methodology serves as a tool for the design and analysis of transportation systems, and is used to provide a theoretical understanding of transportation conditions, to predict their performance, and to solve deterministic problems. The results are based on assumptions and simplifications of real-world conditions and involve the use of mathematical equations to model transportation conditions. The analytical method can be used to predict the behaviour of vehicles under different traffic conditions and to analyze the safety and performance of vehicles, e.g., how a vehicle will respond during turning or braking. The method allows us to analyze the capacity and performance of transportation infrastructure (e.g., roads and public transportation systems), and to estimate traffic congestion and delays on the network (Chislov et al., 2021; Möller, 2014).

For the analytical method to be applied, the problem must be well-defined, and the underlying model must be linear. Parameters for the analytical method can be defined by mathematical equations and assumptions, and the results can be used to make informed decisions about the design and operation of transportation systems. Overall, the analytical methods play a crucial role in transportation engineering. It provides a deeper understanding of transportation systems and their performance, and can be used to make important decisions regarding the design, operation, and maintenance of transportation infrastructure and vehicles (Chislov et al., 2021; Möller, 2014).

1.7.2 Simulation Method

Simulation methods, on the other hand, use computer programs to model the behaviour of a system or network and make predictions regarding the system or network's performance. This method is often used to model complex, non-linear situation. Simulation methods can be used to analyze the behavior of a system under various conditions and can generate a set of possible outcomes rather than a single, exact solution. One of the key advantages of simulation methods is that they can be used to model real-world systems that are too complex or difficult to analyze using analytical methods. For example, in traffic engineering, simulation is widely used for analyzing the impact of HCVs, HCV platooning and passenger vehicles on infrastructure.

Simulation can be macro-simulation, mesoscopic simulation and micro-simulation. Micro-simulation modelling allows transportation professionals to evaluate theoretical and hypothetical traffic networks instead of implementing experiments in real-world traffic conditions. Models use car-following and lane-changing algorithms to simulate the movement of individual vehicles. The models are effective tools for evaluating light to heavy congested traffic conditions, complex geometric configurations, and the network-wide impacts of a proposed transportation plan, but developing and analyzing a micro-simulation model is time-consuming and costly, and calibration is difficult (Kaufmann et al., 2017). The results of such models help to evaluate roadway performance in terms of vehicle speed, travel time, emissions, queue length, delay, level of service of intersections, stop events, vehicle crossings, overtaking, throughput, lane changes, conflicts, conflict angle, and other parameters. Popular micro-simulation tools include Paramics, VISSIM, CORSIM, AIMSUN, etc.

As micro-simulation modelling enables the user to replicate roadway networks and the traffic characteristics, driving behaviour, and transit operations of roadway networks, we used a micro-simulation tool, PTV VISSIM, in this study (PTV, 2021). VISSIM can analyze the performance of individual vehicles in terms of speed, travel time and delay on a study network second-by-second which allows precise evaluation. As HCV platooning is a future concept that must operate on existing infrastructure, it is necessary to investigate the interaction and impact of HCV platooning in the context of all modes of transportation. Micro-simulation analysis can clearly provide useful insights through detailed investigations. This study uses overtaking distance, throughput, vehicle speed, travel time, stop events, number of conflicts as decision matrix to evaluate the impact for HCV platooning opertains.

The simulation methods can also be used in conjunction with analytical methods. In this case, the analytical method is used to provide a theoretical understanding of the situation, and the simulation method is used to generate a set of possible outcomes. Also, the parameters simulation methods can be defined by mathematical equations, assumptions, historical data, or observational data.

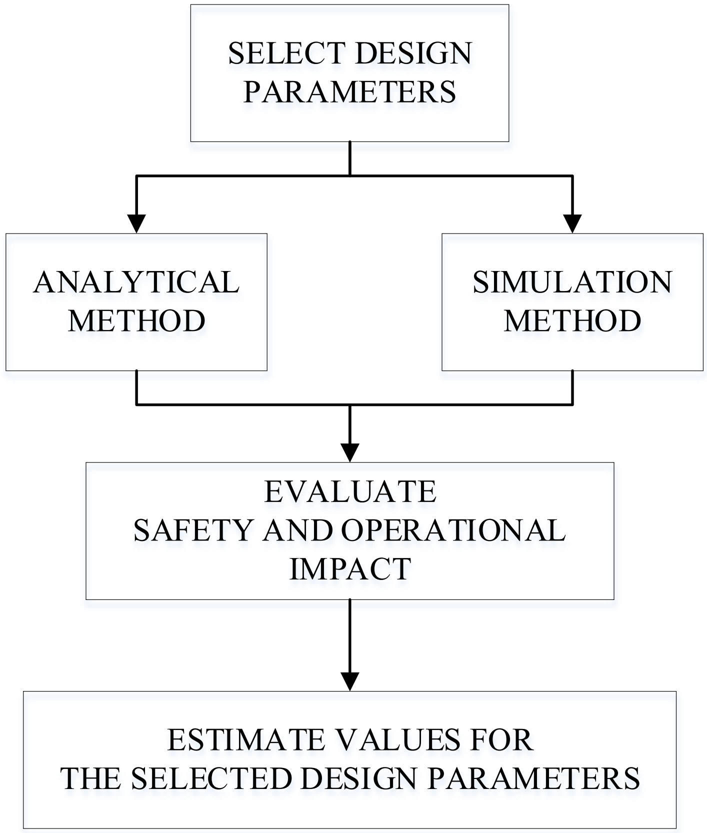


Figure 1-3: Proposed Methodology

The methodology of this research is illustrated in Figure 1-3. The TAC and AASHTO design guidelines suggest recommended values for different design parameters. The recommended values are based on analytical models (AASHTO, 2018; TAC, 2017). However, these analytical models do not factor in uncertainties. To rectify this drawback, this research employs a synergistic combination of analytical and simulation methods. The values for the selected design parameters were initially calculated using analytical methods, and the results were then validated through simulation methods to account for uncertainties and to gauge the impact of different design parameters on safety and operations. This methodology facilitated the ascertainment of recommended values for the selected design parameters.

1.8 Research Goal and Objectives

The goal of this study is to evaluate the safety and operational impact of HCV platooning on the North American roadway network. The study has three main objectives each of which has associated sub-objectives.

Objective 1: Assess the impact of HCV platooning on the North American geometric design guidelines for PSD on two-lane rural highways

- Formulate an analytical method for calculating PSDs for HCV platooning and LCVs on North American two-lane rural highways;
- Determine the appropriate PSDs for HCV platooning and LCVs using an analytical method and then validate with a simulation method; and
- Compare the PSDs estimated in the North American highway geometric standards.

Objective 2: Estimate the operational impact of HCV platooning on urban arterial roadways

- Analyze the impact of SAE level 4 HCV platooning using existing traffic controls (do-nothing scenario) and with traffic signal priority for HCV platoons;
- Evaluate the impact of SAE level 4 HCV platooning with the implementation of traffic signal priority for HCV platoons; and
- Distinguish the effect of three low market penetration rates (0%, 5% and 10%) for SAE level 4 HCV platooning.

Objective 3: Investigate the safety and operational impact of HCV platooning on freeways

- Develop an analytical method to determine the appropriate acceleration lane length for 0.6 sec and 1.2 sec headway HCV platooning operations on the merging section of freeway ramps;
- Determine an appropriate acceleration lane length for 0.6 sec and 1.2 sec time headway HCV platooning operation using an analytical method and then validate with a simulation method; and
- Evaluate the impact of the three low market penetration rates (0%, 5% and 10%) for 0.6 sec and 1.2 sec time headway HCV platooning operation on the merging section of freeway ramp based on the existing and the estimated acceleration lane lengths.

1.9 Research Scope

According to the 2018 AASTHO and the 2017 TAC geometric design guideline, the longest single unit HCV is the WB-20 HCV. This study investigates an HCV platoon consisting of multiple WB-20 HCVs connected via V2V communication (AASHTO, 2018; TAC, 2017). As the CACC system enables HCVs to maintain tight time headway gaps, the study considered 0.6 sec and 1.2 sec constant time headway gap for the platooned HCVs (Nowakowski et al., 2011, 2010; Ramezani et al., 2018a; Shladover et al., 2015). As vehicles cutting in to a platoon of HCVs may reduce fuel consumption benefits and the platoon's vehicle to everything (V2X) communication range leading to a loss of connectivity among platooned vehicles, this study did not allow cut-ins, i.e., we assumed that platooned HCVs maintained convoy formation throughout their journey.

We assumed SAE level 4 HCV platooning, i.e., we assumed that only HCV platooning vehicles could communicate with each other. All the other vehicles were assumed to be driven by humans and to have no V2V communication capabilities. Different circumstances could be considered in future research.

1.10 Dissertation Structure

This dissertation consists of the Introduction and four additional chapters.

Chapter 2 discusses the impact of HCV platooning operations on two-lane rural highways. The chapter focuses on passing sight distance, a major geometric design parameter for two-lane rural highway design. The chapter provides an overview of traffic flow conditions on two-lane rural highways that allow long combination vehicles (LCVs) in Alberta. Chapter 2 uses both analytical and simulation methods for estimating the passing sight distance required for HCV platooning.

Chapter 3 describes the impact of HCV platooning operations on urban arterial roadways. We discuss the sources of data available for assessing the impact of HCV platooning and the methodology for developing a traffic signal priority technique for HCV platoons. We estimate the impact of HCV platooning operations using two measures of effectiveness: travel time and the number of stops.

Chapter 4 discusses the impact of HCV platooning operations on the merging section of freeway ramps. Acceleration lane length is a key parameter for freeway merging segment design. The chapter describes the factors involved in freeway merging segment design. We used the Ontario Ministry of Transportation (MTO) database and a MTO operated acceleration lane to observe conditions on freeway merging lanes. Chapter 4 describes and applies a modified analytical method to estimate the required acceleration lane length for HCV platooning operations. The chapter also develops a simulation method for evaluating the safety (i.e., number of conflicts) and operational consequences (i.e., travel time to merge) of HCV platooning on the merging section of freeway ramps.

Chapter 5 presents the summary of the research into HCV platooning operations and the conclusions for the different roadway types. The chapter also discusses recommendations for how HCV platooning operations can be regulated, and some directions for future research into HCV platooning operations.

Figure 1-4 presents a graphic showing the structure of this dissertation.

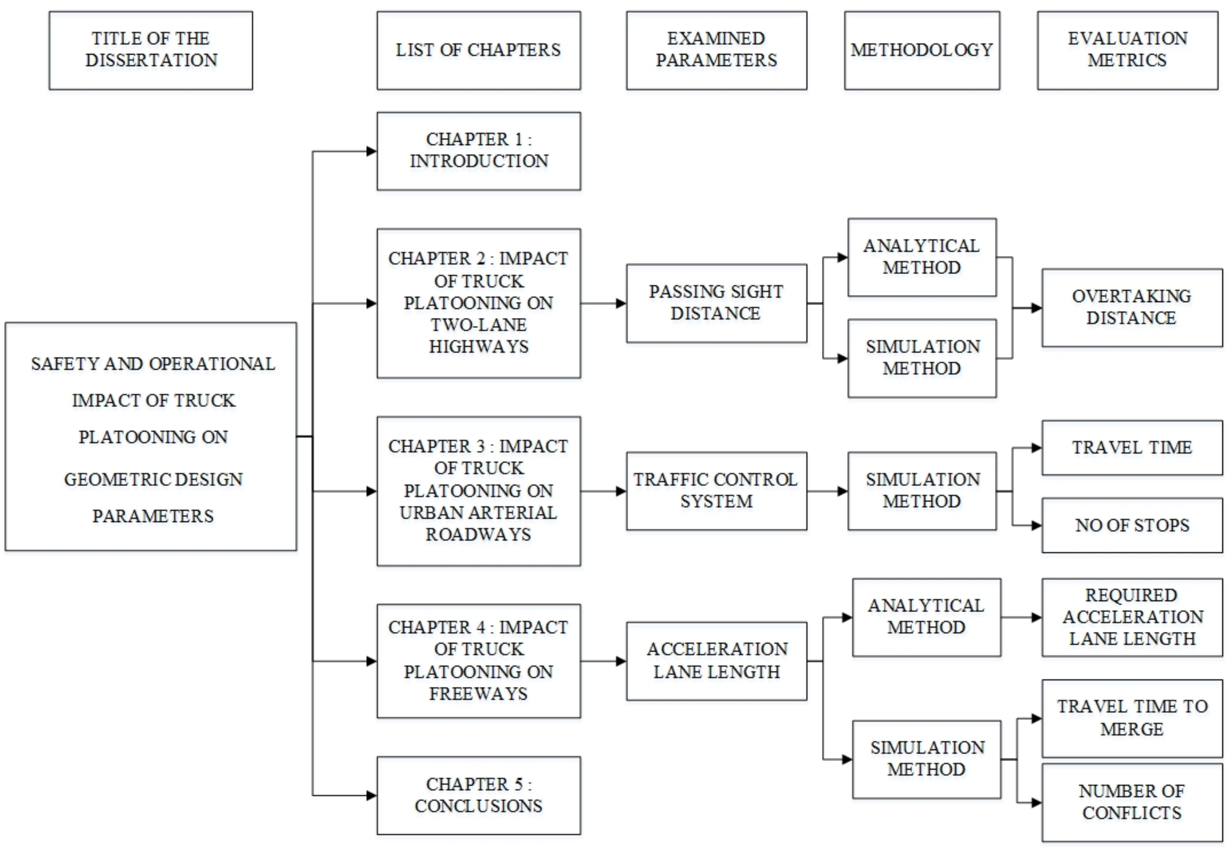


Figure 1-4: Dissertation Structure

1.11 Chapter 1 References

AASHTO. (2011). A Policy on Geometric Design of Highways and Streets (6th ed.). American Association of State Highway and Transportation Officials.

AASHTO. (2018). A Policy on Geometric Design of Highways and Streets (7th ed.). American Association of State Highway and Transportation Officials.

Alam, A., Besselink, B., Turri, V., Martensson, J., & Johansson, K. H. (2015). Heavy-duty vehicle platooning for sustainable freight transportation: A cooperative method to enhance safety and efficiency. IEEE Control Systems Magazine, 35(6), 34–56.

Alkim, T., Van Vliet, A., Aarts, L., & Eckhardt, J. (2016). European truck platooning challenge 2016: Creating next generation mobility. 1–80.

Arbib, J., & Seba, T. (2017). Rethinking Transportation 2020-2030: The Disruption of Transportation and the Collapse of the Internal-Combustion Vehicle and Oil Industries. In A RethinkX Sector Disruption Report May.

Arnold, S., & Roorda, M. (2020). Infrastructure to Enable Freight Platooning Ramp Operations in the GTHA. Transformative Transportation '20, ICity-CATTS Research Day. https://uttri.utoronto.ca/files/2020/06/Arnold-Freight_Platooning-2020-06-02.pdf

Barton, R.A., Morrall, J., (1998). Study of long combination vehicles on two-lane highways. Transportation Research Record, 1613(1), 43–49.

Browand, F., McArthur, J., & Radovich, C. (2004). Fuel saving achieved in the field test of two tandem trucks.

Bureau of Economic Analysis. (2019). Gross Output by Industry. Bureau of Economic Analysis. https://apps.bea.gov/iTable/iTable.cfm?ReqID=51&step=1

Butler, C. (2019). A “demographic tsunami” is about to make Canada’s trucker shortage even worse | CBC News. CBC News. https://www.cbc.ca/news/canada/london/canada-ontario-truck-driver-trucker-shortage-1.5400992

Canadian Trucking Alliance. (2020). CBSA: Truck Crossings Fall 33%. Border & Customs, Business Conditions, COVID-19. http://cantruck.ca/cbsa-truck-crossings-fall-33

CCMTA. (2016). Automated Vehicles in Canada. https://ccmta.ca/images/publications/pdf/CCMTA_WhitePaper_Automated_Vehicles_in_Canada_2017.pdf

Clement, J. (2020). Retail e-commerce revenue in Canada from 2017 to 2024. Statista. https://www.statista.com/statistics/289741/canada-retail-e-commerce-sales

Chislov, O., Zadorozhniy, V., Bogachev, T., Kravets, A., Bogachev, V., Egorova, I. (2021). Methods of Analytical Modeling the Process of Freight Transportation Management in the Regional Transport Complex BT - Decision Support Methods in Modern Transportation Systems and Networks, in: Sierpiński, G., Macioszek, E. (Eds.), . Springer International Publishing, Cham, 197–210.

Chowdhury, T., Park, P.Y., Gingerich, K. (2022). Operational Impact of the Through-Traffic Signal Prioritization for Heavy Commercial Vehicle Platooning on Urban Arterials.

Chowdhury, T.U., Park, P.Y., Gingerich, K. (2022). Estimation of Appropriate Acceleration Lane Length for Safe and Efficient Truck Platooning Operation on Freeway Merge Areas. Sustainability, 14, 12946.

Costello, B. (2019). Truck driver shortage analysis 2019. https://www.trucking.org/sites/default/files/2020-01/ATAs Driver Shortage Report 2019 with cover.pdf

Dally Hlve Staff. (2018). Canada ranked as one of world's most traffic congested countries: Study. Daily Hive. https://dailyhive.com/vancouver/canada-ranks-traffic-congestion-country-world-study

Davis, D. (2020). Amazon's profilts nearly triple in Q3 as North America sales soar 39%. Digital Commerce 360. https://www.digitalcommerce360.com/article/amazon-sales/

Deng, Q. (2016a). A General Simulation Framework for Modeling and Analysis of Heavy-Duty Vehicle Platooning. IEEE Transactions on Intelligent Transportation Systems, 17(11), 3252–3262. https://doi.org/10.1109/TITS.2016.2548502

Deng, Q. (2016b). Heavy-Duty Vehicle Platooning – Modeling and Analysis.

Deng, Q., & Boughout, W. (2016). The impacts of heavy-duty vehicle platoon spacing policy on traffic flow.

Ellwanger, S., & Wohlfarth, E. (2017). Truck Platooning Application. Intelligent Vehicles Symposium (IV), 2017 IEEE, 966–971.

Fagnant, D. J., & Kockelman, K. (2015). Preparing a nation for autonomous vehicles: Opportunities, barriers and policy recommendations. Transportation Research Part A: Policy and Practice, 77, 167–181. https://doi.org/10.1016/j.tra.2015.04.003

FHWA. (2018). Long Combination Vehicle Operations [WWW Document]. URL https://www.fhwa.dot.gov/policy/otps/long_combination_vehicles.cfm

FHWA. (2019). Estimated U.S. Roadway Lane-Miles by Functional System. U.S. Department of Transportation. https://www.fhwa.dot.gov/policyinformation/statistics/2018/hm60.cfm

Fisher, J. (2020, June 18). One driver, two trucks? Paving the way to public automation acceptance. FleetOwner. https://www.fleetowner.com/technology/autonomous-vehicles/article/21134374/one-driver-two-trucks-paving-the-way-to-public-automation-acceptance

FMCSA. (2020). 2019 Pocket Guide to Large Truck and Bus Statistics. In Federal Motor Carrier Safety Administration. https://doi.org/10.1017/CBO9781107415324.004

Forbes, G. (1990). The origin of minimum passing sight distances for no-passing zones. ITE Journal, 60(12), 20–24.

Gao, P., Kaas, H.-W., Mohr, D., & Wee, D. (2016). Automotive revolution–perspective towards 2030 How the convergence of disruptive technology-driven trends could transform the auto industry. Advanced Industries, McKinsey & Company.

Gordon, M., & Turochy, R. E. (2016). Evaluation of the effects of driver assistive truck platooning on freeway traffic flow.

Hanley, P. F., & Forkenbrock, D. J. (2005). Safety of passing longer combination vehicles on two-lane highways. Transportation Research Part A: Policy and Practice, 39(1), 1–15. https://doi.org/10.1016/j.tra.2004.09.001

Harkey, D.L., Council, F.M., Zegeer, C. V. (1996). Operational characteristics of longer combination vehicles and related geometric design issues. Transportation Research Record, 1523(1), 22–28.

Harwood, D. W., Gilmore, D. K., Richard, K. R., Dunn, J. M., & Sun, C. (2008). NCHRP Report 605: Passing sight distance criteria. In Transportation Research Board of the National Academies, Washington, DC. https://doi.org/10.17226/23278

Harwood, D. W., & Glennon, J. C. (1976). Framework for design and operation of passing zones on two-lane highways. Transportation Research Record, 601, 45–50.

Harwood, D. W., & Glennon, J. C. (1989). Passing sight distance design for passenger cars and trucks. Transportation Research Record, 1208, 59–69.

Hassan, Y., Easa, S. M., & El Halim, A. O. A. (1996). Passing sight distance on two-lane highways: Review and revision. Transportation Research Part A: Policy and Practice, 30(6), 453–467.

Hostetter, R. S., & Seguin, E. L. (1969). The Effects of Sight Distance and Controlled Impedance on Passing Behavior. HRB-Singer Incorporated.

INRIX. (2020a). Global Traffic Scorecard. INRIX. https://inrix.com/scorecard/

INRIX. (2020b). INRIX: Congestion Costs Each American 97 hours, $1,348 A Year - INRIX. https://inrix.com/press-releases/scorecard-2018-us/

ITE. (2000). Traffic Engineering Handbook (J. L. Pline (ed.); 5th Editio). Institute of Transportation Engineers (ITE).

Janssen, G. R., Zwijnenberg, J., Blankers, I. J., & de Kruijff, J. S. (2015). Truck platooning: Driving the future of transportation.

Jenkins, J. M. (2004). Modelling the interaction between passenger cars and trucks (Issue August). Texas A&M University.

Kaisar, E. I., Hadi, M., Ardalan, T., & Iqbal, M. S. (2020). Evaluation of Freight and Transit Signal Priority Strategies for Improving Transportation Operations in Urban Corridors. https://fdotwww.blob.core.windows.net/sitefinity/docs/default-source/research/reports/fdot-bdv27-977-14-rpt.pdf

Kaub, A. R., & Berg, W. D. (1988). Design guide for auxiliary passing lanes on rural two-lane highways. Transportation Research Record, 1195, 92–100.

Kaufmann, S., Kerner, B. S., Ag, D., & Usn, R. D. (2017). Aerial Observation of Inner City Traffic and Analysis of Microscopic Data at Traffic Signals. Transportation Research Board 2017 Annual Meeting.

Kenny, B., Kwan, A., Morrall, J. (2000). Design and operational considerations to accommodate long combination vehicles and log haul trucks on rural highways in Alberta, Canada, in: Proceeding 2nd International Symposium. Highway Geometric Design.

Khoury, J., & Amine, K. (2019). Highway Geometric Design Changes in Response to a Fully Autonomous Vehicle Fleet. Transportation Research Board 98th Annual Meeting.

Kockelman, K., Boyles, S., Stone, P., Fagnant, D., Patel, R., Levin, M. W., Sharon, G., Simoni, M., Albert, M., & Fritz, H. (2017). An assessment of autonomous vehicles: traffic impacts and infrastructure needs. University of Texas at Austin. Center for Transportation Research.

Koorey, G. (2007). Passing opportunities at slow-vehicle bays. Journal of Transportation Engineering, 133(2), 129–137.

Kuhn, B., Lukuc, M., Poorsartep, M., Wagner, J., Balke, K. N., Middleton, D., Songchitruksa, P., Wood, N., & Moran, M. (2017). Commercial truck platooning demonstration in Texas–level 2 automation. Texas. Dept. of Transportation. Research and Technology Implementation Office.

Kuijpers, A. G. J. (2017). Truck platooning: a framework to optimize traffic management near the port area of Rotterdam. In Eindhoven University of Technology, Netherlands.

Lazar, C., Tiganasu, A., & Caruntu, C. F. (2018). Arterial Intersection Improvement by Using Vehicle Platooning and Coordinated Start. IFAC-PapersOnLine, 51(9), 136–141.

Lieberman, E. B. (1982). Model for calculating safe passing distances on two-lane rural roads. Transportation Research Record, 869.

Lioris, J., Pedarsani, R., Tascikaraoglu, F. Y., & Varaiya, P. (2017). Platoons of connected vehicles can double throughput in urban roads. Transportation Research Part C: Emerging Technologies, 77, 292–305. https://doi.org/10.1016/j.trc.2017.01.023

Manitoba Transportation and Infrastructure Department. (2022). Transportation and Infrastructure [WWW Document]. Moto Carrier-Permits. URL https://www.gov.mb.ca/mit/mcd/permits/overlength.html

McCutchon, J., Regehr, J.D., Montufar, J. (2006). Safety review of Rocky Mountain double operations on two-lane, undivided rural roads, in: Proceedings of the Sixteenth Canadian Multidisciplinary Road Safety Conference, Winnipeg, Man. pp. 11–14.

Mcauliffe, B. R., Croken, M., Ahmadi-baloutaki, M., & Raeesi, A. (2017). Fuel-Economy Testing of a Three-Vehicle Truck Platooning System (Issue 22).

McCarthy, N. (2020). Congestion Costs U.S. Cities Billions Every Year | . Statista. https://www.statista.com/chart/21085/annual-economic-losses-from-traffic-congestion/

Ministry of Highways - Government of Saskatchewan. (2022). Vehicle Weight and Dimension Regulations, 2010, H-3.01 Reg 8 [WWW Document]. Veh. Weight Dimens. Regul. 2010, H-3.01 Reg 8. URL https://publications.saskatchewan.ca/#/products/31363 (accessed 1.14.23).

Möller, D.P.F. (2014). Introduction to Transportation Analysis, Modeling and Simulation, Simulation Foundations, Methods and Applications. Springer London, London.

Montufar, J., Regehr, J., Rempel, G., McGregor, R. V. (2007). Long combination vehicle (LCV) safety performance in Alberta 1999-2005. Montufar Association. Transportation Consulting.

MTO. (2018). Cooperative Truck Platooning Conditions. Ministry of Transportation Ontario. http://www.mto.gov.on.ca/english/trucks/cooperative-truck-platooning-conditions.shtml

NHTSA. (2020). Vehicle-to-Vehicle Communication. U.S. Department of Transportation. https://www.nhtsa.gov/technology-innovation/vehicle-vehicle-communication#

Nowakowski, C., O'Connell, J., Shladover, S. E., & 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), 2033–2037.

Nowakowski, C., Shladover, S. E., Cody, D., Bu, F., O'Connell, J., Spring, J., Dickey, S., & Nelson, D. (2011). Cooperative adaptive cruise control: Testing drivers' choices of following distances.

Ohene, F. A., & Ardekani, S. A. (1988). Minimum Passing Sight Distance for Completing or Aborting the Passing Maneuver. ITE Journal, 58(7), 29–33.

Paulsen, J. T. (2018). Physical Infrastructure Needs for Autonomous & Connected Trucks-An Exploratory Study. NTNU.

Ploeg, J. (2014). Analysis and design of controllers for cooperative and automated driving.

Proust, E., Smith, P., Pierce, D., Ward, J., & Bevly, D. (2019). Evaluation of Platooning on Resource Roads. 2019 TAC-ITS Canada Joint Conference.

PTV. (2021). PTV Vissim 2021 User Manual. In Karlsruhe, Germany: PTV. PTV AG.

Ramezani, H., Shladover, S. E., Lu, X.-Y., & Chou, F.-C. (2018). Microsimulation Framework to Explore Impact of Truck Platooning on Traffic Operation and Energy Consumption: Development and Case Study (Issue February).

Rampure, R., Gingerich, K., & Park, P. Y. (2019). VISSIM Microsimulation Analysis of Truck Signal Priority. Canadian Institute of Transportation Engineers Poster Presentation.

Regehr, J.D., Montufar, J., Rempel, G. (2009). Safety performance of longer combination vehicles relative to other articulated trucks. Canadian Journal of Civil Engineering, 36(1), 40–49.

Rilett, L. R., Hutchinson, B. G., & Whitney, M. (1990). Mechanics of the passing maneuver and the impact of large trucks. Transportation Research Part A: General, 24(2), 121–128.

Robertson, H.D., Harkey, D.L., Davis, S.E. (1987). Safety Criteria for Longer Combination Vehicles. Final Report.

SAE International Standard. (2016). Automated Driving: Levels of Driving Automation. In SAE J3016.

Saito, M. (1984). Evaluation of the adequacy of the MUTCD minimum passing sight distance requirement for aborting the passing maneuver. ITE Journal, 54(1), 18–22.

Schrank, D., Eisele, B., & Lomax, T. (2012). TTI's 2012 urban mobility report. Texas A&M Transportation Institute. The Texas A&M University System, 4.

Shladover, S. E., Lu, X.-Y., Yang, S., Ramezani, H., Spring, J., Nowakowski, C., & Nelson, D. (2018). Cooperative Adaptive Cruise Control (CACC) For Partially Automated Truck Platooning: Final Report (Issue March). https://escholarship.org/uc/item/260060w4

Shladover, S. E., Nowakowski, C., Lu, X.-Y., & Ferlis, R. (2015). Cooperative adaptive cruise control: Definitions and operating concepts. Transportation Research Record, 2489(1), 145–

152.

Smith, S. W., Kim, Y., Guanetti, J., Li, R., Firoozi, R., Wootton, B., Kurzhanskiy, A. A., Borrelli, F., Horowitz, R., & Arcak, M. (2020). Improving urban traffic throughput with vehicle platooning: Theory and experiments. IEEE Access, 8, 141208–141223.

Statistics Canada. (2020a). General Freight Trucking - 4841. Summary - Canadian Industry Statistics. https://www.ic.gc.ca/app/scr/app/cis/summary-sommaire/484

Statistics Canada. (2020b). Gross domestic product (GDP) at basic prices, by industry, annual average (x 1,000,000). Statistics Canada. https://doi.org/10.25318/3610043401-eng

Statistics Canada. (2020c). Trucking Commodity Industry Activities. https://doi.org/https://doi.org/10.25318/2310021901-eng

Statistics Canada. (2020d). Vehicle registrations, by type of vehicle. Statistics Canada. https://doi.org/https://doi.org/10.25318/2310006701-eng

Steenhof, P., Woudsma, C., & Sparling, E. (2006). Greenhouse gas emissions and the surface transport of freight in Canada. Transportation Research Part D: Transport and Environment, 11(5), 369–376. https://doi.org/https://doi.org/10.1016/j.trd.2006.07.003

TAC. (2017). Geometric design guide for Canadian roads.

Tiaprasert, K., Zhang, Y., & Ye, X. (2019). Platoon recognition using connected vehicle technology. Journal of Intelligent Transportation Systems, 23(1), 12–27.

Transport Canada. (2019a). Cooperative Truck Platooning: Transport Canada's Innovation Centre testing new trucking technologies to reduce emissions and improve safety. Transport Canada. https://tc.canada.ca/en/cooperative-truck-platooning-transport-canada-s-innovation-centre-testing-new-trucking-technologies-reduce-emissions-improve-safety

Transport Canada. (2019b). Transportation in Canada 2018.

Transport Canada. (2020). Transportation in Canada - Overview Report 2020. 105.

USDOT. (2018). Automated Vehicles: Truck Platooning ITS Benefits, Costs, and Lessons Learned: 2018 Update Report. https://www.itsknowledgeresources.its.dot.gov/its/bcllupdate/pdf/BCLL_Automated Vehicles (CMV) Final Draft v4.pdf

USDOT. (2020). Truck Profile. Bureau of Transportation Statistics. https://www.bts.gov/content/truck-profile

Van Valkenburg, G. W., & Michael, H. L. (1971). Criteria for no-passing zones.

Wang, M., van Maarseveen, S., Happee, R., Tool, O., & van Arem, B. (2019). Benefits and Risks of Truck Platooning on Freeway Operations Near Entrance Ramp. Transportation Research Record, 2673(8), 588–602. https://doi.org/10.1177/0361198119842821

Wang, P., Jiang, Y., Xiao, L., Zhao, Y., & Li, Y. (2020). A joint control model for connected vehicle platoon and arterial signal coordination. Journal of Intelligent Transportation Systems, 24(1), 81–92.

Wang, Y., & Cartmell, M. P. (1998). New model for passing sight distance on two-lane highways. Journal of Transportation Engineering, 124(6), 536–545.

Weaver, G. D., & Glennon, J. C. (1972). Design and striping for safe passing operations. Highway Research Record, 390.

WHO. (2018). Global Status Report on Road. In World Health Organization.

Wood, S., Regehr, J.D. (2017). Regulations governing the operation of longer combination vehicles in Canada. Canadian Journal of Civil Engineering, 44(10) , 838–849.

Zhang, L., Chen, F., Ma, X., & Pan, X. (2020). Fuel Economy in Truck Platooning: A Literature Overview and Directions for Future Research. Journal of Advanced Transportation, 2020.

CHAPTER 2: TRUCK PLATOONING ON TWO-LANE HIGHWAYS

2.1 Introduction

Heavy commercial vehicles (HCVs) and long combination vehicles (LCVs) with two or three trailers pulled by a single engine (FHWA, 2010; Woodrooffe et al., 2004) are a central element of modern goods movement and supply chains. This chapter focuses on the first objective of this dissertation. The first objective is to assess the impact of HCV platooning on two-lane rural highway's geometric design parameter i.e., passing sight distance.

Most major warehouses, airports, and other intermodal facilities in urban areas have good freeway access. Yet facilities located in many small towns and rural areas require HCVs to use two-lane rural highways. These rural roads consist of one lane in each direction with no median. The operation of HCV platooning, also known as truck platooning, on two-lane rural highways needs urgent analysis to understand their potential impacts and plan future infrastructure designs accordingly. Some North American jurisdictions (e.g., California, Texas, Florida, Alberta, and Ontario) allow the operation and testing of HCV platooning techniques on freeways only. The restriction is intended to minimize potential negative impacts of HCV platooning (e.g., collisions between platooning HCVs and other vehicles, and collisions between other vehicles due to HCV operation) and to maximize anticipated benefits (e.g., reduced fuel consumption and emissions) (CCMTA, 2016; Kuhn et al., 2017).

Many jurisdictions (e.g., North Dakota, Montana, South Dakota, Alberta, and Saskatchewan) allow LCVs on two-lane rural highways. In Canada, LCVs are allowed to travel on approximately 17,000 kms of highway scattered across the country. The United States allows turnpike double LCVs as large as 34.75 m composed of a truck engine connected with two full-length trailers (AASHTO, 2018). The LCV is defined in Canada with a length greater than the 25.00 m (TAC, 2017). In Canada, The LCV length exceeds 25 m (TAC, 2017) and may be as long as 41 m (Wood and Regehr, 2017). We expect that the operational and safety impact of HCV platooning on two-lane highways will be comparable to LCVs, and it may be possible to allow HCV platoons to operate on the same corridors. The additional length when compared to a single tractor-trailer vehicle will make it more difficult for a passenger vehicle to make a successful passing maneuver when compared with a traditional HCV. The emergence of vehicle-to-vehicle (V2V) technology for HCV platooning therefore requires changes to North American highway geometric design guidelines.

The chapter focuses on passing sight distance (PSD) on two-lane highways. PSD refers to the minimum sight distance required to allow a faster-moving vehicle such as a passenger vehicle to safely pass a slower-moving vehicle. PSD is a fundamental input in two-lane highway design elements such as passing lanes and climbing lanes. In principle, PSD is defined as the 85th percentile value of the overtaking distance required for passing vehicles (Harwood et al., 2008). This definition implies that 15% of vehicles travelling behind a slower-moving vehicle will require a longer distance than the PSD guideline to complete their overtaking maneuvers.

2.1.1 Benefits of HCV Platooning

The anticipated benefits of HCV platooning include fuel savings and reduced emissions due to decreased aerodynamic drag resulting from the tightened gaps between HCVs travelling at a relatively fast speed (Ramezani et al., 2018a). An HCV platoon traveling at higher speeds will observe greater fuel savings. Studies have shown that fuel consumption can be reduced by up to 6% for the lead HCV and by up to 10% for the following HCVs (Alam et al., 2015; Bibeka et al., 2019; Patten et al., 2012; Ramezani et al., 2018a; Tavasszy and Janssen, 2017; Weng et al., 2020).

A future benefit of HCV platooning may be the alleviation of the HCV driver shortage problem. In the United States, Costello (2019) estimated a need for at least 160,000 additional HCV drivers by 2028. In Canada, Reynolds (2020) reported a shortage of about 20,000 HCV drivers in 2018. Butler (2019) has estimated a shortage of 34,000 drivers in Canada by 2024. It is not yet clear when SAE level 4 (or higher) automation will be available to HCV platooning, but SAE level 4 (or higher) automation can generate increased financial benefits as it eliminates one or more human drivers in the following HCVs.

LCV drivers are in even shorter supply than are HCV drivers. This is caused by strict requirements to obtain an LCV permit for the driver and corresponding company. For instance, an LCV driver needs to have at least five years of HCV driving experience and more than 100 hours of classroom instruction and field training before being eligible to drive an LCV in Ontario (MTO, 2021a; Smith G, 2020). The driver shortage was a main motivator for a study in La Tuque, Quebec, Canada where the private firm FPInnovations has been investigating whether HCV platooning can be used on a two-lane rural highway that delivers timber products to a nearby port (Proust et al., 2019). The remote locations for the timber industry further exacerbate the driver shortage.

2.1.2 Study Objectives

To conduct this study, three sub-objectives has been focused on:

- Formulate an analytical method for calculating PSDs for HCV platooning and LCVs on North American two-lane rural highways;
- Determine the appropriate PSDs for HCV platooning and LCVs using an analytical method and then validate with a simulation method; and
- Compare the PSDs estimated in the North American highway geometric standards.

The rest of the sections of this chapter are organized to include a review of PSD literature, a discussion of the methodological approach, and reporting of the major findings. The final section presents the study's conclusions and recommendations.

2.2 Literature Review

Overtaking on two-lane rural highways is a major safety concern in North America. In the United States in 2018, around 111,000 collisions involved overtaking vehicles on two-lane highways. These collisions were associated with 709 fatal collisions making overtaking on two-lane highways the fourth-largest cause of fatal collisions in the United States (USDOT, 2018b, 2018c). In Canada in 2017, around 3,110 of the 289,841 reported collisions involved overtaking (Transport Canada, 2019b).

2.2.1 Passing Sight Distance

The PSD has a major impact on the design, safety, and operational performance of two-lane rural highways. Adequate PSD is essential for faster-moving vehicles to overtake slower-moving vehicles such as HCVs. The PSD also affects the level of service on two-lane rural highways if vehicles do not have enough room to maneuver around a slow-moving vehicle and are forced to remain behind them.

The two main sets of guidelines used to estimate the PSD in North America are the American Association of State Highway and Transportation Officials (AASHTO) (AASHTO, 2018) and the Transportation Association of Canada (TAC, 2017) guidelines. These guidelines use various inputs including design speed, acceleration and deceleration rates, travel speeds, and other factors. Kaub and Berg (1988), for example, argued that overtaking cannot occur if the traffic volume is high on the opposing and/or travelling lane. Early PSD estimates (e.g., AASHTO, 2004) did not consider vehicle length. But many studies have noted this is as a concern (Forbes, 1990; Harwood et al., 2008; Harwood and Glennon, 1989, 1976; Hassan et al., 1996; Jenkins, 2004; Ohene and Ardekani, 1988; Rilett et al., 1990; Saito, 1984; Wang and Cartmell, 1998). Although the most recent AASHTO guidelines (2018) acknowledge the importance of the length of the impeding vehicle, the recommended PSD is still based on the estimated overtaking distance required to pass a slower-moving passenger vehicle rather than a slower-moving HCV (AASHTO, 2018, 2011; Harwood et al., 2008).

Hanley and Forkenbrock (2005) developed a simulation model to estimate the passing time required to overtake an LCV on two-lane rural highways. The study considered the length of the LCV and concluded that the risk associated with overtaking an LCV could be two to six times higher than the risk of passing a single-trailer HCV. The increased risk was due to the additional time and distance required to complete the overtaking maneuver (Hanley and Forkenbrock, 2005).

