SURFACE INFRASTRUCTURE IMPROVEMENT FOR EFFICIENT LONG COMBINATION VEHICLES AND HCV PLATOONING OPERATION

JOWEL AKKEH

A THESIS SUBMITTED TO
THE FACULTY OF GRADUATE STUDIES
IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE
OF
MASTER OF APPLIED SCIENCE

GRADUATE PROGRAM IN CIVIL ENGINEERING

YORK UNIVERSITY
TORONTO, ONTARIO

August 2025

ABSTRACT

The growing demand for freight transportation has led to increased congestion on urban arterial roads, requiring innovative solutions such as long combination vehicles (LCVs) and heavy commercial vehicle (HCV) platooning. However, these approaches face challenges at intersections due to limited green time and insufficient lane storage for left turns.

This study examines the use of Intelligent Transportation Systems (ITS) to enhance truck travel time, specifically through Freight Signal Priority (FSP) and dedicated truck left-turn lanes (DTLL). A methodology was developed to identify intersections requiring truck priority measures. Using PTV VISSIM, a micro-simulation model was created for a 19.2 km corridor with 32 signalized intersections. Freight vehicle composition included 5% LCVs and single-unit trucks. Eight models were used for comparative analysis. Model 1 represents the 'do-nothing' scenario that includes the assumption of 5% LCVs, Model 2 applies the FSP scenario, Model 3 includes the DTLL scenario, and Model 4 combines Models 2 (FSP) and 3 (DTLL). Model 5 assessed a 5% penetration rate of HCV Platooning under existing conditions. Model 6 adds FSP to Model 5, Model 7 adds DTLL to Model 5, and Model 8 combines Models 6 (FSP) and 7 (DTLL).

The study found that implementing both FSP and DTLL together yields better results than applying each individually. This integrated approach demonstrated improvements in efficiency, traffic flow, and sustainability by reducing travel time and greenhouse gas (GHG) emissions for all vehicles.

ACKNOWLEDGMENTS

To my loving mom, Razan — Thank you for your constant care, your comforting presence, and for always knowing when I needed a break (and a snack). Your strength and endless encouragement helped me push through the hardest moments of this journey. I’m so lucky to have you by my side.

To my wonderful dad, Kamal — Thank you for always believing in me and reminding me to stay focused, even when things got overwhelming. Your support, wisdom, and reassurance gave me the confidence to keep going. I couldn’t have done this without your strength behind me.

To my supervisor, Dr. Peter Y. Park — Thank you for your guidance, support, and for challenging me to do better. I’ve learned so much from this experience, and I’m truly grateful. Thank you for seeing the potential in me.

To my mentor, Dr. Tanvir Chowdhury — Thank you for your guidance, support and time. I value all the zoom calls and emails. Your encouragement and patience made this experience so much easier, and I’m incredibly grateful to have had you as a mentor.

To my best friends, Katie and Jay — Thank you for reminding me to take breaks, for the endless laughs, and for listening to my rants. You helped keep me sane through it all and I’m so grateful to have had you both by my side.

From the bottom of my heart, I appreciate each and every one of you

Table of Contents

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1: INTRODUCTION

This study explores surface infrastructure improvements to support the use of intelligent transportation systems (ITS) in improving the operational and environmental performance of freight transportation. The first chapter discusses the importance of exploring the vital role Heavy Commercial Vehicles (HCV) play in the economic growth of urban areas and highlights the importance of ensuring efficient HCV travel times. It also outlines the research goal and objectives, as well as the overall structure of the thesis.

1.1 Background

Nearly every product, from raw materials to finished goods, requires transportation at different stages making goods movement an essential part of the supply chain. Parts are delivered to manufacturing facilities, assembled products go to warehouses, and finished goods are sent to retailers or consumers and so on. This process significantly increases the use of HCVs on urban roads for first- and last-mile deliveries. Although long-haul HCVs predominantly use highways, they cannot avoid traveling on urban roadways. For example, in Canada, any HCV trip under 25 km is classified as urban, with HCVs traveling a total of 126 million km on urban roadways (Statistics Canada, 2020). While in the United States (U.S) HCVs traveled 164 million km on urban roads, with 59.4% of these trips on major and minor arterials (USDOT, 2020). In addition, these deliveries are restricted as they must be completed during standard business hours, forcing the trucks to travel during peak hours (Woudsma, 2001).

Freight transportation is an important contributor to the economic development of any region (FHWA, 2004. Peel Region, 2015). As shown in the 2015 Goods Movement Economic Impact Analysis Report which states that about $1.8 billion worth of goods crosses through the

Peel Region on a daily basis, contributing to an annual GDP of $49 billion. The economic impact of those goods represents approximately 6.3% of the provincial GDP and 3.2% of the federal GDP (Region of Peel, 2015). This significant urban travel highlights the importance for HCV operations along urban intersections; however, it can lead to delays and increased greenhouse gas (GHG) emissions due to congestion. The impact of congestion in the Greater Toronto and Hamilton Area (GTHA), which slows down freight and passenger vehicle movement, is reflected in estimated cost to the regional economy of $6 billion per year (Parker, 2008). According to the Texas Department of Transportation (TxDOT) in 2021, the value of delay time is estimated at $30.54 per passenger car hour and $41.91 per commercial truck hour (Texas Department of Transportation (TxDOT), 2021). In addition, Kurri et al. discussed that the average delay cost for daily goods is approximately 63.11 US$ per metric ton per hour (Kurri, et al., 2000). Therefore, significantly lower the costs associated with goods transportation.