Paulsen (2018) provides the only known research into the distance required to overtake an HCV platoon on a two-lane highway. The research conducted in Norway, considered a platoon of two HCVs (57.17m long) and three HCVs (89.08m long), with a 0.3-second headway between HCVs and a constant speed of 80 km/h. Paulsen reported that the minimum overtaking distance requirement increased up to 300% for a three HCV platoon compared to the PSD given in the Norwegian geometric design standard.

Passing maneuvers on a roadway are extremely complex. The assumptions (e.g., constant travel speed and constant acceleration and deceleration rates) made in studies based solely on an analytical approach are limiting and problematic (Glennon, 1988; Harwood and Glennon, 1989; Llorca and García, 2011; Mampearachchi and Masakorala, 2018; Ohene and Ardekani, 1988). This study applies both analytical and simulation approaches in an attempt to study traffic conditions as close to real world circumstances as possible.

2.3 Analytical Models for Passing Sight Distance

This section discusses the estimation of PSD using analytical models reported by TAC (TAC, 2017) and by AASHTO (AASHTO, 2018). Note that the 2017 TAC model uses the AASHTO analytical model of 2004 model (AASHTO, 2004). The PSD estimates in the 2018 AASHTO and the 2017 TAC guidelines use passenger vehicles and do not explicitly include the option to estimate the PSD required to overtake an HCV, HCV platoon, or LCV.

2.3.1 2017 TAC Model

Equation (2-1) shows the TAC model (TAC, 2017):

$$PSD = d_1 + d_2 + d_3 + d_4 \tag{2-1}$$

Where:

PSD = passing sight distance (m);

d_1 = distance travelled during the perception and reaction time and initial acceleration to the point of encroachment on the opposing lane (m);

d_2 = distance travelled while the faster-moving vehicle occupies the opposing lane (m);

d_3 = distance between the faster-moving vehicle at the end of passing maneuver and the vehicle on the opposing lane (m); and

d_4 = distance travelled by the opposing vehicle after being seen by the passing vehicle. As the opposing vehicle is assumed to be travelling at the same speed as the passing vehicle, d_4 is equal to two-thirds of d_2 (m).

Notice that the 2017 TAC model does not include vehicle length as an input.

2.3.2 2018 AASHTO Model

The 2018 AASHTO model was originally developed by Harwood and Glennon in 1989 (AASHTO, 2018; Glennon, 1988; Harwood and Glennon, 1989) and is shown in Equation (2-2).

$$PSD = 2V_d\left(2.93 + \frac{L_P - \Delta_c}{m}\right); \tag{2-2}$$

$$\Delta_c = L_P + 1.47m\left\{\frac{(2.93m + L_P + L_i)}{1.47(2V_d - m)} - \sqrt{\left[\frac{5.87\,V_d(2.93m + L_P + L_i)}{1.47\,d_a(2V_d - m)}\right]}\right\}$$

Where:

PSD = passing sight distance (ft);

Δ_c = relative position of the front bumpers of the faster-moving (passing) vehicle and the slower-moving (passed) vehicle at the critical position. (A negative Δc means that the faster-moving vehicle is behind the slower-moving vehicle and a positive Δc means that the faster-moving vehicle is in front of the slower-moving vehicle) (ft);

m = speed difference between faster-moving vehicle and slower-moving vehicle (mph);

L_P = length of the faster-moving vehicle (ft);

L_i = length of the slower-moving vehicle (ft);

d_a = deceleration rate (ft /sec2)

V_d = design speed (mph)

Notice that the 2018 AASHTO model uses the length of a passenger vehicle as the inputs for L_P and L_i.

2.3.3 Modified 2018 AASHTO Model

A proposed model modifies relative position calculation in the 2018 AASHTO equation. It uses the number of HCVs in the platoon, the length of the HCVs, and the physical gap between the HCVs to estimate the PSD required to pass an HCV platoon. This model can also take into account the length of an LCV. The equation collapses to the original 2018 AASHTO formula in Equation (2-2) if there is no platoon. The modified relative position is shown in Equation (2-3) which can be used as a replacement in Equation (2-2) to estimate PSD as presented earlier by Chowdhury & Park (2019, 2021).

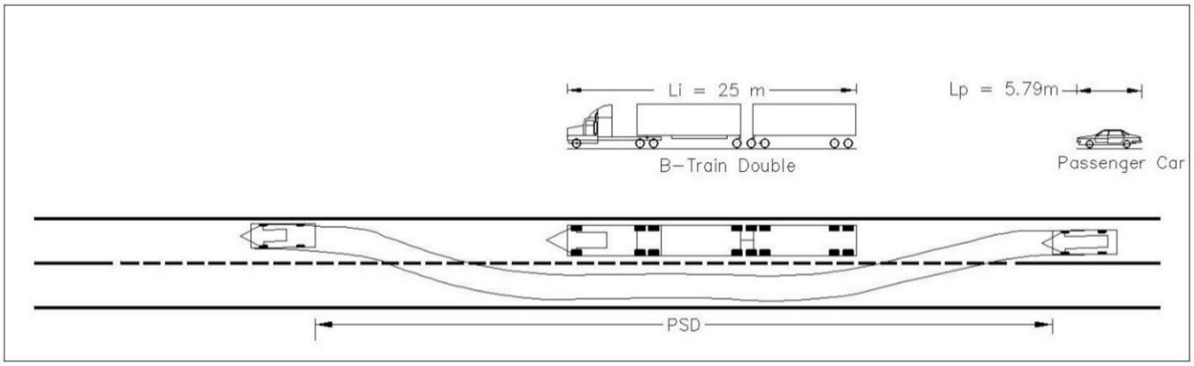
$$\Delta_c = L_P + 1.47m\left\{\frac{(2.93m+L_P+nL_i+(n-1)d)}{1.47(2V_d-m)} - \sqrt{\left[\frac{5.87\,V_d(2.93m+L_P+nL_i+(n-1)d)}{1.47\,d_a(2V_d-m)}\right]}\right\} \quad (2\text{-}3)$$

Where:

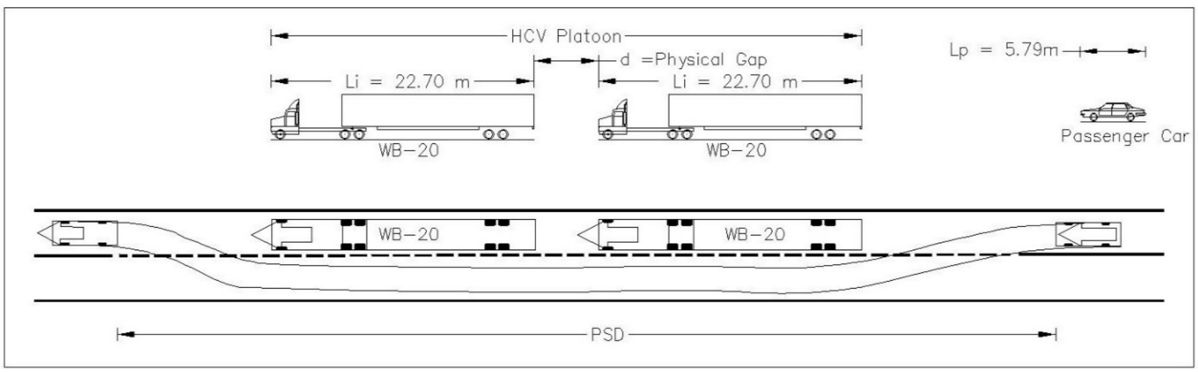
n = number of HCVs in a platoon (one for single vehicles including LCV);

L_i = length of an HCV or an LCV (ft); and

d = physical gap between HCVs (zero for LCV) (ft)



(a) Trajectory of Passenger Vehicle Overtaking a B-Train LCV



(b) Trajectory of Passenger Vehicle Overtaking a platoon of two-HCVs

Figure 2-1: Overtaking Trajectory of a Passenger Vehicle

Figure 2-1 shows the typical trajectory of a passenger vehicle overtaking a B-Train LCV and the typical trajectory of a passenger vehicle overtaking a platoon of two HCVs on a two-lane highway. The United States and Canada both allow the conventional HCV for interstate shipments using the metric WB-20 HCV (22.70 m) classification. The definition of an HCV platoon therefore uses two or three WB-20 HCVs connected via V2V technology (TAC, 2017). The physical gap between the HCVs depends on the time headway and the travel speed.

2.3.4 PSDs Using Analytical Models

The PSD for a passenger vehicle to overtake six different vehicle configurations are calculated as shown in Figure 2-2 including two LCV options and four HCV platoon options (Chowdhury and Park, 2021, 2019). The headways between two platooning HCVs were assumed to be 0.6 or 1.2 sec (Kuhn et al., 2017; Ramezani et al., 2018a;2018b; Shladover et al., 2018). The six options are:

- B-Train LCV (25.00 m; solid cyan line);
- Turnpike-Double LCV (TD LCV; 34.75 m; dashed cyan line);
- 2-HCV Platooning with 0.6 sec headway (2HCVP_0.6H; 58.84 m; solid golden line;);
- 2-HCV Platooning with 1.2 sec headway (2HCVP_1.2H; 72.28 m; dashed golden line);
- 3-HCV Platooning with 0.6 sec headway (3HCVP_0.6H; 94.98 m; solid purple line); and,
- 3-HCV Platooning with 1.2 sec headway (3HCVP_1.2H; 121.86 m; dashed purple line).

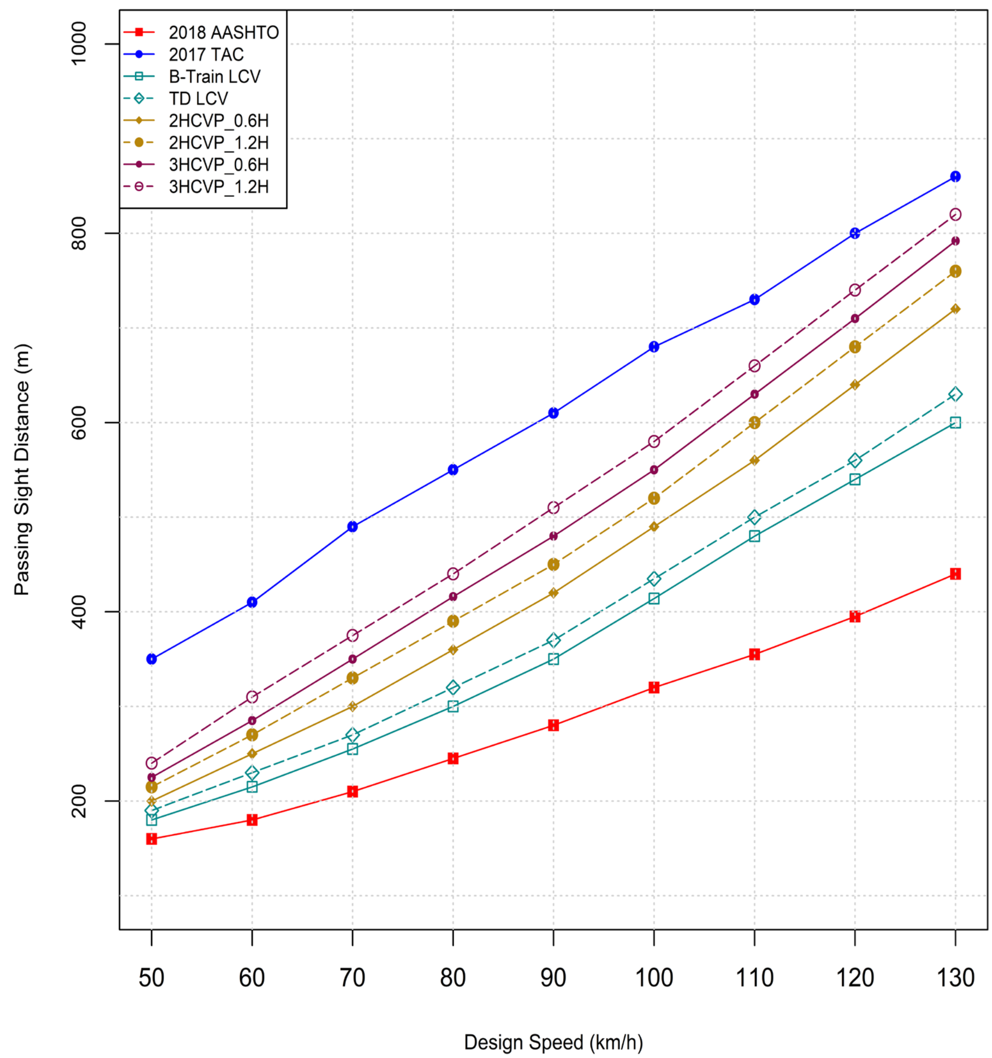


Figure 2-2: Estimated Passing Sight Distance

Figure 2-2 shows the relationship between the estimated PSDs and the design speed for the six HCV options in Equation (2-1) (the blue line in Figure 2-2) and in Equation (2-2) (the red line in Figure 2-2). Note that both AASHTO and TAC assume that a slower-moving vehicle is travelling lower than the design speed. For instance, when a design speed is 100 km/h, the 2018 AASHTO's impeded vehicle's travel speed is assumed to be 81 km/h and the suggested

PSD refers to the minimum length required to overtake a passenger vehicle traveling at 81 km/h.

Figure 2-2 suggests that the 2017 TAC guidelines provide sufficient PSD for a passenger vehicle to pass an LCV or an HCV platoon for all six options considered, but the 2018 AASHTO PSD estimates do not. The AASHTO PSD estimates appear inadequate for all six HCV options considered in this study. For example, the B-Train LCV in option 1 is the shortest HCV option considered, but requires a longer PSD than the 2018 AASHTO PSD over the entire range of design speed. At a design speed of 100 km/h, the PSD for the B-Train LCV using AASHTO's PSD estimate is 320 m whereas the modified model in Equation (2-3) estimates a larger PSD of 414 m.

As expected, the modified model suggests that the PSD estimates are longer for an HCV platoon than for an LCV. For instance, when the design speed is 100 km/h, the PSD for the longest HCV option, 3HCVP_1.2H, is approximately 580 m. This PSD is about 145 m longer than the 435 m PSD estimated for a TD LCV. The 2017 TAC PSD is approximately 680 m or 100 m longer than the modified 2018 AASHTO PSD estimated for 3HCVP_1.2H, while the original 2018 AASHTO guidelines in Equation (2-1) do not provide sufficient distance for any of the six HCV options considered in this study. It is also expected and visible that an HCV platoon with a longer headway (1.2 sec) requires a longer PSD than an HCV platoon with a shorter headway (0.6 sec).

As the 2017 TAC uses the PSD suggested in the 2004 AASHTO guidelines, it can be assumed that many two-lane rural highways in the United States provide sufficient PSD for the six HCV options considered in this study. Two-lane highways built to follow the 2018

AASHTO guidelines may require a PSD investigation before LCVs or HCV platoons are approved to use the roads. These results are based on the analytical analysis. A simulation approach is presented in the next section to further analyse the PSD and give additional perspective to the existing analytical models.

2.4 Estimation of Passing Sight Distance Using Micro-Simulation

Other input parameters, such as travel lane volume, opposing lane traffic volume, and traffic composition play a significant role in overtaking on two-lane rural highways (Kaub and Berg, 1988). But the analytical models discussed earlier do not take all of these important parameters into account. The literature suggests using a micro-simulation model to investigate the impact of additional input parameters on PSD estimation (Figueira and Larocca, 2020; Hanley and Forkenbrock, 2005; Praticò and Giunta, 2012; Romana et al., 2019; Sun et al., 2019). A micro-simulation model requires careful calibration to produce outputs that reflect real-world circumstances as closely as possible (Abdulhai et al., 2002; Figueira and Larocca, 2020; Habtemichael and Picado-Santos, 2013; Jehn and Turochy, 2019; Manjunatha et al., 2013; Várhelyi et al., 2020). This section discusses the calibration of the micro-simulation model and the results obtained.

2.4.1 Calibration of Micro-Simulation Model

The simulations were created using VISSIM software along with the PTV VISSIM COM interface (PTV, 2021) and python programming to create realistic platooning behavior. Traffic volume and other data including the directional volume factor, design hour factor, and different categories of vehicle percentage were collected from Alberta’s two-lane rural highways that allow LCV operation. These locations were utilized in anticipation of their feasibility as initial corridors for HCV platooning. The green lines in Figure 2-3 show approximately 3,800 km of two-lane rural highways that allow LCV operation in Alberta.

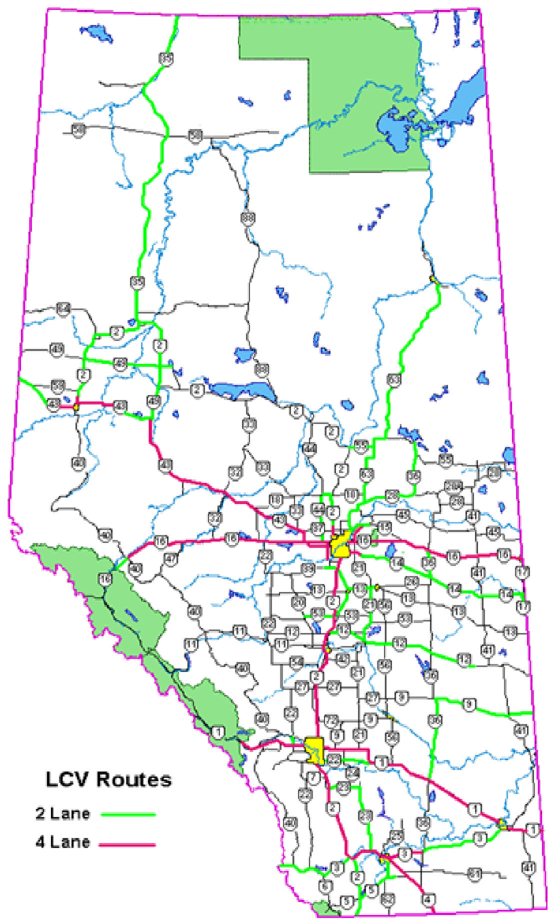


Figure 2-3: Two-Lane Rural Highways that Allow LCV Operation in Alberta

(Alberta Transportation, 2020a)

The annual average daily traffic volume on two-lane highways in Alberta that allow LCV operation ranged from 800 to 8,500 in 2020. Passenger vehicles (PVs) accounted for 68% to 90% of the traffic, HCVs for 3.5% to 25%, and recreational vehicles (RVs) for 0.6% to 8.4% (Alberta Transportation, 2020b). The dataset also showed that the design hour factor (K-factor) varied from 0.093 to 0.155 and the directional volume factor (D-factor) ranged from 0.50 to

0.75. These values are used to estimate the directional design hourly volumes in the simulations. The segment of a typical two-lane rural highway in Alberta was created in VISSIM as a 22 km level-tangent highway section.

The simulations are performed for five vehicle types (PV, B-Train LCV, Turnpike Double B-Train LCV, RV, WB-20) and used AASHTO (2018) guidelines to determine the length of each vehicle. The simulation environment uses the PTV COM interface to employ HCV platooning for some WB-20 HCVs with 20 m wheelbase dimensions. We used the same acceleration and deceleration rate for all HCVs in the simulation (Pline, 1999; PTV, 2021). The literature was followed to utilize the Wiedemann 99 car-following model with consideration of two headways (i.e., 0.6 and 1.2 sec) (discussed in Section 2.3) for the HCV platooning. A values of 1.5 sec was used as the input headway for PVs and 2.5 sec as the headway for LCVs/RVs as suggested by Houchin et al. (2015).

Ideally, a very large number of scenarios would be tested to understand how the parameters affected PSD, but this was not practical. The literature suggests sampling to reduce the number of simulation scenarios and save computer processing time (Essa and Sayed, 2016; Girianna and Benekohal, 2004; Park et al., 2006). This study applied the Latin-Hypercube (LH) algorithm, a popular sampling method that aims to improve the reliability in an experimental design. The LH algorithm allows simultaneous consideration of multi-dimensional input factors and helps to produce a near-random sample that reflects the variability found in the original dataset. In transportation engineering, the LH algorithm has been widely used to control the number of simulation runs (Essa and Sayed, 2016; Park et al., 2006).

The LH algorithm was executed using several input factors crucial to traffic flow. These factors included travel lane volume, opposing lane traffic volume, and traffic composition. The parameters were specifically defined as: travel lane traffic volume ranging from 50 to 600 vph; opposing lane traffic volume from 50 to 300 vph; proportion of passenger vehicles from 68% to 90%; proportion of HCVs from 3.5% to 25%; and proportion of RVs set at 5.5%. With these input parameters, the LH algorithm was able to generate three distinct simulation scenarios. The three scenarios encompassed the wide range of variance within the parameters and allowed us to observe variability in overtaking distance required by passenger vehicles under different traffic flow conditions.

Table 2-1 provides details of the three scenarios.

Table 2-1: Three Simulation Scenarios

Scenario No.	Travelling Lane Traffic Volume (vph)	Opposing Lane Traffic Volume (vph)	PV %	HCV %	RV %
Scenario 1	600	200	86.87	7.63	5.5
Scenario 2	200	250	76.65	17.85	5.5
Scenario 3	250	100	71.66	22.84	5.5

Note: PV and RV represent passenger vehicle and recreational vehicle respectively.

The three simulation scenarios for each of the six HCV options were tested for a total of 18 simulation cases. The overtaking distance distribution was observed in each simulation. There were 30 simulations conducted for each of the 18 cases based on the Wisconsin Department of Transportation's (WisDOT) guideline for micro-simulation, resulting in a total of 540 individual simulations. The generated traffic volumes and the 95% confidence level for the input parameters of each scenario are shown in Table 2-1 (WisDOT, 2019). The model goodness of fit is tested using the Geoffrey E. Havers (GEH) statistic using traffic volume as the measure of performance. The GEH is less than 5 indicating that the calibrated model sufficiently demonstrates the observed traffic volume (see Table 2-1).

The travel speeds of passenger vehicles and HCVs are also crucial input parameters when estimating PSD via simulation (AASHTO, 2018; Figueira and Larocca, 2020; Hanley and Forkenbrock, 2005; Praticò and Giunta, 2012; TAC, 2017). The speed distribution of each vehicle class provided seed information for replicating real-world traffic and was an essential input when developing the simulation environment. Real-world speed data (2014) were collected from a weigh-in-motion (WIM) system installed on a two-lane highway (Trans-Canada Highway 1). These data were used to validate the analytical model's outcome. The WIM system also collected individual vehicles' travelling speed, length, vehicle classification, etc. (Weigh2GoBC, 2020).

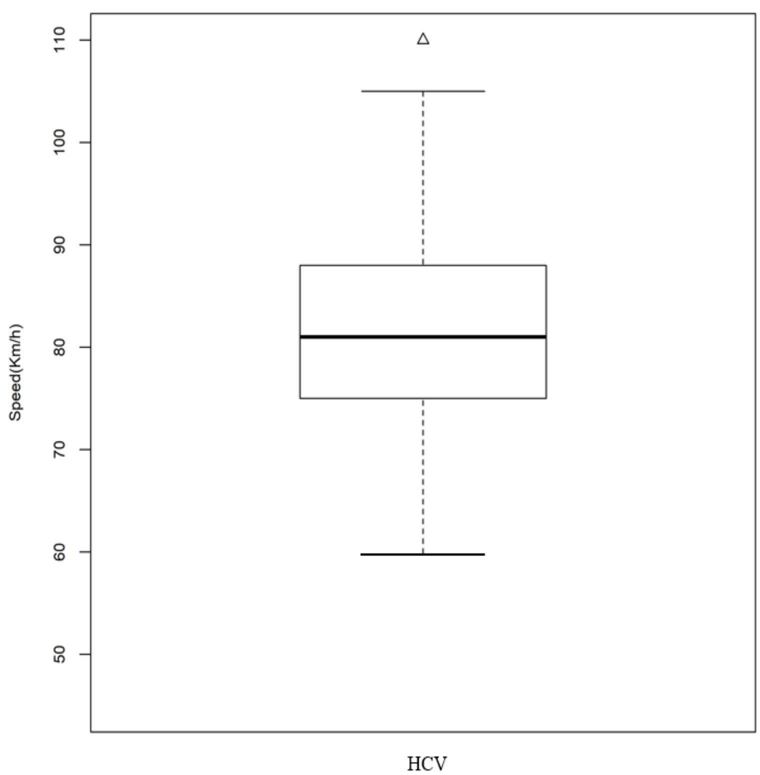


Figure 2-4: Average HCV Speed Distribution Collected through WIM system

Figure 2-4 presents the speed data of individual HCVs. The data include single unit HCVs and LCVs. The speed data in Figure 2-4 show, for example, that on a section with a posted speed limit of 100 km/h, the average speed of HCVs (e.g., WB-20 and B-Train LCV) was 81km/h. The minimum speed was 60 km/h and the maximum speed was 110 km/h (Mingyue Wang et al., 2019).

A two-sample t-test was also used to validate the accuracy of the simulation models (WisDOT, 2019). The null hypothesis was that the mean speed of the observed speed data (the WIM data) and the mean speed of the simulated speed data were equal.

Table 2-2 shows the results for the 18 cases. The p-values associated with the t-tests are insignificant (> 0.05) for all scenarios at the 95% confidence level indicating that the null hypothesis cannot be rejected as the observed and simulated speeds are close to each other. The results of a Kolmogorov–Smirnov (K-S) test, shown in Table 2-2, provide a further test of the similarity between the speed distributions (Arafat et al., 2020). The K-S test results are close to zero for all scenarios again indicating that the observed and simulated speeds are close to each other.

Table 2-2: Statistical Test Results for 18 Cases

Case	HCV Type	Scenario	Mean Speed [Simulation Result] (Standard Deviation) (Km/h)	Two Sample		KS -Test
				t-stat (degrees of freedom)	p-value	
1	B-Train LCV	Scenario 1	80.90 (13.64)	-1.29 (15,144)	0.20	0.16
2		Scenario 2	80.91 (12.88)	-1.10 (15,483)	0.27	0.10
3		Scenario 3	81.09 (14.65)	0.96 (15,034)	0.33	0.16
4	TD (Turnpike Double) LCV	Scenario 1	80.96 (13.72)	-0.49 (15,138)	0.62	0.15
5		Scenario 2	80.97 (12.82)	-0.37 (15,456)	0.71	0.10
6		Scenario 3	81.03 (14.48)	0.26 (14991)	0.79	0.15
7	2HCVP_0.6H	Scenario 1	80.85 (12.38)	-1.88 (14,578)	0.06	0.13
8		Scenario 2	81.09 (12.75)	0.98 (14,858)	0.33	0.10
9		Scenario 3	80.86 (13.29)	-1.70 (14,429)	0.09	0.11
10	2HCVP_1.2H	Scenario 1	80.91 (12.44)	-1.19 (14,588)	0.23	0.13
11		Scenario 2	81.04 (12.77)	0.41 (14,860)	0.68	0.10
12		Scenario 3	80.99 (13.34)	-0.20 (14,435)	0.84	0.10
13	3HCVP_0.6H	Scenario 1	81.02 (11.75)	0.16 (14,929)	0.87	0.12
14		Scenario 2	80.85 (12.56)	-1.77 (15,359)	0.08	0.09
15		Scenario 3	81.01 (12.88)	0.04 (14,703)	0.97	0.11
16	3HCVP_1.2H	Scenario 1	80.85 (11.79)	-1.78 (14,934)	0.08	0.12
17		Scenario 2	81.01 (12.29)	0.02 (15,095)	0.98	0.09
18		Scenario 3	80.95 (12.87)	-0.63 (14,701)	0.53	0.11

The testing results suggest that the VISSIM model successfully replicated the real-world traffic environment shown in Table 2-1. The estimated overtaking distance from the simulation model is compared with the observed overtaking distance reported in NCHRP Report 605 (Harwood et al., 2008). The NCHRP report gave the mean value of overtaking distance between two passenger vehicles (i.e., both the leading and the following vehicles were passenger vehicles) as 302 m (std. dev. = 69 m) based on 165 passenger vehicle overtaking maneuvers observed on various highways in Missouri, Pennsylvania, and Texas States. These results were used as input parameters for the Wiedemann 99 (W99) car-following model applied in the VISSIM simulation model developed in this study.

Table 2-3 provides information for our study's calibrated input parameters. All the parameters in Table 2-3 were input via the PTV VISSIM COM interface (PTV, 2021).

Table 2-3: Input Parameters

Input Parameters	Wiedemann 99 (W99)				
	VISSIM Default Value	**Passenger Vehicle**	**B Train LCV/ TD LCV**	**HCV Platoon ing**	**RV**
Standstill distance (m) for following a Passenger Vehicle	1.5	1.5	3.77	3.77	3.77
Standstill distance (m) for following a RV	1.5	4.07	3.05	3.05	3.05
Standstill distance (m) for following a B-Train LCV/ TD LCV	1.5	4.07	3.05	3.05	3.05
Standstill distance (m) for a following HCV platoon	1.5	4.07	3.05	1.00	3.05
Time headway (s) for following a Passenger Vehicle	0.9	1.5	2.5	2.5	2.5
Time headway (s) for following a RV	0.9	2.5	2.5	2.5	2.5
Time headway (s) for following a B-Train LCV/ TD LCV	0.9	2.5	2.5	2.5	2.5
Time headway (s) for a following HCV platoon	0.9	2.5	2.5	0.6/1. 2	2.5
Following distance oscillation (m)	4.00	4.93	4.93	4.93	4.93
Threshold for entering "Following" (s)	-8	-8.4	-8.43	-8.43	-8.43
Lane changing rule	Free Lane Selection	Slow lane rule	Slow lane rule	Slow lane rule	Slow lane rule
Cooperative lane changes	Not Selected	Selected	Selected	Selected	Selected
Maximum deceleration for cooperative braking (m/s^2)	-3	-3	-1.62	-1.62	-3
Safety distance reduction factor (m)	0.6	0.6	0.6	1	0.6
Number of interaction objects	2	1	1	2	1
Number of interaction vehicles	99	1	1	2	1
Maximum look ahead distance (m)	250	250	250	300	250
Maximum look back distance (m)	150	150	150	300	150

The input parameters are worth considering in some detail:

- The "standstill distance for a following car," "standstill distance for a following RV," "standstill distance for a following B-Train LCV/TD LCV," and "standstill distance for a following HCV platoon" indicate the minimum distance required to avoid a collision between a lead vehicle and following vehicle. The model uses 1.5 m for the standstill distance between two passenger vehicles, 3.05 m for the standstill distance between two consecutive LCVs, and 3.05 m for the standstill distance between two consecutive RVs. However, when a passenger car is following a RV, LCV or HCV platoon, the standstill distance is 4.07m, and when a RV, LCV or HCV platoon is following a passenger vehicle, the standstill distance is 3.77m as suggested by Lu et al., (2021). As suggested by Deng (2016) and Deng and Boughout (2016), we used 1.00 m for the standstill distance between two HCVs in the same platoon.
- The "time headway" indicates the distance from the front of the leading vehicle to the front of the following vehicle and is additional to the standstill distance. We used 1.5 seconds as the headway for passenger vehicles and 2.5 seconds as the headway for LCVs/RVs as suggested by Houchin et al., (2015). As discussed in Section 2.3.3, we followed previous studies and applied two headways (0.6 and 1.2 sec) for HCV platooning.
- The "following distance oscillation" indicates the maximum additional distance accepted for a "following" vehicle beyond the desired safety distance. The "threshold for becoming a following vehicle" defines the amount of time a vehicle required to decelerate before reaching the safety distance. W99 model suggests a 4.0 m following distance oscillation and a -8.0 second threshold for defining a "following" vehicle (PTV, 2021). We noticed

that the overtaking distance was less than the field observed overtaking distance and conducted a sensitivity analysis in which we changed the following distance oscillation to 0.01 m and the threshold for entering "following" to 0.1 second. We used 4.93 m for the following distance oscillation for passenger vehicles, LCVs, HCV platoons, and RVs. We assigned -8.4 seconds as the threshold for a passenger vehicle to become a "following" vehicle and -8.43 seconds for an LCV, HCV platoon and RV to become a "following" vehicle. These values were chosen to reproduce the field observations of overtaking distance.

- The "lane changing rule" indicates the lane in which a vehicle will consider performing a lane change. We modified the lane-changing rule by selecting the slow lane rule, but we allowed cooperative lane changes for passenger vehicles, LCV, HCV platoons, and RVs.
- The "maximum deceleration rate for cooperative braking" refers to the rate at which a target vehicle will decelerate in order to allow lane changes for another vehicle in order to enter the target vehicle's lane. Harwood et al. (2003) suggested a maximum deceleration value of -1.62 m/s^2 for conventional HCVs. We used Harwood et al.'s deceleration rate for a B-train LCV/TD LCV and for platooned HCVs.
- The lane-changing model also includes a "safety distance reduction factor" that reduces the minimum safety distance between a lead and following vehicle when the lead vehicle initiates a lane change. When a lead vehicle changes lane, a value of 0.6 indicates that an additional 40% reduction in the following vehicle's safety distance is accepted. Ahmed et al., (2021), however, suggested an extremely conservative value of 1.0 for HCVs in a

platoon. This value implies that platooned HCVs maintain the full minimum safety distance when changing lane.

- The term "number of interaction objects" refers to the interaction (i.e., communication) a vehicle has with objects such as traffic controls and other vehicles. The "number of interaction vehicles" refers only to the number of vehicle interactions. As conventional passenger vehicles, LCVs and RVs are controlled by humans, this study defined the number of interaction objects and the number of interaction vehicles for the passenger vehicle, LCV and RV as 1, as suggested by PTV (2021). The value of 1 means that a human controlled vehicle interacts (communicates) with other objects one at a time. The number of interaction objects and vehicles is greater than 1 for HCV platooning because an HCV in a platoon communicates simultaneously and automatically with other HCVs in the platoon (Sukennik, 2019).
- The “maximum look ahead” and “maximum look back” distances represent the maximum distance a driver can see forward and backward while changing lanes. This study used fixed values (250m and 150m respectively). The distances given for HCV platooning (300 m) are the distance over which an autonomous HCV can wirelessly communicate with another autonomous HCV and are based on suggestions made by NHTSA (2020). The two parameters affect mainly the number of overtaking maneuvers in a given time window. The “maximum look ahead” and “maximum look back” distances are important for simulating passing maneuvers as they define the opportunity for changing lanes according to the traffic volumes on opposite lane (an issue that is certainly outside the scope of this study). As the

distances do not affect the passing sight distance estimated, the two parameters are less important than other parameters in this particular study.

Table 2-4 shows the t-test results for the three scenarios. The Table shows the results for the estimated mean values of the overtaking distance. No result was statistically significant (p-value > 0.05) at the 95% confidence level indicating that the simulation model mimics real-world overtaking circumstances well. The calibration efforts and testing indicate that the simulation model can be used to estimate the passing sight distance required to overtake a truck platoon.

Table 2-4: T-Test Results for Three Scenarios

Scenarios	Microsimulation Results			Degrees of freedom	t-stat	p-value
	No of Observations	Mean Overtaking Distance (m)	Std. Dev. of Overtaking Distance (m)			
Scenario 1	2,052	307.66	59.35	187.92	1.09	0.28
Scenario 2	422	310.38	60.88	289.28	1.44	0.15
Scenario 3	891	311.09	54.91	212.11	1.71	0.09

2.4.2 Estimated PSD Using Micro-simulation

Figure 2-5 provides a box plot of the simulated distribution of the estimated overtaking distance for each of the three scenarios shown on Table 2-1 and six options considered. As mentioned earlier, PSD is defined as the 85th percentile value in an overtaking distance distribution (Harwood et al., 2008). Each box plot shows five statistics related to the overtaking distance: 1) minimum overtaking distance, 2) 15th percentile overtaking distance, 3) mean overtaking distance, 4) 85th percentile overtaking distance, and 5) maximum overtaking distance. Figure 2-5 also shows the estimated PSDs suggested by the 2018 AASHTO and 2017 TAC guidelines, and the proposed modified 2018 AASHTO model based on Equation (2-3).

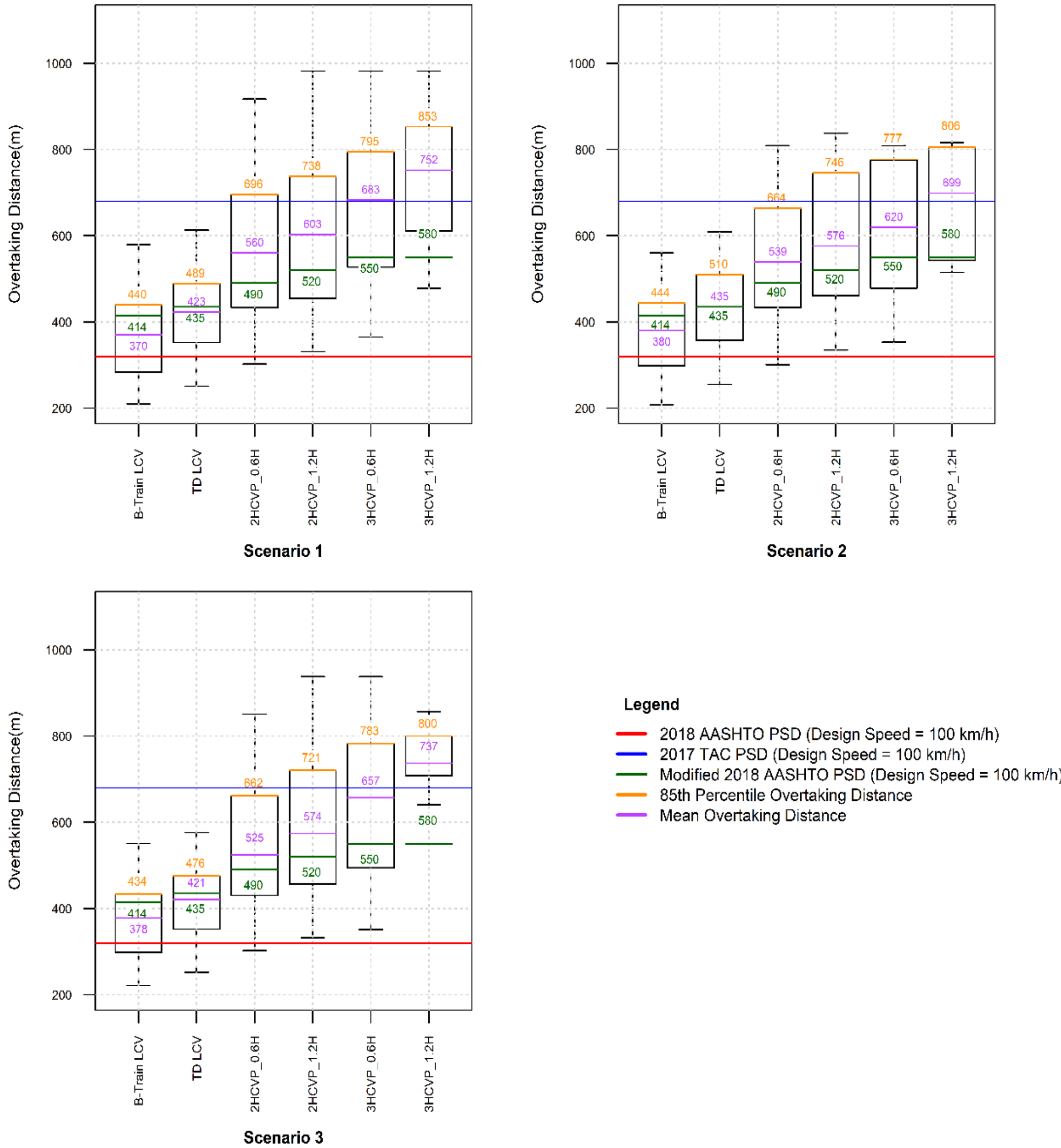


Figure 2-5: Overtaking Distances Estimated by Simulation

We observed the following:

- The estimated 85th percentile overtaking distance for the two LCV options (B-train and turnpike double B-train LCVs) is generally lower than the 2017 TAC PSD (blue line). For example, in scenario 2, the simulated 85th percentile overtaking distance for turnpike double B-train LCV is estimated as 510 m representing the highest of the three scenarios. The simulated PSD is still much shorter than the 2017 TAC PSD (680 m). Since the 2017 TAC PSD is the same as the earlier 2004 AASHTO PSD, this may imply that many two-lane rural highways in North America provide sufficient PSD for passing a slower-moving LCV, but the 2018 AASHTO PSD (320 m) did not provide sufficient space for passing maneuvers in any of the three scenarios.

- The estimated 85th percentile overtaking distance (orange line) for all six HCV options is much longer than the 2018 AASHTO PSD (red line) or the modified 2018 AASHTO PSD (green line). This is a concern.
- In general, the estimated 85th percentile overtaking distance for the two 3HCV platoon options is much longer than the PSD required for the 2HCV platoon options. For example, in scenario 1, the estimated 85th percentile overtaking distance for the 3HCVP_1.2H option requires 853 m which is 173 m longer than the 2017 TAC PSD (680 m). In all cases, the 2018 AASHTO PSD is much shorter than the 85th percentile PSD estimated for the 3HCV option by simulation. These simulation results suggest that operating a 3HCV option on two-lane rural highways in North America could be very challenging as many highway sections would not provide sufficient PSD for overtaking a 3HCV platoon.
- The 2017 TAC PSD corresponds to approximately the 85th percentile PSD simulated for the 2HCV_0.6H, but is somewhat shorter than the 85th percentile PSD simulated for the 2HCV_1.2H. Considering that the 2017 TAC PSD is much longer than our study's modified 2018 AASHTO PSD, the simulation results may imply that two vehicle HCV platooning operations on two-lane rural highways may be possible on two-lane rural

highways. However, these operations may require frequent passing lanes and the prohibition of passing maneuvers on other sections of two-lane highways especially for 2HCV_1.2H operation. The length of the passing lane based on PSD can reach up to 750m (see scenario 2 showing 746 m as the 85th percentile overtaking distance for 2HCV_1.2H).

- The 2018 AASHTO PSD (red line) was even lower than the 15th percentile of overtaking distance for all HCV platoon options considered in three scenarios. It is expected that two-lane rural highways that follow this guideline and assume an overtaking length of a passenger vehicle will experience major challenges in allowing HCV platooning.

2.5 Design Guidelines

The North American geometric guidelines can be adapted using this study's findings to modify estimates of minimum PSD for HCV platooning and LCVs. The simulation approach demonstrated more conservative results in comparison to the PSDs estimated by the analytic approach. The simulation PSDs subsequently suggested longer requirements than existing guidelines. As the development of a separate simulation model for every study corridor is not practical, we suggest using the modified 2018 AASHTO formula given in Equation (2-3) to provide explicit consideration to the length of platoons with additional modification using the simulation results. One method of that can be adopted is a scaling factor based on the ratio between the PSD estimated by the simulation approach and the PSD estimated by the analytic approach.

For example, for two-lane rural highways in mountainous regions where the design speed is expected to be relatively low (e.g., 60 km/h), the applicable scale factors are 2.05 for B-Train LCVs, 2.22 for TD LCV, 2.73 for 2HCVP_0.6H, 2.76 for 2HCVP_1.2H, 2.78 for

3HCVP_0.6H and 2.80 for 3HCVP_1.2H. For two-lane rural highways in flat terrain where the design speed can be higher (e.g., 100 km/h), the applicable scale factors are 1.06 for B-Train LCVs, 1.17 for TD LCV, 1.42 for 2HCVP_0.6H, 1.43 for 2HCVP_1.2H, 1.45 for 3HCVP_0.6H, and 1.47 for 3HCVP_1.2H. Equation (2-4) shows this calibration process with scaling factor F applied to the PSD given earlier in Equation (2-3).

$$PSD_{calibrated} = \mathrm{F} \ \mathrm{x\ PSD} \tag{2-4}$$

2.6 Conclusions and Recommendations

The goal of this first objective discussed in this chapter was to investigate how the introduction of HCV platooning on two-lane rural highways in North America might affect highway safety especially in terms of passing sight distance (PSD) parameter used in existing geometric design guidelines. Analytical and simulation methods were used to examine this important issue.

2.6.1 Summary of Results

The PSD recommended in the most recent (i.e., 2018) AASHTO guidelines is based on the overtaking distance required to pass a passenger vehicle rather than for an HCV (AASHTO, 2018, 2011; Harwood et al., 2008) although the PSD required clearly increases with vehicle length. In Canada, the recommended PSD is based on the 2004 AASHTO guidelines. As an HCV is much longer than a passenger vehicle and a platoon of HCVs will be even longer. It is likely that problems will arise for overtaking vehicles if platooned HCVs are allowed to use two-lane highways without appropriate PSD considerations.

The analytical contribution is based on development of a modified 2018 AASHTO model which was used to investigate the PSD required for passing six options: two different lengths of LCV, a two-vehicle HCV platoon travelling with a shorter headway between the

HCVs, a two-vehicle HCV platoon travelling with a longer headway between the HCVs, a three-vehicle HCV platoon travelling with a shorter headway between the HCVs, and a three-vehicle HCV platoon travelling with a longer headway between the HCVs.

The analytical results show that the 2017 TAC PSD guideline provides sufficient PSD for a passenger vehicle to pass all six HCV options over the entire range of design speed (50 – 130 km/h). This result should be viewed with caution based on the simulation results discussed in the next paragraph. The 2018 AASHTO PSD provides inadequate PSD for each of the six HCV options. For instance, when the design speed was 100 km/h, the gap between this study's required PSD and the 2018 AASHTO guideline varies from 94 m (for B-Train LCV) to 260 m (for 3HCVP_1.2H).

Three simulation scenarios based on the LH algorithm were used to create a suitable range of scenarios. The simulations showed differences when compared with the existing guidelines shown using the analytical approach. The simulation showed that the 2018 AASHTO PSD estimates do not provide sufficient length for a passenger vehicle to overtake any of the six HCV options when a passenger vehicle length is assumed. The 2017 TAC PSD estimates provide sufficient length for a passenger vehicle to pass the two LCV options and sufficient length for passenger vehicles to pass a 2HCV platoon, but falls short of the required 85th percentile overtaking distance for operating 3HCV platoon. The simulation showed that it appears to be very challenging for a passenger vehicle to pass a 3HCV platoon.

The results of this study are applicable to mountainous regions as the data are based on the speed data collected from WIM stations located on highways in mountainous area of British

Columbia. For two-lane rural highways on flat terrain, the study's proposed process can be used to estimate the applicable PSD.

It is likely that HCV platooning will negatively affect mobility on two-lane rural highways. For example, due to the increased PSD required by HCV platoons, HCV platooning is likely to reduce the number of passing opportunities and degrade the highway's level of service. The 2018 AASHTO's design guideline do not put highway designers in a position to adequately design passing lanes of the required length. Inadequate passing lanes may contribute to an increase in the number of severe collisions head-on collisions (Kaub and Berg, 1988; Mwesige et al., 2017).

The results of our analytical and simulation studies indicate that passing an HCV platoon by a passenger vehicle is challenging. This suggests that a situation in which one HCV platoon passes another HCV platoon would be even more difficult and would raise serious concerns in terms of the safe operation of HCVs involved. Therefore, it is recommended that the overtaking maneuver for an HCV platoon by another HCV platoon on two-lane rural highways be prohibited.

The analytical and simulation analyses suggest that many existing two-lane rural highways designed in accordance with the PSD requirement in the 2004 AASHTO or 2017 TAC guidelines could be used for LCVs. This is encouraging as several North American jurisdictions already allow LCV operations on certain two-lane rural highway corridors. The analytical and simulation analyses also suggest that 2HCV platooning may be feasible on two-lane rural highways that meet the 2004 AASHTO or 2017 TAC guidelines for PSD, but we suggest that providing frequent passing lanes on highway sections designated for 2HCV platooning would reduce possible safety concerns.

2.6.2 Limitations and Future Research

This study has some limitations that can be addressed in future work using this research as a starting point. There are areas of uncertainty arising from future V2V technology and impact on traffic conditions. For example, if future V2V technology allows vehicles to overtake safely without the need for a passing lane, the PSD requirement estimated in this study may provide some insights for determining the minimum distance for communicating between a vehicle wishing to overtake and an oncoming vehicle on the opposite lane.

Passing opportunities are an important metric for evaluating and enhancing the efficiency of a two-lane highway's traffic flow and help to define the operational performance of two-lane rural highways. Passenger vehicle drivers may be tempted to break the law if they are forced to wait behind a slow-moving HCV for an extended period of time due to decreased opportunities to overtake (Hostetter and Seguin, 1969). Passing opportunities are limited by the volume of traffic in the opposite lane. For instance, when volume on the opposite lane traffic volume is high, overtaking passenger vehicles will face potential conflicts more frequently (Harwood et al., 1985). It could be difficult to maintain two-lane highway's current operational performance after an HCV platoon has been deployed. Future research should examine operational performance measures such as overtaking time and overtaking frequency on two-lane rural highways under HCV platoon operation.

The simulations performed here used a fixed minimum headway of 1.5 seconds for passenger vehicles and 2.5 seconds for HCVs and LCVs. These values were based on the observed headways reported by Houchin et al., (2015). Unfortunately, due to the scarcity of HCV platoon operations in real-world traffic environments, no study has yet reported observed headway values for HCV platoons (i.e., the headway between a platoon and a vehicle ahead). Similarly, there is no evidence based on field observations that the minimum headway between a passenger vehicle and an HCV platoon ahead will be maintained at 1.5 seconds. Future work will need to consider different headways for HCV platooning especially when a considerable number of vehicles on the road can communicate each other in a V2V environment. In such a case, the minimum headways could be very different from those assumed in this study. It will, however, take time to collect enough data, as HCV platooning is not yet commonplace on two-lane rural highways in North America.

Existing V2V technology already allows a passenger vehicle to cut-in and cut-out safely between platooning HCVs (Shladover et al., 2018; Xiao et al., 2017), but for the sake of simplicity, this study did not consider cut-in/cut-out maneuvers between HCVs in a platoon during a overtaking maneuver. It was assumed that the overtaking vehicle would pass the HCV platoon in a single maneuver regardless of the number of HCVs in a platoon. We also did not consider possible cooperation between the platooning HCVs to assist the overtaking vehicles. In reality, HCVs in a platoon may adjust their operating speed or create gaps when needed to ensure the safe passing of overtaking vehicles.

It should also be noted that the research did not consider the impact of vertical slope on PSD. A steep slope will substantially reduce the speed of an HCV platoon and the acceleration capability of the overtaking vehicle. Nonetheless, we think that the findings of this research can be regarded as valuable seed information for transportation engineers considering HCV platooning operation on two-lane highways. It is strongly suggested that the modifications to the existing guidelines presented in this research are utilized to increase the PSD when designing two-lane rural highways for HCV platoons and LCVs. This contribution helps establish appropriate PSD estimates on two-lane rural highways.

It is further noted that a limited number of two-lane rural highways would be newly constructed. However, the task of updating lane marking on two-lane rural highways is often undertaken by ministries during their regular highway maintenance. If a ministry is willing to permit the operation of HCV platooning on their two-lane rural highways, re-striping of the overtaking segments could be executed according to the proposed PSD requirements for HCV platoons suggested in this study. Additionally, LCVs are regulated in several North American jurisdictions. As in the case of LCV regulation, the operation of HCV platoons could be restricted to designated routes during specific times of the day. Future research should be conducted to determine the appropriate time window for HCV platoon operation.

2.7 Chapter 2 References

AASHTO. (2004). A Policy on Geometric Design of Highways and Streets (5th ed.). American Association of State Highway and Transportation Officials.

AASHTO. (2011). A Policy on Geometric Design of Highways and Streets (6th ed.). American Association of State Highway and Transportation Officials.

AASHTO. (2018). A Policy on Geometric Design of Highways and Streets (7th ed.). American Association of State Highway and Transportation Officials.

Abdulhai, B., Sheu, J.-B., & Recker, W. W. (2002). Development and performance evaluation of an ITS-ready microscopic traffic model for Irvine, California. Journal of Intelligent Transportation Systems, 7(1), 79–102.

Ahmed, H. U., Huang, Y., & Lu, P. (2021). A Review of Car-Following Models and Modeling Tools for Human and Autonomous-Ready Driving Behaviors in Micro-Simulation. Smart Cities, 4(1), 314–335.

Alam, A., Besselink, B., Turri, V., Martensson, J., & Johansson, K. H. (2015). Heavy-duty vehicle platooning for sustainable freight transportation: A cooperative method to enhance safety and efficiency. IEEE Control Systems Magazine, 35(6), 34–56.

Alberta Transportation. (2020a). Long Combination Vehicle Program. Government of Alberta. https://www.alberta.ca/long-combination-vehicle-program.aspx

Alberta Transportation. (2020b). Traffic Volumes on Links in the Highway Network. Government of Alberta. https://open.alberta.ca/opendata/traffic-volumes-on-links-in-the-highway-network#related

Arafat, M., Nafis, S. R., Sadeghvaziri, E., & Tousif, F. (2020). A data-driven approach to calibrate microsimulation models based on the degree of saturation at signalized intersections. Transportation Research Interdisciplinary Perspectives, 8, 100231.

Bibeka, A., Songchitruksa, P., & Zhang, Y. (2019). Assessing environmental impacts of ad-hoc truck platooning on multilane freeways. Journal of Intelligent Transportation Systems, 1–12.

Bureau of Economic Analysis. (2019). Gross Output by Industry. Bureau of Economic Analysis. https://apps.bea.gov/iTable/iTable.cfm?ReqID=51&step=1

Butler, C. (2019). A "demographic tsunami" is about to make Canada's trucker shortage even worse | CBC News. CBC News. https://www.cbc.ca/news/canada/london/canada-ontario-truck-driver-trucker-shortage-1.5400992

Canadian Trucking Alliance. (2020). CBSA: Truck Crossings Fall 33%. Border & Customs, Business Conditions, COVID-19. http://cantruck.ca/cbsa-truck-crossings-fall-33

CCMTA. (2016). Automated Vehicles in Canada. https://ccmta.ca/images/publications/pdf/CCMTA_WhitePaper_Automated_Vehicles_in_Canada_2017.pdf

Chowdhury, M. T. U., & Park, P. Y. (2019). Implication of truck platooning on passing sight distance on two-lane rural highways in Canada. 29th Canadian Association of Road Safety Professionals (CARSP) Conference.

Chowdhury, M. T. U., & Park, P. Y. (2021). Impact of truck platooning on passing sight distance of two-lane highways in North America. Transportation Research Board 100th Annual MeetingTransportation Research Board, TRBAM-21-00207.

Clement, J. (2020a). Retail e-commerce revenue in Canada from 2017 to 2024. Statista.

https://www.statista.com/statistics/289741/canada-retail-e-commerce-sales

Clement, J. (2020b). Retail e-commerce sales in the United States from 2017 to 2024. Statista. https://www.statista.com/statistics/272391/us-retail-e-commerce-sales-forecast

Costello, B. (2019). Truck driver shortage analysis 2019. https://www.trucking.org/sites/default/files/2020-01/ATAs Driver Shortage Report 2019 with cover.pdf

Deng, Q. (2016). Heavy-Duty Vehicle Platooning – Modeling and Analysis.

Deng, Q., & Boughout, W. (2016). The impacts of heavy-duty vehicle platoon spacing policy on traffic flow.

Essa, M., & Sayed, T. (2016). A comparison between PARAMICS and VISSIM in estimating automated field-measured traffic conflicts at signalized intersections. Journal of Advanced Transportation, 50(5), 897–917. https://doi.org/10.1002/atr.1381

FHWA. (2010). Freight Facts and Figures 2010. https://ops.fhwa.dot.gov/freight/freight_analysis/nat_freight_stats/docs/10factsfigures/figure3_4.htm

Figueira, A. C., & Larocca, A. P. C. (2020). Analysis of the factors influencing overtaking in two-lane highways: a driving simulator study. Transportation Research Part F: Traffic Psychology and Behaviour, 69, 38–48.

Forbes, G. (1990). The origin of minimum passing sight distances for no-passing zones. ITE Journal, 60(12), 20–24.

Girianna, M., & Benekohal, R. F. (2004). Using genetic algorithms to design signal coordination for oversaturated networks. Journal of Intelligent Transportation Systems, 8(2), 117–129.

Glennon, J. C. (1988). New and improved model of passing sight distance on two-lane highways. Transportation Research Record, 1195, 132–137.

Habtemichael, F., & Picado-Santos, L. (2013). Sensitivity analysis of VISSIM driver behavior parameters on safety of simulated vehicles and their interaction with operations of simulated traffic. 92nd Annual Meeting of the Transportation Research Board. Washington, DC.

Hanley, P. F., & Forkenbrock, D. J. (2005). Safety of passing longer combination vehicles on two-lane highways. Transportation Research Part A: Policy and Practice, 39(1), 1–15. https://doi.org/10.1016/j.tra.2004.09.001

Harwood, D.W., John, A.D.S., Warren, D.L. (1985). Operational and safety effectiveness of passing lanes on two-lane highways. Transportation Research Record, 1026, 31–39.

Harwood, D W., & Glennon, J. C. (1989). Passing sight distance design for passenger cars and trucks. Transportation Research Record, 1208, 59–69.

Harwood, D W, Gilmore, D. K., Richard, K. R., Dunn, J. M., & Sun, C. (2008). NCHRP Report 605: Passing sight distance criteria. In Transportation Research Board of the National Academies, Washington, DC. https://doi.org/10.17226/23278

Harwood, D W, & Glennon, J. C. (1976). Framework for design and operation of passing zones on two-lane highways. Transportation Research Record, 601, 45–50.

Harwood, Douglas W, Torbic, D. J., Richard, K. R., Glauz, W. D., & Elefteriadou, L. (2003). NCHRP Report 505 : Review of truck characteristics as factors in roadway design. Transportation Research Board.

Hassan, Y., Easa, S. M., & El Halim, A. O. A. (1996). Passing sight distance on two-lane highways: Review and revision. Transportation Research Part A: Policy and Practice, 30(6), 453–467.

Hostetter, R.S., Seguin, E.L. (1969). The Effects of Sight Distance and Controlled Impedance on Passing Behavior. HRB-Singer Incorporated.

Houchin, A., Dong, J., Hawkins, N., & Knickerbocker, S. (2015). Measurement and Analysis of Heterogenous Vehicle Following Behavior on Urban Freeways: Time Headways and Standstill Distances. 2015 IEEE 18th International Conference on Intelligent Transportation Systems, 888–893. https://doi.org/10.1109/ITSC.2015.149

Jehn, N. L., & Turochy, R. E. (2019). Calibration of Vissim Models for Rural Freeway Lane Closures: Novel Approach to the Modification of Key Parameters. Transportation Research Record, 2673(5), 574–583.

Jenkins, J. M. (2004). Modelling the interaction between passenger cars and trucks (Issue August). Texas A&M University.

Kaub, A. R., & Berg, W. D. (1988). Design guide for auxiliary passing lanes on rural two-lane highways. Transportation Research Record, 1195, 92–100.

Kuhn, B., Lukuc, M., Poorsartep, M., Wagner, J., Balke, K. N., Middleton, D., Songchitruksa, P., Wood, N., & Moran, M. (2017). Commercial truck platooning demonstration in Texas–level 2 automation. Texas. Dept. of Transportation. Research and Technology Implementation Office.

Llorca, C., & García, A. (2011). Evaluation of passing process on two-lane rural highways in spain with new methodology based on video data. Transportation Research Record, 2262, 42–51. https://doi.org/10.3141/2262-05

Lu, C., Dong, J., Houchin, A., & Liu, C. (2021). Incorporating the standstill distance and time headway distributions into freeway car-following models and an application to estimating freeway travel time reliability. Journal of Intelligent Transportation Systems, 25(1), 21–40. https://doi.org/10.1080/15472450.2019.1683450

Mampearachchi, W. K., & Masakorala, S. R. (2018). Analytical model for passing sight distance design criteria of two-lane roads in Sri Lanka. Transport and Telecommunication, 19(1), 10–20. https://doi.org/10.2478/ttj-2018-0002

Manjunatha, P., Vortisch, P., & Mathew, T. V. (2013). Methodology for the Calibration of VISSIM in Mixed Traffic. Transportation Research Board 92nd Annual Meeting, 11.

MTO. (2021). Long Combination Vehicle (LCV) Program Conditions. Ontario Ministry of Transportation. http://www.mto.gov.on.ca/english/trucks/long-combination-vehicles-program-conditions.shtml?fbclid=IwAR3ghZcHpUs03yyuOazz9RVixLVOTZq1EOEbuc3Auo9I88owVnC50k0on14

Mwesige, G., Farah, H., Bagampadde, U., & Koutsopoulos, H. (2017). Effect of passing zone length on operation and safety of two-lane rural highways in Uganda. IATSS Research, 41(1), 38–46. https://doi.org/10.1016/j.iatssr.2016.09.001

NHTSA. (2020). Vehicle-to-Vehicle Communication. U.S. Department of Transportation. https://www.nhtsa.gov/technology-innovation/vehicle-vehicle-communication#

Ohene, F. A., & Ardekani, S. A. (1988). Minimum Passing Sight Distance for Completing or Aborting the Passing Maneuver. ITE Journal, 58(7), 29–33.

Park, B., Won, J., & Perfater, M. A. (2006). Simulation model calibration and validation: phase II: development of implementation handbook and short course. Virginia Transportation

Research Council.

Patten, J., McAuliffe, B., Mayda, W., & Tanguay, B. (2012). Review of aerodynamic drag reduction devices for heavy trucks and buses. National Research Council Canada NRC Technical Report CSTT-HVC-TR, 205, 3.

Paulsen, J. T. (2018). Physical Infrastructure Needs for Autonomous & Connected Trucks-An Exploratory Study. NTNU.

Pline, J. L. (Ed. . (1999). Traffic Engineering Handbook (5th Editio). Institute of Transportation Engineers (ITE).

Praticò, F. G., & Giunta, M. (2012). Modeling operating speed of two lane rural roads. Procedia-Social and Behavioral Sciences, 53, 664–671.

Proust, E., Smith, P., Pierce, D., Ward, J., & Bevly, D. (2019). Evaluation of Platooning on Resource Roads. 2019 TAC-ITS Canada Joint Conference.

PTV. (2021). PTV Vissim 2021 User Manual. In Karlsruhe, Germany: PTV. PTV AG.

Ramezani, H., Shladover, S. E., Lu, X.-Y., & Chou, F.-C. (2018a). Microsimulation Framework to Explore Impact of Truck Platooning on Traffic Operation and Energy Consumption: Development and Case Study (Issue February).

Ramezani, H., Shladover, S. E., Lu, X. Y., & Altan, O. D. (2018b). Micro-Simulation Of Truck Platooning with Cooperative Adaptive Cruise Control: Model Development and A Case Study. Transportation Research Record, 2672(19), 55–65. https://doi.org/10.1177/0361198118793257

Reynolds, C. (2020). Report sounds alarm over truck driver shortage as job vacancies rise | The Star. The Canadian Press. https://www.thestar.com/business/2020/03/11/report-sounds-alarm-over-truck-driver-shortage-as-job-vacancies-rise.html

Rilett, L. R., Hutchinson, B. G., & Whitney, M. (1990). Mechanics of the passing maneuver and the impact of large trucks. Transportation Research Part A: General, 24(2), 121–128.

Romana, M. G., Martin-Gasulla, M., & Moreno, A. T. (2019). Comparing Alternatives of a 2+ 1 Highway with Two-lane Highways through Simulation. Transportation Research Board 98th Annual Meeting.

SAE International Standard. (2016). Automated Driving: Levels of Driving Automation. In SAE J3016.

Saito, M. (1984). Evaluation of the adequacy of the MUTCD minimum passing sight distance requirement for aborting the passing maneuver. ITE Journal, 54(1), 18–22.

Shladover, S. E., Lu, X.-Y., Yang, S., Ramezani, H., Spring, J., Nowakowski, C., & Nelson, D. (2018). Cooperative Adaptive Cruise Control (CACC) For Partially Automated Truck Platooning: Final Report (Issue March). https://escholarship.org/uc/item/260060w4

Smith G, J. (2020, February 20). Canada's Truck Drivers to Require 103.5 hours of Training. Trucknews.Com. https://www.trucknews.com/transportation/canadas-truck-drivers-to-require-103-5-hours-of-training/1003136596/

Statistics Canada. (2020). Gross domestic product (GDP) at basic prices, by industry, annual average (x 1,000,000). Statistics Canada. https://doi.org/10.25318/3610043401-eng

Sukennik, P. (2019). Micro-Simulation Guide for Automated Vehicles-D2.5. CoXEist, 1-29.

Sun, J., Liu, H., & Ma, Z. (2019). Modelling and simulation of highly mixed traffic flow on two-lane two-way urban streets. Simulation Modelling Practice and Theory, 95, 16–35.

TAC. (2017). Geometric design guide for Canadian roads.

Tavasszy, L. A., & Janssen, R. (2017). The value case for truck platooning. working paper. January.

Transport Canada. (2019). National Collision Database. Transport Canada. https://open.canada.ca/data/en/dataset/1eb9eba7-71d1-4b30-9fb1-30cbdab7e63a

USDOT. (2018a). Automated Vehicles: Truck Platooning ITS Benefits, Costs, and Lessons Learned: 2018 Update Report. https://www.itsknowledgeresources.its.dot.gov/its/bcllupdate/pdf/BCLL_Automated Vehicles (CMV) Final Draft v4.pdf

USDOT. (2018b). FARS Encyclopedia: Vehicles - All Vehicles. National Highway Traffic Safety Administration. https://www-fars.nhtsa.dot.gov/Vehicles/VehiclesAllVehicles.aspx

USDOT. (2018c). Vehicles Involved in Single- and Two-Vehicle Crashes, by Vehicle Maneuver and Crash Severity, 2018. National Highway Traffic Safety Administration. https://cdan.nhtsa.gov/SASStoredProcess/guest

Várhelyi, A., Kaufmann, C., Johnsson, C., & Almqvist, S. (2020). Driving with and without automation on the motorway–an observational study. Journal of Intelligent Transportation Systems, 1–22.

Wang, M., Nevland, E. ., & Park, P. Y. (2019). Average Speed Enforcement for Heavy Vehicles by Weight Classification. CITE Annual Conference.

Wang, Y., & Cartmell, M. P. (1998). New model for passing sight distance on two-lane highways. Journal of Transportation Engineering, 124(6), 536–545.

Weigh2GoBC. (2020). Weigh2GoBC - Province of British Columbia. British Columbia Ministry of Transportation. https://www2.gov.bc.ca/gov/content/transportation/vehicle-safety-enforcement/services/weigh2gobc-join

Weng, Y., Salehi, R., Ge, X., Rizzo, D., Castanier, M. P., Heim, S., & Ersal, T. (2020). Model-free speed management for a heterogeneous platoon of connected ground vehicles. Journal of Intelligent Transportation Systems, 1–15.

WisDOT. (2019). Traffic Analysis and Modeling Section 20: Microscopic Simulation Traffic Analysis. In Traffic Engineering, Operations & Safety Manual (pp. 1–47). Wisconsin Department of Transportation. https://wisconsindot.gov/dtsdManuals/traffic-ops/manuals-and-standards/teops/16-20.pdf#16-20-8

Wood, S., & Regehr, J. D. (2017). Regulations governing the operation of longer combination vehicles in Canada. Canadian Journal of Civil Engineering, 44(10), 838–849.

Woodrooffe, J., Anderson, D., & Ash, L. (2004). The influence of policy on crash rate of long combination vehicles. Proceedings of the 8th International Symposium on Heavy Vehicle Weights.

Xiao, L., Wang, M., & Van Arem, B. (2017). Realistic car-following models for microscopic simulation of adaptive and cooperative adaptive cruise control vehicles. Transportation Research Record, 2623(2623), 1–9. https://doi.org/10.3141/2623-01

CHAPTER 3: TRUCK PLATOONING ON URBAN ARTERIAL ROADWAYS

3.1 Introduction

This chapter focuses on the second objective of this dissertation. The second objective of this study is to estimate the operational impact of heavy commercial vehicle (HCV) platooning on urban arterial roadways. A set of PTV VISSIM micro-simulation models have been developed to measure the mobility of HCV platooning with and without traffic signal priority condition. HCVs will prefer to use large highway infrastructure where possible but, in many cases, cannot avoid urban travel for the first-mile and last-mile trip components. In the United States in 2018, HCVs travelled a total of 304,864 million miles (Mm) of which 164,321Mm (54%) was on urban roadways. The urban roadways can be further disaggregated into 66,727Mm (40.6%) on urban freeways and 97,594Mm (59.4%) on other urban roadways such as major and minor arterials (USDOT, 2020).

Current vehicle-to-vehicle (V2V) technologies can provide wireless connections that allow two or more HCVs to travel in a platoon (Alam et al., 2015; Browand et al., 2004; Patten et al., 2012; Ramezani et al., 2018a; Tavasszy and Janssen, 2017; Zabat et al., 1995). According to the Society of Automotive Engineers (SAE), HCV platooning is an example of Level 3 to Level 5 automation. SAE level 3 platooning requires a human driver in every vehicle. Most HCV platooning tests have been conducted at this level to date. At SAE level 4, a human driver is required in the leading vehicle, but one or more of the following vehicles may be driverless. At SAE level 5, none of the vehicles in a platoon have a human driver (Bishop, 2020; SAE International Standard, 2016; USDOT, 2018a). Several North American jurisdictions including

Alberta, California, Florida, Ontario, and Texas, have permitted SAE level 3 HCV platoon testing on designated freeway corridors (CCMTA, 2016; Kuhn et al., 2017). The tests have shown that a platoon tightens the gaps between the HCVs and helps to minimize aerodynamic drag leading to reduced fuel consumption and emissions. At 80km/h (49.7mi/h) on freeways, fuel consumption can be reduced by up to 6% for the lead HCV and by up to 10% for the following HCVs (Alam et al., 2015; Browand et al., 2004; Patten et al., 2012; Ramezani et al., 2018a; Tavasszy and Janssen, 2017; Zabat et al., 1995). For a platoon travelling at 70km/h (43.5mi/h) on a freeway, Alam et al. (2010) found a 4.7% reduction in fuel consumption for the lead HCV and a 7.7% reduction for the following HCVs.

HCVs often need to travel on urban arterials when, for example, picking up or delivering goods to warehouses, airports, and intermodal facilities (e.g., railroad yards). Travel on urban arterials involves signalized intersections and posted speed limits which are often lower than 70km/h (43.5mi/h), therefore reductions in fuel consumption and emissions for HCV platoons on urban arterials are expected to be lower than on freeways. HCV platooning on urban arterial networks may, however, offer benefits especially when compared with a long combination vehicle (LCV). An LCV is a tractor-trailer combination with two or more trailers driven by a single driver. An LCV is therefore similar to an HCV platoon since both approaches use multiple trailers, but the former can gain fuel savings without the need for autonomous technology. Yet the additional length of an LCV requires more physical space. LCVs require additional horizontal clearance and increased turning radii when compared to standard tractor-trailers and therefore encounter more difficulties with many urban intersections and roundabouts (AASHTO, 2018; TAC, 2017). An HCV platoon can use the same horizontal clearance and turning radius as a single HCV. The increased physical dimensions of an LCV will also require more space at truck parking facilities and may struggle with existing truck parking availability (Nevland et al., 2020; Park, 2019).

To ensure safe operations, the requirement for LCV driver licensing is more onerous when compared with traditional HCVs. In Ontario, for example, an LCV driver must have at least five years of HCV driving experience and more than 100 hours of classroom training (MTO, 2021a; Smith G, 2020). HCV platooning at SAE level 4 or higher may help to alleviate the shortage of truck drivers without the additional restrictions of LCVs. Costello (2019) reported that the United States will need approximately 160,000 new HCV drivers by 2028, and Butler (2019) reported that Canada will need 34,000 new HCV drivers by 2024. In 2018, FPInnovations tested the technical feasibility of SAE level 4 HCV platooning on two-lane rural highways connecting logging sites to a nearby port. The platooned HCVs were driven by a single driver in the lead HCV (Proust et al., 2019). We found that most of the past studies discussing SAE level 3 HCV platooning focused on investigating the impact on fuel consumption and emissions. There is a clear research need to investigate the operational impact of SAE level 4 (or higher) HCV platooning under the existing roadway and traffic environment especially in urban setting.

3.1.1 Problem Statements

Most HCV platooning studies have been conducted on freeways which are very different from the geometric and traffic environment of arterials and other urban roadways where at grade intersections make traffic signals and other measures necessary. Numerous studies have investigated special traffic control strategies that include a priority signal phase for a targeted transportation mode such as transit buses, emergency vehicles, or freight transportation (Balke et al., 2000; Beak et al., 2018; Guler and Menendez, 2014; Ikiriko et al., 2019; Islam et al., 2018; Kuang and Xu, 2012; Rodriguez and Danaher, 2014). Changes in travel time are typically used to measure the impact of different traffic control strategies on operational performance. Beak et al., (2018) investigated the impact of signal priority on transit buses on an 8.2km (5.1mi) arterial with 13 signalized intersections along Redwood corridor in Salt Lake City, Utah. The study reported that transit signal priority reduced overall network travel time by 15.5 s per vehicle and for transit vehicles travel time was reduced by 8.3 s per vehicle. Kaisar et al., (2020) investigated two independent signal priorities strategies, one for transit buses and one for freight vehicles. The study was conducted for traffic passing through nine signalized intersections on a 7.1km (4.4mi) corridor in Broward County, Florida. Transit signal priority reduced overall corridor travel times by 18.1 seconds per vehicle, and freight signal priority reduced travel times by 84.2 seconds per vehicle. However, transit signal priority reduced travel times by 251.2 seconds per transit vehicle, and freight signal priority reduced travel times by 175.3 seconds per freight vehicle. Kaisar et al., (2020) also observed an increase in average travel times for cross-street traffic due to the signal priority systems. This increase occurred because the extended green time provided for transit and freight vehicles reduced the green time available to cross-street traffic. The study reported an average travel time increase of 50 seconds for cross-street traffic movements when freight signal priority was applied.

Researches by Tiaprasert et al. (2019) and Wang et al. (2020) investigated traffic signal priority strategies for platooned passenger vehicles on urban arterial roadways although these two studies differed in their approach. Tiaprasert et al. (2019) employed an analytical analysis while Wang et al. conducted a micro-simulation. Both studies found that the signal priority strategies reduced the travel time and number of stops at intersections for platooned passenger vehicles. No study has yet investigated the impact of signal priority strategies on HCV platoons which will behave differently due to differences in vehicle length and acceleration/deceleration rates, etc. Automated HCV platoons require further attention as the vehicles need to remain close together to result in any benefits. For such platoons, the green phase at signalized intersections must be able to accommodate more than one HCV. This aspect of HCV platooning especially SAE level 4 or higher has implications for existing and future surface infrastructure and traffic control systems at signalized intersections as re-establishing an HCV platoon broken by signal interruption is very challenging in urban traffic environments with high traffic volumes. Note that we were unable to find any study that has applied signal priorities for more than one directional traffic flows at an intersection, such as signal priority applied for both through and left turning traffics simultaneously. This is not surprising as prioritizing traffic flow in one direction will have a negative trade-off with other directions.

The market penetration rate of platooned vehicles refers to the proportion of vehicles of the same vehicle classification traveling as a convoy and has been identified as a key issue in the operational performance of platooned vehicles (Bujanovic and Lochrane, 2018). In the case of platooned passenger vehicles, market penetration rates of 5% to 100% have been analyzed, usually by micro-simulation (Arnaout and Bowling, 2011; Bujanovic and Lochrane, 2018; Van Arem et al., 2006; Zhao and Sun, 2013). Van Arem et al. (2006) showed that a 40% or higher market penetration rate for platooned passenger vehicles on freeways can increase freeway capacity by 3%. Arnaout and Bowling (2011) reported no substantial change in traffic throughput on a freeway if the market penetration rate of platooned passenger vehicles is less than 40%. Lioris et al., (2017) and Smith et al., (2020) investigated the impact of passenger vehicle platooning on arterials. Both studies assumed a 100% market penetration rate, and both showed that this condition can double the passenger vehicle throughput. Gordon and Turochy (2016) investigated the operational impact of HCV platooning on a freeway by estimating travel time delay changes on 8.5km (5.3mi) of interstate highway I-85 in Alabama. They compared simulated travel times delay with baseline travel times delay for traffic flows with no platooning, resulting in 19.1 seconds per vehicle. The study found that an HCV platooning market penetration rate of 20% reduced travel time delay by 7.7 seconds (40%) for passenger vehicles and HCVs. A 100% market penetration rate reduced travel time delay by 13.3 seconds (69%) for passenger vehicles and HCVs. Notice that all existing studies have investigated operational impact of varying market penetration rate of HCV platooning on freeways and no study has been published to discuss its impact on urban arterials. Knowing, however, that many roadways surrounding major distribution centres and logistic companies are urban arterials with frequent signalized intersections, it is important to assess the impact of market penetration rates for platooned HCVs on urban arterial mobility.

As this study investigates the operational impact of SAE level 4 HCV platooning, which requires fully functional network-wide vehicle-to-infrastructure (V2I) technology, it is uncertain when, or if, a roadway will exhibit 100% market penetration for platooned vehicles in this level of automation. Although many studies have discussed relatively high market penetration rate for vehicle platooning, we think it is unlikely that SAE level 4 HCV platooning can be widespread in a foreseeable future as it requires not only further development in vehicle technology but also requires large capital investments by government to enable the seamless wireless communication between numerous traffic control systems installed at many intersections and numerous HCVs traveling on our roadway. Nonetheless, there is a need for investigation into the impact of relatively low percentages of HCV platooning operation on the mobility of urban roadways. A high percentage is not expected in the near future as the HCV platooning technology is first utilized between HCVs in the same fleet that travel along the same route. This is notable for large establishments requiring multiple trucks to make regular and frequent deliveries between a given origin and destination. In the longer term, a higher penetration rate may occur as the technology sees widespread acceptance and usage. However, this situation is beyond the scope of the paper. The driving attributes of passenger cars and other HCV will need to be revisited in such a case to accommodate a system-wide change to all vehicles for automated vehicle (AV) adoption.

3.1.2 Study goal and objectives

To achieve the goal of the second objective of this study discussed in this chapter, two following sub-objectives has been considered:

- Analyze the impact of SAE level 4 HCV platooning using existing traffic controls (do-nothing scenario) and with traffic signal priority for HCV platoons;
- Evaluate the impact of SAE level 4 HCV platooning with the implementation of traffic signal priority for HCV platoons; and
- Distinguish the effect of three low market penetration rates (0%, 5% and 10%) for SAE level 4 HCV platooning.

The two traffic control scenarios and the three market penetration rates were tested by micro-simulation as SAE level 4 HCV platooning is still under development so real-world HCV platooning data are not readily available (Ioannou, 2015; Mjogolo et al., 2019; Ramezani et al., 2018a; Zhao and Ioannou, 2016). The study uses PTV VISSIM software (Version 2021) as the main simulation tool (PTV, 2021). Two measures of performance applied to evaluate the results include the changes in travel time and the number of stops for all vehicles, passenger vehicles, and HCVs.

3.2 Study Area and Data

The study corridor was a section of Derry Road. Derry Road is a major arterial and designated HCV route located northwest of Toronto in Mississauga, Peel Region, Ontario. The road has some of the highest HCV traffic volumes on all major arterials in Ontario with up to approximately 960 vehicles per hour (vph) per segment (Ferguson et al., 2014; Sureshan and Branch, 2009).

Figure 3-1 shows the 9.2km (5.7mi) section of Derry Road selected as the study corridor. The corridor runs along the northern boundary of Toronto Pearson International Airport which is the largest airport in Canada and one of the largest passenger traffic and HCV traffic attractors in Ontario. The east end of the study corridor provides a connection to Highway 427, a major Ontario freeway with annual average daily truck traffic (AADTT) of approximately 17,000, i.e., high HCV traffic volumes (MTO iCorridor, 2021). The Derry Road corridor has three lanes in each direction and 16 signalized intersections resulting in 15 segments from Kennedy Road in the west to Goreway Drive in the east.The two green dots in Figure 3-1 show the ends of the study corridor. The eight red dots show the major intersections connecting Derry Road to other major arterials. The eight blue dots show the remaining minor intersections, for instance, that are connected to nearby small plazas. The study examined west bound traffic only.