Due to the increased traffic of freight vehicles and the growing demands of goods movements on roadways, long combination vehicles (LCVs) are introduced. LCVs are specialized tractors designed to tow two full-length semi-trailers, which is an extended length compared to standard configurations of a conventional single unit truck. Figure 1 illustrates the three common LCV configurations in Canada: turnpike doubles (turnpikes), Rocky Mountain doubles (Rockies) and B-Train double (AASHTO, 2018; TAC, 2017). Turnpikes and Rockies both consist of a tractor, attached to one 16.2 m (53 ft) semi-trailer. Turnpikes include a second 16.2 m (53 ft) trailer, while Rockies have a second, shorter 8.5 m (28.5 ft) trailer (Wood & Regehr, 2017). The overall length of Rockies is 29.67 m, while turnpikes are 34.75 m (Wood & Regehr, 2017). B-Train double, on the other hand, consist of a tractor pulling two semi-trailers with a “B-train” hitch, resulting in an overall length of 25.0 and 27.5 m.

While western Canadian provinces allow LCVs up to 40–41 meters, including turnpike doubles, the Transportation Association of Canada (TAC) specifies a maximum LCV length of 25 meters for B-Train doubles, which are more commonly operated in Ontario and several other provinces without special permits (Wood & Regehr, 2017; TAC, 2017). Additionally, longer configurations such as turnpike doubles, recommended at lengths up to 34.75 meters by AASHTO, are less prevalent in urban areas due to infrastructure constraints. Although some provinces, like Manitoba and Saskatchewan, have increased allowable B-Train lengths to 28 meters, the 25-meter B-Train double remains the standard for much of Canada's urban freight operations (Manitoba Transportation and Infrastructure Department, 2022; Ministry of Highways - Government of Saskatchewan, 2022).