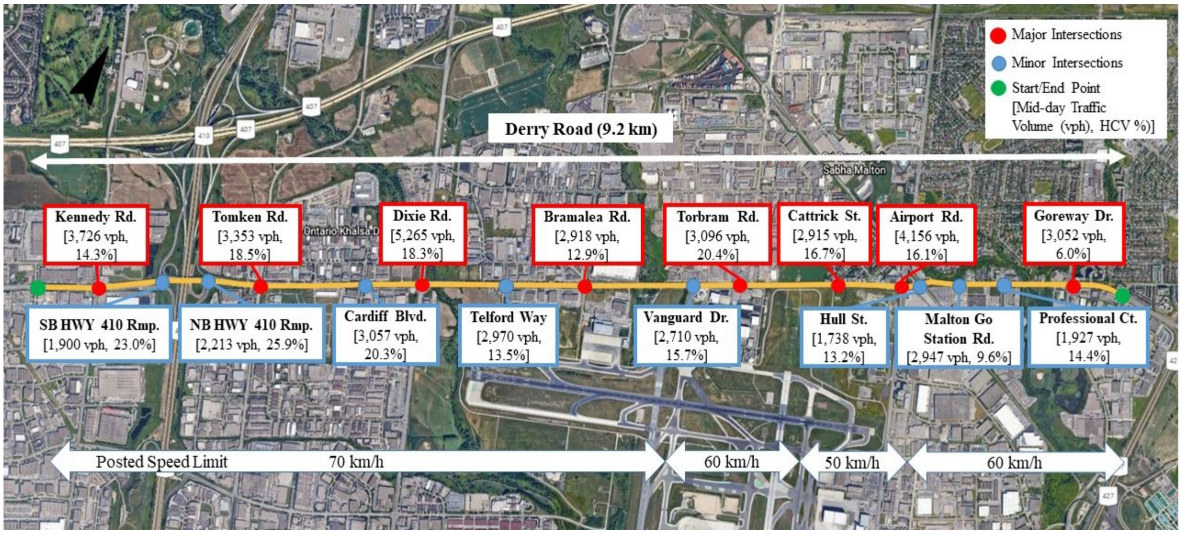


Figure 3-1: Mid-Day Traffic Conditions on the Study Corridor

Note: Mid-day = 1:00 to 2:00 p.m.; vph = vehicles per hour; Rd. = Road; St. = Street; Dr. = Drive; SB = southbound; NB; = northbound; HWY 410 Rmp. = Highway 410 Ramp; Blvd. = Boulevard; Ct. = Court.

Traffic volumes supplied by Peel Region were collected during the 2016 fall season from September to November. The study relied on Google Maps and Bing Maps satellite images to extract important input parameters needed to develop a VISSIM model. These parameters included but are not limited to, the number of lanes, posted speed limit, turning radius for each intersection along the corridor, start and end position of tapered lanes used for exclusive left and right turning movements, and the road width. Peel Region supplied additional traffic and operations data contained in Synchro files, including the 2016 hourly turning movement counts (12 months) at all intersections, the percentage of HCVs, and traffic control information including signal control mode (actuated or semi-actuated), signal split, cycle length, signal offset, and coordination information.

Turning movement count data were obtained for the AM peak hour (7:15am to 8:15am), the Mid-day hour (1:00pm to 2:00pm), and the PM peak hour traffic (4:30pm to 5:30pm) for each day of the week. Many intersections in the study area were heavily congested during the AM and PM peak hours. For example, the average traffic volume entering the 16 intersections during the PM peak hour was 5,761 vph and the level-of-service was D or poorer for all major intersections. With such high traffic volumes, an examination of the impact of different traffic control strategies on HCV platooning operation was not feasible as it would not be possible to observe differences at the clearly oversaturated intersections. The Mid-day hour was subsequently selected for simulation. The average Mid-day traffic volume entering the intersections was 2,997 vph. This is substantially less congested (48% lower volume than the PM peak hour). Figure 3-1 provides details of Mid-day traffic volumes. During the Mid-day hour, HCVs averaged 16.2% of total traffic at intersections, with the highest percentage being 20.4% at the Torbram intersection.

The Ministry of Transportation of Ontario's (MTO) 24-hour travel time data collected by the Transportation Tomorrow Survey (TTS) (MTO, 2016) was used to further calibrate the VISSIM model. TTS collects various traffic flow data (traffic volume, travel speed, travel time, etc.) on behalf of government agencies in southern Ontario. The TTS travel time data was collected for Tuesdays to Thursdays in 2016 during the fall season to match relevant seasonal traffic volumes. The ITE Handbook (Harwood et al., 2003; ITE, 2000) was used to fill in other relevant input parameters. For example, maximum acceleration rate of passenger vehicle 1.26 m/s^2 and for HCVs 0.3 m/s^2; deceleration rates of passenger vehicles 3.4 m/s^2 and for HCVs 1.6 m/s^2 have been assigned.

3.3 Model Development

This section discusses three important issues in developing the micro-simulation models for this study: 1) HCV platoon length, 2) input parameters, and 3) model calibration.

3.3.1 HCV Platoon Length

The total length of an HCV platoon can vary widely depending on the number of HCVs in the platoon, the length of each HCV, and the time headway between the platooning vehicles.

Number of HCVs in a platoon

Studies of HCV platooning have considered platoons of two to five vehicles (Maarseveen, 2017; Ramezani et al., 2018a; Yang et al., 2019). Ramezani et al., (2018a), for instance, investigated platoons of five HCVs on test freeways and assumed that, if necessary, the platooned HCVs could easily leave or join the platoon for the entire journey. The majority of studies of platoons of three or more HCVs have focused on: 1) testing SAE level 3 HCV platooning technology with every HCV containing a human driver, and 2) understanding how HCV platooning affects fuel consumption and emissions (Alam et al., 2015; Browand et al., 2004; Patten et al., 2012; Ramezani et al., 2018a; Tavasszy and Janssen, 2017; Zabat et al., 1995). Urban arterials present HCV platoons with additional challenges such as intersections where, for example, the green phase of a signalized intersection may not provide enough time for a whole platoon to pass through without interruption. This problem naturally increases as the number of HCVs in a platoon increase.

This study considers platoons of two HCVs. This is because: 1) it is expected that most imminent HCV platooning operations will be for two HCVs; and 2) platooning with three or more vehicles will not be feasible if two HCV platoons are found to present major challenges on urban arterials.

Length of HCVs in platoon

The WB-20 category was selected for all HCVs. A WB-20 vehicle is 22.70 m (74.5 ft) long and is the longest typical single-trailer HCV available in North America (AASHTO, 2018; TAC, 2017). If a platoon of two WB-20 HCVs can pass a signalized intersection, it is reasonable to expect that any combination of two platooning HCVs will be successful.

Time Headway between Platooning HCVs

Studies of time headways between two consecutive HCVs in a platoon on freeways have used values ranging from 0.6 sec to 1.2 sec (Nowakowski et al., 2011, 2010; Ramezani et al., 2018a; Shladover et al., 2015). Since slower traveling speeds on arterials mean that platooning vehicles can maintain tighter proximity on urban arterials (Lazar et al., 2018; Milanés et al., 2013), a value of 0.6 sec between HCVs was adopted for the time headway between platooning HCVs.

3.3.2 Input Parameters

Car-following and lane-changing models in a micro-simulation traffic model are particularly important to simulate real-world traffic flows as closely as possible. In VISSIM, Wiedemann 74 (W74) is the most popular car-following and lane-changing model to simulate conventional traffic flows on urban arterials, but Wiedemann 99 (W99) is known to be more appropriate for simulating the driving behavior of autonomous vehicles (PTV, 2021; VDOT, 2020; Zeidler et al., 2019). This study used W74 to simulate the behavior of conventional passenger vehicles and HCVs, and W99 to simulate the travel behavior of HCV platoons. Table 3-1 provides information for the 10 input parameters used in this study. All parameters in Table 3-1 were input via the PTV VISSIM COM interface and python script (PTV, 2021).

Table 3-1: Simulation Input Parameters

Input Parameters	Wiedemann 74			Wiedemann 99	
	Default	Passenger	HCV	Default	HCV Platoon
Maximum look ahead distance (m)	250	250	250	250	300
Maximum look back distance (m)	150	150	150	150	300
Number of interaction objects	4	1	1	2	3
Number of interaction vehicles	99	1	1	99	2
Average standstill distance (m) for a following car	2	2.87	3.77	NA	3.77
Average standstill distance (m) for a following HCV	2	4.07	3.37	NA	3.37
Standstill distance (m) for a following HCV platoon	NA	NA	NA	1.5	1.00
Time headway (s)	NA	NA	NA	0.9	0.6
Maximum deceleration for cooperative braking (m/s^2)	-3	-3	-1.62	-3	-1.62
Safety distance reduction factor (m)	0.6	0.6	0.6	0.6	1

Note: NA indicates a value is not applicable.

The input parameters are discussed in greater detail below.

- The “maximum look ahead distance” and “maximum look back distance” for passenger vehicles and conventional HCVs are the maximum distances a human driver can see ahead or behind when observing the surrounding traffic environment. The distances given are those typically used in previous studies (PTV, 2021). The value for HCV platooning is identified as the distance over which an autonomous HCV can wirelessly communicate with another autonomous HCV. The 300m (984.2ft) distance given for HCV platooning is based on suggestions made by NHTSA (2020).

- The "number of interaction objects" refers to a vehicle's interaction (i.e., communications) frequency with other objects such as traffic controls and nearby vehicles. The "number of interaction vehicles" indicates a subset containing only the number of interactions with other vehicles. As conventional passenger vehicles and HCVs are controlled by humans, this study set the number of interaction objects and number of interaction vehicles for both passenger cars and conventional HCVs to a value of 1 as suggested by PTV (2021). This means that a human controlled vehicle interacts (communicates) with other objects one at a time. The number of interaction objects and number of interaction vehicles for HCV platooning are higher than 1 because an HCV in a platoon needs to communicate simultaneously and automatically with other HCVs in the same platoon and with upcoming traffic controls (Sukennik, 2019).

- The "average standstill distance for a following car" and the "average standstill distance for a following HCV" indicate the minimum distance required to avoid a collision between a lead vehicle and following vehicle. The model uses 2.87m (9.42ft) for the average standstill distance between two passenger vehicles and 3.37m (11.06ft) for the average standstill distance between two consecutive HCVs as suggested by Lu et al. (2021).

- The "standstill distance for a following HCV platoon" indicates the minimum distance required to avoid a collision between two HCVs in the same platoon. This study used 1.00 m (3.28ft) as suggested by Deng (2016) and Deng and Boughout (2016).

- The “time headway” indicates the distance from the front of the leading vehicle or object to the front of the following vehicle and is additional to the standstill distance. A value of 0.6 sec was defined for platooning HCVs.
- The "maximum deceleration rate for cooperative braking" indicates the deceleration rate required for a target vehicle to allow another vehicle to change lane and enter the target vehicle’s lane. This study used Harwood et al.’s (2003) value of -1.62 m/s^2 (-5.31ft/s^2) for conventional HCVs and platooned HCVs.
- The "safety distance reduction factor" is a factor applied to the lane-changing model to reduce the minimum safety distance required between the lead and following vehicles when the lead vehicle initiates a lane change. A value of 0.6 indicates that when a following vehicle changes to a target lane, the following vehicle can accept a 40% reduction in the safety distance with the lead vehicle when completing the lane change maneuver. Ahmed et al., (2021), however, proposed using a value of 1 as the value for HCVs in a platoon to reflect the conservative behavior of HCV platoons. A value of 1 means that platooned HCVs make no compromise with safety distance and maintain full minimum safety distance when changing lanes.

3.3.3 Model Calibration

A Base Model representing the do-nothing scenario has been designed to replicate real-world traffic flow conditions and variability. A micro-simulation model is stochastic in nature as the values of many parameters such as acceleration/deceleration rate and vehicle speed are randomly generated from an assumed probabilistic distribution for each parameter. As a result, each simulation generates somewhat different results and multiple simulation runs are required to obtain reliable results. This study followed the Wisconsin Department of Transportation's (WisDOT) micro-simulation guidelines closely. Using these guidelines, 30 simulation runs were produced for the base scenario. The model produced traffic volumes that simulated an hour of real-world traffic volumes at the 95% confidence level. The two main measure of effectiveness (MOE) for calibration included traffic volume and travel time. As suggested in WisDOT guideline, we used GEH (Geoffrey E. Harver) statistic to validate traffic volume and correlation (ρ-value) to validate travel time (WisDOT, 2019).

Traffic Volume

The GEH (Geoffrey E. Havers) statistic is used to measure model goodness-of-fit (Beeston et al., 2021; WisDOT, 2019). In this study, the GEH statistic was used to assess the similarity between observed and simulated Mid-day traffic. A GEH of less than 5 $\left(\sqrt{vehicle/hour}\right)$ is usually considered a good fit (Doustmohammadi et al., 2017; Dowling et al., 2004). Equation (3-1) shows the GEH formula:

$$\mathrm{GEH} = \sqrt{\frac{2(\mathrm{m}-\mathrm{c})^2}{\mathrm{m}+\mathrm{c}}} \tag{3-1}$$

Where:

GEH = Geoffrey E. Havers statistic;

m = simulated Mid-day traffic volume for an hour; and

c = observed Mid-day traffic volume for an hour.

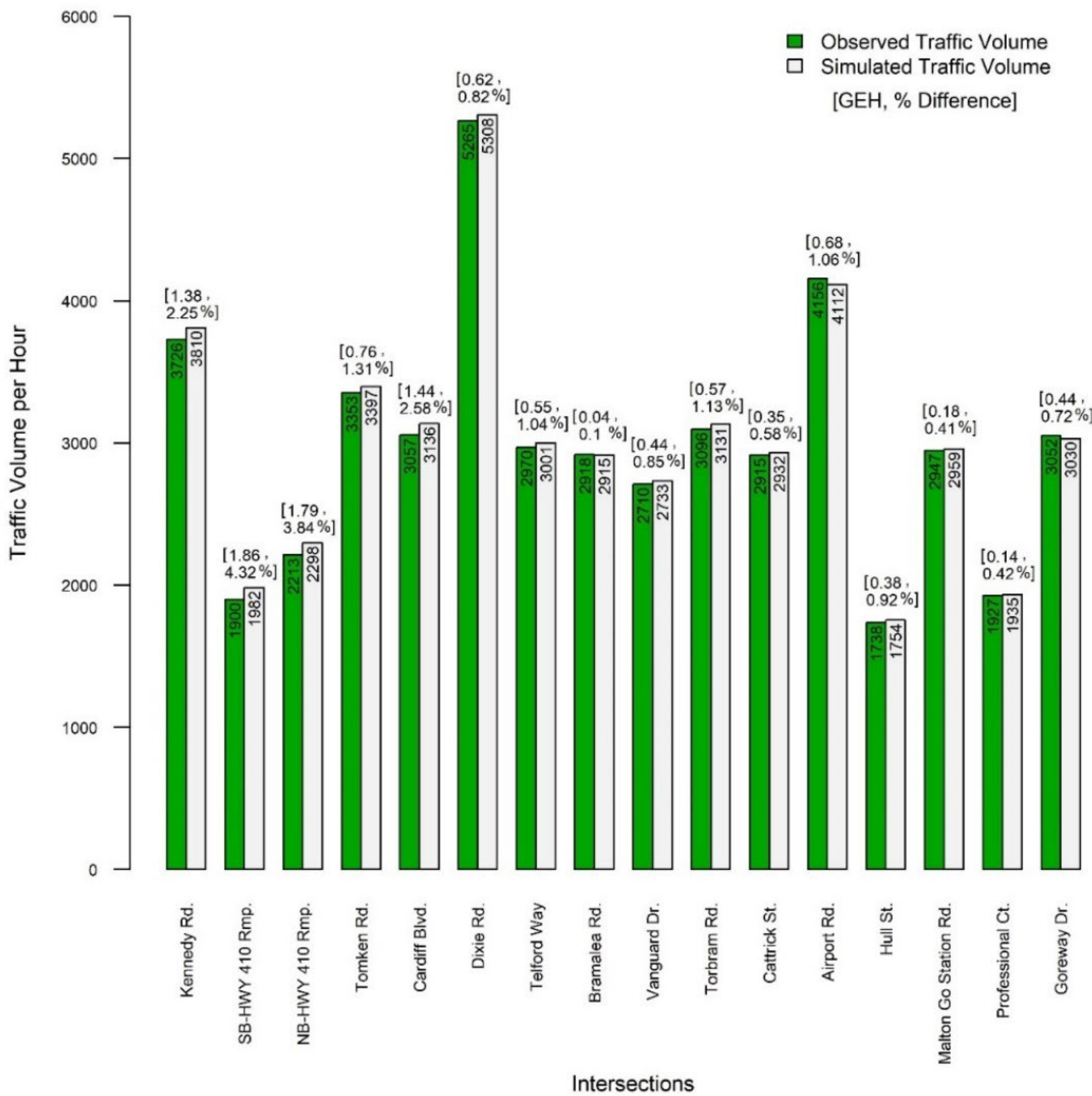


Figure 3-2: Calibration Results for Base Scenario Traffic Volumes

Note: GEH = Geoffrey E. Havers statistic; Rd. = Road; SB = southbound; NB; = northbound; HWY 410 Rmp. = Highway 410 Ramp; Blvd. = Boulevard; Dr. = Drive; St. = Street; Ct. = Court

Figure 3-2 compares the Base Model results for observed traffic volumes (green bars) with the simulated traffic volumes (white bars). The data include all 16 intersections on the study corridor. For direct comparison, the results include the percentage difference between the observed and simulated traffic volumes and the resulting GEH value.

At most intersections, the Base Model slightly over-estimated the traffic volume, but the differences were small ranging from 1.06% (Airport Road) to 4.32% (SB HWY 410). The GEH was well under 5.0 for all 16 intersections, with the highest GEH value of 1.86 corresponding to the Southbound (SB) Highway 410 intersection. These results suggest that the Base Model adequately simulated real-world traffic volumes.

Travel Time

A second calibration using another MOE was performed. The MOE was average travel time which included traffic control delay time. Mid-day travel time data were used for a typical weekday average travel time between 1 pm to 2 pm. The data provided second by second information, but through traffic movement data were available for only nine of the study corridor segments. Figure 3-3 compares the observed Mid-day travel times with the Base Model's hourly simulated travel times on the nine segments. The simulated travel times were computed by averaging the results of 30 simulation runs.

In Figure 3-3 the nine segments are shown as small open circles or as a green or orange dot. The small open circles are the seven segments between the eight major intersections for which data were available. The orange dot is the segment on the western edge of the study corridor (Goreway Drive to Rexwood Road), and the green dot is the segment on the eastern edge of the study corridor (Kennedy Road to Tomken Road).

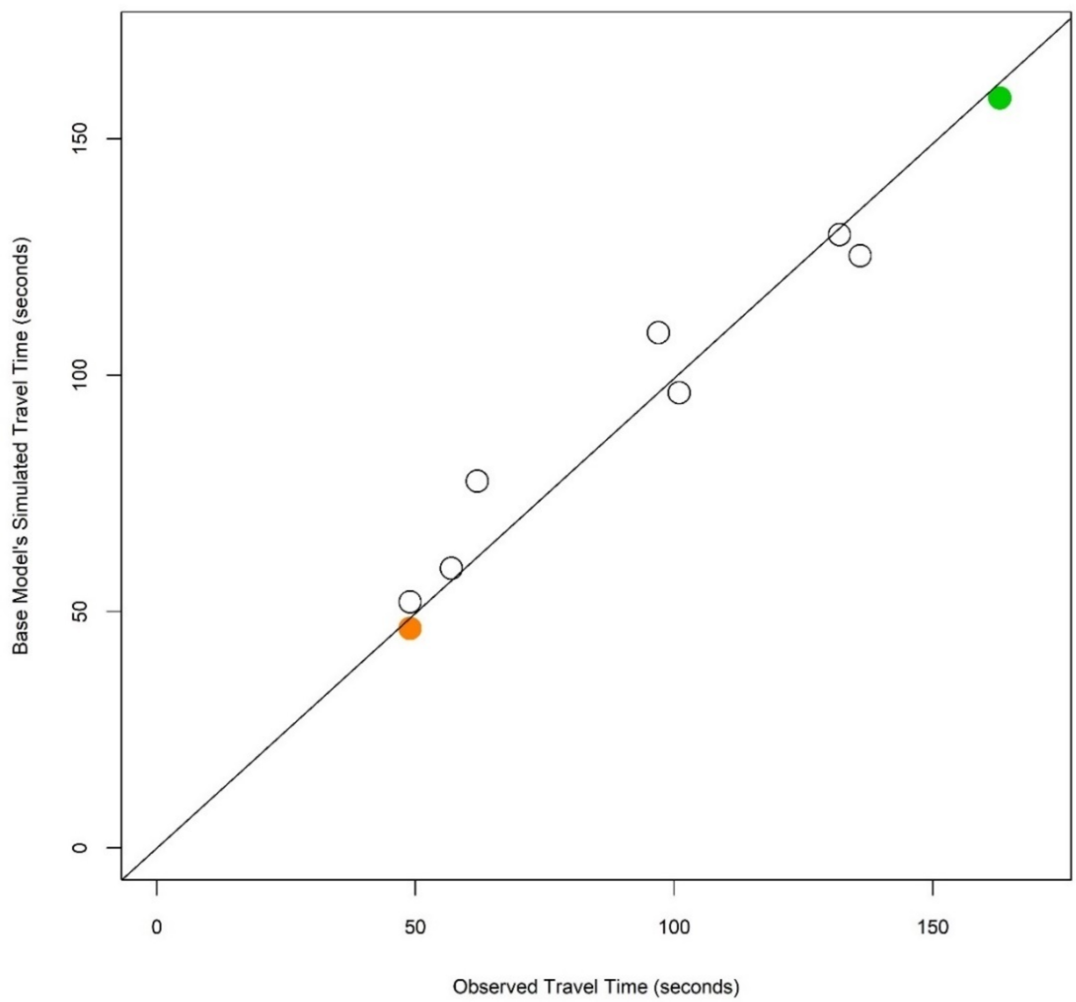


Figure 3-3: Results of Calibration for Base Scenario Travel Time

Each data point shown in Figure 3-3 represents the observed travel time (see x-axis) and the simulated average travel time (see y-axis) for the segment. For example, the green dot's observed travel time is 163 seconds and its simulated average travel time is 160 seconds. The orange dot has the shortest travel times (50 seconds for the observed travel time and 49 seconds for the simulated average travel time). The observed and simulated travel times for the nine segments show a very strong positive correlation (ρ = 0.983) and indicate an accurate representation of real-world travel times.

3.4 Development of Test Scenarios

A set of scenarios were developed to investigate the operational impact of SAE level 4 HCV platooning on urban arterials with existing traffic controls and with the addition of traffic signal priority (TSP) for HCV platoons. These scenarios included multiple tests to analyze 0%, 5% and 10% market penetration rates.

The TSP investigated in this study was designed to provide an extended green phase allowing all platooned HCVs to pass through an intersection together. This TSP approach was installed at each of the eight major intersections on the study corridor (the eight red dots in Figure 3-1 to help through traffic only. As a result, the TSP in this study is not intended to prioritize left-turn or right-turn vehicle movements. Eight minor intersections on the study corridor (the eight blue dots in Figure 3-1) were assumed to operate using existing signal phasing. The existing signal control timing had longer phases for traffic on Derry Road to accommodate the high levels of traffic along the road when compared with the intersecting minor roads. As a result, this study developed a total of five VISSIM models: the Base Model and four Alternative Models. NP refers to existing traffic controls with no priority, TP refers to TSP conditions, and the number after NP or TP refers to the HCV platooning percentage (5% or 10%). The five models were:

- Base Model (NP0) represents a do-nothing scenario with no TSP and 0% HCV platooning;
- Alternative Model 1 (NP5) simulates existing traffic controls with no TSP and the truck volume adjusted to include 5% HCV platooning;
- Alternative Model 2 (NP10) simulates existing traffic controls with no TSP and the truck volume adjusted to include 10% HCV platooning;

- Alternative Model 3 (TP5) simulates a TSP system with the truck volume adjusted to include 5% HCV platooning; and
- Alternative Model 4 (TP10) simulates a TSP system with the truck volume adjusted to include 10% HCV platooning.

TP5 and TP10 used the ring barrier controller and vehicle detection function (simulated loop detectors) embedded in VISSIM. In a micro-simulation model involving a TSP system, the location of the loop detectors before each intersection is important as it determines the length of the extended green. In this study, the location of the loop detectors determines the length of the extended green allowed for a platoon of HCVs to pass through the intersection uninterrupted. According to Kaisar et al., (2020), most simulations use the minimum stopping sight distance (MSSD) defined by AASHTO (AASHTO, 2018) to determine the location of the loop detectors. We used the posted speed limit for each segment to estimate the MSSD of each segment and to locate the appropriate position for the loop detectors. VISSIM refers the simulated loop detector as the check-in detector.

If we use the segment approaching Dixie Road (see Figure 3-1) as an example, the posted speed limit is 70km/h (43.5 mi/h) which gives an estimated MSSD of 105 m (344.5ft). The location of the simulated loop detectors is therefore placed 105m (344.5ft) before the Dixie Road intersection stop-line. In this instance, the ring barrier controller extends the green time by 9 seconds with 6 seconds covering the 105m (344.5ft) travel time from the loop detectors to the stop bar and an additional 3 seconds of slack time. The slack time accounts for variability in the arrival times of the approaching HCVs in the platoon.

3.5 Analysis and Results

The study conducted 150 simulations in total with 30 runs completed for each of the 5 models such as NP0, NP5, NP10, TP5, and TP10. The two measures of performance included changes in average travel time as a primary measure and the number of stops at traffic lights as a secondary measure (FDOT, 2014). The measures were used to explore the impact of HCV platooning on three vehicle categories: 1) all vehicles, 2) passenger vehicles, and 3) conventional or platooned HCVs for travelling through 16 signalized intersections.

3.5.1 Average Travel Time

Figure 3-4 is a set of boxplots showing the average travel time of the three vehicle categories. A typical boxplot shows median, first and third quartile values from the median, maximum and minimum values, but Figure 3-4 shows the mean value (μ) (the middle thick horizontal line in the middle of the box), the mean value ± one standard deviation ($\mu \pm \sigma$) (the lower and upper limit of each box), and the mean value ± two standard deviations ($\mu \pm 2\sigma$) (the minimum and maximum value of each vertical line. $\mu \pm 2\sigma$ can be regarded as the estimated 95% confidence interval (CI). For example, the Base Model's mean average travel time (based on 30 simulations) for individual passenger vehicles was slightly less than 14.0 minutes with a CI ranging from 13.32 minutes to 14.64 minutes.

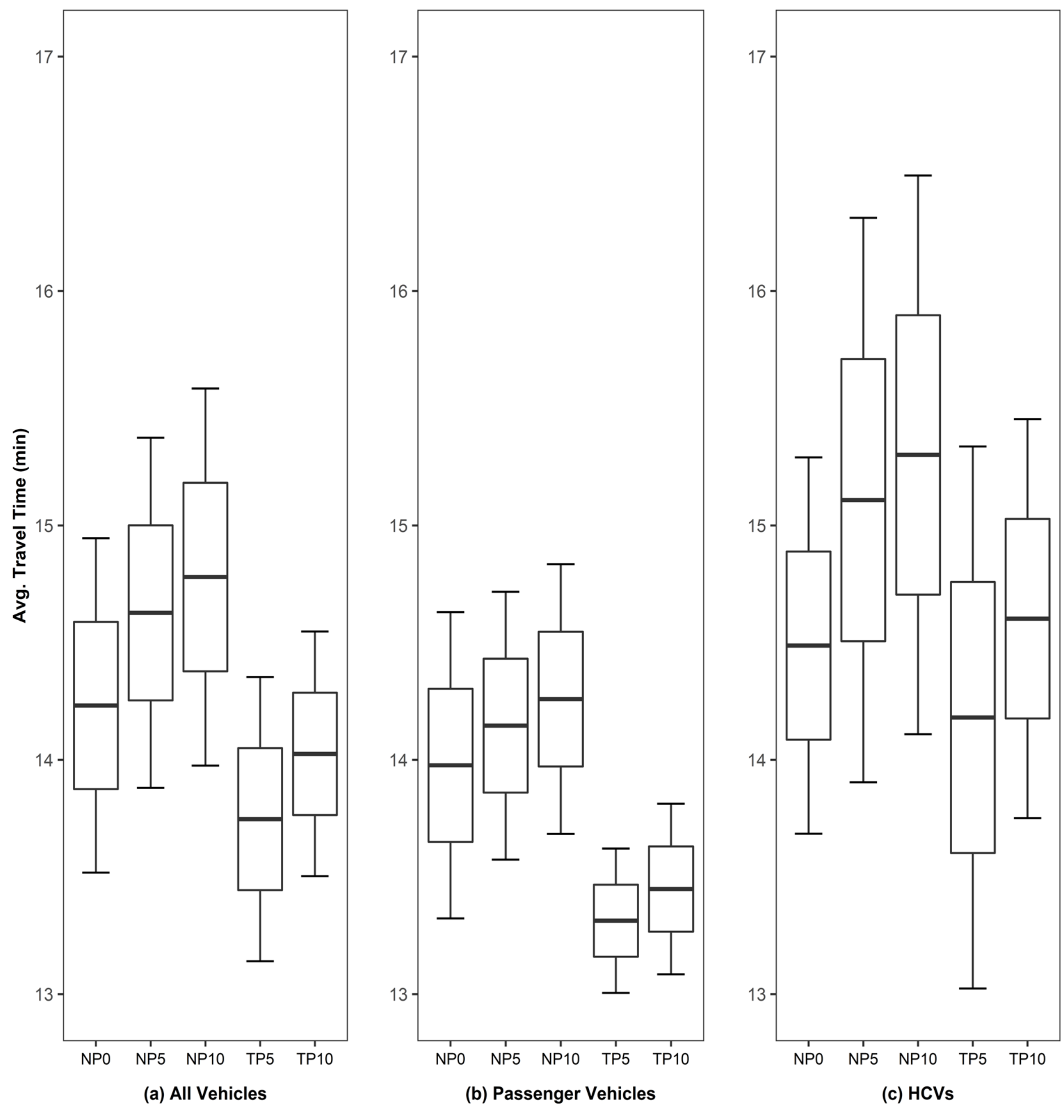


Figure 3-4: Average Travel Times Estimated by the Five Models

Note: Avg. = average.

The information shown in Figure 3-4 was used as to conduct a set of two-sample Welch's t-tests (Welch, 1947), which are also known as unequal variances t-tests. This provided a statistical basis for comparing the average travel times of the Base Model with the average travel times of the four Alternative Models. The null hypothesis was that the average travel time for each Alternative Model was equal to the Base Model's travel time. The t-statistic and degrees of freedom were calculated using Equation (3-2) and Equation (3-3):

$$t = \frac{\mu_1 - \mu_2}{\sqrt{\frac{\sigma_1^2}{n_1} + \frac{\sigma_2^2}{n_2}}} \tag{3-2}$$

$$df = \frac{\left(\frac{\sigma_1^2}{n_1} + \frac{\sigma_2^2}{n_2}\right)^2}{\frac{\sigma_1^4}{n_1^2(n_1 - 1)} + \frac{\sigma_2^4}{n_2^2(n_2 - 1)}} \tag{3-3}$$

Where,

t= t-statistic;

μ_1= Base Model's average travel time for passenger vehicles, HCVs (including platooned HCVs) and all vehicles;

μ_2= each Alternative Model's average travel time for passenger vehicles, HCVs (including platooned HCVs) and all vehicles;

σ_1= Base Model's standard deviation for travel time for passenger vehicles, HCVs (including platooned HCVs) and all vehicles;

σ_2= each Alternative Model's standard deviation for travel time for passenger vehicles, HCVs (including platooned HCVs) and all vehicles;

n_1= number of observations (30) in Base Model; and

n_2= number of observations (30) in each Alternative Model.

df= degrees of freedom.

Table 3-2: T-Test Results for Average Travel Time (min)

Vehicle Category	VISSIM Model	Mean	SD	df	t-statistic	p-value
All Vehicles	NP0	14.23	0.36	NA	NA	NA
	NP5	14.63	0.37	57.88	-4.19	9.60E-05***
	NP10	14.78	0.40	57.19	-5.58	6.80E-07***
	TP5	13.75	0.30	56.52	5.67	5.01E-07***
	TP10	14.03	0.26	53.12	2.56	0.013**
Passenger Vehicles	NP0	13.98	0.33	NA	NA	NA
	NP5	14.15	0.29	56.99	-2.14	0.04**
	NP10	14.26	0.29	57.09	-3.55	7.71E-04***
	TP5	13.31	0.15	41.27	10.06	1.16E-12***
	TP10	13.45	0.18	45.41	7.73	7.99E-10***
HCVs	NP0	14.49	0.40	NA	NA	NA
	NP5	15.11	0.60	50.53	-4.70	2.04E-05***
	NP10	15.30	0.60	50.82	-6.20	1.00E-07***
	TP5	14.18	0.58	51.69	2.39	0.02**
	TP10	14.60	0.43	57.80	-1.08	0.29

Note: SD = standard deviation; df = degrees of freedom; NA = not applicable.

Significance level: <0.01 ‘***’; <0.05 ‘**’; >0.1 ‘ ’

Table 3-2 summarizes the results of the t-tests. From Figure 3-4 and Table 3-2, a discussion on these results is presented below.

All vehicles

For all vehicles, the boxplots in Figure 3-4 (a) and tabular results in Table 3-2 show that the NP0’s average travel time was 14.23 min. NP5 (existing traffic controls with 5% HCV platooning) increased travel time by 24 seconds (≈ (14.63 minutes -14.23 minutes)×60 seconds) per vehicle. NP10 (existing traffic controls with 10% HCV platooning) increased travel time by 33 seconds per vehicle. The t-tests showed that the increased travel times for all vehicles were statistically significant at the 99.9% confidence level. These results indicate that a small percentage of HCV platooning without improved traffic control systems created additional delays on the study corridor.

TP5 (TSP with 5% HCV platooning) reduced travel time for all vehicles by 29 seconds per vehicle, and TP10 (TSP with 10% HCV platooning) reduced travel for all vehicles by 12 seconds per vehicle. The t-tests showed that the decreased travel times for all vehicles were statistically significant at the 99.9% confidence level for TP5 and at the 95% confidence level for TP10. These results suggest that a TSP strategy with 5% to 10% of HCV platooning can improve the travel times for all vehicles on the corridor.

Passenger vehicles

Figure 3-4 (b) shows the pattern for passenger vehicle travel times. With the existing traffic control system, 5% HCV platooning (NP5) increases passenger vehicle travel times by 10 seconds per vehicle, and 10% HCV platooning (NP10) increases passenger vehicle travel times by 17 seconds per vehicle. The t-tests showed that the increased passenger vehicle travel times were statistically significant at the 95% confidence level for 5% HCV platooning and at the 99.9% confidence level for 10% HCV platooning. TP5 reduced passenger vehicle travel times by 40 seconds per vehicle, and TP10 reduced passenger vehicle travel times by 32 seconds per vehicle. Saving 40 seconds of travel time could allow a passenger vehicle to travel an extra 670 m (60km/h) to 780 m (70km/h). The t-tests showed that the TP5 and TP10 results were statistically significant at the 99.9% confidence level and suggest that an extended green phase targeting platooned HCVs could also help passenger vehicles to pass through major intersections with reduced delay.

HCVs

Figure 3-4 (c) shows that the pattern for HCVs was similar to the patterns for all vehicles and passenger vehicles for three of the Alternative Models: compared to the NP0 for HCVs, NP5 (travel time increased by 37 seconds per vehicle), NP10 (travel time increased by 49 seconds per vehicle), and TP5 (travel time decreased by 19 seconds per vehicle). TP10, however, increased rather than decreased HCV travel time. The increase was 7 seconds. TP10 did not improve HCV travel time and this model failed to reject the null hypothesis. This result suggests that a 10% or higher rate of HCV platooning may create significant delays especially for HCVs even with TSP installed at all the study corridor's major intersections. Notice, however, that the TSP strategy is able to effectively offset the negative impacts on traffic congestion without traffic control improvement with the same percentage (10%) of HCV platoon shown in NP10.

Table A-1 shows directional movements at the major intersections along the study corridor and summarizes the average travel time results of all vehicles for the NP0, NP5, NP10, TP5, and TP10 models. The Table also shows the percentage difference from the Base Model (NP0).

The results in Table A-1 show increased travel times for cross-street traffic for both 5% and 10% HCV platooning. The average travel times for 10% HCV platooning were higher than for 5% HCV platooning. This result is consistent with the results shown in Table 3-2 and Figure 3-4. The results are similar for the TP5 and TP10 signal priority scenarios, i.e., average travel times increased with 5% HCV platooning and especially with 10% HCV platooning.

Average travel times for each of the eight signalized cross-street intersections with signal priority decreased by 5 seconds per vehicle from NP0 to TP5. In the case of cross-streets, average travel times increased by 0.6 sec per vehicle from NP0 to TP10, a negligible difference. For comparison, Kaisar et al. (2020) observed a 50 seconds average travel time increase for cross-street traffic for non-platoon HCV signal priority. We hypothesize that the larger travel times in their study occurred due to higher traffic volumes.

3.5.2 Number of Stops

Figure 3-5 is a set of boxplots showing changes in the number of stops for the three different vehicle categories. The number of stops directly affects fuel consumption and greenhouse gas (GHG) emission (FDOT, 2014; Steenhof et al., 2006). With similar formatting to the previous boxplots, Figure 3-5 shows the average, ±1 standard deviation, and ±2 standard deviations for the number of stops in each of the five models. Table 3-3 shows the results of the two-sample Welch's t-tests. The null hypothesis was that the number of stops of each Alternative Model would equal to the number of stops of the Base Model.

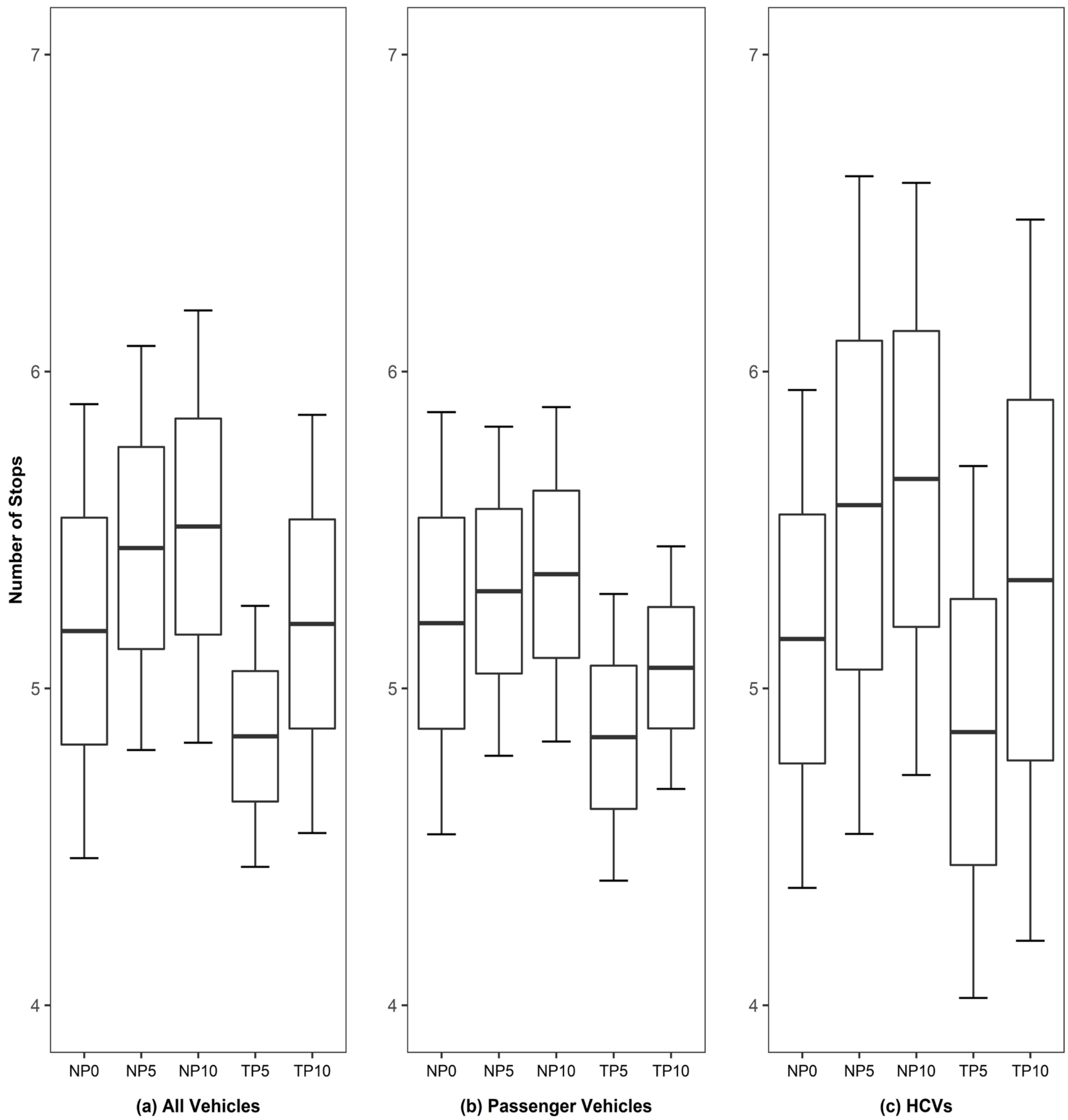


Figure 3-5: Number of Stops Estimated by the Five Models

Table 3-3: T-Tests Results for Number of Stops

Vehicle Category	VISSIM Model	Mean	SD	df	t-statistic	p-value
All Vehicles	NP0	5.18	0.36	NA	NA	NA
	NP5	5.44	0.32	57.24	-3.00	4.01E-03**
	NP10	5.51	0.34	57.87	-3.66	5.47E-04***
	TP5	4.85	0.21	48.76	4.10	1.58E-04***
	TP10	5.20	0.33	57.62	-0.26	0.8
Passenger Vehicles	NP0	5.21	0.33	NA	NA	NA
	NP5	5.31	0.26	54.74	-1.31	0.2
	NP10	5.36	0.26	55.12	-1.99	0.05*
	TP5	4.85	0.23	51.05	4.90	1.02E-05***
	TP10	5.07	0.19	46.27	2.00	0.05*
HCVs	NP0	5.16	0.39	NA	NA	NA
	NP5	5.58	0.52	54.02	-3.55	7.96E-04***
	NP10	5.66	0.47	56.34	-4.53	3.09E-05***
	TP5	4.86	0.42	51.68	2.69	9.59E-03**
	TP10	5.34	0.57	51.52	-1.47	0.15

Note: SD = standard deviation; df = degrees of freedom; NA = not applicable; Significance level: <0.01 ‘***’; <0.05 ‘**’; <0.1 ‘*’

The results shown in Figure 3-5 and Table 3-3 are discussed below.

All vehicles

Compared to the NP0, the number of stops for both NP5 and NP10 significantly increased. NP10, for instance, required all vehicles to stop an average of 0.34 (= 5.51 - 5.18) additional stops when traveling along the study corridor. As the Mid-day hour’s average traffic volume on the corridor is close to 3,000 vph, NP10 would introduce approximately 990 additional stops per hour along the study corridor by all vehicles compared to the NP0. TP10 also significantly increased the number of stops for all vehicles, but the change was not statistically significant. Only TP5 decreased the number of stops for all vehicles. The decrease was statistically significant at the 99.9% confidence level.

Passenger vehicles

NP5, NP10 and TP10 increased the number of stops for passenger vehicles. The increases were statistically significant for NP10 and TP10 (both with 90% confidence level). Only TP5 decreased the number of stops for passenger vehicles. The decrease was statistically significant at the 99.9% confidence level.

HCVs

The HCV results followed a similar pattern with NP5, NP10 and TP10 increasing the number of stops HCVs. The NP5 and NP10 increases were statistically significant at the 99.9% confidence level. Only TP5 decreased the number of stops for HCVs. The decrease was statistically significant at the 95% confidence level.

3.5.3 Analysis Results Summary

TP5 produced different results from NP5, NP10 and TP10. It was the only Alternative Model to show a statistically significant decrease in both the travel time and the number of stops for all three vehicle categories. This result suggests that TSP with 5% HCV platooning may help to reduce travel times, fuel consumption and GHG emissions. TSP with 10% HCV platooning (TP10), however, increased the number of stops, although not as much as NP5 and NP10, suggesting that the extended green phase could not handle a 10% (or higher) market penetration rate for platooned HCVs when compared with NP0. Not all the platooned HCVs will be able to cross the signalized intersection within an extended green time of 9 seconds. As the rate of HCV platooning increases, there will be an increased likelihood that some vehicles will not cross the intersection in time.

In summary, this study attempted to observe the impact of HCV platooning at low levels (5% and 10%) on urban arterial roadways as a step towards understanding the consequences of introducing HCV platooning operation on urban arterials in the near future. HCV platooning penetration is expected to increase slowly as V2X (Vehicle-to-Everything) technology progresses. It is, however, reasonable to expect that due to unforeseen technological shifts, the accuracy of current hypothetical scenarios will decrease for predictions made further into the future.

3.6 Conclusions and Recommendations

The goal of the second objective of this study was to investigate the impact on mobility of SAE level 4 HCV platooning on traffic control systems at signalized intersections on arterial roadways. SAE level 4 HCV platooning requires a human driver in the lead vehicle, but one or more closely following HCVs may be driverless. The study first investigated the operation of SAE level 4 HCV platooning on arterials with signalized intersections. It was conducted using VISSIM micro-simulations comparing the Base Model (0% HCV platooning) with four alternatives. These Alternative Models included: existing traffic controls with 5% HCV platooning, existing traffic controls with 10% HCV platooning, a TSP system with 5% HCV platooning, and a TSP system with 10% HCV platooning. Two measures of performance were used including the average travel time and the number of stops. These measures were assessed with respect to all vehicles, passenger vehicles, and HCVs. The study corridor was a known HCV heavy corridor in Peel Region, Ontario, Canada. The main findings were:

- As SAE level 4 HCV platooning has communication capability with the traffic controllers and running with tight headway gap, initially we expected with the increase of HCV platooning that the operational performance might improve. However, under the existing traffic control environment, the introduction of HCV platooning on the study corridor would lead to a significant deterioration in the corridor's operational performance especially for HCVs. The findings were observed for low levels of HCV platooning (5% and 10%) yet worsening conditions can be expected if the rate increases further. The implication is that our current surface infrastructure is not yet ready for the introduction of HCV platooning operations on urban arterials; and,

- If signalized intersections can be improved by providing all major intersections with TSP for HCV platooning, it may be possible to allow up to approximately 5% HCV platooning on the tested roadway corridor of Derry Road. At this level of HCV platooning, the average travel times and the number of stops were similar to those of the base (do-nothing) model. Prior to conducting the microsimulation analyses, we expected TSP would be helpful for both 5% and 10% HCV platooning for improving the operational performances. This result also indicates that strategies such as TSP can mitigate the negative implications of 5% HCV platooning.

A cost-benefit analysis can be applied to evaluate travel time changes from TSP for HCV platooning. The value of time for passenger vehicle occupants and the value of time for HCV drivers are not the same, since goods shipped by HCVs have extra costs from travel delays. For example, Kaisar et al. (2020) estimated the value of time for HCVs and passenger vehicles to be $80 per hour and $15 per hour respectively. Using these estimates, we converted the travel time savings in our study to dollar value savings. The highest benefit estimated was for 5% HCV platooning under TSP condition (all vehicles saved an average of 3.4%).

Passenger vehicles had savings of 4.8% and HCVs savings of 2.1% savings for 5% HCV platooning operation under TSP. With 10% HCV platooning under TSP, the savings benefit was only 1.4% savings for all vehicles.

The analysis made by this study suggests that HCV platooning under existing traffic control conditions will reduce mobility on urban arterial roadways. An HCV platoon will be more likely than a single HCV to have to stop at an intersection due to the additional length requiring more green time. The average travel time and the number of stops will increase with a rise in the HCV platooning penetration rate. The application of TSP at a 5% HCV platooning rate will improve the mobility and operational performance of the selected urban arterial corridor, but this improvement will not occur if the penetration rate exceeds 5%. It is possible that the trucking industry would consider the financial gains expected from operating HCV platooning to exceed the costs associated with a slight increase in the average duration of travel for 10% HCV platooning operation. It is also possible that an alternative technique, such as a dedicated HCV lane, may offer advantages for 10% HCV platooning. However, the cost of constructing a dedicated lane may be higher than the value of the time saved.

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In many cities, LCVs are not allowed to operate during peak hours or are allowed to operate only at night. Restrictions are usually required by a permit to drive an LCV in a city. For instance, in cities like London, New York and Toronto, LCVs are only permitted to operate on certain streets during off-peak periods such as mid-day or nighttime (Lightstone et al., 2021; NYC DOT, 2023; Transport for London, 2020). Given that many cities have rules about how LCVs can be used, future research should explore regulations on peak hours HCV platooning operations, and the possible effects of HCV platooning during peak hours. The findings will provide a more comprehensive understanding of the benefits and drawbacks of using HCV platoons in urban areas and will inform decision-making around their deployment. Additionally, it would be beneficial to study the impact of such restrictions on the efficiency and productivity of HCV platoons, and to identify potential solutions to mitigate any negative effects.

Existing passenger vehicles and HCVs are still mostly human-driven and do not have interaction capabilities with HCV platooning. Increased V2X communication will improve mobility by reducing the average travel time and the number of stops. This technology may be a cost-effective method for offsetting the negative operational impact of HCV platooning demonstrated in this paper.

Future research could consider the limitations of this study and improve our understanding of the operational impact of HCV platooning on urban arterials. For example:

- The TSP system here was assumed to have perfect detection of two consecutive HCVs movements as a platoon. Existing TSP systems are not currently designed to detect platooned HCVs;
- This study considered TSP for platooned HCVs for through traffic movements only. We note, however, that a future study may benefit from the evaluation of TSP for platooned HCVs on other turning movements (e.g., left turning HCV platooning). The investigation of TSP for other turning movement will generate valuable inputs for more rigorous analyses that can assist in selecting the most suitable intersections as well as the most suitable directional traffic flows for maximum benefit;
- Future studies should conduct a detailed investigation into the different levels of traffic volume and the level of service of the intersection in order to accommodate HCV platooning operations. The benefits of TSP would be diminished if the intersections are close to or exceeding the capacity of the infrastructure;
- Future studies should conduct rigorous benefit and cost analyses to justify a decision to install TSP for HCV platooning at targeted signalized intersections. The analyses need to include the costs associated with the installation, maintenance, and operation of TSP at numerous signalized intersections along the HCV platooning route;
- In the current study of urban arterial road conditions, we have considered the relatively near future in which passenger vehicles are expected to remain human-driven and the maximum HCV platoon rate is not expected to exceed 10%. We think that it is not realistic to evaluate the distant future and scenarios such as 50% HCV platooning until V2X technology is

adapted for vehicle classifications (e.g., passenger vehicles). We expect that when such technology is available, future studies will consider a higher percentage of HCV platooning;

- Future studies should perform pairwise comparison tests to quantify whether the differences between the considered models, such as NP5 and NP10, or NP5 and TP5, or NP0 and TP10, and so forth, are statistically significant;
- Future studies need to provide a framework for selecting the urban arterials where TSP for HCV platooning can deliver the greatest benefits.

The results of this study will help transportation engineers and decision makers to understand the mobility challenges associated with HCV platooning on urban arterials.

3.7 Chapter 3 References

AASHTO. (2018). A Policy on Geometric Design of Highways and Streets (7th ed.). American Association of State Highway and Transportation Officials.

Ahmed, H. U., Huang, Y., & Lu, P. (2021). A Review of Car-Following Models and Modeling Tools for Human and Autonomous-Ready Driving Behaviors in Micro-Simulation. Smart Cities, 4(1), 314–335.

Al Alam, A., Gattami, A., & Johansson, K. H. (2010). An experimental study on the fuel reduction potential of heavy duty vehicle platooning. 13th International IEEE Conference on Intelligent Transportation Systems, 306–311.

Alam, A., Besselink, B., Turri, V., Martensson, J., & Johansson, K. H. (2015). Heavy-duty vehicle platooning for sustainable freight transportation: A cooperative method to enhance safety and efficiency. IEEE Control Systems Magazine, 35(6), 34–56.

Arnaout, G., & Bowling, S. (2011). Towards reducing traffic congestion using cooperative adaptive cruise control on a freeway with a ramp. Journal of Industrial Engineering and Management (JIEM), 4(4), 699–717.

Balke, K. N., Dudek, C. L., & Urbanik, T. (2000). Development and evaluation of intelligent bus priority concept. Transportation Research Record, 1727(1), 12–19.

Beak, B., Zamanipour, M., Head, K. L., & Leonard, B. (2018). Peer-to-peer priority signal control strategy in a connected vehicle environment. Transportation Research Record, 2672(18), 15–26.

Beeston, L., Blewitt, R., Bulmer, S., & Wilson, J. (2021). Traffic Modelling Guidelines v4.

Bishop, R. (2020). New Moves, New Markets For Truck Platooning Revealed At AVS2020.

Forbes:Transportation. https://www.forbes.com/sites/richardbishop1/2020/09/27/new-moves-new-markets-for-truck-platooning-revealed-at-avs2020/#7e0ebe1e6297

Browand, F., McArthur, J., & Radovich, C. (2004). Fuel saving achieved in the field test of two tandem trucks.

Bujanovic, P., & Lochrane, T. (2018). Capacity predictions and capacity passenger car equivalents of platooning vehicles on basic segments. Journal of Transportation Engineering, Part A: Systems, 144(10), 4018063.

Butler, C. (2019). A “demographic tsunami” is about to make Canada’s trucker shortage even worse | CBC News. CBC News. https://www.cbc.ca/news/canada/london/canada-ontario-truck-driver-trucker-shortage-1.5400992

CCMTA. (2016). Automated Vehicles in Canada. https://ccmta.ca/images/publications/pdf/CCMTA_WhitePaper_Automated_Vehicles_in_Canada_2017.pdf

Costello, B. (2019). Truck driver shortage analysis 2019. https://www.trucking.org/sites/default/files/2020-01/ATAs Driver Shortage Report 2019 with cover.pdf

Deng, Q. (2016). Heavy-Duty Vehicle Platooning – Modeling and Analysis.

Deng, Q., & Boughout, W. (2016). The impacts of heavy-duty vehicle platoon spacing policy on traffic flow.

Doustmohammadi, M., Anderson, M., Kesaveraddy, S., & Jones, S. (2017). Examining Model Accuracy: How Well did We do in the 1990’s Predicting 2015.

Dowling, R., Skabardonis, A., Halkias, J., McHale, G., & Zammit, G. (2004). Guidelines for calibration of microsimulation models: framework and applications. Transportation Research Record: Journal of the Transportation Research Board, 1876, 1–9.

FDOT. (2014). Traffic Analysis Handbook. A Reference for Planning and Operations 2014.

Ferguson, M., Lavery, T., & Higgins, C. (2014). Truck Freight Generators & Attractors in the Province of Ontario. McMaster Institute for Transportation and Logistics.

Gordon, M., & Turochy, R. E. (2016). Evaluation of the effects of driver assistive truck platooning on freeway traffic flow.

Guler, S. I., & Menendez, M. (2014). Analytical formulation and empirical evaluation of pre-signals for bus priority. Transportation Research Part B: Methodological, 64, 41–53.

Harwood, D. W., Torbic, D. J., Richard, K. R., Glauz, W. D., & Elefteriadou, L. (2003). NCHRP Report 505 : Review of truck characteristics as factors in roadway design. Transportation Research Board.

Ikiriko, S., Chimba, D., & Mbuya, C. (2019). Impact of Transit Signal Priority on Isolated Intersection Operations: A Microscopic Simulation Evaluation. Proceedings of 98 Th Transportation Research Board (TRB) Annual Meeting.

Ioannou, P. (2015). Design and Evaluation of Impact of Traffic Light Priority for Trucks on Traffic Flow. https://rosap.ntl.bts.gov/view/dot/29105

Islam, T., Vu, H. L., Hoang, N. H., & Cricenti, A. (2018). A linear bus rapid transit with transit signal priority formulation. Transportation Research Part E: Logistics and Transportation Review, 114, 163–184.

ITE. (2000). Traffic Engineering Handbook (J. L. Pline (Ed.); 5th Editio). Institute of Transportation Engineers (ITE).

Kaisar, E. I., Hadi, M., Ardalan, T., & Iqbal, M. S. (2020). Evaluation of Freight and Transit Signal Priority Strategies for Improving Transportation Operations in Urban Corridors. https://fdotwww.blob.core.windows.net/sitefinity/docs/default-source/research/reports/fdot-bdv27-977-14-rpt.pdf

Kuang, X., & Xu, L. (2012). Real-time traffic signal intelligent control with transit-priority. Journal of Software, 7(8), 1738–1743.

Kuhn, B., Lukuc, M., Poorsartep, M., Wagner, J., Balke, K. N., Middleton, D., Songchitruksa, P., Wood, N., & Moran, M. (2017). Commercial truck platooning demonstration in Texas–level 2 automation. Texas. Dept. of Transportation. Research and Technology Implementation Office.

Lazar, C., Tiganasu, A., & Caruntu, C. F. (2018). Arterial Intersection Improvement by Using Vehicle Platooning and Coordinated Start. IFAC-PapersOnLine, 51(9), 136–141.

Lightstone, A., Belony, T., Cappuccilli, J.-F. (2021). Understanding Goods Movement in Canada: Trends and Best Practices. Ottawa.

Lioris, J., Pedarsani, R., Tascikaraoglu, F. Y., & Varaiya, P. (2017). Platoons of connected vehicles can double throughput in urban roads. Transportation Research Part C: Emerging Technologies, 77, 292–305. https://doi.org/10.1016/j.trc.2017.01.023

Lu, C., Dong, J., Houchin, A., & Liu, C. (2021). Incorporating the standstill distance and time headway distributions into freeway car-following models and an application to estimating freeway travel time reliability. Journal of Intelligent Transportation Systems, 25(1), 21–40. https://doi.org/10.1080/15472450.2019.1683450

Maarseveen, S. Van. (2017). Impacts of Truck Platooning at Motorway On-ramps.

Milanés, V., Shladover, S. E., Spring, J., Nowakowski, C., Kawazoe, H., & Nakamura, M. (2013). Cooperative adaptive cruise control in real traffic situations. IEEE Transactions on Intelligent Transportation Systems, 15(1), 296–305. https://doi.org/10.1109/TITS.2013.2278494

Mjogolo, F., Sando, T., & Soloka, M. (2019). OPERATIONAL EFFECTIVENESS OF TRUCK PRIORITY SYSTEM: A MICROSCOPIC SIMULATION APPROACH. Transportation Research Board, 98th Annual Meeting, 1–21.

MTO. (2016). Transportation Tomorrow Survey. Ontario Ministry of Transportation. http://www.mto.gov.on.ca/english/transit/transportation-tomorrow-survey.shtml

MTO. (2021). Long Combination Vehicle (LCV) Program Conditions. Ontario Ministry of Transportation. http://www.mto.gov.on.ca/english/trucks/long-combination-vehicles-program-conditions.shtml?fbclid=IwAR3ghZcHpUs03yyuOazz9RVixLVOTZq1EOEbuc3Auo9I88owVnC50k0on14

MTO iCorridor. (2021, September 1). Historical AADT & AADTT. MTO. https://icorridor-mto-on-ca.hub.arcgis.com/datasets/e951ab3b116d44de8676501ffbeb679b/explore?location=43.716655%2C-79.613062%2C16.00

Nevland, E. A., Gingerich, K., & Park, P. Y. (2020). A data-driven systematic approach for identifying and classifying long-haul truck parking locations. Transport Policy, 96, 48–59.

NHTSA. (2020). Vehicle-to-Vehicle Communication. U.S. Department of Transportation. https://www.nhtsa.gov/technology-innovation/vehicle-vehicle-communication#

Nowakowski, C., O'Connell, J., Shladover, S. E., & 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), 2033–2037.

Nowakowski, C., Shladover, S. E., Cody, D., Bu, F., O'Connell, J., Spring, J., Dickey, S., & Nelson, D. (2011). Cooperative adaptive cruise control: Testing drivers' choices of following distances.

NYC DOT. (2023). Commercial Vehicle Restrictions [WWW Document]. NYC Bus. URL https://www.nyc.gov/nycbusiness/description/commercial-vehicle-restrictions (accessed 1.18.23).

Park, J. (2019, October 24). Why Waste Time on Platooning When LCVs are More Efficient? Heavy Duty Trucking. https://www.truckinginfo.com/343167/why-waste-time-with-platooning-when-lcvs-are-more-efficient

Patten, J., McAuliffe, B., Mayda, W., & Tanguay, B. (2012). Review of aerodynamic drag reduction devices for heavy trucks and buses. National Research Council Canada NRC Technical Report CSTT-HVC-TR, 205, 3.

Proust, E., Smith, P., Pierce, D., Ward, J., & Bevly, D. (2019). Evaluation of Platooning on Resource Roads. 2019 TAC-ITS Canada Joint Conference.

PTV. (2021). PTV Vissim 2021 User Manual. In Karlsruhe, Germany: PTV. PTV AG.

Ramezani, H., Shladover, S. E., Lu, X.-Y., & Chou, F.-C. (2018a). Microsimulation Framework to Explore Impact of Truck Platooning on Traffic Operation and Energy Consumption: Development and Case Study (Issue February).

Rodriguez, A., & Danaher, A. R. (2014). Operational comparison of transit signal priority strategies. Transportation Research Record, 2418(1), 84–91.

SAE International Standard. (2016). Automated Driving: Levels of Driving Automation. In SAE J3016.

Shladover, S. E., Nowakowski, C., Lu, X.-Y., & Ferlis, R. (2015). Cooperative adaptive cruise control: Definitions and operating concepts. Transportation Research Record, 2489(1), 145–152.

Smith G, J. (2020, February 20). Canada's Truck Drivers to Require 103.5 hours of Training. Trucknews.Com. https://www.trucknews.com/transportation/canadas-truck-drivers-to-require-103-5-hours-of-training/1003136596/

Smith, S. W., Kim, Y., Guanetti, J., Li, R., Firoozi, R., Wootton, B., Kurzhanskiy, A. A., Borrelli, F., Horowitz, R., & Arcak, M. (2020). Improving urban traffic throughput with vehicle platooning: Theory and experiments. IEEE Access, 8, 141208–141223.

Steenhof, P., Woudsma, C., & Sparling, E. (2006). Greenhouse gas emissions and the surface transport of freight in Canada. Transportation Research Part D: Transport and Environment, 11(5), 369–376. https://doi.org/https://doi.org/10.1016/j.trd.2006.07.003

Sukennik, P. (2019). Micro-Simulation Guide for Automated Vehicles-D2.5. CoXEist, 1-29.

Sureshan, S., & Branch, T. P. (2009). Impact of Intercity Trucking on Urban Environment Greater Toronto and Hamilton Area Case Study. 2009 ANNUAL CONFERENCE AND EXHIBITION OF THE TRANSPORTATION ASSOCIATION OF CANADA-TRANSPORTATION IN A CLIMATE OF CHANGE.

TAC. (2017). Geometric design guide for Canadian roads.

Tavasszy, L. A., & Janssen, R. (2017). The value case for truck platooning. working paper. January.

Tiaprasert, K., Zhang, Y., & Ye, X. (2019). Platoon recognition using connected vehicle technology. Journal of Intelligent Transportation Systems, 23(1), 12–27.

Transport for London. (2020). Operating a commercial vehicle in London [WWW Document]. URL https://tfl.gov.uk/modes/driving/operating-a-commercial-vehicle-in-london

USDOT. (2018). Automated Vehicles: Truck Platooning ITS Benefits, Costs, and Lessons Learned: 2018 Update Report. https://www.itsknowledgeresources.its.dot.gov/its/bcllupdate/pdf/BCLL_Automated Vehicles (CMV) Final Draft v4.pdf

USDOT. (2020). Truck Profile. Bureau of Transportation Statistics. https://www.bts.gov/content/truck-profile

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

VDOT. (2020). VDOT VISSIM User Guide. In Virginia Department of Transportation (VDOT) . https://www.virginiadot.org/business/resources/VDOT_Vissim_UserGuide_Version2.0_Final_2020-01-10.pdf

Wang, P., Jiang, Y., Xiao, L., Zhao, Y., & Li, Y. (2020). A joint control model for connected vehicle platoon and arterial signal coordination. Journal of Intelligent Transportation Systems, 24(1), 81–92.

Welch, B. L. (1947). The generalization of ‘STUDENT’S’problem when several different population varlances are involved. Biometrika, 34(1–2), 28–35.

WisDOT. (2019). Traffic Analysis and Modeling Section 20: Microscopic Simulation Traffic Analysis. In Traffic Engineering, Operations & Safety Manual (pp. 1–47). Wisconsin Department of Transportation. https://wisconsindot.gov/dtsdManuals/traffic-ops/manuals-and-standards/teops/16-20.pdf#16-20-8

Yang, D., Kuijpers, A., Dane, G., & van der Sande, T. (2019). Impacts of large-scale truck platooning on Dutch highways. Transportation Research Procedia, 37, 425–432.

Zabat, M., Stabile, N., Farascaroli, S., & Browand, F. (1995). The aerodynamic performance of platoons: A final report.

Zeidler, V., Buck, H. S., Kautzsch, L., Vortisch, P., & Weyland, C. M. (2019). Simulation of Autonomous Vehicles Based on Wiedemann's Car Following Model in PTV Vissim.

Zhao, L., & Sun, J. (2013). Simulation framework for vehicle platooning and car-following behaviors under connected-vehicle environment. Procedia-Social and Behavioral Sciences, 96, 914–924.

Zhao, Y., & Ioannou, P. (2016). A Traffic Light Signal Control System with Truck Priority. IFAC-PapersOnLine, 49(3), 377–382. https://doi.org/https://doi.org/10.1016/j.ifacol.2016.07.063

CHAPTER 4: TRUCK PLATOONING ON FREEWAYS

4.1 Introduction

This chapter focuses on the third objective of this dissertation. This third objective of this study is to investigate the safety and operational impact of heavy commercial vehicle (HCV) platooning on freeways. Vehicles merging from an on-ramp to freeway inevitably create complex lane changing interactions resulting in operational and safety challenges such as travel delays and collisions. Collisions on freeway merge areas associated with on-ramps are a significant issue. Zhang (2016), for example, investigated three years of collisions from 2010 to 2012 on 60 different interchanges in Missouri, United States. The study examined 844 collisions and identified 96 (11%) occurred along freeway on-ramps. Acceleration lanes in merge areas are designed to improve safety for vehicles merging in these areas (AASHTO, 2018; TAC, 2017), but it is necessary to consider the appropriate length for the safe and efficient operation of truck platoons emerging on our roadways.

4.1.1 Acceleration Lane

The American Association of State Highway and Transportation Officials (AASHTO) (2018) guideline identifies an acceleration lane on a freeway merge area as a speed change lane for vehicles traveling from an on-ramp to the mainline freeway. Two common designs for the acceleration lane include parallel and taper styles with the former parallel design suggested for heavy commercial vehicle (HCV) operations (AASHTO, 2018; TAC, 2017). Vehicles use the acceleration lane to accelerate to a target speed before merging into the mainline freeway traffic. The methodology used to estimate acceleration lane length was first discussed in

AASHTO (1965) with a minimum length required for an acceleration lane and remained same in AASHTO (2018) which was 1,200 ft (360 m) including 300 ft taper section. The taper section refers to the end of the merging ramp where the width of the travelling lane is gradually reduced.

Past studies have noted that vehicle length and acceleration rate are key factors contributing to the determination of the length of acceleration lanes (Bareket and Fancher, 1993; Dabbour et al., 2021; Fitzpatrick and Zimmerman, 2007; Gattis et al., 2008; Guo et al., 2017; Harwood et al., 2003; Lee, 2006; Qi et al., 2019; Reilly et al., 1989; Torbic et al., 2012; Yang et al., 2016). Reilly et al., (1989) discussed the relationship between vehicle length and acceleration lane length and showed that longer vehicles require more time, and a subsequently longer acceleration lane length, to find an acceptable gap when merging into the mainline freeway.

Although many studies have shown that the length of HCVs affects driving behaviour, including lane changing behaviour on freeways (Ferrari, 2009; Qi et al., 2019; Ran et al., 1999), the acceleration lane length in existing geometric design guidelines was estimated by considering merging maneuverers between passenger vehicles and is expected to be much shorter than the length required to accommodate HCVs (Reilly et al., 1989). Using HCV speed profile data collected in the United States, Harwood et al. (2003) recommended that acceleration lane length for HCVs should be longer by 95 ft, or 1.5 times the length given in the AASHTO (2018) design guideline. Qi et al. (2019) developed an analytical model calibrated using the observed time gap required for HCVs to change lane. They also suggested that the AASHTO acceleration lane length was too short for HCV operation and proposed a much longer acceleration lane length. For example, Qi et al. (2019) suggested that the acceleration lane for merging should be 1,692 ft instead of 1,200 ft suggested in AASHTO (AASHTO, 2018) design guideline for a freeway with 1,100 vph, a design speed of 60 mph speed limit on the freeway, and a design speed of 30 mph on the ramp. Bareket and Fancher (1993) recommended adding 300 ft with AASHTO's recommended acceleration lane length for ramp roadways with frequent long-combination vehicles (LCVs). An LCV is a tractor-trailer combination with two or more trailers attached to a single tractor.

The literature identifies the critical time gap as another major factor when determining acceleration lane length (Fitzpatrick and Zimmerman, 2007; Marczak et al., 2013; Qi et al., 2019; Reilly et al., 1989; Sun et al., 2018). The critical time gap indicates the minimum gap between vehicles on the freeway that is acceptable for on-ramp vehicles to safely complete the merging maneuver. Qi et al.'s (2019) field observations found that the critical time gap was 2.58 sec for passenger vehicles and 3.06 sec for HCVs. A longer critical time gap for HCVs influences the acceleration lane length design since a greater distance enables greater opportunities for the gap to be encountered by the merging vehicle.

There are no studies found to estimate a suitable acceleration lane length for HCV platooning. An HCV platoon consists of two or more HCVs in a convoy connected wirelessly by advanced vehicle-to-vehicle (V2V) communication technologies. Depending on the level of human control, an HCV platoon can be an example of connected autonomous vehicles (CAVs). The amount of technological control on the vehicles can vary as per the levels of driving automation defined by the Society of Automotive Engineers (SAE) (SAE International Standard, 2016). An autonomous HCV platoon at SAE Level 3 (hereafter, Level 3) needs human drivers in all vehicles involved in the platoon. An HCV Platoon at SAE Level 4 (hereafter, Level 4) requires human driver involvement for the lead HCV but not the following HCV. An HCV platoon at SAE Level 5 (hereafter, Level 5) does not require a human driver for the lead HCV or following HCV.

In SAE Level 4, for instance, automation reduces or eliminates human driver involvement from one or more of the HCVs in the platoon (Bishop, 2020; USDOT, 2018a). As the length of an HCV platoon can be even longer than the length of an LCV, HCV platoons require particular consideration in merging areas to ensure safe and efficient transition from ramps to freeways. The review of past studies suggests that freeway merging areas may experience additional challenges due to the operation of Level 4 HCV platooning(Arnold and Roorda, 2020; Faber et al., 2020; Kuijpers, 2017; Lee et al., 2021; Meng Wang et al., 2019b; Ye and Wang, 2022).

4.1.2 Heavy Commercial Vehicle Platooning

Many studies have reported reductions in fuel consumption, usually between 6% and 10%, as a primary benefit of HCV platooning (Alam et al., 2015; Browand et al., 2004; Patten et al., 2012; Ramezani et al., 2018a; Tavasszy and Janssen, 2017; Zabat et al., 1995). However, some logistics companies in North America prioritize the benefits of HCV platooning to overcome the driver shortage and reduce labour costs. Since 2018, FPInnovations, for example, has tested Level 5 HCV platooning, with no human drivers required, for the forestry industry where severe driver shortages can be found in remote locations. The platoons transport timber from forests to a nearby port (Proust et al., 2019).

Level 3 HCV platooning requires human drivers in all the HCVs, but provides flexibility when engaging and disengaging HCVs in a convoy. Level 4 or Level 5 HCV platooning is considered less flexible than Level 3 and may not easily allow other vehicles to cut-in and cut-out of an HCV platoon. One reason for the lack of flexibility is the need to maintain proximate distance between the HCVs for the whole journey from origin to destination to maintain a consistent and stable wireless connection between the lead HCV and the following HCVs. The close distance creates a challenge for Level 4 and Level 5 HCV platooning when the vehicles attempt to merge into a mainline freeway together. It is anticipated that a longer acceleration length will be needed for the platooning vehicles to find an appropriate time gap that allows two or more HCVs to make a simultaneous lane change.

Many studies have examined the operational benefits and challenges of HCV platooning, but these studies were based mainly on simulations or field tests on freeway sections. The studies assumed that each HCV in a platoon can always engage or disengage as required by the traffic and vehicles cutting-in and cutting-out. The studies therefore assumed SAE level 3 automation and did not consider the impact of HCV platooning with one of more driverless HCVs. Ramezani et al. (2018a), for instance, considered a maximum of five HCVs in a platoon on a freeway and assumed that any HCV in the platoon could easily leave or re-join the platoon during the entire travel whenever needed. Such studies did not consider SAE level 4 or level 5.

The market penetration rate refers to the proportion of platooned vehicles as a percentage of the number of HCVs using the road (Bujanovic and Lochrane, 2018), i.e., the percentage of HCVs operating as a platoon. Few studies have considered the operational level impact of the market penetration rate of platooned HCVs on the mobility and safety of traffic flows, and these studies typically rely on simulations. Gordon and Turochy (2016) reported that a 20% market penetration of HCV platooning can reduce travel time delay by 40% travel time (7.7 sec per vehicle) on average for both passenger vehicles and HCVs when compared to no platooning average travel time delay 19.1 sec per vehicle. The study simulated operations on 5.3 miles of Interstate Highway (I-85) in Alabama. Other studies, however, have reported that an HCV platooning market penetration rate of more than 25% can increase travel time and result in delays and additional conflicts which introduce safety issues, especially on freeway merging areas (Arnold and Roorda, 2020; Kuijpers, 2017; Meng Wang et al., 2019b). To reduce delays and address the concerns for HCV platooning, Arnold and Roorda (2020) suggested providing an additional 50 metres of acceleration lane to the distance recommended by the AASHTO (2018) Design Guideline.

4.1.3 Study Goal and Objectives

The goal of the third objective discussed in this chapter is to investigate the operational impact of SAE level 4 HCV platooning on freeway parallel-type merge areas in terms of safety and mobility. To conduct this research, three sub-objectives have been considered:

- Develop an analytical method to determine the appropriate acceleration lane length for 0.6 sec and 1.2 sec headway HCV platooning operations on the merging section of freeway ramps;
- Determine an appropriate acceleration lane length for 0.6 sec and 1.2 sec time headway HCV platooning operation using an analytical method and then validate with a simulation method; and

- Evaluate the impact of the three low market penetration rates (0%, 5% and 10%) for 0.6 sec and 1.2 sec time headway HCV platooning operation on the merging section of freeway ramp based on the existing and the estimated acceleration lane lengths.

To achieve the considered sub-objective of this study, we modified an existing analytical model to reflect the total length of platooned HCVs. The total length of an HCV platoon can vary depending on the length of the different HCVs and the physical gap between two consecutive HCVs. Section 4.3 discusses these issues.

We assumed relatively low market penetration rates of 0%, 5% and 10% as it is uncertain when, or if, a substantially higher market penetration rate would be realistic. Despite the expectation that some levels of platooning using advanced V2V technologies will eventually be applied on public roads, we consider it unlikely that SAE level 4 HCV platooning at a market penetration rate higher than 10% will be widespread in the near future.

Like previous studies (Arnold and Roorda, 2020; Gordon and Turochy, 2016; Kuijpers, 2017; Lee et al., 2021; Li et al., 2021; Maarseveen, 2017; Seraj and Qiu, 2021; Meng Wang et al., 2019b), this study undertook the simulation by developing a set of micro-simulation models using PTV Vissim. The US FHWA Surrogate Safety Assessment Model (SSAM) is used to assess the safety performance of platooned HCVs on freeway merge areas (Gettman et al., 2008; Habtemichael and de Picado Santos, 2013).

Section 4.2 describes the study area and study data. Section 4.3 discusses the estimation of acceleration lane length using the analytical models specified in the 2018 AASHTO design guidelines. Section 4.4 explains the simulation models. Section 4.5 presents and discusses the results of the analytical and simulation models. Section 4.6 presents the conclusions and recommendations.

4.2 Study Area and Data Descriptions

Merging maneuvers are affected by freeway and ramp traffic and the freeway and ramp design speed (Qi et al., 2019; Reilly et al., 1989). To determine appropriate merging segment acceleration lane length using an analytical or simulation model, it is necessary to know freeway and merging ramp traffic volumes, the percentage of vehicles by classification, the right-most lane traffic distribution factor (the closest lane on the freeway where number of traffic flow will be directly interrupted with merging ramp traffic), and vehicle acceleration rates.

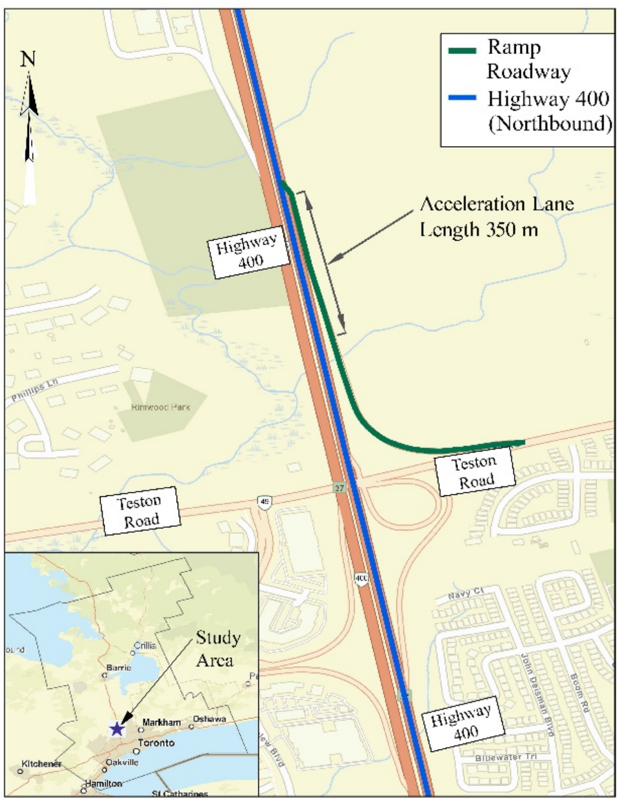

Figure 4-1: Study Interchange on Highway 400 in Vaughan, Ontario, Canada

Figure 4-1 shows the study interchange on Highway 400 in Vaughan, Ontario, Canada. The blue star denotes the study location on Highway 400. The blue line indicates a northbound freeway (Highway 400), and the green line refers to a ramp roadway connecting Teston Road to Highway 400. A 23 km segment of northbound Highway 400 in Ontario, Canada, is selected for this study. The selected segment includes a northbound merging ramp at the Teston Road partial cloverleaf interchange. The posted speed limits are 100 km/h on the freeway. The Teston Road northbound merging ramp is a single lane with a 350 m acceleration lane including 90 m taper section and merging traffic from Teston Road to the five lanes of Highway 400. The posted speed limits are 50 km/h on the ramps. The acceleration lane was constructed according to Transportation Association of Canada (TAC) (2017) geometric design guidelines and AASHTO (2018) geometric design guidelines (AASHTO, 2018).