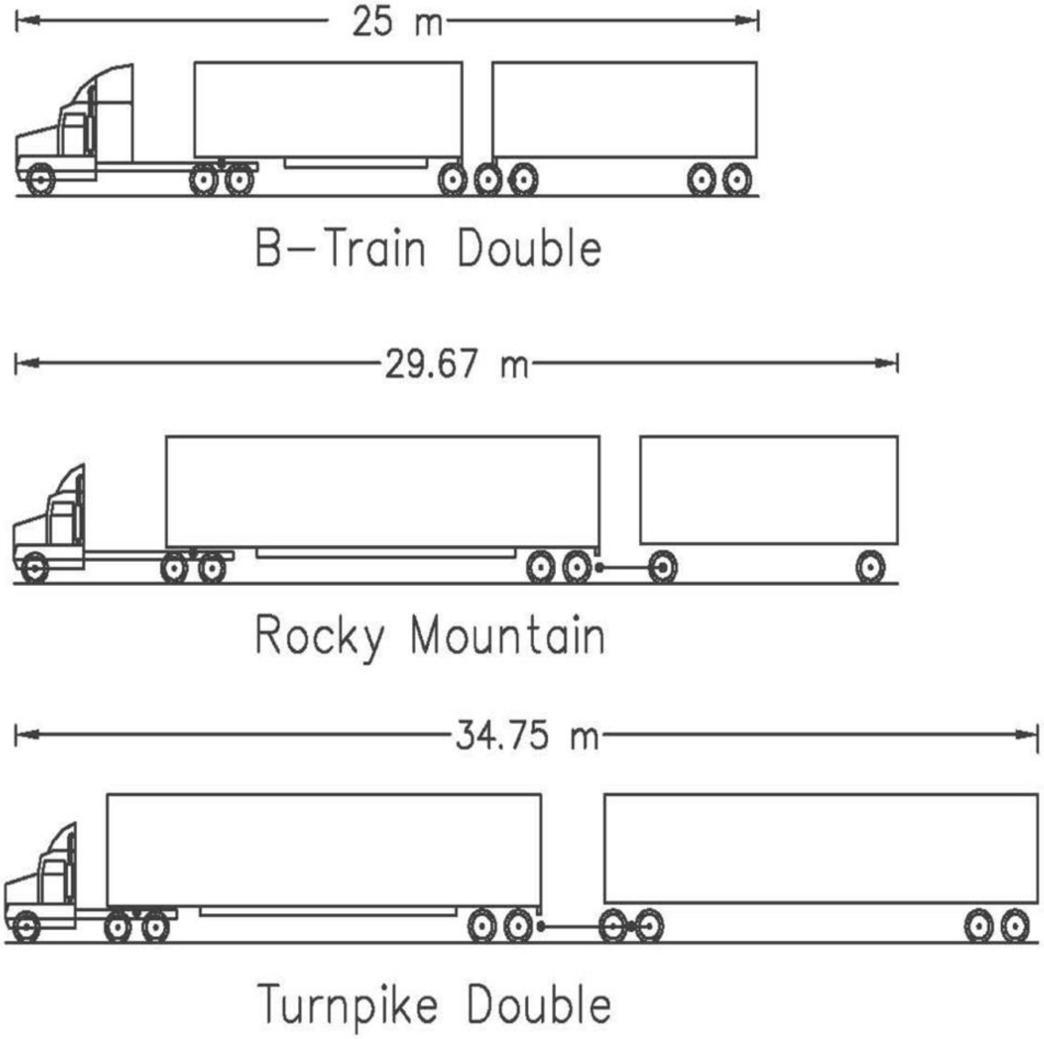


Figure 1: Three Configurations of LCVs

In addition, eight provinces and one territory, shown in Table 1, across Canada require special permits to operate LCVs (Ministry of Transportation, 2021). These permits are designed to ensure that only qualified carriers with suitable equipment, training and safety measures, operate LCVs on roadways. In Ontario, where this study is set, carriers who operate LCVs do need a special permit. To get this permit, carriers must follow specific rules set by the Ministry of Transportation of Ontario (MTO). They must also sign an agreement with the MTO to meet the requirements for safely operating these large vehicles on approved routes. Only carriers that meet these conditions are allowed to use LCVs on designated roads or areas that connect to their destinations (Ministry of Transportation, 2021). Table 1 shows whether different provinces in Canada require a permit to operate LCVs, the type of LCVs approved and the permit duration (Saha, 2021).

Table 1: LCV Permit Requirements in Different Provinces in Canada

Province or Territory	Permit Required	Permitted LCVs	Permit Duration	Safety Rating Maintenance
British Columbia	Yes	RMD, TPD	N/A	Yes
Alberta	Yes	RMD, TPD, Triple	12 months	No
Saskatchewan	Yes	RMD, TPD, Triple	12 months	No
Manitoba	Yes	RMD, TPD, Triple	12 months	No
Ontario	Yes	TPD	12 months	Yes
Quebec	Yes	TPD	3 to 9 months	No
New Brunswick	Yes	TPD	12 months	Yes
Nova Scotia	Yes	TPD	12 months	Yes
Northwest Territories	Yes	RMD	12 months	Yes

When compared to two tractor-trailers with a similar volume, LCVs offer economic and environmental benefits. Due to their increased length, LCVs can transport more goods in a single trip, lowering transportation costs for retailers and manufacturers and has better fuel efficiency (Ministry of Transportation, 2011). In addition, the lead truck operates on methanol and liquid petroleum gas, which are known as cleaner gases (Geuy, 1989), and by pulling along the connected trailers, requires less fuel compared to standard tractor-trailers (Region of Peel, 2021). According to the Ministry of Transportation in 2013, Greenhouse gas emissions (GHGs) caused by freight transportation could be reduced by one-third if the industry transitions to using LCVs. In addition, it is expected to save shippers and consumers up to $320 million annually by reducing fuel consumption by 70 million liters and cutting emissions by 190,000 tonnes (Ministry of Transportation, 2011).

Despite their advantages, LCVs also have downsides. Their extended length requires more physical space on roadways, resulting in increased turning radii and wider horizontal clearance. Due to these constraints, LCVs are restricted to specific, carefully studied areas rather than being permitted everywhere as seen in Figure 2 that shows the roadways in the Greater Toronto Area that permit LCVs (Ministry of Transportation, 2021).

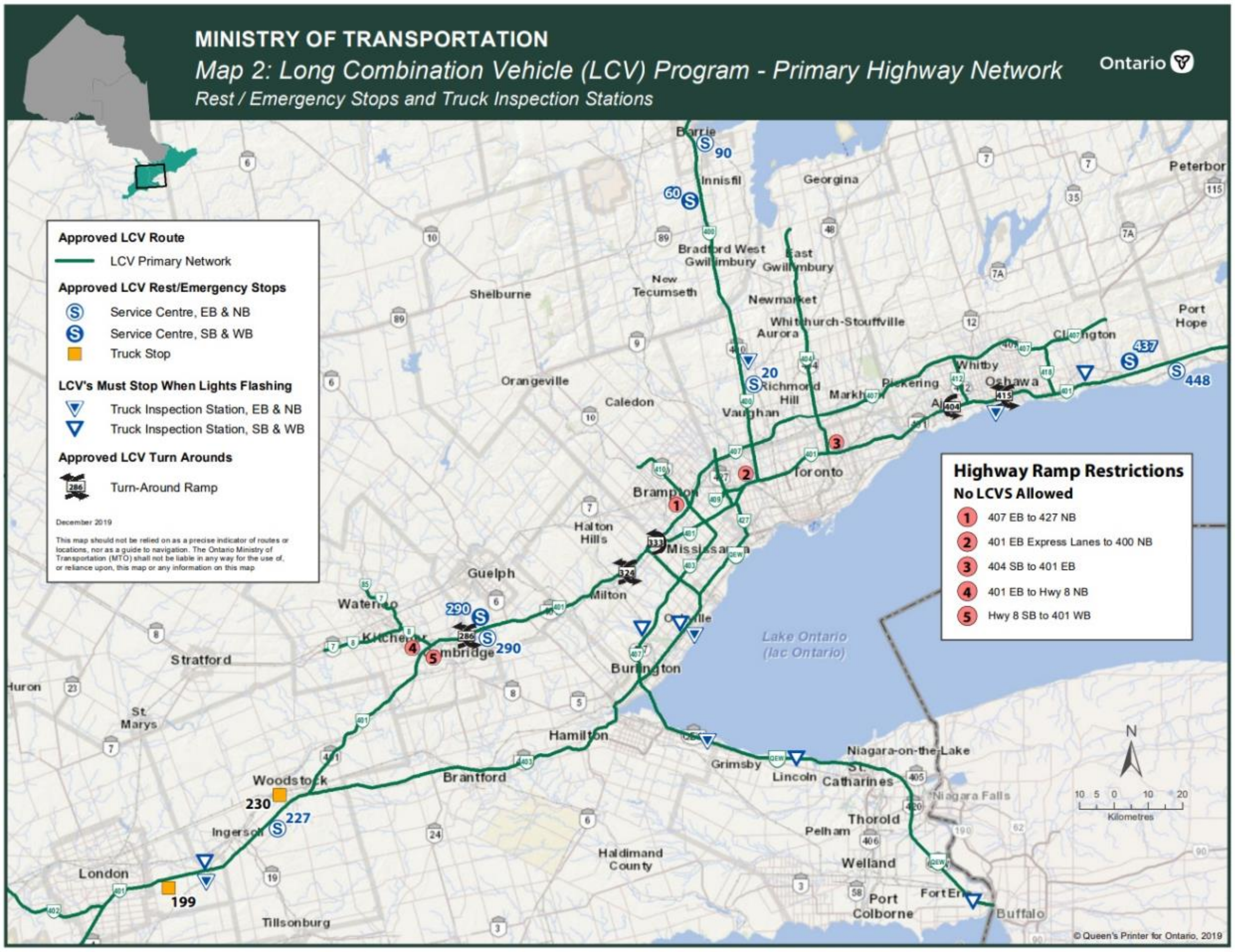


Figure 2: LCV Map Roadways

In Ontario, specific requirements are needed to be fulfilled to become an LCV driver, including having at least five years of HCV driving experience and over 100 hours of classroom training (Ministry of Transportation, 2021; Smith, 2020). Given these rigorous training requirements, Butler reported that Canada will need 34,000 new HCV drivers by 2024 (Butler, 2019). In addition, the United States will need 160,000 new drivers by 2028 (Costello, 2019). In response to this challenge, HCV platooning emerges as a promising alternative.

HCV platooning, also known as HCV platooning, allows multiple HCVs to travel closely together in a coordinated and automated manner. Unlike LCVs, which face spatial limitations such as needing wider lane width and larger turning radii, HCV platoons do not encounter these issues as they use the same horizontal clearance and turning radius as a single HCV. By utilizing vehicle-to-vehicle (V2V) technology, HCV platoons can maintain safe distance and coordination between convoys, which can reduce aerodynamic drag and increase fuel efficiency (Browand, et al., 2004; Alam, et al., 2015; Patten, et al., 2012).

According to the Society of Automotive Engineers (SAE), HCV platoons operate at automation levels between 3 and 5. To see the benefits of HCV platooning, automation levels should start at level 3. Level 3 indicates that the leading and following vehicles have human drivers, but the following vehicles can operate autonomously in specific conditions such as highway driving, requiring driver intervention when necessary. At Level 4, only the leading vehicle requires a human driver, while the following vehicles are autonomous. Level 5 shows full autonomy for all vehicles in the platoon (U.S. Department of Transportation, 2018; Bishop, 2020; SAE International Standard, 2016). Up to now, North American jurisdictions, including Alberta, California, Florida, Ontario, and Texas, have primarily tested Level 3 automation in pilot projects (Kuhn, et al., 2017; Canadian Council of Motor Transport Administrators, 2016). However, Level 4 automation has the potential to address the shortage of HCV drivers with the automation levels. Since only the lead vehicle requires a human operator, a single driver could operate multiple HCVs (e.g. four or more HCVs per driver instead of one-to-one). While LCVs in Canada are typically limited to two trailers per driver, which is a less efficient usage of available drivers. Therefore, this automation level can significantly improve driver utilization and overall efficiency.