Traffic and speed data is obtained from the Ontario Ministry of Transportation (MTO) for a week between October 28,2018 to November 4, 2018. The traffic volume dataset provided 24-hour hourly traffic volumes for the freeway and merging ramp, including the number of passenger vehicles, and different categories of HCVs (i.e., single-unit HCV, LCV etc.).

For the same week, map data was obtained from the American Transportation Research Institute (ATRI) via MTO (MTO, 2021b) and from HERE (HERE, 2021). This data provided travel speed information derived from anonymous GPS tracking for passenger vehicles and HCVs for each lane of the freeway.

The MTO traffic data showed that, from 1:00pm to 2:00pm, an average of 6,100 vehicles used the freeway and an average of 1,100 vehicles used the Teston Road merging on-ramp. The freeway traffic was composed of 88.2% passenger vehicles, 11.2% HCVs, and 0.6%

LCVs. The on-ramp traffic was composed of 93.8% passenger vehicles, 4.7% HCVs, and 1.5% LCVs (MTO, 2021b).

From the start of the ramp to the start of the acceleration lane (i.e., the gore-point), the average passenger vehicle and HCV travel times were identical in the MTO data and the map data: both passenger vehicles and HCVs travelled the distance in 66 sec. The traffic volume and speed data profile are used as inputs for the analytical and simulation models to analyse, calibrate and validate the models.

4.3 Acceleration Lane Length Using Analytical Models

This section discusses the estimation of acceleration lane length using the analytical models specified by AASHTO (2018) and TAC (2017), by Qi et al. (2019), and by the National Cooperative Highway Research Program (NCHRP). The Qi et al model is known as the 2019 Center for Advanced Multimodal Mobility Solutions and Education (CAMMSE) model, and the NCHRP model is known as the NCHRP 3-35 Model.

The AASHTO (2018) and TAC (2017) guidelines used passenger vehicle acceleration rates to compute acceleration lane length. Neither set of guidelines took HCV or HCV platooning operations into account when calculating the acceleration lane length required for a merging a passenger vehicle. The AASHTO guidelines also recognized that HCVs and buses have slow acceleration rates compared with passenger vehicles, and therefore need longer acceleration lanes, but did not consider the critical time gap which is directly associated with vehicle length. Lee (2006) suggested that total accepted gap can be calculated using Equation (4-1):

$$\text{Total Accepted Gap} = G_{nt}^{lead,cr} + L_i + G_{nt}^{lag,cr} \tag{4-1}$$

Where:

$G_{nt}^{lead,cr}$ = Lead critical gap (m) of n individuals at time t;

$G_{nt}^{lag,cr}$ = Lag critical gap (m) of n individuals at time t; and

L_i = Length of merging vehicle i (m)

4.3.1 AASHTO Model

The recent 2018 AASHTO model was first referenced in the 1965 AASHTO guidelines (AASHTO, 2018, 1965). The model is shown in Equation (4-2):

$$A = \frac{(1.47V_m)^2 - (1.47V_r)^2}{2a} \tag{4-2}$$

Where:

A = Acceleration length (ft);

V_m = Freeway design speed (mph);

V_r = Ramp design speed (mph); and

a = Acceleration rate (ft/s^2).

4.3.2 CAMMSE Model

Qi et al. (2019) suggested the CAMMSE model, a new analytical model which included traffic volume and HCV operations. According to the CAMMSE model, the acceleration lane length represents the summation of acceleration (L_1) and gap searching segment (L_2). The CAMMSE model is shown in Equations (4-3), (4-4) and (4-5). Equation (4-3) is used to estimate acceleration lane length:

$$L = L_1 + L_2 \tag{4-3}$$

Where:

L = Total acceleration lane length (ft);

L_1 = Acceleration segment length (ft); and

L_2 = Gap searching length (ft).

The L_1 and L_2 length components can be calculated as follows:

$$L_1 = \frac{(1.47V_m)^2 - (1.47V_r)^2}{2a} \tag{4-4}$$

$$L_2 = V_m d \tag{4-5}$$

$$d = \frac{e^{qT} - qT - 1}{q(1 - e^{-qT})} \tag{4-6}$$

Where:

T = Critical time gap (s);

d = Gap searching time or merging delay (s); and

q = Average freeway traffic volume (vps/ln).

The CAMMSE model also considered the maximum distance from merging ahead $(V_m + 5\ mph)$ and merging behind $(V_m - 5\ mph)$ conditions as shown in Equation (4-7) where subscript (a) and (b) denotes merging ahead and merging behind respectively:

$$L = Max(L_a, L_b) \tag{4-7}$$

When determining gap searching length, the CAMMSE model considered only merging ramp traffic volume. Merging delay (d) was estimated by field observations of passenger vehicles and HCVs. However, for a safe merging maneuver, gap must be accepted, and gap acceptance is dominated by freeway right-most lane traffic volume which is also indicated by Greenshields et al. (1946) and Reilly et al. (1989).

4.3.3 NCHRP 3-35 Model

The NCHRP 3-35 model was generated by Reilly et al. (1989). Reilly et al. (1989) considered acceleration (L_1) and gap searching segment (L_2) when estimating acceleration lane length. Reilly et al. (1989) suggested Equation (4-8) for estimating the gap searching length (L_2) including gap acceptance zone:

$$L_2 = L_{AP} + d_{hr} \tag{4-8}$$

Where:

L_2 = Gap searching length acceptance for safe merging;

d_{hr} = Distance required to search and accept a headway gap including delay due to ramp vehicle (ft); and

L_{AP} = Length of the ramp vehicle's adjust position zone (ft), in the event when ramp vehicle needs to reject the initial lag gap and modify its relative position based on the speed of freeway right-most lane vehicle

The adjust position length L_{AP} can be calculated as follows:

$$L_{AP} = v_{rm1}t + \frac{a_1}{2}t^2 \tag{4-9}$$

$$t = \frac{2(\Delta d)}{\Delta v + \sqrt{(\Delta v)^2 + 2\,(\Delta a)(\Delta d))}} \tag{4-10}$$

Where:

t = Ramp vehicle time to collide with freeway right-most lane's lag vehicle (sec);

Δd = Difference between absolute distances travelled by the freeway and ramp vehicles during the vehicle adjustment process (ft);

$\Delta v =$ Speed differential between freeway right-most lane and ramp vehicles at the start of gap searching and gap acceptance zone (ft/sec); and

$\Delta a =$ Difference in acceleration rates of ramp and lag vehicle in freeway right-most lane at the end of acceleration segment (ft/sec^2).

Equation (4-10) can be re-written as follows:

$$t = \frac{2(\alpha v_f + L_i)}{(v_f - v_{rm1}) + \sqrt{\left((v_f - v_{rm1})^2 + 2\,(a_f - a_{rm})(\alpha v_f + L_i)\right)}} \tag{4-11}$$

Where:

$\alpha =$ Car following constant (sec);

$v_{rm1} =$ Speed of ramp vehicle at the starting of gap searching lane/ Speed of ramp vehicle at the end of accelerating section (ft/sec);

$a_{rm} =$ Average acceleration rate of ramp vehicle at the starting of gap searching lane/at the end of accelerating section (ft/sec^2);

$a_f =$ Average acceleration rate of freeway right most lane vehicle (ft/sec^2); and

$L_i =$ Length of merging vehicle such as a passenger vehicle or an HCV (ft).

In Equation (4-8), the distance required to search and accept a headway gap including delay due to ramp vehicle can be estimated as follows:

$$d_{hr} = \frac{d_q}{d_s} d_h \tag{4-12}$$

Where:

$d_h =$ Distance required searching for and accepting a gap without effect of ramp volume (ft);

d_s = Average traffic delay to a merging vehicle (sec); and

d_q = Average traffic delay to a merging vehicle with ramp volume effect (sec).

$$\frac{d_q}{d_s} = \frac{B + \frac{\sigma^2 + (B)^2}{2\left(\frac{1}{p} - B\right)}}{B} \tag{4-13}$$

In Equation (4-13), B and d_h can be written as follows:

$$B = \frac{1}{\left(\frac{kq}{3600N}\right)\left(1 - \frac{v_{rm}}{v_f}\right)}\left(e^{\left(\frac{kq}{3600N}\right)\left(1 - \frac{v_{rm}}{v_f}\right)T} - \left(\frac{kq}{3600N}\right)\left(1 - \frac{v_{rm}}{v_f}\right)T - 1\right) \tag{4-14}$$

$$d_h = \frac{v_{rm}}{\left(\frac{kq}{3600N}\right)\left(1 - \frac{v_{rm}}{v_f}\right)^2}\left(e^{\left(\frac{kq}{3600N}\right)\left(1 - \frac{v_{rm}}{v_f}\right)T} - \left(\frac{kq}{3600N}\right)\left(1 - \frac{v_{rm}}{v_f}\right)T - 1\right) \tag{4-15}$$

Where:

k = Right-lane distribution factor;

v_f = Freeway Speed (ft/sec);

v_{rm} = Ramp Design Speed (ft/sec);

p = Ramp Volume (vps);

σ^2 = Variance of time spent in a queue (sec2);

λ = Volume in right lane (vps);

N = Number of freeway lanes;

q = Total freeway volume (vph); and Acceptable time headway (sec)

T = Acceptable time headway (sec)

4.3.4 Proposed Model

In this paper, we propose an analytical model that can estimate an appropriate acceleration lane length for efficient and safe truck platooning operations. The proposed model adapts the 2018 AASHTO, CAMMSE, and NCHRP 3-35 models, and includes acceptable gap searching length. The proposed model also considers the length of HCVs (L_i), the number of HCVs in platoon (n), and the physical distance between HCVs (d). No previous research has considered the latter two variables. The model can also be used to estimate the acceleration lane length required for LCVs.

The accepted gap equation from Lee (2006) did not consider the number of platooned HCVs or the physical distance between HCVs, therefore we propose using Equation (4-16) instead of Equation (4-1) to incorporate the number of HCVs in platoon (n), the physical distance between HCVs (d), and the length of HCVs (L_i) to estimate total accepted gap for HCV platooning.

$$\text{Total Accepted Gap} = G_{nt}^{lead,cr} + (nL_i + (n-1)d) + G_{nt}^{lag,cr} \tag{4-16}$$

Furthermore, Equation (4-17) can be used to replace Equation (4-11):

$$t = \frac{2\left(\alpha v_f + (nL_i + (n-1)d)\right)}{(v_f - v_{rm1}) + \sqrt{\left((v_f - v_{rm1})^2 + 2\,(a_f - a_{rm})\left(\alpha v_f + (nL_i + (n-1)d)\right)\right)}} \tag{4-17}$$

In both Equations (4-16) and (4-17):

$n =$ Number of vehicles in a platoon;

$L_i =$ Length of merging vehicle i.e., an HCV or an LCV or passenger vehicle (ft); and

$d =$ Physical gap between platoon vehicles (zero for single vehicle) (ft)

As suggested by Qi et al., (2019) regarding the merging ahead condition, the proposed model uses V_h instead of V_m in Equation (4-4), where $V_h = V_m + 5mph$. Acceleration segment length can be estimated as shown in Equation (4-18).

$$L_1 = \frac{(1.47V_h)^2 - (1.47V_r)^2}{2a} \tag{4-18}$$

Since field observed gap searching time is not still available for HCV platooning, therefore we propose to use of Equation (4-8) instead of Equation (4-5) to estimate gap searching length and the use of Equation (4-16) as a replacement of Equation (4-11). By summing proposed acceleration segment length and gap searching length equations, the required acceleration lane length can be calculated.

4.3.5 Estimation of Acceleration Lane Length Using Analytical Model

We used the proposed analytical model to estimate the acceleration lane length required for passenger vehicles and WB-20 HCVs. We based our estimation on the observed freeway traffic volume of 6,100 vph and the observed ramp volume of 1,100 vph (see Section 4.2). For passenger vehicles, we used the acceleration rate suggested in AASHTO (2018), and for WB-20 HCVs we used the acceleration rate suggested for HCVs by Torbic et al. (2012).

We compared the estimated critical time gap with Qi et al.'s (2019) field observations before using this result for the calculation of acceleration lane length. A two-sample t-test is used for passenger vehicles and for WB-20 HCVs. The null hypothesis was that the estimated and observed critical time gaps were equal (WisDOT, 2019).

Table 4-1 shows the t-test results for the critical time gap. The results show that the null hypothesis cannot be rejected, i.e., the differences were not statistically significant at the 95%

confidence level (p-value > 0.05) and the observed and estimated time gaps could be considered close enough.

Table 4-1: T-Test Results for Critical Time Gap

Vehicle Classifications	Estimated Time Gap (sec)	Observed Critical Time Gap (sec) (Qi et al., 2019)	t-test	P-Value
Passenger Vehicle	2.60	2.58	0.89	0.44
WB-20 HCV	3.07	3.06	1.41	0.25

Next, we compared the acceleration lane lengths given by the CAMMSE and 2018 AASHTO models with the acceleration lane lengths estimated by the proposed models. The comparisons were undertaken for a ramp design speed of 65 km/h and 81 km/h, and for a freeway speed of 105 km/h. The absolute differences between the acceleration lane lengths estimated by the established models (CAMMSE and 2018 AASHTO models) and our proposed model were less than 5%. We used a two-sample t-test for the statistical comparison. The null hypothesis was that the estimated acceleration lane length for a ramp design speed of 81 km/h was equal to both the CAMMSE and 2018 AASHTO acceleration lane lengths. Table B-1 shows the t-test results for acceleration lane length according to the CAMMSE and 2018 AASHTO models. The t-test results indicated that we cannot reject the null hypothesis because the p-value at the 95% confidence level was greater than 0.05. These results suggest that it is reasonable to use the proposed model to estimate the acceleration lane length required for HCV platoons to merge onto the mainline freeway.

The AASHTO (2018) guidelines recommend allowing at least 360 m for an acceleration lane without taper-section (2018). The TAC (2017) guidelines recommend allowing 350 m an acceleration lane with parallel-type merging regardless of the ramp design speed or freeway speed. The AASHTO guidelines also recommend a maximum length of 610 m for an acceleration lane only when a vehicle's speed at the beginning of the ramp is zero, freeway speed is 130 km/h, and ramp design speed is 92 km/h.

Our estimation of the acceleration lane length required for HCV platooning was based on platoons of two WB-20 HCVs with each vehicle length equal to 22.70 m. Ramezani et al. (2018b) reported 0.6 sec and 1.2 sec between two consecutive HCVs as the two most stable headways that HCVs can maintain while they are travelling in a convoy. Therefore, these two headway values are selected in this study for further analyses: 0.6 sec (HCVP_0.6H; 58.84 m) and 1.2 sec (HCVP_1.2H; 72.28 m) (Kuhn et al., 2017; Ramezani et al., 2018a; 2018b; Shladover et al., 2018). Here HCVP_0.6H refers two HCV platooning connected with 0.6 sec headway and the overall length including physical gap between platoon HCVs is 58.84 m. Similarly, HCVP_1.2H demonstrates two HCV platooning connected with 1.2 sec headway and the overall length is 72.28 m. We also considered eight ramp design speeds (from 49 km/h to 102 km/h) and seven average running speeds (from 44 km/h to 81 km/h) at the start of the ramp. Vehicles that started on the ramp with a speed that was equal to or more than the ramp design speed, were not required to accelerate while on the ramp.

Table 4-2 shows the acceleration lane lengths estimated by the proposed model.

Table 4-2: Estimated Acceleration Lane Length

Freeway Speed, V_h (km/h)	Ramp Design Speed, V_r (km/h)	Initial Speed at the Beginning of Ramp (km/h)						
		44	**50**	**57**	**63**	**70**	**76**	**81**
		Required Acceleration Lane Length (m)						
		2 HCV Platooning 0.6 sec Headway						
105	49	390						
105	57	365	420					
105	65	340	395	405				
105	73	310	370	390	450			
105	81	275	325	350	410	480	585	
105	89	235	280	305	360	430	490	630
105	92	215	260	285	335	405	500	605
105	102	155	190	215	260	320	400	490
		2 HCV Platooning 1.2 sec Headway						
105	49	400						
105	57	375	430					
105	65	350	405	420				
105	73	320	385	405	470			
105	81	285	340	370	430	510	620	
105	89	245	295	325	380	455	545	685
105	92	230	275	305	360	435	540	660
105	102	170	205	240	285	350	445	545

Note: Initial Speed indicates Average Running Speed at the Beginning of Ramp

Table 4-2 shows the following:

- HCV platoons with a longer headway (1.2 sec) require a longer acceleration lane than HCV platoons with a shorter headway (0.6 sec); and
- The longest acceleration lane length estimated is 685 m for a platoon with a headway of 1.2 sec traveling at 81 km/h at the start of the ramp with a ramp design speed of 89 km/h.

If we compare the results in Table 4-2 (calculated acceleration lane length for HCV platooning) with 2018 AASHTO and 2017 TAC suggested acceleration lane length (on the basis of passenger vehicle merging maneuverers), we find that:

- Our model's longest acceleration lane length estimate (685 m) is approximately 75 m longer than the 2018 AASHTO maximum recommended acceleration lane length. This difference is particularly striking as our model was estimated for platooned HCVs merging onto a freeway with a 25 km/h lower speed than the 2018 AASHTO speed. Furthermore, the estimated acceleration lane is 325 m longer than the 2018 AASHTO's minimum recommended value.
- The acceleration lane recommended by 2017 TAC is about 350 m [2], i.e., considerably less than many of our estimates and 335 m less than our highest estimate of 685 m;
- As stated in the 2018 AASHTO and the 2017 TAC, the minimum acceleration lane length is defined as the 85th percentile of vehicles merging onto the freeway in the provided acceleration lane to meet the desired freeway speed. This results in some acceleration lane lengths in 2018 AASHTO and the 2017 TAC that are smaller than their stated minimum values. Our model also estimated some acceleration lane lengths that are shorter than the minimum values given in the 2018 AASHTO (360 m) and the 2017 TAC (350 m). For example, for a platoon with a headway of 1.2 sec travelling on a ramp with a design speed of 102 km/h (63 mph), the acceleration lane length estimated by our proposed model is less than the minimum values given in both North American design guidelines. This is primarily caused by some platooned HCVs on the ramp roadway having already reached a 102 km/h (63 mph) speed prior to matching the freeway's 105 km/h (65 mph) speed. By contrast, it will take a longer distance for platooned HCVs accelerating from a slow-speed ramp, i.e., 57 km/h (35 mph), to reach the freeway 105 km/h (65 mph) speed;

- The estimated acceleration lane length for platooned HCVs for our proposed model is always longer than the suggested value for the different speed ramp roadways in the design guidelines. This is due to the gap searching length that was not considered in either the 2018 AASHTO or 2017 TAC;
- Regardless of ramp speed, the acceleration lane length estimated by our proposed model for merging passenger vehicles is about half the length required for merging HCV platoons travelling with a headway of 1.2 sec;
- The 2017 TAC recommended acceleration lane lengths are also noticeably shorter than those estimated by our model. For instance, in platooned HCVs with a headway of 1.2 sec travelling through a ramp of 57km/h (35 mph) speed, our estimated acceleration lane length is longer than the 350 m minimum stated in the 2017 TAC. In this circumstance, platooned HCVs need to accelerate to 105 km/h (65 mph) in the acceleration lane and find a suitable gap to merge onto the freeways. The acceleration segment length and gap searching length factors lead to the necessity for a longer acceleration lane length than the 2017 TAC minimum value.

Except for situations when HCV platooning are merging onto high-speed ramp roadways, our proposed model suggests that the acceleration lane length for an HCV platoon is longer than the minimum acceleration lane lengths recommended in the 2018 AASHTO and 2017 TAC. The results and comparison suggest that the acceleration lane lengths estimated by our proposed model for an HCV platoon are longer than the acceleration lane lengths recommended for passenger vehicles in 2018 AASHTO and 2017 TAC. The acceleration lane lengths suggested by 2018 AASHTO and 2017 TAC are not sufficient for the HCV platoons investigated in this study regardless of the speed on the ramp. Due to the inadequacy of acceleration lane length for merging HCV platoons, the platoons may experience significant delay and pose a safety risk. This issue has been reported in simulation-based studies such as Arnold and Roorda (2020), Kuijpers (2017), Maarseveen (2017), and Wang et al. (2019). For an HCV platoon to travel uninterrupted on the ramp and merge onto a 105 km/h freeway, the analytical model's findings suggest that the acceleration lane should be 600 m long rather than the 360 m recommended by 2018 AASHTO or the 350 m recommended by 2017 TAC.

Analytical models provide an approach that can quickly generate results. However, this expediency comes at the cost of simplifying assumptions and ignore the stochastic nature of vehicle-to-vehicle interactions. Section 4 of this chapter continues the investigation using a micro-simulation model.

4.4 A Micro-Simulation Model to Estimate Acceleration Lane Length

The literature recommends micro-simulation modelling for detailed study of acceleration lane performance (Arnold and Roorda, 2020; Kuijpers, 2017; Maarseveen, 2017; Meng Wang et al., 2019b). This section discusses the development of the micro-simulation model followed by calibration. Section 4.5 presents the results of the micro-simulation modelling.

4.4.1 Model Development

The Base Model was developed to replicate current real-world traffic flow conditions and variability. The model required data on freeway traffic volume, merging ramp traffic, traffic composition (vehicle type and proportion of HCVs), infrastructure (acceleration lane length, etc.), and regulatory data (speed limits). We used data collected from Ontario highways for hourly traffic volumes for freeways and ramps, travel speeds and travel times.

The development of the model relied heavily on car-following and lane-changing behavior. For freeway and autonomous vehicle modelling, we used the Wiedemann 99 (W99) car following model and lane changing model (PTV, 2021; VDOT, 2020; Zeidler et al., 2019). The values for the acceleration and deceleration of passenger vehicles and HCVs were assigned in accordance with the ITE Handbook (Harwood et al., 2003; ITE, 2000). This section discusses two important issues including the input parameters and model calibration.

Input Parameters

To simulate existing traffic conditions, we specified explicit driving behavior criteria for each vehicle type. As LCV and HCV features are comparable except for vehicle length, LCV driving behavior was characterised as HCV driving behavior (AASHTO, 2018; TAC, 2017). To simulate HCV platooning, we used the PTV COM interface and python programming (PTV, 2021; Sukennik, 2020). Table 4-3 shows the input parameters for passenger vehicles, HCVs, and HCV platooning.

Table 4-3: Simulation Input Parameters

Input Parameters	Wiedemann 99 (W99) Car Following Model			
	Default	Passenger Vehicles	HCVs[2] or LCVs[3]	HCV Platooning
Maximum look ahead distance (m)	250	250	250	300
Maximum look back distance (m)	150	150	150	300
Number of interaction objects	2	1	1	3
Number of interaction vehicles	99	1	1	2
Standstill distance (m) for following Passenger vehicle	1.5	1.5	3.77	3.77
Standstill distance (m) for following HCV or HCV platooning	1.5	3.05	3.37	3.37
Standstill distance (m) for following HCV in Platoon	1.5	NA[1]	NA[1]	1
Time headway (s) for following passenger vehicle	0.9	1.8	1.84	1.84
Time headway (s) for following HCV or an HCV platoon	0.9	2.39	1.84	NA
Time headway (s) between HCVs in platoon	0.9	NA[1]	NA[1]	0.6/ 1.2
Following distance oscillation (m)	4	4	14	14
Negative speed difference (m/s)	-0.35	-1.65	-2.07	-2.07
Positive speed difference (m/s)	0.35	1.65	2.07	2.07
Oscillation acceleration (m/s^2)	0.25	0.09	0.097	0.097
Acceleration from standstill (m/s^2)	3.5	0.5	0.3	0.3
Acceleration at 80 km/h (m/s^2)	1.5	0.45	0.25	0.25
	Lane Changing Model			
Maximum deceleration (m/s^2)	-3	-3	-1.62	-1.62
Safety distance reduction factor	0.6	0.6	0.6	1

[1] Note: NA indicates that a value is not applicable.

[2] Note: HCV indicates heavy commercial vehicle (WB-20 HCVs).

[3] Note: LCV indicates long combination vehicle.

The input parameters are discussed below.

- The "maximum look ahead distance" and "maximum look back distance" are the farthest distance a driver may view in front and behind in order to notice the surrounding traffic. The maximum look ahead and look back distances for passenger vehicles and HCVs were assigned in accordance with PTV (2021)'s recommendations. As SAE level 4 HCV platooning allows HCVs to communicate up to a distance of about 300 m (Ahmed et al., 2021; NHTSA, 2020; Sukennik, 2020), we used 300 m the maximum look head and look back distance for HCV platooning. This distance allows platooning vehicles to examine the freeway's right-most lane and determine whether the gap available is adequate.

- "Number of interaction objects" refers to the interaction of a vehicle with a variety of objects including traffic signals and other vehicles. The "number of interaction vehicles" refers only to interaction with other vehicles. Because passenger vehicles and HCVs have human drivers, the number of interaction objects and the number of interaction vehicles are defined as one for passenger vehicles and HCVs as recommended by PTV (2021). As HCV platoons can communicate with HCVs within the same platoon, the number of interaction vehicles and the number of interaction objects is defined as greater than one (Sukennik, 2019).
- The "standstill distance for following passenger vehicle," "standstill distance for following HCV or HCV platooning" and "standstill distance for following HCV in Platoon" indicate the minimum desired distance needed to avoid a collision between a leading and following vehicle. For the standstill distances for following passenger vehicles, we used the distances suggested by Lu et al. (2021) for passenger vehicles, HCVs and HCV platoons. For the standstill distance for an HCV platoon following an HCV platoon, we used the distance suggested by Deng (2016) and Deng and Boughout (2016).
- The "time headway" refers to distance from the front of the lead vehicle or object to the front of the following vehicle and is additional to the standstill distance. As in previous

studies, we assigned two different time headway (0.6 sec and 1.2 sec) to HCVs in a platoon (Kuhn et al., 2017; Ramezani et al., 2018a; 2018b; Shladover et al., 2018) .

- The “following distance oscillation (m)” indicates the maximum additional distance that a following vehicle driver can accept in addition to the desired safety distance. We used Durrani et al.’s (2016) observed following distance oscillation for HCVs and for HCV platoons.
- The “negative speed difference” refers to the relatively lower (negative) speed a following vehicle driver may adopt compared to the lead vehicle’s slower speed, and the “positive speed difference” refers to the relatively higher (positive) speed a following vehicle driver may adopt compared to the lead vehicle’s faster speed. We used the values suggested by Durrani et al. (2016).
- “Oscillation acceleration” refers to the minimum acceleration/deceleration rate of the following vehicle while one vehicle is following another one in front it. We used the values suggested by Durrani et al. (2016).
- “Acceleration from standstill” refers to the acceleration rate of a following vehicle (i.e., a passenger vehicle, an HCV or an HCV platoon) from a standstill. “Acceleration at 80km/h” refers to the acceleration rate of a following vehicle traveling at 80km/h. We used the values suggested by Durrani et al. (2016).
- In the lane changing model, "maximum deceleration rate for cooperative braking" refers to the rate at which a target vehicle needs to decelerate in order to allow another vehicle to

perform a lane change and enter the target vehicle's lane. We used the values suggested by Harwood et al. (2003).

- The "safety distance reduction factor" indicates when a lead vehicle initiates a lane changing maneuver, and the following vehicle on the target lane accepts a reduced minimum safety distance between the lead and following vehicles. A value of 0.6 for the safety distance reduction factor" 0.6 means that the vehicle on the target lane accepts an additional 40% reduction in the safety distance. Ahmed et al. (2021) suggested a value of one for HCVs in a platoon, i.e., they suggested that HCV platoons must use extremely cautious behavior and maintain the minimum safe distance when changing lane.

The micro-simulation model also considers “lane changing distance.” This input parameter refers to the point from which a vehicle will start to change lane. As the study area’s acceleration lane length is about 350 m, we modified the lane changing distance to 350 m instead of PTV (2021)’s recommended value of 200 m (VDOT, 2020).

We used SSAM to conduct the safety performance evaluation (Shahdah et al., 2014). This approach identifies potential conflicts between two vehicles. A conflict is defined as an interaction between two vehicles that has the potential for a collision. Based on SSAM, conflicts are categorized as crossing conflicts, rear-end conflicts and lane changing conflicts. The evaluation identifies conflicts that have a high correlation with crash frequency and estimates time-to-collision (TTC) and post-encroachment time (PET). TTC is defined as the time before a collision between two vehicles to collide if they do not change direction, speed or acceleration. PET is the time difference between the time at which a first vehicle left a location and the time at which a second vehicle arrived at the same location (Hydén, 1987;

Shelby, 2011). We used a TTC of 1.5 sec and a PET of 5 sec as suggested by Gettman et al. (2008).

Calibration of Micro-Simulation Model

Following the Wisconsin Department of Transportation's (WisDOT) guidelines, we simulated the Base Model 30 times to replicate existing roadway conditions at the 95% confidence level (Beeston et al., 2021; Dowling et al., 2004; WisDOT, 2019). We then applied the Geoffrey E. Havers (GEH) statistical test and the Welch two-sample t-test (Welch, 1947). We used hourly traffic volume on the freeway and merging ramp as the measure of performance for GEH (Doustmohammadi et al., 2017; WisDOT, 2019). The GEH value was less than 5 (see Table 4-4) indicating that the Base Model simulation of hourly traffic volume was similar to the observed traffic volume.

Table 4-4: GEH Base Model Test Results

Roadway Type	Field Observed Traffic Volume (vph)	Simulated Base Model Traffic Volume (vph)	GEH Value
Freeway	6,100	6,033	0.86
Ramp	1,100	1,058	1.28

We used the Welch t-test to validate the speed accuracy (Welch, 1947). Our null hypothesis was that the simulation and field observations of the average speed on the freeway's five lanes were equal. Table 4-5 summarises the results and shows that the average speed for each freeway lane was not significant at the 95% confidence level (p-value >0.05). As the null hypothesis cannot be rejected, we considered the Base Model simulation of freeway travel speeds to be acceptably close to the observed speed observations.

Table 4-5: Two-Sample T-Test Base Model Results

Freeway Lanes	Average Speed [Simulation Result] (Km/h)	Standard Deviation (Km/h)	Two Sample		
			Degrees of Freedom (df)	t-statistic	p-value
Lane 1	105.69	5.15	6,093.10	-1.56	0.12
Lane 2	97.75	6.38	6,095.30	0.87	0.38
Lane 3	95.62	7.63	6,094.40	-1.03	0.31
Lane 4	92.98	8.55	6,094.70	-0.91	0.36
Lane 5	91.69	8.55	6,093.60	-0.44	0.66

We also compared speeds on the ramp with the speeds simulated by the Base Model. According to the HERE (HERE, 2021) database, vehicles required an average of 66 sec to travel from the start of the ramp to the gore point. In the Base Model, passenger vehicles and HCVs travelled the ramp within 66 sec (standard deviation ± 8.04 sec). The Welch t-test was used again to compare the HERE database with the Base Model. As the results were not statistically significant at the 95 % confidence level (df = 1,057; t-statistic =0.29; p-value = 0.77), the Base Model travel times provided a reasonable simulation of the HERE database on the ramp.

4.4.2 Development of Test Scenarios

The Base Model (BM) represented the do-nothing scenario and have been developed with 350 m acceleration lane length as mentioned in Section 4.2. However, the estimated acceleration lane length using proposed analytical model (discussed in section 4.3) suggests a minimum 600 m acceleration lane length for two HCV platooning operations regardless of different time headways (0.6 sec and 1.2 sec). Therefore, eight test scenarios (alternative models) were considered to investigate the operational impact of SAE level 4 HCV platooning on combinations of different acceleration lane lengths (existing 350 m and extended to 600 m), different time headways (0.6 sec and 1.2 sec), and different market penetration rates (0%, 5% and 10%). The extended acceleration lane length was designed to provide extra time that would allow platooned HCVs to merge on the freeway together without facing delay.

The study developed a total of eight Alternative Models in VISSIM as comparisons with the Base Model. Table 4-6 shows the configuration for considered alternative models.

Table 4-6: Alternative Model Parameters

Alternative Models	Headway (sec)	Market Penetration Rates (%)	Acceleration Lane Length(m)
AM1	0.6	5	350
AM2	1.2		
AM3	0.6	10	
AM4	1.2		
AM5	0.6	5	600
AM6	1.2		
AM7	0.6	10	
AM8	1.2		

4.5 Results of Micro-Simulation Modeling

This section presents the results of the micro-simulation modelling. We performed a total of 270 simulations (9 models × 30 runs) to examine the operational and safety impact of HCV platooning on the study area's freeway merging segment. We used the travel time each vehicle required to merge onto the freeway from the start of the ramp and the number of conflicts as the measures of effectiveness (MOE) (FDOT, 2014).

4.5.1 Travel Time to Merge

Two approaches including box plots and statistical testing were used to analyse the impact of HCV platooning on all vehicles (i.e., passenger vehicles as well as HCVs) and only HCVs. In

Figure 4-2, both box plots show the time required to merge onto the freeway by all vehicles. Box plot (a) is for all vehicles and box plot (b) is for HCVs, including conventional HCVs in the Base Model and platooned HCVs in the alternative models. Each box plot shows the results for five statistics related to the travel time to merge: 1) minimum travel time to merge, 2) 15th percentile travel time to merge, 3) average travel time to merge, 4) 85th percentile travel time to merge, and 5) maximum travel time to merge.

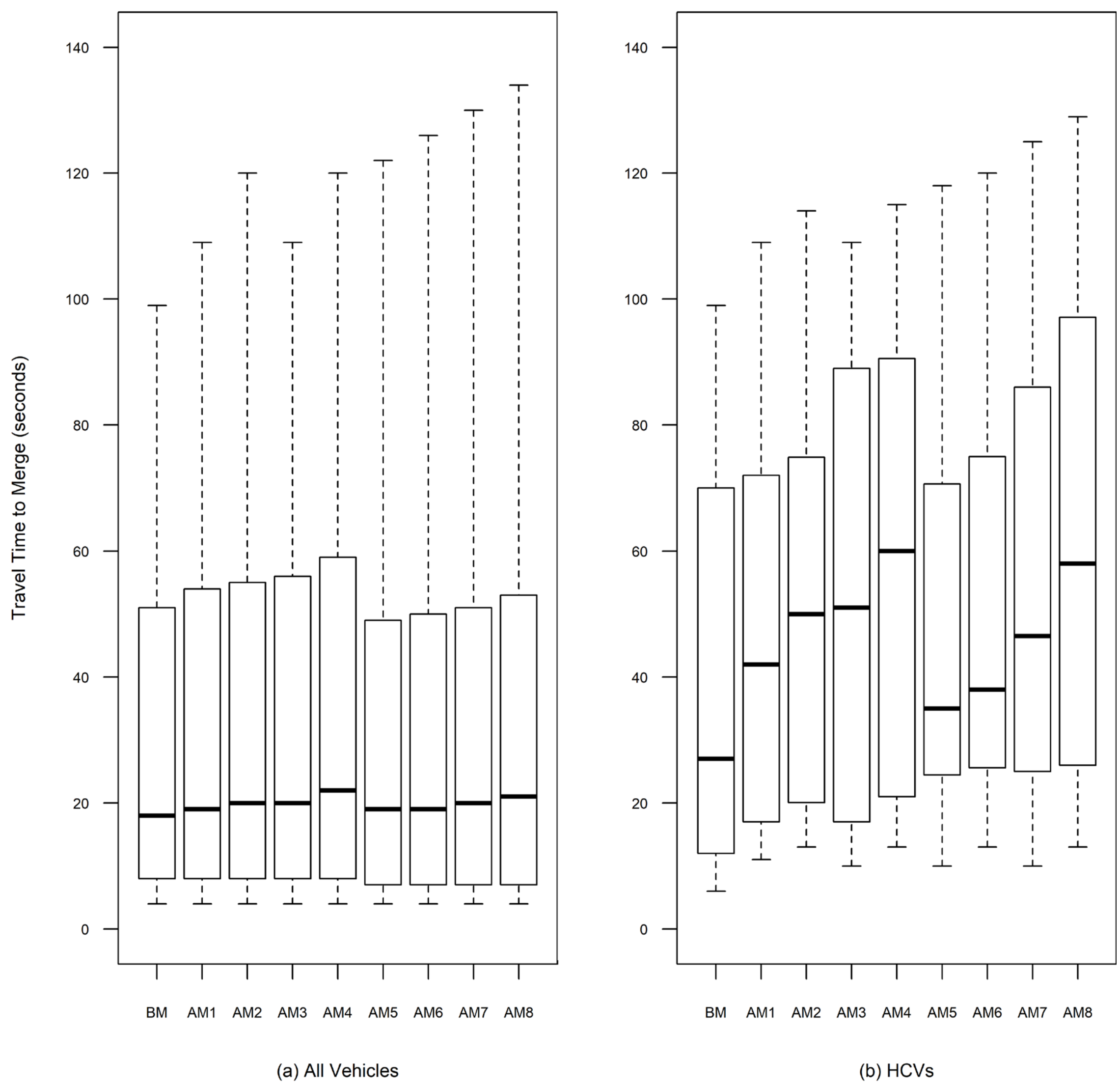

Figure 4-2: Model Comparison for Estimated Travel Time to Merge

Vehicles seek to merge onto the freeway from the acceleration lane immediately, but if there is no acceptable gap, vehicles need to travel on the acceleration lane or may need to wait at the end of acceleration lane to look for an adequate gap for merging. This gap searching and waiting time causes an increase in the merging time or delays. Similar to the real-world merging circumstance, in Figure 4-2 the lowest travel time to merge result indicates that vehicles merge immediately without needing additional time to merge because merging vehicle have encountered fewer vehicle on the freeway's right-most lane. The maximum travel time to merge result, however, demonstrates a delay or increase in travel time since merging vehicles had to wait on the merging lane until they found a safe, adequate gap due to traffic on the freeway's rightmost lane. The above discussion illustrates that, the outcomes are consistent with actual merging circumstances.

The t-test and Kolmogorov–Smirnov (KS) test are widely used to compare data from two samples. The t-test compares the values of the means, but our estimated results do not follow a normal distribution and are unsuitable in this instance. The KS test is an alternative that compares the cumulative distribution of the two samples (Arafat et al., 2020; Marsaglia et al., 2003; Simard and L'Ecuyer, 2011) .

KS tests were applied to the information shown in Figure 4-2 to investigate whether the time to merge cumulative distributions obtained from a comparison of the BM were similar to the time to merge cumulative distributions obtained from alternative models. The KS test's D-statistic provided a statistical basis for comparing the travel times required to merge. The null hypothesis was that the travel time required to merge in each alternative model was equal to the travel time required to merge in the Base Model. We calculated the D-statistic using equation (4-19):

$$D = max|F_{n1}(X) - F_{n2}(X)| \tag{4-19}$$

Where:

$F_{n1}(X)$ = Cumulative frequency distribution of BM; and

$F_{n2}(X)$ = Cumulative frequency distribution of alternative model.

Table 4-7 summarizes the results of the travel times to merge analyses for all vehicles and for HCVs for all the models. The Table shows the 15th percentile, average and 85th percentile time to merge speeds, the KS test D-statistic, the p-value, and the significance level of the comparisons with the BM. Most comparisons were significant at the 99% confidence level.