Since HCV platoons prefer to travel on freeways, significant fuel savings at higher speeds. At 80 km/h, fuel consumption can be reduced by up to 6% for the lead HCV and up to 10% for the following vehicles. Similarly, when platooning at 70 km/h, a 4.7% reduction in fuel consumption for the lead HCV and a 7.7% reduction for the following HCVs has been observed (Al Alam, et al., 2010). However, HCV platooning will be used on arterial roadways in urban settings as they may need to complete first- and last-mile deliveries. Since the speed limits in urban areas are often below 70 km/h, the aerodynamic benefits are reduced.

To implement HCV platooning in this study, it is necessary to assume the adoption rate of this technology. Milakis et al. predicted trends in the urban freight adoption of automated vehicle technology, identifying two distinct approaches (Milakis, et al., 2017). The first, a regulated approach, envisions rapid adoption of connected autonomous vehicles (CAVs) with regulatory limitations swiftly resolved, targeting a 5% adoption rate by 2031. The second, a conservative approach, adopts a cautious stance towards CAVs, projecting a 5% adoption rate by 2034 (Ministry of Transportation of Ontario, 2020). Additionally, the study forecasted personal CAV adoption rates, with an average trendline aiming for 5% adoption by 2022 (Organisation for Economic Co-operation and Development (OECD), 2017), and a conservative trendline predicting 5% adoption by 2031 (Ministry of Transportation of Ontario, 2020). This contrast highlights the cautious adoption of automated vehicle technologies in urban freight logistics compared to personal CAV use.

The U.S. Department of Transportation (DOT) has developed a plan to accelerate the implementation of Vehicle-to-everything (V2X) technology, which allows for the vehicles to communicate with each other and with infrastructure, such as traffic lights and road signs. However, the plan suggests that the infrastructure to support V2X is still in the early stages of development. The DOT's short-term goals include equipping 20% of the National Highway System with V2X technology and ensuring that 25% of signalized intersections in the top 75 metro areas have V2X capabilities by 2024-2028. While long term goals aim for full utilization of V2X technology across the National Highway System and 85% of signalized intersections in the top 75 metro areas V2X-enabled by 2032-2036 (United States Department of Transportation, 2024).

Since the launch of this plan, Salt Lake City which is the 47th largest metropolitan area in the united stated, is close to meeting the short-term goal with around 20% of signalized intersections equipped with V2X technology and cover the remaining 5% by the end of the year (Utah Department of Transportation, 2024). However, in Canada the deployment of V2X-equipped intersections is still in its early stages, with various pilot projects and trials rather than extensive network coverage. For example, the City of Calgary has tested V2I technology as part of its 16 Avenue North "V2I Test Bed" project. This project involved a connected corridor of 14 intersections designed to test and implement connected vehicle application (City of Calgary, 2021) In Ontario where the study area takes place, the City of Toronto has an action plan with MoveTO set for 2021 to 2025. It suggests implementing smart traffic signals and intelligent intersections at 500 and 100 locations over the next 5 years (City of Toronto, 2020).

In addition, the adoption of V2X and automated vehicle technology faces limitations as there is a lack of policies and regulations. As they require coordination between various stakeholders, including the Department of Transportation (DOT), Federal Communications

Commission (FCC), automakers, and state and local governments. The adoption of fully autonomous trucks (Level 4 or 5 automation) is still in its infancy stages, as companies such as Waymo, TuSimple, and Aurora are testing autonomous trucks on select routes in the U.S. However, the lack of compatibility across different regions and systems hinders large-scale automated vehicle deployment (United States Department of Transportation, 2024).

While many studies examine vehicle platooning at market penetration rates ranging from 5% up to 100%, especially for passenger vehicles on freeways, these higher penetration assumptions may not be realistic for HCV platooning in urban environments (Arnaout and Bowling, 2011; Van Arem et al., 2006; Lioris et al., 2017). For instance, Gordon and Turochy (2016) reported benefits at 20% and 100% HCV platooning rates on freeways, but such levels are ambitious given the complexities of urban arterials with frequent signalized intersections and variable traffic conditions.

The 5% market penetration rate adopted in this study, therefore, represents a deliberately conservative yet ambitious target when compared to these prior works, acknowledging the significant technological, infrastructural, and operational hurdles currently limiting higher adoption rates for HCV platooning in urban areas. This more cautious benchmark aligns better with current real-world conditions and anticipated near-term deployment scenarios.

The adoption of SAE Level 4 HCV platooning requires not only advanced vehicle technology but also robust, city-wide vehicle-to-infrastructure (V2I) communication networks, significant investments in infrastructure, and coordinated policy and regulatory frameworks. Such requirements limit the potential for rapid, widespread deployment and instead point toward an initial focus on fleet-specific operations where multiple trucks from the same company travel regularly along fixed routes. This fleet-based approach naturally restricts market penetration to relatively low percentages during the early years of implementation.

Given these constraints, focusing on a 5% market penetration rate allows this study to provide a realistic and practical evaluation of HCV platooning impacts on urban arterial mobility, avoiding overly optimistic assumptions that could misinform planners and policymakers. By assessing operational effects at a more feasible adoption level, this research offers actionable insights for near- and mid-term transportation planning, while recognizing that higher penetration rates and their associated benefits may only be attainable in the longer term, contingent on continued technological advancement and infrastructure development.

1.2 Problem Statement

This study focuses on the short trips freight vehicles make on urban roads, such as the first and last-mile trips from their origins to destinations. Unlike long-haul trips that take place on highways or freeways, all freight movement must begin or end in local, urban areas, whether it is a truck leaving a warehouse or making its final delivery to a store or customer. These urban segments are unavoidable and often the most complex part of the journey due to traffic, signals, and limited road space. According to Sureshan, about 85% of truck trips have at least one trip-end inside the region, suggesting a strong urban freight presence (Sureshan, 2009). This presence, while only representing the end or beginning of the truck's total journey, can have a significant impact on urban traffic flow. With the increasing demand for freight transportation in urban areas, congestion at signalized intersections is expected to worsen, leading to longer travel times and reduced efficiency in goods movement. Addressing these challenges is essential to improving traffic flow and supporting economic growth.

This study explores potential engineering solutions to improve the mobility of Heavy Commercial Vehicles (HCVs) using Intelligent Transportation Systems (ITS) and surface infrastructure improvements. One strategy is Freight Signal Priority (FSP), which adjusts traffic signal timings to give priority to freight vehicles at intersections, reducing delays and improving traffic flow. In addition to FSP, Dedicated Truck Left-Turn Lanes (DTLL) offer a surface infrastructure solution larger trucks by reducing conflicts and improving safety and intersection efficiency. While other strategies exist, such as dynamic routing, this study focuses on FSP and DTLL due to their practicality, compatibility to existing infrastructure, and potential for measurable impact on urban freight corridors.

Evaluating multiple strategies enables a comprehensive assessment of their relative effectiveness and trade-offs within the urban context. The purpose of this evaluation is to determine which individual, or combined solutions can most effectively improve freight mobility, alleviate congestion, and reduce environmental impacts. This evidence-based approach aims to support regional transportation planners and decision makers in selecting targeted, feasible interventions that enhance both freight operations and overall traffic performance

1.3 Research Goal and Objectives

The goal of this study is to investigate the mobility and environmental impacts of Intelligent Transportation System (ITS) strategies, such as freight signal priority (FSP) and dedicated truck lanes (DTL) on LCVs and SAE Level 4 HCV platooning along urban arterial roads, with particular emphasis on left-turning movements. Given the operational challenges associated with left turns, such as limited storage capacity and green time allocation for left turning, the analysis focuses on how these strategies influence both through and turning traffic. Microsimulation tools (e.g., VISSIM) allow the simulation of future traffic scenarios, such as HCV platooning, enabling researchers to generate and analyze data under controlled conditions. This approach provides valuable insights into potential mobility and environmental impacts. The detailed model development process will be discussed in a later section.

The study has three objectives:

1. Develop a methodology for identifying and selecting signalized intersections that are suitable for implementing freight priority measures based on key operational and freight-related criteria.
2. Calibrate and validate a microsimulation model (using VISSIM) to evaluate the operational impact on the study corridor.
3. Evaluate the feasibility and impacts of LCVs and HCV platooning on mobility and sustainability (i.e. travel time and GHG emissions), particularly focusing on left-turn movements at urban intersections.

1.4 Research Scope

The scope of this research focuses on evaluating the mobility and environmental impacts of intelligent transportation systems (ITS) strategies, including freight signal priority and dedicated truck lanes, in urban areas. The study specifically examines how these strategies can support the operation of Long Combination Vehicles (LCVs) and Heavy Commercial Vehicle (HCV) platoons, particularly Level 4 HCV platoons, on urban arterial roadways. The study concentrates on how ITS strategies can improve freight mobility while reducing congestion and emissions. Additionally, this research will investigate the effectiveness of these strategies for all vehicles.

1.5 Research Constraints

This study is constrained by several factors that shape the scope and applicability of its findings. Specifically, this thesis is designed as a case study focused on the Region of Peel, meaning that the methodology, data inputs, and resulting insights are closely tied to the specific transportation context and operational challenges of that region. While the findings provide valuable direction for freight mobility improvements in Peel Region, they may not be broadly generalizable to other municipalities with differing roadway configurations, traffic dynamics, or policy goals.

Another constraint is the study's limited flexibility. Because the research responds to a real-world transportation issue rather than a purely academic question, many aspects, such as the study area, selection of ITS strategies, and simulation design that were influenced by practical considerations and regional priorities. This applied nature reduces the opportunity for broad theoretical exploration or scenario diversification. Additionally, the study places emphasis on generating actionable insights rather than advancing theoretical frameworks. As a result, the research leans more toward problem-solving than hypothesis testing, focusing on identifying feasible, data-supported solutions for urban freight operations. While academic rigor is maintained in the modeling and analysis, the thesis is grounded in real-world relevance, which naturally narrows its academic scope.