Table 4-7: KS-Tests Results for Travel Time to Merge

Vehicle Category	VISSIM Model	15th Percentile	Average	85th Percentile	KS Test D-Statistic	p-value	Significance Level*
All Vehicles	BM	8	18	51	NA	NA	
	AM1	8	19	54	0.021	0.2	
	AM2	8	20	55	0.042	2.20E-16	***
	AM3	8	20	56	0.039	2.20E-16	***
	AM4	8	22	59	0.063	2.20E-16	***
	AM5	7	19	49	0.141	2.20E-16	***
	AM6	7	19	50	0.135	2.20E-16	***
	AM7	7	20	51	0.065	2.20E-16	***
	AM8	7	21	53	0.062	2.20E-16	***
HCVs	BM	12	27	70	NA	NA	
	AM1	17	42	72	0.034	0.14	
	AM2	20	50	75	0.277	0.002	**
	AM3	17	51	89	0.252	7.32E-07	***
	AM4	21	60	91	0.327	2.42E-11	***
	AM5	24	35	71	0.387	4.77E-06	***
	AM6	26	38	75	0.371	1.01E-05	***
	AM7	25	46	86	0.428	2.22E-16	***
	AM8	26	58	97	0.414	1.22E-15	***
*Significance level: <0.01 '***'; <0.05 '**'; <0.1 '*'; >0.1' '							

Note: NA indicates a value is not applicable.

We made the following observations from Figure 4-2 and Table 4-7 for all vehicles:

The finding of this study suggests that the operation of HCV platooning increased the average merging time. For all vehicles, the average travel times to merge for 0%, 5% and 10% HCV platooning were slightly lower for the 0.6 sec compared to 1.2 sec headways. The average merging time for the operation of 5% HCV platooning with 0.6 sec headways was lower than 5% HCV platooning with 1.2 sec headways and the average travel time to merge for 5% HCV platooning with 0.6 sec headways was also higher than 0% HCV platooning operation. These results indicate that the number of HCVs in a platoon, and the physical gap between platooned HCVs, are contributing factors to a longer merging time.

For all vehicles and existing acceleration lane length (350 m), the box plot in Figure 4-2 (a) and Table 4-7 shows that the BM's 85th percentile travel time to merge was 51 sec per vehicle. AM1 (5% HCV platooning, 0.6 sec headway) increased travel time to merge by 3 sec (i.e., to 54 sec) per vehicle. The 85th percentile travel times to merge increased for AM2 (5% HCV platooning, 1.2 sec headway), AM3 (10% HCV platooning, 0.6 sec headway) and AM4 (10% HCV platooning, 1.2 sec headway). AM4 shows the largest increase (8 sec) compared to BM. This result suggests that, market penetration rate is another contributing factor in addition to the physical gap between platooned HCVs and the number of HCVs in a platoon. The increase in the number of platooned HCVs on the freeway merging ramp will lead to more delay.

The KS test for all vehicles found that the distribution of travel times in AM1 was not statistically significant, i.e., operational conditions under HCV platooning with existing acceleration lane length, 5% HCV platooning and 0.6 sec headway are likely to be comparable to existing operational conditions. In the case of AM2, AM3 and AM4, the distributions of travel times were statistically significant at the 99.9% confidence level, i.e., a small percentage of HCV platooning with the existing 350 m of acceleration lane created significant delays on the study corridor merging ramp.

For all vehicles and the extended acceleration lane length (600 m), the boxplots in Figure 4-2(a) and Table 4-7 show that AM5 (5% HCV platooning, 0.6 sec headway) reduced the 85th percentile travel time to merge by 2 sec per vehicle in comparison to the BM and 5 sec per vehicle in comparison to AM1. The finding suggests that the extended acceleration lane allows all vehicles in AM5 to find a suitable gap and merge faster without experiencing delay when compared to all vehicles using AM1's acceleration lane length (350 m).

AM6 (5% HCV platooning, 1.2 sec headway) reduced travel time to merge for all vehicles by 1 sec per vehicle in comparison to the BM , 4 sec per vehicle in comparison to AM1 and 5 sec per vehicle in comparison to AM2. The AM6's travel time to merge result indicates that, the extended acceleration lane length, like AM5, is beneficial for improving merging time. In contrast, AM6 merge travel time is longer for all vehicles than AM5. The comparison of AM5 and AM6 merging times for all vehicles suggests an increase in merging time for extending the physical distance between platooned HCVs.

For AM7 (10% HCV platooning, 0.6 sec headway) the 85th percentile travel time was the same as for the BM, and for AM8 (10% HCV platooning, 1.2 sec headway) the 85th percentile travel time increased by 2 sec. However, compared to AM3 and AM4, for AM7 and AM8 all vehicle travel time was reduced. This outcome indicates the advantage of reducing merging time for the extended acceleration lane length. However, the comparison of both AM7 and AM8 (10% HCV platooning) with AM5 and AM6 (5% HCV platooning) model also suggest that, the increase in market penetration HCVs of platooning cause to reduce travel time saving benefit even with the extended acceleration lane length.

The KS-test results for all vehicles showed that the distribution of travel times to merge for all vehicles for AM5, AM6, AM7 and AM8 were statistically significant at the 99.9% confidence level. This result illustrates that, the extended (600m) acceleration lane improved merging time significantly on the study corridor merging ramp, however the increase in platooned HCVs reduced the merging time saving benefit.

We made the following observations from Figure 4-2 and Table 4-7 for HCVs:

Figure 4-2 (b) and Table 4-7 shows that the travel time to merge pattern for HCVs was similar to the patterns for all vehicles for eight alternative models. The result demonstrates that, HCVP_1.2H require more time to merge compared to HCVP_0.6H. On the other hand, the increase in platooned HCVs has increased the overall merging time for HCVs.

Compared to the BM for HCVs, AM1 (5% HCV platooning, 0.6 sec headway) 85th percentile travel time to merge increased by 2 sec per HCV in platoon, for 5% HCVP_1.2H operation travel time to merge for AM2 increased by 5 sec, for AM3 (10% HCVP_0.6H) increased by 19 sec, and for AM4 85th percentile travel time to merge increased by 21 sec per platoon of HCVs. Notice that, the magnitude of increased in 85th percentile merging time for HCVs is higher than all vehicles merging time. This result implies that, platooned HCVs are responsible for an increase in merging time.

From Figure 4-2 (b), we also observe that to travel on existing acceleration lane (350 m) 5% HCVP_0.6H (AM1) require 1.6 times (average 42 sec) more merging time in comparison to BM, while both AM2 (average 50 sec) and AM3 (average 51 sec) require 1.9 times more merging time than BM (average 27 sec). Similarly, 10% HCVP_1.2H (AM4) need 2.2 times (average 60 sec) more merging time than BM’s conventional HCVs.

The 600 m of acceleration lane enables a reduction in the average merging time compared to AM1, AM2, AM3 and AM4; though the average merging time in comparison to BM is 1.3 times higher for AM5, 1.4 times higher for AM6, 1.7 times higher for AM7, and 2.2 times higher for AM8.

From AM5 travel time to merge result for HCVs, we observe that the extension of acceleration lane allows HCVP_0.6H to merge in 71 sec, which is only 1 sec more than BM's HCV travel time to merge and 1 sec less than AM1's HCV travel time to merge. Similar to AM5, AM6 model indicates that HCVP_1.2H require 75 sec travel time to merge, which indicates no changes in merging time compared to AM2's HCV travel time to merge.

For AM7 and AM8, however, even with the extension of acceleration lane HCVs' merging time increased rather than decreased. The increase was 16 sec for AM7 compared to BM's HCV merging time and for AM8 27 sec compared to BM's HCV merging time. The increase in merging time by 27 sec in AM8 explains that HCVP_1.2H can travel approximately 750 m less distance at 100 km/h than conventional HCVs even if both conventional HCVs and platooned HCVs start their journey at the same time.

The extension of acceleration lane allows platooned HCVs to travel on the acceleration lane more to find out the required gap for merging instead of waiting and developing spillback on the merging ramp, and results in increasing the merging time. During this situation, other vehicles such as passenger vehicles and conventional HCVs can merge whenever they find an adequate merging gap.

The KS-test result indicates that HCV merging time for the alternative model AM1 is not statistically significant at 90% confidence level when compared with the base model BM. This implies that the existing acceleration lane length of 350 m is sufficient for the 5% HCVP_0.6H scenario without deteriorating roadway operational performance.

The overall findings of this study suggest that the operation of HCV platooning regardless of different headways will cause negative impact for merging through the existing

350 m acceleration lane. The recommended 600 m acceleration lane length based on the estimation of our proposed analytical model, however, will be beneficial to keep maintaining overall same operational performance as the BM (existing) condition. Nevertheless, compared to all vehicles, HCVs will encounter more acute operational condition for HCV platooning operation. On the other hand, the physical gap between platooned HCVs has significant effect on the freeway merging ramp operation. HCV platooning with 1.2 sec headways require more time to merge on the freeway from the ramp compared to HCV platooning with 0.6 sec headways. Furthermore, an HCV platooning penetration rate of 10% may create significant delays compared to 0% and 5% HCV platooning not only for HCVs but also for all vehicles. A higher penetration rate will likely further increase the delays even with the extended 600 m acceleration lane length. Extending the length of the acceleration lane will improve operational performance by reducing 85th percentile merging time 3.9% for the operation of 5% HCV platooning with 0.6 sec headways.

4.5.2 Number of Conflicts

To understand the risk associated with HCV platooning, we performed a surrogate safety assessment in which the total number of conflicts are estimated for all nine models. As mentioned earlier, conflicts can be categorized as crossing conflicts, rear-end conflicts and lane changing conflicts. All three conflict types are aggregated together for this analysis.

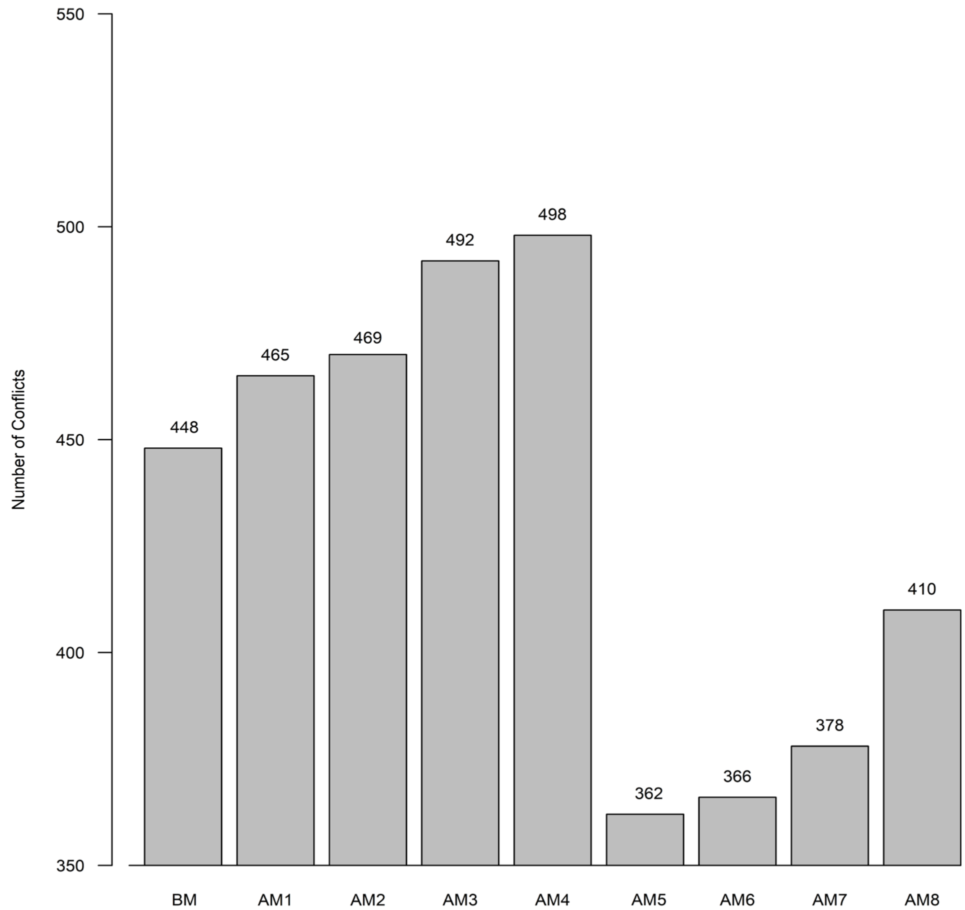

Figure 4-3: Estimated Number of Conflicts for Each Model

We used the SSAM approach (FDOT, 2014; Gettman et al., 2008) to estimate the number of potential conflicts. Figure 4-3 shows the estimated number of conflicts for each model.

- Figure 4-3 shows that Compared to the BM, the models for the existing acceleration lane length of 350 m (AM1, AM2, AM3, and AM4) have a higher number of conflicts. This result implies that an acceleration lane length of 350 m in this context leads to serious safety concerns on the merging ramp segment regardless of HCV platooning penetration rate or headway. Compared to the BM value (350 m acceleration lane length) of 448 conflicts, the models for the extended acceleration lane length of 600 m have reduced conflicts of 362, 366, 378, and 410 for AM5, AM6, AM7, and AM8, respectively.

- Within the models for an acceleration lane length of 350 m, the number of conflicts is higher for the 1.2 sec headway models than for the 0.6 sec. headway models, and the number of conflicts is higher for the 10% market penetration models than for the 5% market penetration models. The same relationship is observed for the extended acceleration lane length of 600 m.

The result suggests that the 600 m acceleration lane length for HCV platooning regardless of different headway (0.6 sec and 1.2 sec headway) on the basis of proposed analytical model provides substantial conflict reductions benefit. The extension of acceleration lane length to 600 m will improve safety by reducing number of conflicts 19.2% for the 5% HCV platooning operation (0.6 sec headway). The safety concerns increase with a greater percentage of HCV platooning and a larger distance between platooned vehicles.

4.6 Conclusions and Recommendations

V2V technology appears to offer promising potential for future goods movement. SAE level 4 HCV platooning requires the lead vehicle to have a human driver, but one or more closely following HCVs may be driverless. The third objective of this research was to evaluate how the introduction of HCV platooning on freeway merging segment in North America may influence highway safety and operational performance under mixed traffic conditions based on the analytical and simulation methods, notably in terms of the acceleration lane length parameter utilized in existing geometric design standards.

4.6.1 Summary of Results

The analytical approach used a newly proposed model in this study to estimate the required acceleration length for two HCV options (two WB-20 HCV platoons travelling with a shorter and longer headway between the HCVs). As expected, our proposed model for an HCV platoon anticipates longer acceleration lane lengths than recommended by 2018 AASHTO and 2017 TAC. Both 2018 AASHTO and 2017 TAC acceleration lane lengths are insufficient for HCV platoons' operation. Analytical model findings suggest the minimum acceleration lane length is about 600 m for the operation of platooned HCVs regardless of different headways (0.6 sec and 1.2 sec headway) for the selected freeway and merging ramp instead of at least 360m acceleration lane length recommended by 2018 AASHTO and 350m recommended by 2017 TAC. The insufficient acceleration lane length may cause significant safety concern and considerable delays to merging traffic especially for HCV platooning.

The simulation approach used a micro-simulation tool to analyze the impact of HCV platooning. We first tested SAE level 4 HCV platooning impact at low penetration rate and two different time headway following existing geometric design guideline using VISSIM micro-simulation model. We evaluated the effect on operational performance of HCV platooning by measuring the required travel time for merging. The BM's average travel time to merge has been compared to the average travel time of eight other alternative models. The simulation analysis revealed that the HCV platooning merging time is significantly longer than the average merging time for all vehicles. In addition, the average merging time of HCV platooning through a 350 m acceleration lane is longer than that of a 600 m acceleration lane. The result indicates an improvement in average merging time for the extension of acceleration lane. The average merging time of 5% HCV platooning through 600 m acceleration lane regardless 0.6 sec or 1.2 sec headway is significantly lower than the average merging time through 350 m long acceleration lane of 5% HCV platooning for both 0.6 sec and 1.2 sec headway. Similar trend has been observed for the average merging time of 10% HCV platooning.

The simulation result showed that the average travel time for merging has been increased for both 5% and 10% HCV platooning operation when compared to 0% HCV platooning operation. On the other hand, for the same market penetration, platoons with a 1.2 sec headway needed more merging time than a 0.6 sec headway.

We also analyzed the safety impact on the total number of conflicts for each scenario. A higher number of conflicts have been observed for both 5% and 10% HCV platooning regardless of 0.6 sec and 1.2 sec headway for merging through 350 m long acceleration lane when compared to the base scenario. The safety analysis results suggested significant improvement in terms of reducing the number of conflicts for both 5% and 10% HCV platooning if acceleration lane is extended to 600 m. The increased distance will need to be considered as a trade-off with increased construction cost and available space but may be worthwhile on facilities with substantial goods movement and HCV platoons.

4.6.2 Limitations and Future Research

There are some limitations with this study that can be addressed in future research. Future V2V technology and traffic conditions are still uncertain. Existing V2V technology allows a passenger vehicle to cut in and out safely between platooning HCVs (Shladover, 2018; Xiao et al., 2017), but this study did not consider such maneuvers. Furthermore, based on the recent progression of V2V communication range, the National Highway Traffic Safety

Administration (NHTSA) affirms that vehicles equipped with V2V technology will be capable of communicating with one another at a distance of approximately 300 metres (NHTSA, 2020). If future V2V technology allows long range communication and permits cut-in and cut-out between platooned vehicles, the requirement of acceleration lane length estimated in this study may be less. Furthermore, yielding of the freeway right most lane traffic, while HCV platooning is merging on the freeway from ramp proper, would alleviate potential safety concerns for HCV platooning and other vehicles (Meng Wang et al., 2019a).

Due to a lack of HCV platoon operations in the real-world traffic, no study has yet calculated typical headway values for HCV platoons with other vehicles (i.e., the headway between a platoon and a vehicle ahead or behind). Field observations do not indicate the headway between a passenger vehicle and an HCV platoon. This study considers minimum 1.5 sec headway between a passenger vehicle and an HCV platoon, since Houchin et al., (2015) observed 1.5 sec headway between a passenger vehicle and an HCV based on the field observation. Future work must consider different platoon headways for HCVs, especially in a V2V environment where many vehicles can communicate. In this case, minimum headways could differ from those assumed in the study. It will take time to collect enough data, as HCV platooning operation from ramp roadways to freeway is not yet common in North America, however, testing of HCV platooning operation is ongoing in many areas of the world. Furthermore, this research did not consider vertical slope's effect on estimating acceleration lane length. Steep slopes reduce the speed of an HCV platoon and the merging vehicle's acceleration, which may impact on the acceleration lane length estimation.

To minimize disruptions in traffic flow and improve overall safety of roadways, future research should explore the most appropriate times of day and days of the week for allowing HCV platoons to operate on designated freeways and merging ramp segments.

As mentioned, AASHTO (2018) suggests a minimum 360 m long acceleration lane length, however it also recommends different acceleration lane length for different speeds of the freeway and merging on-ramp. Similarly, our proposed model also asserts acceleration lane length for different freeway and merging ramp's design speed. Several estimated acceleration lane lengths for HCV platooning considering slow-speed freeways and merging ramps fell within AASHTO (2018)'s recommended value. However, from the simulation analysis, we observe negative impact from HCV platooning operation regardless of different headways and market penetration rate along the selected corridor's 360 m long acceleration lane. On the other hand, the 600 m acceleration lane length shows significant improvement in terms of safety and operation. Several North American jurisdictions already allow LCV operations on freeway corridors during specific times of the day. Analytical and simulation analysis indicate that the freeway merging segment designated for LCV operation with minimum 600 m acceleration lane length could be used for HCV platooning. Nevertheless, HCV platooning will encounter less traffic when merging on the freeway where traffic volume is low on the freeway and the merging ramp. The recommended level of service should be investigated in a future study at which 5% HCV platooning (0.6 sec headway) could be operated without interruptions. As a result, we propose that during certain hours of the day, freeway and merging ramp with low traffic volume could be permitted to allow 5% of platooned HCVs (0.6 sec headway) to operate like LCV operations.

The findings in this study will help transportation engineers as well as planners understand the implications of HCV platoons and determine appropriate locations to permit HCV platooning on freeways.

4.7 Chapter 4 References

AASHTO. (1965). A Policy on Design Standards, Interstate System. American Association of State Highway Officials.

AASHTO. (2018). A Policy on Geometric Design of Highways and Streets (7th ed.). American Association of State Highway and Transportation Officials.

Ahmed, H. U., Huang, Y., & Lu, P. (2021). A Review of Car-Following Models and Modeling Tools for Human and Autonomous-Ready Driving Behaviors in Micro-Simulation. Smart Cities, 4(1), 314–335.

Alam, A., Besselink, B., Turri, V., Martensson, J., & Johansson, K. H. (2015). Heavy-duty vehicle platooning for sustainable freight transportation: A cooperative method to enhance safety and efficiency. IEEE Control Systems Magazine, 35(6), 34–56.

Arafat, M., Nafis, S. R., Sadeghvaziri, E., & Tousif, F. (2020). A data-driven approach to calibrate microsimulation models based on the degree of saturation at signalized intersections. Transportation Research Interdisciplinary Perspectives, 8, 100231.

Arnold, S., & Roorda, M. (2020). Infrastructure to Enable Freight Platooning Ramp Operations in the GTHA. Transformative Transportation '20, ICity-CATTS Research Day. https://uttri.utoronto.ca/files/2020/06/Arnold-Freight_Platooning-2020-06-02.pdf

Bareket, Z., & Fancher, P. S. (1993). Effect of large trucks on traffic safety operations. The University of Michigan Transportation Research Institute: Ann Arbor, MI, USA.

Beeston, L., Blewitt, R., Bulmer, S., & Wilson, J. (2021). Traffic Modelling Guidelines v4.

Bishop, R. (2020). New Moves, New Markets For Truck Platooning Revealed At AVS2020. Forbes:Transportation. https://www.forbes.com/sites/richardbishop1/2020/09/27/new-moves-new-markets-for-truck-platooning-revealed-at-avs2020/#7e0ebe1e6297

Browand, F., McArthur, J., & Radovich, C. (2004). Fuel saving achieved in the field test of two tandem trucks. University of California: Berkeley, CA, USA.

Bujanovic, P., & Lochrane, T. (2018). Capacity predictions and capacity passenger car equivalents of platooning vehicles on basic segments. Journal of Transportation Engineering, Part A: Systems, 144(10), 4018063.

Dabbour, E., Easa, S. M., & Dabbour, O. (2021). Minimum Lengths of Acceleration Lanes Based on Actual Driver Behavior and Vehicle Capabilities. Journal of Transportation Engineering, Part A: Systems, 147(3), 04020162. https://doi.org/10.1061/jtepbs.0000496

Deng, Q. (2016). A general simulation framework for modeling and analysis of heavy-duty vehicle platooning. IEEE Transactions on Intelligent Transportation Systems, 17(11), 3252–3262.

Deng, Q., & Boughout, W. (2016). The impacts of heavy-duty vehicle platoon spacing policy on traffic flow.

Doustmohammadi, M., Anderson, M., Kesaveraddy, S., & Jones, S. (2017). Examining Model Accuracy: How Well did We do in the 1990's Predicting 2015. International Journal of Traffic and Transportation Engineering, 6(1), 15-21.

Dowling, R., Skabardonis, A., Halkias, J., McHale, G., & Zammit, G. (2004). Guidelines for calibration of microsimulation models: framework and applications. Transportation Research Record: Journal of the Transportation Research Board, 1876, 1–9.

Durrani, U., Lee, C., & Maoh, H. (2016). Calibrating the Wiedemann's vehicle-following model using mixed vehicle-pair interactions. Transportation Research Part C: Emerging

Technologies, 67, 227–242.

Faber, T., Delft, T. U., Sharma, S., Ssharma-tudelftnl, T. U. D., Snelder, M., Delft, T. U., Klunder, G., Tavasszy, L., Delft, T. U., Lint, H. Van, & Delft, T. U. (2020). Evaluating Traffic Efficiency and Safety by Varying Truck ToGRIP Platoon Characteristics in a Critical Traffic Situation. 2020.

FDOT. (2014). Traffic Analysis Handbook. A Reference for Planning and Operations 2014.

Ferrari, P. (2009). The effect of the competition between cars and trucks on the evolution of the motorway transport system. Transportation Research Part C: Emerging Technologies, 17(6), 558–570.

Fitzpatrick, K., & Zimmerman, K. (2007). Potential updates to 2004 Green Book's acceleration lengths for entrance terminals. Transportation Research Record, 2023, 130–139. https://doi.org/10.3141/2023-14

Gattis, J. L., Bryant, M., & Duncan, L. K. (2008). Acceleration Lane Design for Higher Truck Volumes. (No. MBTC FR 2094/3003), Mack-Blackwell National Rural Transportation Study Center, USA, December, 1–104.

Gettman, D., Pu, L., Sayed, T., & Shelby, S. (2008). Surrogate Safety Assessment Model and Validation: Final Report.

Gordon, M., & Turochy, R. E. (2016). Evaluation of the effects of driver assistive truck platooning on freeway traffic flow. The 95th Transportation Research Board: Washington, DC, USA, 1-15.

Greenshields, B. D., Schapiro, D., & Ericksen, E. L. (1946). Traffic performance at urban street intersections. Bureau Highway Traffic, Yale University & Eno Foundation for Highway

Traffic Control, Washington, DC, USA, 1-15.

Guo, Y., Xiang, Q., Li, S., Zhang, T., & Yao, R. (2017). Impacts of Large Vehicles on Traffic Safety in Freeway Interchange Merging Areas and Improvement Measures. MATEC Web of Conferences, 124, 1–7. https://doi.org/10.1051/matecconf/201712404004

Habtemichael, F. G., & de Picado Santos, L. (2013). Safety and operational benefits of variable speed limits under different traffic conditions and driver compliance levels. Transportation Research Record, 2386(1), 7–15.

Harwood, D. W., Torbic, D. J., Richard, K. R., Glauz, W. D., & Elefteriadou, L. (2003). NCHRP Report 505 : Review of truck characteristics as factors in roadway design. Transportation Research Board.

HERE. (2021). Map Data | Static Map API . HERE.COM. https://www.here.com/platform/map-data

Houchin, A., Dong, J., Hawkins, N., & Knickerbocker, S. (2015). Measurement and Analysis of Heterogenous Vehicle Following Behavior on Urban Freeways: Time Headways and Standstill Distances. 2015 IEEE 18th International Conference on Intelligent Transportation Systems, 888–893. https://doi.org/10.1109/ITSC.2015.149

Hydén, C. (1987). The development of a method for traffic safety evaluation: The Swedish Traffic Conflicts Technique. Bulletin Lund Institute of Technology Department, Trafikteknik Tekniska Hoegskdan i Lund. 70, 1-57.

ITE. (2000). Traffic Engineering Handbook (J. L. Pline (ed.); 5th Editio). Institute of Transportation Engineers (ITE).

Kuhn, B., Lukuc, M., Poorsartep, M., Wagner, J., Balke, K. N., Middleton, D., Songchitruksa, P., Wood, N., & Moran, M. (2017). Commercial truck platooning demonstration in Texas–level 2 automation. Texas. Dept. of Transportation. Research and Technology Implementation Office, 1-222.

Kuijpers, A. G. J. (2017). Truck platooning: a framework to optimize traffic management near the port area of Rotterdam. Master's Thesis, Eindhoven University of Technology, Netherlands.

Lee, G. (2006). Modeling gap acceptance at freeway merges. PhD Thesis, Massachusetts Institute of Technology.

Lee, S., Oh, C., & Lee, G. (2021). Impact of automated truck platooning on the performance of freeway mixed traffic flow. Journal of Advanced Transportation, 2021.

Li, H., Zhang, J., Li, Y., Huang, Z., & Cao, H. (2021). Modeling and simulation of vehicle group collaboration behaviors in an on-ramp area with a connected vehicle environment. Simulation Modelling Practice and Theory, 110, 102332.

Lu, C., Dong, J., Houchin, A., & Liu, C. (2021). Incorporating the standstill distance and time headway distributions into freeway car-following models and an application to estimating freeway travel time reliability. Journal of Intelligent Transportation Systems, 25(1), 21–40. https://doi.org/10.1080/15472450.2019.1683450

Maarseveen, S. Van. (2017). Impacts of Truck Platooning at Motorway On-ramps. Master's Thesis, Delft University of Technology, Delft, The Netherlands.

Marczak, F., Daamen, W., & Buisson, C. (2013). Key Variables of Merging Behaviour: Empirical Comparison between Two Sites and Assessment of Gap Acceptance Theory. Procedia - Social and Behavioral Sciences, 80, 678–697.

https://doi.org/10.1016/j.sbspro.2013.05.036

Marsaglia, G., Tsang, W. W., & Wang, J. (2003). Evaluating Kolmogorov's distribution. Journal of Statistical Software, 8(18), 1–4.

MTO. (2021a). 2019 travel speed and performance measure-truck. MTO ICorridor.

MTO. (2021b). Hourly Traffic. MTO ICorridor.

NHTSA. (2020). Vehicle-to-Vehicle Communication. U.S. Department of Transportation. https://www.nhtsa.gov/technology-innovation/vehicle-vehicle-communication#

Patten, J., McAuliffe, B., Mayda, W., & Tanguay, B. (2012). Review of aerodynamic drag reduction devices for heavy trucks and buses. National Research Council Canada NRC Technical Report CSTT-HVC-TR, 205, 3.

Proust, E., Smith, P., Pierce, D., Ward, J., & Bevly, D. (2019). Evaluation of Platooning on Resource Roads. 2019 TAC-ITS Canada Joint Conference.

PTV. (2021). PTV Vissim 2021 User Manual. In Karlsruhe, Germany: PTV. PTV AG.

Qi, Y., Zhao, Q., Liu, S., Qu, W., & Li, J. (2019). Determination of Freeway Acceleration Lane Length for Smooth and Safe Truck Merging. CAMMSE: Charlotte, NC, USA.

Ramezani, H., Shladover, S. E., Lu, X.-Y., & Chou, F.-C. (2018a). Microsimulation Framework to Explore Impact of Truck Platooning on Traffic Operation and Energy Consumption: Development and Case Study. University of California: Berkeley, CA, USA, 1-54.

Ramezani, H., Shladover, S. E., Lu, X. Y., & Altan, O. D. (2018b). Microsimulation of Truck Platooning with Cooperative Adaptive Cruise Control: Model Development And A Case Study. Transportation Research Record, 2672(19), 55–65. https://doi.org/10.1177/0361198118793257

Ran, B., Leight, S., & Chang, B. (1999). A microscopic simulation model for merging control on a dedicated-lane automated highway system. Transportation Research Part C: Emerging Technologies, 7(6), 369–388.

Reilly, W. R., Pfefer, R. C., Michaels, R. M., Polus, A., & Schoen, J. M. (1989). NCHRP 3-35: Speed-Change lanes. JHK & Associates.

SAE International Standard. (2016). Automated Driving: Levels of Driving Automation. SAE J3016.

Seraj M, Qiu TZ. (2021). Multilane Microscopic Modeling to Measure Mobility and Safety Consequences of Mixed Traffic in Freeway Weaving Sections. Journal of Advanced Transportation. July 15.

Shahdah, U., Saccomanno, F., & Persaud, B. (2014). Integrated traffic conflict model for estimating crash modification factors. Accident Analysis & Prevention, 71, 228–235.

Shelby, S. G. (2011). Delta-V as a measure of traffic conflict severity. 3rd International Conference on Road Safety and Simulati. September, 14–16.

Shladover, S. E. (2018). Connected and automated vehicle systems: Introduction and overview. Journal of Intelligent Transportation Systems, 22(3), 190–200.

Shladover, S. E., Lu, X.-Y., Yang, S., Ramezani, H., Spring, J., Nowakowski, C., & Nelson, D. (2018). Cooperative Adaptive Cruise Control (CACC) For Partially Automated Truck Platooning: Final Report (Issue March). https://escholarship.org/uc/item/260060w4

Simard, R., & L'Ecuyer, P. (2011). Computing the two-sided Kolmogorov-Smirnov distribution. Journal of Statistical Software, 39(11), 1–18.

Sukennik, P. (2020). Micro-Simulation Guide for Automated Vehicles—Final. Deliverable 2.11

of the CoEXist Project. https://www.h2020-coexist.eu/wp-content/uploads/2020/04/D2.11-Guide-for-the-simulation-of-AVs-with-microscopic-modelling-tool-Final.pdf

Sukennik, P. (2019). Micro-Simulation Guide for Automated Vehicles-D2.5. CoXEist, 1-29.

Sun, J., Zuo, K., Jiang, S., & Zheng, Z. (2018). Modeling and Predicting Stochastic Merging Behaviors at Freeway On-Ramp Bottlenecks. Journal of Advanced Transportation, 2018. https://doi.org/10.1155/2018/9308580

TAC. (2017). Geometric design guide for Canadian roads.

Tavasszy, L. A., & Janssen, R. (2017). The value case for truck platooning. working paper. Delft University of Technology: Delft, The Netherlands.

Torbic, D. J., Hutton, J. M., Bokenkroger, C. D., & Brewer, M. A. (2012). Design guidance for freeway main-line ramp terminals. Transportation Research Record, 2309(1), 48–60.

USDOT. (2018). Automated Vehicles: Truck Platooning ITS Benefits, Costs, and Lessons Learned: 2018 Update Report. https://www.itsknowledgeresources.its.dot.gov/its/bcllupdate/pdf/BCLL_Automated Vehicles (CMV) Final Draft v4.pdf

VDOT. (2020). VDOT VISSIM User Guide. In Virginia Department of Transportation (VDOT) . https://www.virginiadot.org/business/resources/VDOT_Vissim_UserGuide_Version2.0_Final_2020-01-10.pdf

Wang, M., van Maarseveen, S., Happee, R., Tool, O., & van Arem, B. (2019). Benefits and risks of truck platooning on freeway operations near entrance ramp. Transportation Research Record, 2673(8), 588–602.

Welch, B. L. (1947). The generalization of ‘STUDENT’S’problem when several different population varlances are involved. Biometrika, 34(1–2), 28–35.

WisDOT. (2019). Traffic Analysis and Modeling Section 20: Microscopic Simulation Traffic Analysis. In Traffic Engineering, Operations & Safety Manual (pp. 1–47). Wisconsin Department of Transportation. https://wisconsindot.gov/dtsdManuals/traffic-ops/manuals-and-standards/teops/16-20.pdf#16-20-8

Xiao, L., Wang, M., & Van Arem, B. (2017). Realistic car-following models for microscopic simulation of adaptive and cooperative adaptive cruise control vehicles. Transportation Research Record, 2623(2623), 1–9. https://doi.org/10.3141/2623-01

Yang, G., Xu, H., Tian, Z., & Wang, Z. (2016). Vehicle speed and acceleration profile study for metered on-ramps in California. Journal of Transportation Engineering, 142(2). https://doi.org/10.1061/(ASCE)TE.1943-5436.0000817

Ye, X., & Wang, X. (2022). Operational design domain of automated vehicles at freeway entrance terminals. Accident Analysis & Prevention, 174, 106776.

Zabat, M., Stabile, N., Farascaroli, S., & Browand, F. (1995). The aerodynamic performance of platoons: A final report. University of California: Berkeley, CA, USA.

Zeidler, V., Buck, H. S., Kautzsch, L., Vortisch, P., & Weyland, C. M. (2019). Simulation of Autonomous Vehicles Based on Wiedemann's Car Following Model in PTV Vissim.

Zhang, M. (2016). Empirical study of freeway interchange crash characteristics and influence areas. University of Missouri--Columbia.

CHAPTER 5: CONCLUSIONS

This research presented in this dissertation assessed the safety and operational implications of SAE level 4 HCV platooning on the North American road network. The road network was classified into three categories in accordance with North American geometric design guidelines: two-lane rural highways, urban arterials, and freeways. To examine the impact of HCV platooning operations on these three types of roadway, the research was designed with three primary objectives. To achieve these objectives, the research investigated from a number of parameters, including passing sight distance, traffic control systems, and acceleration lane length, from safety and operational perspectives. At the initial likely low stages of market penetration (i.e., 0%, 5% and 10%), two headways of platooned HCV operations, 0.6 sec and 1.2 sec, were investigated. The research into the potential real-world effects of platooned HCVs was conducted using an analytical model and a micro-simulation model.

Modified analytical models were proposed to estimate the minimum requirements of design parameters for HCV platooning operations on different types of road. Through investigation, the research identified roads where HCV platooning operations could be permitted without modifications to the existing infrastructure. In addition, the research would assist decision-makers in quantifying the initial safety and operational impacts of HCV platooning operations in order to make effective decisions on whether HCV platoon operations could be allowed on North American roadways.

The findings of the research are summarised in the following sections of this chapter. Chapter 5 also discusses the efficacy of the research and ways through which transportation professionals and agencies can benefit from its findings in terms of taking decisions for permitting HCV platooning. In addition, Chapter 5 discusses the contributions made by this study, makes recommendations regarding how this research may be improved, and provides direction for future research.

5.1 Research Summary

The first objective of this study was to explore **two-lane rural highways** geometric design parameters in North America. The focus was on passing sight distance (PSD) which could clearly be affected by HCV platooning. To understand how HCV platooning might affect two-lane rural highway's PSD, analytical and simulation methods were used.

The study proposed a modified PSD model based on AASHTO 2018 to estimate minimum PSD requirements for HCV platooning and LCVs. Six HCV options (B-Train LCV, Turnpike double LCV, two-HCV platoon travelling with 0.6 sec headway between the HCVs, two HCV platoon travelling with 1.2 sec headway between the HCVs, three-HCV platoon travelling with 0.6 sec headway between the HCVs, and three-HCV platoon travelling with 1.2 sec headway between the HCVs) were analyzed using the modified 2018 AASHTO model. For overtaking maneuvers, the PSD required for passenger cars passing two- or three-HCV platoons differed greatly from the overtaking distance required for passenger cars to pass an LCV. The study showed that the 2017 TAC PSD is adequate for passenger vehicles to pass all six HCV options over roadway design speeds of 50-130 km/h, but that the AASHTO 2018 PSD is insufficient for each of the six HCV options.

Micro-simulations were used to test the same six HCV options travelling under three different real-world scenarios. The results differed from those obtained by the analytical method. The AASHTO 2018 PSDs were inadequate for passenger cars to safely pass any of the six simulated HCV alternatives. The 2017 TAC PSDs, however, provided enough distance for passenger vehicles to pass two LCVs and two-HCV platoon configurations. The 85th percentile passing distance for overtaking three HCV platoons was found to be too short for passenger cars. According to the simulation, passing a three-HCV platoon is a difficult maneuver for a passenger car. To avoid potential safety issues, the provision of frequent passing lanes on designated two-lane highway segments is recommended, although the analytical and simulation methods suggest this is feasible on two-lane rural highways following AASHTO 2004 or TAC 2017 guidelines for PSD. Therefore, it is necessary to update the design guidelines with consideration of HCV platooning in order to maintain acceptable safety and operation on two-lane highways.

The second objective of this study was to evaluate the impact of HCV platooning operations at signalized intersections on **urban arterial roadways** under mixed traffic conditions. To conduct this study, micro-simulation was used to assess the impact of HCV platooning at three differential low penetration rates (0%, 5% and 10%) under existing urban traffic conditions on a heavy HCV corridor in Peel Region, Ontario, Canada. Two-HCV platoons maintaining a 0.6 sec time headway were considered, and the modelling evaluated two traffic control systems: the existing traffic control system, and TSP for HCV platoons. The study considered as two measures of performance, average travel time and the number of stops, for passenger vehicles and for HCVs.

The findings showed that HCV platooning operations on urban arterial roadways may degrade operational performance under the existing traffic control system, and conditions could become more severe as more facilities start using HCV platooning techniques for goods movement. To improve urban roadway operational condition, TSP for HCV platooning could be applied in the earlier stages, i.e., 5% of HCV platoon operations. TSP would provide travel time savings and reduced number of stops benefits not only the 5% level of platooning, but also to other categories of vehicle such as passenger cars and human-driven HCVs. At higher penetration rates, i.e., 10% of HCV platoon operation, HCV platooning would, however, be challenging even with TSP. The study findings also suggested that it might be possible to accommodate 5% HCV platooning on the tested roadway corridor of Derry Road if TSP is provided for HCV platooning at major intersections.

The third objective of this study was to assess the impact of HCV platooning on **freeway** safety and operational performance in mixed traffic conditions. The study examined how HCV platooning operations would affect the freeway acceleration lane length in the North American geometric design standards. The analytical and micro-simulation analyses were undertaken on a Ministry of Transportation (MTO) operated acceleration lane.