Despite these constraints, the work contributes meaningful insight to the field of urban freight and ITS planning, especially for rapidly growing urban regions like Peel Region where freight-related congestion and infrastructure challenges are increasingly pressing.

1.6 Anticipated Benefits of the Research

This research is the first to investigate the effects of freight signal priority and dedicated truck left-turn lane measures specifically for left-turning vehicles at intersections along arterial roadways. Typically, freight signal priority technologies have focused on through movements, while dedicated truck left-turn lane (DTLL) have only been implemented on freeways, not on urban arterials. The anticipated benefits include improved traffic flow by minimizing delays at signalized intersections, which will help reduce congestion and enhance overall intersection efficiency. More predictable and shorter travel times for freight vehicles will not only reduce delivery delays but also lower operational costs for logistics companies, making goods distribution more efficient. Enhancing urban freight movement in this way will support economic growth by improving supply chain reliability and attracting businesses to urban centers.

Beyond economic and mobility benefits, the study will also contribute to policy and infrastructure planning by providing a framework for evidence based decision-making in urban freight management. The findings will help municipalities prioritize infrastructure investments that deliver the highest mobility benefits and inform future policies related to automation, intelligent transportation systems (ITS), and targeted infrastructure improvements. Additionally, reducing truck idling times at intersections can lead to lower greenhouse gas emissions, improving urban air quality, while enhanced traffic flow and lane separation can reduce crash risks associated with heavy commercial vehicles making left turns. By addressing these challenges and exploring innovative freight management strategies, this research will offer valuable insights for regional municipalities in Ontario and serve as a model for other urban centers in Canada looking to improve goods movement efficiency while balancing passenger traffic and sustainability.

1.7 Thesis Outline

The structure of the thesis consists of an introduction and six additional chapters.

- Chapter 2 offers a literature overview of various signal priority techniques. This includes discussing current implementations of freight signal priority measures, as well as the usage of dedicated truck lanes in urban environments.
- Chapter 3 discusses the criterion shown in previous studies and how it was adapted to produce a methodology that implements FSP and dedicated truck left lane on certain intersections.
- In Chapter 4, the study area and the data acquired from Peel Region are discussed.
- Chapter 5 includes a detailed explanation of the micro-simulation models (VISSIM), and the associated parameters utilized in this project. This chapter also delves into the simulation scenarios.
- Chapter 6 evaluates the results from the analysis of different scenarios developed by the microsimulation model in terms of the performance measures.
- In Chapter 7, the findings are summarized, and recommendations for future research and research gaps are provided.

CHAPTER 2: LITERATURE REVIEW

This chapter provides a summary and analysis of previous studies on Intelligent Transportation System (ITS) technologies and surface improvement infrastructure. These measures are designed to enhance freight mobility, reduce delays, and improve overall network efficiency. It also identifies research gaps and examines the environmental impacts associated with these technologies.

Section 2.1 reviews discusses transit signal priority (TSP) and freight signal priority (FSP) methods. Section 2.2 considers different enhancements that could be made to the physical elements of roadways and transportation networks that are visible at or near the surface level. This includes dual left lanes, dedicated truck lanes and intersection geometry modifications such as turning radii and lane widths.

2.1 Signal Priority

Signal Priority is one of the many Intelligent Transportation Systems (ITS) strategies used to improve traffic operations and reduce delays for specific vehicle classes. Common signal priority techniques include Transit Signal Priority (TSP) and Freight Signal Priority (FSP); however, it also consists of vehicle-to-infrastructure (V2I) technology that implements HCV platooning.

Transit Signal Priority is an operational system designed through prioritization to improve the mobility of transit vehicles, emergency vehicles, and/or trucks at signalized intersections. It relies on detectors, fixed location of check-in and check-out detectors, that identify the presence of specific types of approaching vehicles and provides a priority to the signal phase for that approaching vehicle.

The first study on Transit Signal Priority was conducted in the Unites States by Salter and Shahi in 1979, which found that while giving priority to buses reduced bus delays, it resulted in increased delays for passenger vehicles (Hu, et al., 2015). Since then, conventional FSP systems have been applied to 109 cities in North America, Europe, and Asia (Liao & Davis, 2007). In Toronto, the use of FSP started in the 1990's, and by now, 420 signalized intersections are equipped with FSP, with over 80 of them implemented in the past two years (Gray, 2025). This highlights how widespread the application of FSP and how effective it is in improving the effectiveness and efficiency of transit operations and cost effectiveness.

There are several strategies used to modify the operation of traffic signals when prioritizing specific vehicles. It is split into four types of priority, that decide when and why transit vehicles get priorities, the four types of signal adjustment techniques are how the signals are adjusted for FSP. The four priority types are (Shalaby, et al., 2006).

1) Passive Priority:

This type of priority involves the pre-emptive adjustment of traffic signals to prioritize transit or freight vehicles based on fixed schedules or conditions, without real-time adjustments. This approach was the initial technique used in FSP systems, as communication technologies in transit vehicles were still in their early stages. In addition, passive priority is a relatively low-cost and easy strategy to implement and operate.