A modified AASHTO analytical model was used to evaluate the time taken for two-HCV platooning configurations to achieve freeway speeds and find adequate gaps for merging into the freeway. In the test case, the acceleration lane length was inadequate which could cause merging delays for HCV platoons and other road users. Vehicles may have to stay for extended periods on merging ramps while waiting for an adequate gap to merge onto the freeway. The findings suggest that the acceleration lane lengths recommended by TAC 2017 and AASHTO 2018 are insufficient for allowing both two-HCV platooning options (0.6 sec and 1.2 sec headway) to merge.

Micro-simulation was used to evaluate safety and operational performance under existing road conditions. The results showed a notable degradation in the safety and operational performance of the freeway-merging segment. An extension of acceleration lane length could help to reduce merging delays and improve safety for HCV platooning, but the construction costs may outweigh the benefits.

The analytical and simulation analyses recommended that at 5% market penetration, HCV platoons maintaining 0.6 sec headways could safely use the minimum 600m long freeway merging segment. As suggested by Wang et al., (2019), for HCV platoons to merge safely onto the freeway from ramps, freeway traffic in the right-most lane could practise courtesy yielding to platoons. Courtesy yielding would improve the safety of HCV platooning and other road users.

5.2 Major Contributions

While conducting the research into the impact of HCV platooning, a number of limitations in the North American geometric design guidelines were identified. The contributions made by the research may help to overcome these shortcomings. The significant contributions are:

- The time headway or physical gap between platooned vehicles is a factor affecting roadway design parameters such as passing sight distance, traffic control system and acceleration lane length. The research found that changes in the headway between platooned HCVs had a significant impact (longer overtaking distance, longer travel time, an increase in number of stops and an increase in number of conflicts) on two-lane highways, urban arterial roads and freeways.

- When estimating minimum PSD and acceleration lane length, North American roadway geometric design guidelines have not considered the physical gap or headway between platooned vehicles. The modified analytical model recommended in this research can estimate the minimum PSD and acceleration lane length taking the physical gap between platooned vehicles into account regardless of vehicle classification.
- When estimating the minimum PSD and acceleration lane length, neither the TAC geometric design standards nor the AASHTO geometric design guidelines take vehicle length or the number of vehicles in a platoon into account. This study proposes a modified analytical model for determining the required minimum PSD and acceleration lane length. The modified model considers vehicle length, the number of vehicles in a platoon, and whether the vehicles are in a platoon or not.
- The North American roadway geometric design guidelines recommended PSD on the basis of a passenger vehicle overtaking another passenger vehicle. The research reported in this dissertation notes that the passenger vehicle PSD are longer when overtaking an HCV, LCV or HCV platoon on two-lane highway. The study suggests that the recommended PSD should take worst-case scenarios into account to reduce safety concerns.
- The minimum PSD for two-lane highways recommended in the geometric design guidelines is based on the analytical model's outcome, but the micro-simulation model suggests that the PSD suggested by the geometric design guidelines and estimated by the modified analytical model is too short to ensure safe overtaking maneuvers. The estimated PSD should be scaled using the simulation results for the 85th percentile vehicle's overtaking distance.

- For freeways, the minimum acceleration lane length recommended in the North American design guideline is based only on the merging vehicle's acceleration rate. The time spent searching for an adequate gap is a critical factor for safe merging maneuvers. The research reported in this dissertation proposes a revised analytical model for the estimation of acceleration lane length. The revised analytical model takes into account the time and distance required for gap searching, the vehicle length, and the number of vehicles in a platoon.
- This research also shows that the market penetration rate for HCV platooning should be considered when analyzing the impact of HCV platooning.
- Earlier research on HCV platooning highlighted the benefits of reduced fuel consumption when HCV platoons are travelling on freeways. This research, however, identifies negative safety and operation impacts. These negative impacts include long overtaking distance, increased travel time, increased number of stops and increased number of conflicts, and apply to two-lane rural highways, urban arterials and freeways.

5.3 Major Findings

The overall findings of this research recommend caution in permitting HCV platooning operations on roadways even if HCV platooning helps reduce fuel consumption and greenhouse gas emissions. The major findings are as follows:

- HCV platooning operations have negative impacts in terms of increasing travel time on each roadway classification investigated, i.e., two-lane rural highways, urban arterials and freeways.

- The detailed investigation of North American roadway geometric design guidelines suggests that HCV vehicle length or the overall length of platooned HCVs is a key consideration for defining geometric design requirements.
- Compared to HCV platoons with 0.6 sec time headway, platoons with a longer time headway (1.2 sec) increase the detrimental effects of HCV platoons on each roadway classification investigated. The longer headways have increases in passing sight distance, travel time, number of stops, and number of conflicts.
- The minimum PSD and acceleration lane length design requirements for HCV platooning operations for both the 0.6 sec and 1.2 sec headways are higher than for passenger cars and HCVs.
- Modified analytical models can be used to estimate the minimum PSD and acceleration lane length requirements for HCV platooning operations on different types of road.
- The HCV platooning market penetration rate affects safety and operations. As the market penetration increases from 0% to 5% and then 10% HCV platooning, the negative impact increases, i.e., an increased HCV platooning market penetration rate is associated with increases in passing sight distance, travel time, number of stops, and number of conflicts.
- Two-HCV platooning with 0.6 sec time headway can be operated on existing two-lane rural highways, but passing lanes are recommended for safe overtaking maneuvers.
- On urban arterials, truck signal priority techniques, i.e., an extension of green time for a 5% HCV platooning market penetration rate (0.6 sec time headway) and for less than a 5% HCV platooning market penetration rate (0.6 sec time headway), are recommended.

- This research also identified significant merging delays and an increase in the number of conflicts on freeway-merging segments for HCV platooning operations. The study recommends allowing 5% two-HCV platooning (0.6 sec headway) operations if the freeway merging segments are at least 600 m long. The introduction of courtesy yielding for the right-most lane of freeway traffic is recommended for HCV platoons.

The findings of this study will assist policymakers in deciding whether to allow platooned HCVs on North American roadways. The study provides analytical and simulation methodologies that can be used by municipalities to estimate and assess the minimum requirement of different geometric parameters for HCV platoon operation to maximize safety and smooth operations for all road users. Different municipalities can apply the methodology to their specific regions. The results can inform transportation policy decisions and provide guidelines for municipalities to develop regulations, best practices, and future infrastructure improvements. The guidelines include recommendations for addressing safety concerns, managing traffic flow, and other logistical issues specific to the municipalities. Appropriate legislative action from government agencies and municipalities will signal to private logistic companies that there is a supportive environment for the development and deployment of HCV platooning technology, encouraging companies to invest in and adopt the technology. The results of the study will help to inform transportation engineers, government agencies, stakeholders such as supply-chain distributors, and other decision-makers about the challenges associated with implementing HCV platooning on two-lane rural highways, urban arterials, and freeways.

5.4 Recommendations for Future Work

The limitations to this study may be considered for future research:

- The study assumes no cut-in/cut-out maneuvers between HCVs in a platoon. Future studies should explore cut-in/cut-out maneuvers.
- The study considered V2V communication only between vehicles in an HCV platoon. With a progression in V2X communications, passenger cars, non-platooned HCVs, and transit vehicles could communicate not only with each other, but also with infrastructure such as roadside furniture. Future studies should explore scenarios in which all road users can communicate with each other and a range of roadside furniture.
- The study considered a 1.5 sec time headway between a passenger vehicle and an HCV platoon. The minimum headways in V2V environments might differ from the headway and standstill distances assumed in this study. Future studies should investigate time headway and standstill distances to determine minimum headways in V2V environments.
- The study did not consider communication of overtaking vehicle with oncoming traffic and the safety and operational issues involved. The PSD requirements evaluated in this study may help to estimate the minimum communication distances required between two vehicles travelling in opposite directions on a two-lane rural highway where one vehicle is willing to overtake and the other vehicle is oncoming in the oncoming lane. Through future V2V technology, this research would permit vehicles to overtake safely without needing a passing lane. Operational performance measures such as the level of service of a two-lane highway may be impacted as HCV platooning may increase the potential for conflicts

(Kaub and Berg, 1988). The conflicts will reduce the number of passing opportunities. Future studies should explore passing opportunities in such circumstances.

- This study proposes the implementation of passing lanes as a solution for ensuring the safe operation of HCV platoons. However, in order to maintain and improve the safety and operation of existing roadways, future studies should examine the frequency of passing lane provision and the required length of the passing lane, while considering other relevant factors including the cost of the necessary infrastructure.
- Future studies should investigate the impact of HCV platoons on two-lane rural highways, freeways and urban roadways. The studies should take into account suitable times and days for operation to minimize disruptions in traffic flow and improve safety. Restrictions similar to those for LCVs could be applied to HCV platoons.
- When evaluating HCV platooning impact on urban arterials, this study only considered through traffic effects. For better decision-making, future studies should investigate left-turning traffic movements and cross-street traffic impacts.
- The study was limited in terms of the range of traffic flow and levels of service investigated. Future studies should explore various levels of traffic flow and levels of service in order to advise how HCV platooning operations may be handled in the future.
- The consideration of climate change and any associated impact on HCV platooning was outside the scope of the study.
- The findings of this study suggest that in order to allow for HCV platooning, the minimum requirements for design parameters may need to be increased. It is important for future

research to explore the potential impact of increased requirements on all road users' right of way, and the implications for safety, traffic flow, and the cost of infrastructure.

We believe that the findings of this study may serve as valuable seed information for transportation engineers considering HCV platooning on North American road networks and for future research into this important issue.

5.5 Chapter 5 References

Kaub, A. R., & Berg, W. D. (1988). Design guide for auxiliary passing lanes on rural two-lane highways. Transportation Research Record, 1195, 92–100.

Wang, M., van Maarseveen, S., Happee, R., Tool, O., & van Arem, B. (2019). Benefits and Risks of Truck Platooning on Freeway Operations Near Entrance Ramp. Transportation Research Record, 2673(8), 588–602. https://doi.org/10.1177/0361198119842821.

APPENDIX

APPENDIX A: TRAVEL TIME FOR INITIAL MARKET PENETRATIONS OF HCV PLATOONING ON URBAN ARTERIAL ROADWAYS

Table A-1: Average Travel Time (min) of Directional Movements

Intersection	Turn*	NP0	NP5**	NP10**	TP5**	TP10**	Turn*	NP0	NP5**	NP10**	TP5**	TP10**
Kennedy Rd.	EBL	1.48	1.54	1.54	1.52	1.53	NBL	1.06	1.06	1.06	1.06	1.03
	( )		(-4.0%)	(-4.0%)	(-2.7%)	(-3.3%)	( )		(0.0%)	(0.0%)	(0.0%)	(2.9%)
	EBT	0.99	1.01	1.05	0.98	1.06	NBT	1.04	1.04	1.04	1.04	1.03
	( )		(-2.0%)	(-6.1%)	(1.0%)	(-7.1%)	( )		(0.0%)	(0.0%)	(0.0%)	(1.0%)
	EBR	0.38	0.38	0.38	0.38	0.38	NBR	0.29	0.29	0.29	0.29	0.29
	( )		(0.0%)	(0.0%)	(0.0%)	(0.0%)	( )		(0.0%)	(0.0%)	(0.0%)	(0.0%)
	WBL	1.52	1.56	1.57	1.54	1.58	SBL	0.96	0.96	0.97	0.96	0.97
	( )		(-2.6%)	(-3.2%)	(-1.3%)	(-3.9%)	( )		(0.0%)	(-1.0%)	(0.0%)	(-1.0%)
	WBT	0.51	0.52	0.53	0.52	0.53	SBT	0.93	0.93	0.93	0.94	0.94
	( )		(-1.9%)	(-3.8%)	(-1.9%)	(-3.8%)	( )		(0.0%)	(0.0%)	(-1.1%)	(-1.1%)
	WBR	0.41	0.42	0.42	0.42	0.42	SBR	0.26	0.26	0.26	0.26	0.26
	( )		(-2.4%)	(-2.4%)	(-2.4%)	(-2.4%)	( )		(0.0%)	(0.0%)	(0.0%)	(0.0%)
Tomken Rd.	EBL	0.65	0.67	0.68	0.66	0.66	NBL	1.56	1.58	1.59	1.55	1.56
	( )		(-3.0%)	(-4.5%)	(-1.5%)	(-1.5%)	( )		(-1.3%)	(-1.9%)	(0.6%)	(0.0%)
	EBT	2.64	2.67	2.72	2.63	2.73	NBT	1.13	1.16	1.17	1.12	1.13
	( )		(-1.1%)	(-3.0%)	(0.4%)	(-3.4%)	( )		(-2.6%)	(-3.5%)	(0.9%)	(0.0%)
	EBR	0.42	0.43	0.43	0.41	0.42	NBR	0.57	0.58	0.58	0.58	0.57
	( )		(-2.4%)	(-2.4%)	(2.4%)	(0.0%)	( )		(-1.7%)	(-1.7%)	(-1.7%)	(0.0%)
	WBL	1.09	1.1	1.12	1.09	1.1	SBL	1.22	1.23	1.26	1.19	1.21
	( )		(-0.9%)	(-2.7%)	(0.0%)	(-0.9%)	( )		(-0.8%)	(-3.2%)	(2.5%)	(0.8%)
	WBT	1.41	1.42	1.44	1.41	1.42	SBT	1.24	1.26	1.28	1.24	1.27
	( )		(-0.7%)	(-2.1%)	(0.0%)	(-0.7%)	( )		(-1.6%)	(-3.2%)	(0.0%)	(-2.4%)
	WBR	0.86	0.88	0.89	0.87	0.88	SBR	0.35	0.37	0.38	0.35	0.36
	( )		(-2.3%)	(-3.4%)	(-1.2%)	(-2.3%)	( )		(-5.6%)	(-8.2%)	(0.0%)	(-2.8%)
Dixie Rd.	EBL	1.73	1.76	1.77	1.7	1.72	NBL	1.36	1.39	1.41	1.38	1.4
	( )		(-1.7%)	(-2.3%)	(1.7%)	(0.6%)	( )		(-2.2%)	(-3.6%)	(-1.5%)	(-2.9%)
	EBT	2.09	2.13	2.18	2.12	2.13	NBT	1.06	1.08	1.09	1.08	1.09
	( )		(-1.9%)	(-4.3%)	(-1.4%)	(-1.9%)	( )		(-1.9%)	(-2.8%)	(-1.9%)	(-2.8%)
	EBR	0.45	0.44	0.44	0.44	0.44	NBR	0.33	0.35	0.37	0.34	0.35
	( )		(2.2%)	(2.2%)	(2.2%)	(2.2%)	( )		(-5.9%)	(-1.4%)	(-3.0%)	(-5.9%)
	WBL	2.01	2.08	2.15	1.99	2.15	SBL	1.65	1.66	1.68	1.63	1.68
	( )		(-3.4%)	(-6.7%)	(1.0%)	(-6.7%)	( )		(-0.6%)	(-1.8%)	(1.2%)	(-1.8%)
	WBT	0.77	0.8	0.82	0.78	0.8	SBT	1.18	1.19	1.21	1.17	1.19
	( )		(-3.8%)	(-6.3%)	(-1.3%)	(-3.8%)	( )		(-0.8%)	(-2.5%)	(0.9%)	(-0.8%)
	WBR	0.52	0.53	0.53	0.52	0.53	SBR	0.46	0.47	0.48	0.46	0.47
	( )		(-1.9%)	(-1.9%)	(0.0%)	(-1.9%)	( )		(-2.2%)	(-4.3%)	(0.0%)	(-2.2%)
Bramalea Rd.	EBL	0.83	0.84	0.84	0.82	0.82	NBL	1.43	1.44	1.45	1.43	1.4
	( )		(-1.2%)	(-1.2%)	(1.2%)	(1.2%)	( )		(-0.7%)	(-1.4%)	(0.0%)	(2.1%)
	EBT	1.82	1.9	1.92	1.7	1.75	NBT	1.36	1.39	1.41	1.36	1.37
	( )		(-4.4%)	(-5.5%)	(6.6%)	(3.9%)	( )		(-2.2%)	(-3.6%)	(0.0%)	(-0.7%)
	EBR	0.56	0.56	0.56	0.56	0.56	NBR	0.5	0.5	0.5	0.49	0.47
	( )		(0.0%)	(0.0%)	(0.0%)	(0.0%)	( )		(0.0%)	(0.0%)	(2.0%)	(6.2%)
	WBL	0.94	0.93	0.94	0.83	0.85	SBL	1.35	1.37	1.39	1.34	1.35
	( )		(1.1%)	(0.0%)	(12.4%)	(10.1%)	( )		(-1.5%)	(-2.9%)	(0.7%)	(0.0%)
	WBT	0.71	0.71	0.71	0.57	0.58	SBT	1.1	1.11	1.13	1.09	1.13
	( )		(0.0%)	(0.0%)	(21.9%)	(20.2%)	( )		(-0.9%)	(-2.7%)	(0.9%)	(-2.7%)
	WBR	0.48	0.48	0.48	0.48	0.48	SBR	0.44	0.46	0.46	0.45	0.45
	( )		(0.0%)	(0.0%)	(0.0%)	(0.0%)	( )		(-4.4%)	(-4.4%)	(-2.2%)	(-2.2%)

Intersection	Turn*	NP0	NP5**	NP10**	TP5**	TP10**	Turn*	NP0	NP5**	NP10**	TP5**	TP10**
Torbram Rd.	EBL	1.71	1.71 (0.0%)	1.71 (0.0%)	1.7 (0.6%)	1.71 (0.0%)	WBR	0.56	0.58 (-3.5%)	0.59 (-5.2%)	0.57 (-1.8%)	0.58 (-3.5%)
	EBT	1.6	1.61 (-0.6%)	1.63 (-1.9%)	1.4 (12.5%)	1.5 (6.3%)	SBL	1.27	1.28 (-0.8%)	1.29 (-1.6%)	1.27 (0.0%)	1.26 (0.8%)
	WBT	0.61	0.62 (-1.6%)	0.62 (-1.6%)	0.53 (14.0%)	0.57 (6.8%)	SBR	0.32	0.33 (-3.1%)	0.34 (-6.1%)	0.33 (-3.1%)	0.34 (-6.1%)
Cattrick St.	EBL	0.33	0.33 (0.0%)	0.33 (0.0%)	0.33 (0.0%)	0.33 (0.0%)	NBL	1.49	1.5 (-0.7%)	1.51 (-1.3%)	1.47 (1.4%)	1.49 (0.0%)
	EBT	0.87	0.88 (-1.2%)	0.89 (-2.3%)	0.86 (1.2%)	0.88 (-1.2%)	NBT	0.00	0.00 (0.0%)	0.00 (0.0%)	0.00 (0.0%)	0.00 (0.0%)
	EBR	0.24	0.25 (-4.1%)	0.25 (-4.1%)	0.24 (0.0%)	0.25 (-4.1%)	NBR	0.25	0.26 (-3.9%)	0.27 (-7.7%)	0.23 (8.3%)	0.24 (4.1%)
	WBL	0.27	0.28 (-3.6%)	0.29 (-7.1%)	0.26 (3.8%)	0.25 (7.7%)	SBL	1.45	1.46 (-0.7%)	1.47 (-1.4%)	1.43 (1.4%)	1.45 (0.0%)
	WBT	0.17	0.17 (0.0%)	0.17 (0.0%)	0.16 (6.1%)	0.16 (6.1%)	SBT	0.00	0.00 (0.0%)	0.00 (0.0%)	0.00 (0.0%)	0.00 (0.0%)
	WBR	0.23	0.25 (-8.3%)	0.26 (-12.2%)	0.21 (9.1%)	0.22 (4.4%)	SBR	0.23	0.23 (0.0%)	0.23 (0.0%)	0.23 (0.0%)	0.23 (0.0%)
Airport Rd.	EBL	0.89	0.91 (-2.2%)	0.93 (-4.4%)	0.87 (2.3%)	0.88 (1.1%)	NBL	1.08	1.11 (-2.7%)	1.14 (-5.4%)	1.06 (1.9%)	1.09 (-0.9%)
	EBT	1.3	1.36 (-4.6%)	1.42 (-9.2%)	1.28 (1.5%)	1.43 (-10%)	NBT	1.02	1.03 (-1.0%)	1.04 (-1.9%)	1.02 (0.0%)	1.04 (-1.9%)
	EBR	0.26	0.27 (-3.8%)	0.28 (-7.4%)	0.26 (0.0%)	0.27 (-3.8%)	NBR	0.54	0.56 (-3.6%)	0.57 (-5.4%)	0.55 (-1.8%)	0.56 (-3.6%)
	WBL	0.8	0.81 (-1.2%)	0.82 (-2.5%)	0.77 (3.8%)	0.79 (1.3%)	SBL	1.09	1.13 (-3.6%)	1.14 (-4.5%)	1.11 (-1.8%)	1.08 (0.9%)
	WBT	1.05	1.08 (-2.8%)	1.1 (-4.7%)	1.00 (4.9%)	1.01 (3.9%)	SBT	0.93	0.95 (-2.1%)	0.96 (-3.2%)	0.91 (2.2%)	0.92 (1.1%)
	WBR	0.89	0.9 (-1.1%)	0.9 (-1.1%)	0.86 (3.4%)	0.87 (2.3%)	SBR	0.25	0.26 (-3.9%)	0.27 (-7.7%)	0.23 (8.3%)	0.24 (4.1%)
Goreway Dr.	EBL	1.54	1.57 (-1.9%)	1.58 (-2.6%)	1.53 (0.7%)	1.56 (-1.3%)	NBL	1.39	1.41 (-1.4%)	1.42 (-2.1%)	1.38 (0.7%)	1.4 (-0.7%)
	EBT	2.16	2.2 (-1.9%)	2.21 (-2.3%)	1.95 (9.7%)	2.05 (5.1%)	NBT	1.14	1.15 (-0.9%)	1.15 (-0.9%)	1.15 (-0.9%)	1.15 (-0.9%)
	EBR	0.31	0.31 (0.0%)	0.31 (0.0%)	0.3 (3.3%)	0.3 (3.3%)	NBR	0.32	0.32 (0.0%)	0.32 (0.0%)	0.32 (0.0%)	0.32 (0.0%)
	WBL	0.62	0.62 (0.0%)	0.62 (0.0%)	0.61 (1.6%)	0.61 (1.6%)	SBL	1.45	1.46 (-0.7%)	1.48 (-2.0%)	1.45 (0.0%)	1.48 (-2.0%)
	WBT	0.67	0.68 (-1.5%)	0.68 (-1.5%)	0.67 (0.0%)	0.68 (-1.5%)	SBT	1.17	1.17 (0.0%)	1.17 (0.0%)	1.18 (-0.9%)	1.18 (-0.9%)
	WBR	0.28	0.28 (0.0%)	0.28 (0.0%)	0.28 (0.0%)	0.28 (0.0%)	SBR	1.00	1.00 (0.0%)	1.00 (0.0%)	1.00 (0.0%)	1.00 (0.0%)

*L-Left, T-Through, R-Right; EB-East Bound, NB-North Bound, SB-South Bound, WB-West Bound

** Values represented as: travel time in minutes (% difference with NP0)

Table A-2: Average Travel Time (min) of TP15

Vehicle Category	VISSIM Model	Mean
All Vehicles	TP15	14.44
Passenger Vehicles		14.25
HCVs		15.86

APPENDIX B: ESTIMATED ACCELERATION LANE LENGTH VALIDATION AND COMPARISON

Table B-1: T-Test Results for Acceleration Lane Length

Vehicle Classification	Models	Existing Acceleration Lane Length (m)	Estimated Acceleration Lane Length (m)	t-test	P-Value
Passenger Vehicle	CAMMSE (Qi et al., 2019)	183	175	1.59	0.11
	2018 AASHTO	184	175	1.41	0.15

Table B-2: Estimated Acceleration Lane Length for Passenger Vehicle and WB-20 HCV

Freeway Speed, V_h (km/h)	Ramp Design Speed, V_r (km/h)	Initial Speed at the Beginning of Ramp (km/h)						
		44	50	57	63	70	76	81
		Required Acceleration Lane Length (m)						
		Passenger Vehicle						
105	49	225						
105	57	210	230					
105	65	185	215	240				
105	73	170	200	215	240			
105	81	150	175	190	215	265	320	
105	89	125	140	160	185	225	290	350
105	92	115	130	145	165	200	275	330
105	102	80	95	100	115	145	215	265
		WB 20 HCV						
105	49	355						
105	57	335	380					
105	65	310	360	355				
105	73	280	335	345	390			
105	81	240	290	305	345	400	475	
105	89	200	240	255	295	350	355	490
105	92	185	220	235	275	320	390	460
105	102	125	150	165	195	235	295	350

Table B-3: Required Acceleration Lane Length Compared with Passenger Vehicle

Freeway Speed, V_h (km/h)	Ramp Design Speed, V_r (km/h)	Initial Speed at the Beginning of Ramp (km/h)						
		44	50	57	63	70	76	81
		In Comparison with Passenger Vehicle (Multiplier)						
		WB 20 HCV						
105	49	1.58						
105	57	1.60	1.65					
105	65	1.68	1.67	1.48				
105	73	1.65	1.68	1.60	1.63			
105	81	1.60	1.66	1.61	1.60	1.51	1.48	
105	89	1.60	1.71	1.59	1.59	1.56	1.22	1.40
105	92	1.61	1.69	1.62	1.67	1.60	1.42	1.39
105	102	1.56	1.58	1.65	1.70	1.62	1.37	1.32
		2 HCV Platooning 0.6 sec Headway						
105	49	1.73						
105	57	1.74	1.83					
105	65	1.84	1.84	1.69				
105	73	1.82	1.85	1.81	1.88			
105	81	1.83	1.86	1.84	1.91	1.81	1.83	
105	89	1.88	2.00	1.91	1.95	1.91	1.69	1.80
105	92	1.87	2.00	1.97	2.03	2.03	1.82	1.83
105	102	1.94	2.00	2.15	2.26	2.21	1.86	1.85
		2 HCV Platooning 1.2 sec Headway						
105	49	1.78						
105	57	1.79	1.87					
105	65	1.89	1.88	1.75				
105	73	1.88	1.93	1.88	1.96			
105	81	1.90	1.94	1.95	2.00	1.92	1.94	
105	89	1.96	2.11	2.03	2.05	2.02	1.88	1.96
105	92	2.00	2.12	2.10	2.18	2.18	1.96	2.00
105	102	2.13	2.16	2.40	2.48	2.41	2.07	2.06

Table B-4: Required Acceleration Lane Length Compared with WB 20 HCV

Freeway Speed, V_h (km/h)	Ramp Design Speed, V_r (km/h)	Initial Speed at the Beginning of Ramp (km/h)						
		44	50	57	63	70	76	81
		In Comparison with WB 20 HCV (Multiplier)						
		2 HCV Platooning 0.6 sec Headway						
105	49	1.10						
105	57	1.09	1.11					
105	65	1.10	1.10	1.14				
105	73	1.11	1.10	1.13	1.15			
105	81	1.15	1.12	1.15	1.19	1.20	1.23	
105	89	1.18	1.17	1.20	1.22	1.23	1.38	1.29
105	92	1.16	1.18	1.21	1.22	1.27	1.28	1.32
105	102	1.24	1.27	1.30	1.33	1.36	1.36	1.40
		2 HCV Platooning 1.2 sec Headway						
105	49	1.13						
105	57	1.12	1.13					
105	65	1.13	1.13	1.18				
105	73	1.14	1.15	1.17	1.21			
105	81	1.19	1.17	1.21	1.25	1.28	1.31	
105	89	1.23	1.23	1.27	1.29	1.30	1.54	1.40
105	92	1.24	1.25	1.30	1.31	1.36	1.38	1.43
105	102	1.36	1.37	1.45	1.46	1.49	1.51	1.56

APPENDIX C: DATA PROCESSING

The following scripts are written in the python language for processing the output produced by PTV VISSIM (2021). These scripts provide an example of the data processing, but caution should be used when adapting them for other analyses.

The scripts follow the order for estimation of overtaking distance, freeway merging time.

Script 1: Purpose - Process VISSIM output file to perform Analysis.

```
import csv
def record_csv(filepath,row):
    with open(filepath,'a') as f:
        writer=csv.writer(f)
        writer.writerow(row)
    return


ftruckspeed="Truck Speed.csv"
record_csv(ftruckspeed,['Speed'])
######################################################
def simulate(fzp_filepath, primary_selection_filepath, trucklist_filepath, carlist_filepath):
    f01=open(fzp_filepath,"r")
    fprimarystr01=open(primary_selection_filepath,"w+")
    ftruckstr01=open(trucklist_filepath,"w+")
    fcarstr01=open(carlist_filepath,"w+")
    l=[]
    k=[]
    r=0
    Speed=[]
    trucklist=[]
    carlist=[]
```

```
    for i in f01:
        i=i.split(";")
        if(r==0):
            k.append(i)
        else:
            type = i[14]
            type = int(type)
            if (type==8):
                trucklist.append(i[1])
                Speed = i[24]
                Speed = float(Speed)
                Speed = int(Speed)
                Lane = i[2]
                Lane = float(Lane)
                truckid = i[1]
                record_csv(ftruckspeed, [Speed])
            elif (type<6 and type>0):
                carlist.append(i[1])
            l.append(i)
        r=r+1
    l=sorted(l,key = lambda x: (x[1]))
    trucklist = list(set(trucklist))
    carlist = list(set(carlist))
    for i in trucklist:
        ftruckstr01.write(str(i) + "\n")
    for i in carlist:
        fcarstr01.write(str(i) + "\n")
for i in l:
        x=";"
        x=x.join(i)
```

```
        fprimarystr01.write(str(x))
fzp_filepath = "PSD-TP"
primary_selection_filepath = "Primary_Selection"
trucklist_filepath = "trucklist"
carlist_filepath = "carlist"
for i in range(1, 41, 1):
    num="%0.2d" % i
    fzp_filepath_filepath_here = fzp_filepath + num + ".txt"
    primary_selection_filepath_here = primary_selection_filepath + num + ".txt"
    trucklist_filepath_here = trucklist_filepath +  num + ".txt"
    carlist_filepath_here = carlist_filepath +  num + ".txt"
    simulate(fzp_filepath_filepath_here, primary_selection_filepath_here, trucklist_filepath_here, carlist_filepath_here)
```

Script 2: Purpose - Create the passenger car list.

```
def simulate(primary_selection_filepath, trucklist_filepath, Only_Carlist_filepath):
    f01=open(primary_selection_filepath,"r")
    ftruck01=open(trucklist_filepath,"r")
    fcar01=open(Only_Carlist_filepath,"w+")
    l=[]
    k=[]
    r=0
    g=[]
    for i in ftruck01:
        g.append(int(i))
    print(g)

for i in f01:
        i=i.split(";")
        vehno = i[1]
        #print(type)
        vehno = int(vehno)
```

```
            #n=0
            t=vehno in g
            #for j in g:
            #    if(j==type):
            #        n==1
            #        break
            if(t==False):
                l.append(i)
            r=r+1
    l=sorted(l,key = lambda x: (x[1]))
    for i in l:
        x = ";"
        x = x.join(i)
        fcar01.write(str(x))
primary_selection_filepath = "Primary_Selection"
trucklist_filepath = "trucklist"
carlist_filepath = "carlist"
for i in range(1, 41, 1):
    num="%0.2d" % i
    primary_selection_filepath_here = primary_selection_filepath + num + ".txt"
    trucklist_filepath_here = trucklist_filepath +  num + ".txt"
    carlist_filepath_here = carlist_filepath +  num + ".txt"
    simulate(primary_selection_filepath_here, trucklist_filepath_here, carlist_filepath_here)
```

Script 3: Purpose - Estimate Overtaking Distance

```
import csv
def record_csv(filepath,row):
    with open(filepath,'a') as f:
        writer=csv.writer(f)
        writer.writerow(row)
    return
```

```
fspeed_distance="TP2-0.6-Speed_Pdist(LCV).csv"
record_csv(fspeed_distance,['Speed','Distance','Time_to_overtake', 'Lane_Information','Overtaking_Carid', 'Car_Speed'])
def simulate(primary_selection_filepath, rampvehiclelist_filepath):
    f01=open(primary_selection_filepath,"r")
    ftruck01=open(trucklist_filepath,"r")
    l=[]
    prev_row=[]
    r=0
    trucklist=[]
    for i in ftruck01:
    trucklist.append(int(i))
    x=""
    y=""
    prev_truck=""
    prev_car=""
    g=-6
    v=0
    Car_Speed=""
    Slow_Speed=""
    Passing_distance=""
    Lane_Information=""
    Time_to_overtake=""
    Overtaking_Carid=""
    for i in f01:
        #import ipdb;ipdb.set_trace()
        i=i.split(";")
        passtype = i[28]
        Lanestart= i[31]
        if(passtype=="Pass" and Lanestart=="Left"):
                carid= prev_row[1]
```

```
        carid = int(carid)
        Start_Veh_position = prev_row[4]
        Start_Veh_position=float(Start_Veh_position)
        Start_Veh_position= int(Start_Veh_position)
        trucktype = i[29]
        trucktype = int(trucktype)
        t = trucktype in trucklist
        if (t == True or t==False):
            x=prev_row
            prev_slow_Speed= prev_row[24]
            prev_slow_Speed = float(prev_slow_Speed)
            prev_slow_Speed = int(prev_slow_Speed)
            Start_time_to_Overtake= prev_row[0]
            Start_time_to_Overtake = float(Start_time_to_Overtake)
            Lane = prev_row[2]
            Lane = float(Lane)
            if (Lane==3 or Lane==5 or Lane==7):
                Lane= prev_row [2]
                Lane = float(Lane)
            else:
                Lane= i[2]
                Lane=float(Lane)
            prev_car= str(carid)
            prev_truck=str(trucktype)
            v=1
    change = i[31]
    temp_car = i[1]
    if(change=="Right" and v==1):
        g=1
    elif (change == "None" and v == 1):
```

```
        if (g == 1):
          g = 2
          if (temp_car == prev_car):
            g = 3
            temp = i[29]
            if (temp != prev_truck):
                g = 4
                Speed = i[24]
                Speed = float(Speed)
                Speed_diff = (Speed - prev_slow_Speed)
                Speed_diff2 = i[26]
                Speed_diff2 = float(Speed_diff2)
                End_Veh_position = i[4]
                End_Veh_position = float(End_Veh_position)
                End_Veh_position = int(End_Veh_position)
                diff = End_Veh_position - Start_Veh_position
                End_time_to_Overtake = i[0]
                End_time_to_Overtake = float(End_time_to_Overtake)
                # print(End_time_to_Overtake)
                Overtaking_time = End_time_to_Overtake - Start_time_to_Overtake
                  g = 5
                  y = i
                  Slow_Speed = prev_slow_Speed
                  Passing_distance = diff
                  Time_to_overtake = Overtaking_time
                  Lane_Information = Lane
                  Overtaking_Carid = prev_car
                  Car_Speed = Speed
                  record_csv(fspeed_distance, [Slow_Speed, Passing_distance, Time_to_overtake, Lane_Information,
Overtaking_Carid, Car_Speed])
```

```
                g = -6
                x = ""
                y = ""
                v = 0
            else:
                g = -6
        else:
            g = -6
        prev_row = i
    print("DONE: " + primary_selection_filepath + ", " +  trucklist_filepath)
## Main runner
primary_selection_filepath = "Primary_Selection"
trucklist_filepath = "trucklist"
for i in range(1, 31, 1):
    num="%0.2d" % i
    primary_selection_filepath_here = primary_selection_filepath + num + ".txt"
    trucklist_filepath_here = trucklist_filepath +  num + ".txt"
    simulate(primary_selection_filepath_here, trucklist_filepath_here)
```

Script 4: Purpose - Estimation of freeway merging time

```
import csv
def record_csv(filepath,row):
    with open(filepath,'a') as f:
        writer=csv.writer(f)
        writer.writerow(row)
    return
framp_time="Ramp_Ptime.csv"
record_csv(framp_time,['Merging_Carid', 'Position', 'Time_to_Merge',  'Veh_type'])
def simulate(primary_selection_filepath, rampvehiclelist_filepath):
    f01=open(primary_selection_filepath,"r")
    framp01=open(rampvehiclelist_filepath,"r")
```

```
l=[]
prev_row =[]
r=0
# trucklist=[]
# for i in ftruck01:
#     trucklist.append(int(i))
rampvehiclelist=[]
for i in framp01:
    rampvehiclelist.append(int(i))
id_dic = {}
id_dic1 = {}
x=""
y=""
prev_car=""
g=-6
v=0
Veh_type=""
Time_to_Merge=""
Merging_Carid=""
for i in f01:
    i=i.split(";")
    Link = int(i[4])
    Lane = int(i[3])
    Lanechange = i[7]
    Vehicletype = int(i[6])
    Vehicleid = int(i[1])
    if Vehicleid not in id_dic1:
        id_dic1[Vehicleid] =[-1]
    if Vehicleid not in id_dic:
        id_dic[Vehicleid] =[-1, -1]
```

```
t = Vehicleid in rampvehiclelist
if(t == True and r > 0):
    carid= prev_row[1]
    carid = int(carid)
    x=prev_row
    Veh_startposition = float(i[5])
    if ((Link == 3)) :
        x=prev_row
        prev_car= str(carid)
        Start_time= prev_row[0]
        Start_time = float(Start_time)
        id_dic1[Vehicleid][0] = max(id_dic1[Vehicleid][0], float(i[0]))
        v=1
temp_car = i[1]
# print (Start_time)
if(t == True and (Link == 4 or Link == 10001)and Lanechange=="Left" and v==1):
    g=1
    # elif (change == "Left" and v == 1):
    if(Lane == 2 and g==1):
        g=2
        if(temp_car==prev_car):
            carid = i[1]
            carid = str(carid)
            Vehicletype = float(i[6])
            Veh_position = float(i[5])
            id = carid
            Position = Veh_position
            if (Vehicletype == 5):
                Veh_type="Passenger Car"
            elif (Vehicletype==8):
```

```
        Veh_type="HCV"
    elif (Vehicletype==16):
        Veh_type="HCVP"

    if Link == 4:
        id_dic[Vehicleid][0] = max(id_dic[Vehicleid][0], float(i[5]))
        id_dic[Vehicleid][0]+= 0
    elif Link == 10001:
        id_dic[Vehicleid][1] = max(id_dic[Vehicleid][1], float(i[5]))
        id_dic[Vehicleid][1] += 300
for id in id_dic:
    if id_dic[id][1]!=-1:
        id=id
        Position= str(id_dic[id][1])
        Veh_type= Veh_type
        #print("id: "+str(id)+" LAKE 10001"+" position: "+str(id_dic[id][1]))
    elif id_dic[id][0]!=-1:
        id=id
        Position= str(id_dic[id][0])
        Veh_type = Veh_type
        # record_csv(framp_distance, [id, Position, Veh_type])
    #print("id: "+str(id)+" LAKE 4"+" position: "+str(id_dic[id][0]))
    g=3
if (g==3):
    g=4
    End_time = i[0]
    End_time = float(End_time)
    #print(End_time_to_Overtake)
    Time_to_Merge= End_time - Start_time
    Position=float(Position)
```

```
                g = 5
                y = i
                Position = round(Position, 2)
                Time_to_Merge = round(Time_to_Merge, 2)
                Merging_Carid = id
                Veh_type = Veh_type
                record_csv(framp_time, [Merging_Carid, Position, Time_to_Merge, Veh_type])
            g=-6
            x=""
            y=""
            v=0
        else:
            g=-6
    else:
        g=-6
    prev_row=i
    r = r + 1
print("DONE: " + primary_selection_filepath + ", " +  rampvehiclelist_filepath)
## Main runner
primary_selection_filepath = "Primary_Selection"
rampvehiclelist_filepath = "rampvehiclelist"
for i in range(1, 41, 1):
    num="%0.2d" % i
    primary_selection_filepath_here = primary_selection_filepath + num + ".txt"
    rampvehiclelist_filepath_here = rampvehiclelist_filepath +  num + ".txt"
    simulate(primary_selection_filepath_here, rampvehiclelist_filepath_here)
```