A key limitation of this approach is that it gives signal priority to buses or prioritized vehicles at specific times, regardless of their actual arrival at the intersection. As a result, if no transit or prioritized vehicles are present, the system would still give preferential signal timing, causing unnecessary delays for non-prioritized vehicles and cross traffic. Therefore, this method is most effective on signalized intersections with high-frequency transit services, predictable travel times, and light to moderate traffic volumes (Vincent, et al., 1978)

2) Active Priority (Shalaby, et al., 2006):

Active priority involves dynamically adjusting the traffic signal to give transit vehicles priority in real-time. When a transit vehicle is detected approaching the intersection, the signal phases are actively modified to allow the vehicle to pass without significant delay. This approach is more efficient than passive priority, as it only adjusts the signal when a transit vehicle is present, which eliminates unnecessary delays caused by pre-allocated priority times.

By providing real-time adjustments, active priority improves the flow of transit vehicles along arterial corridors, helping them maintain faster and more reliable travel times. However, a disadvantage of active priority is that it can sometimes give priority to transit vehicles when it may not be necessary. For example, if a bus is ahead of schedule or has a low number of passengers, giving priority could lead to unnecessary delays for non-prioritized traffic and cross traffic. This could be problematic as the system gives priority based only on the detection of a transit vehicle, rather than considering if it needs the priority (Shalaby, et al., 2006).

3) Conditional Active Priority (Shalaby, et al., 2006):

Conditional active priority is a kind of active priority where the signal adjustment will give priority based on certain conditions, such as if the transit vehicle is running late, if traffic is light or it has been a long time since priority was allocated. This system utilizes an Automated Vehicle Location (AVL) system to track the real-time location of transit vehicles using GSP or similar technologies. In addition, it relies on an Automated Passenger Counter (APC) system that counts the number of passengers boarding and alighting the transit vehicle in real-time. This ensures that priority is not given to a nearly empty bus, but instead is optimizing the signal cycle length for a bus carrying a high number of passengers. Therefore, this priority system minimizes the negative impacts on nonpriority vehicles and cross traffic by granting priority only when necessary.

4) Adaptive Priority:

Adaptive priority adjusts the signal timing based on real-time traffic conditions and can modify its behavior over time, learning and making dynamic decisions on when to give priority to transit vehicles. For example, if a bus arrives during peak hours and there is minimal congestion in its direction of travel, but cross traffic is heavily congested, the system may decide not to give priority. This helps buses run on a more consistent schedule, reduces overall delays for all vehicles on the road, and allows more people to move through the area efficiently.

However, this control system often relies on regularly updated traffic and transit location data to adjust signal timing, helping it respond more effectively to quickly changing traffic and transit conditions. Due to the inaccuracies of real-time traffic updates, this strategy has mainly been evaluated in simulation studies.

To implement the types of priorities, different techniques are used to adjust the signal to handle the different types of priorities. A study conducted by the National Academies of Sciences, surveyed 28 transit agencies about their deployment of FSP strategies, with seven agencies in Canada (National Academies of Sciences, Engineering, and Medicine, 2020). The survey results, Table 2, presented that the most common priority technique is called extended green and early green, which are both passive and active types of priority measures. Therefore, the most common and widely used type of priority in FSP is the Active and Passive priority.

Table 2: Survey Deployment for Different Priority Types

Type of Priority	Deployment Count
Extended green	28
Early green	16
Phase insertion, rotation, or skipping	4
Special bus-only signal	7
Other	4
Deployment Groups with a Response	31

Note: Respondents could select more than one answer

When employing the Passive Priority, the most common technique seen in Table 2 is called the Green Extension method which involves extending the green phase when a priority vehicle is detected approaching the signal. While the green time extension is seen to range between 3 and 30 seconds in the surveyed agencies, the average extension is between 6 to 10 seconds. This approach is widely adopted and aims to optimize signal timing for enhanced traffic flow. While, if the Active Priority is chosen to be employed the Early Green or Red Truncation technique to adjust the signal is likely to be used. The Early Green or Red Truncation involves activating the green light sooner as a priority vehicle approaches during a red phase. This adjustment allows the priority vehicle to access a green signal sooner, thus facilitating smoother traversal through the intersection. The transit agencies surveyed that the early green length range is from 3 to 60 seconds, which is longer than the green extension. However, the average early green length is still between 6 to 10 seconds as it shows the least delay for cross traffic.

Figure 3 shows the different priority strategies in terms of 3-time cycles (Imran, et al., 2021). The usual bus arrival conditions states that if the bus arrives during the second- or third-time cycle which is denoted as red time, the bus must wait until the green time to go. However, in priority strategy ‘a’, the green time extends to accommodate the bus trajectory for green time extension technique. While priority strategy ‘b’, shows that the red time is shortened, and the green time is started early to prioritize the bus that approached the signal.

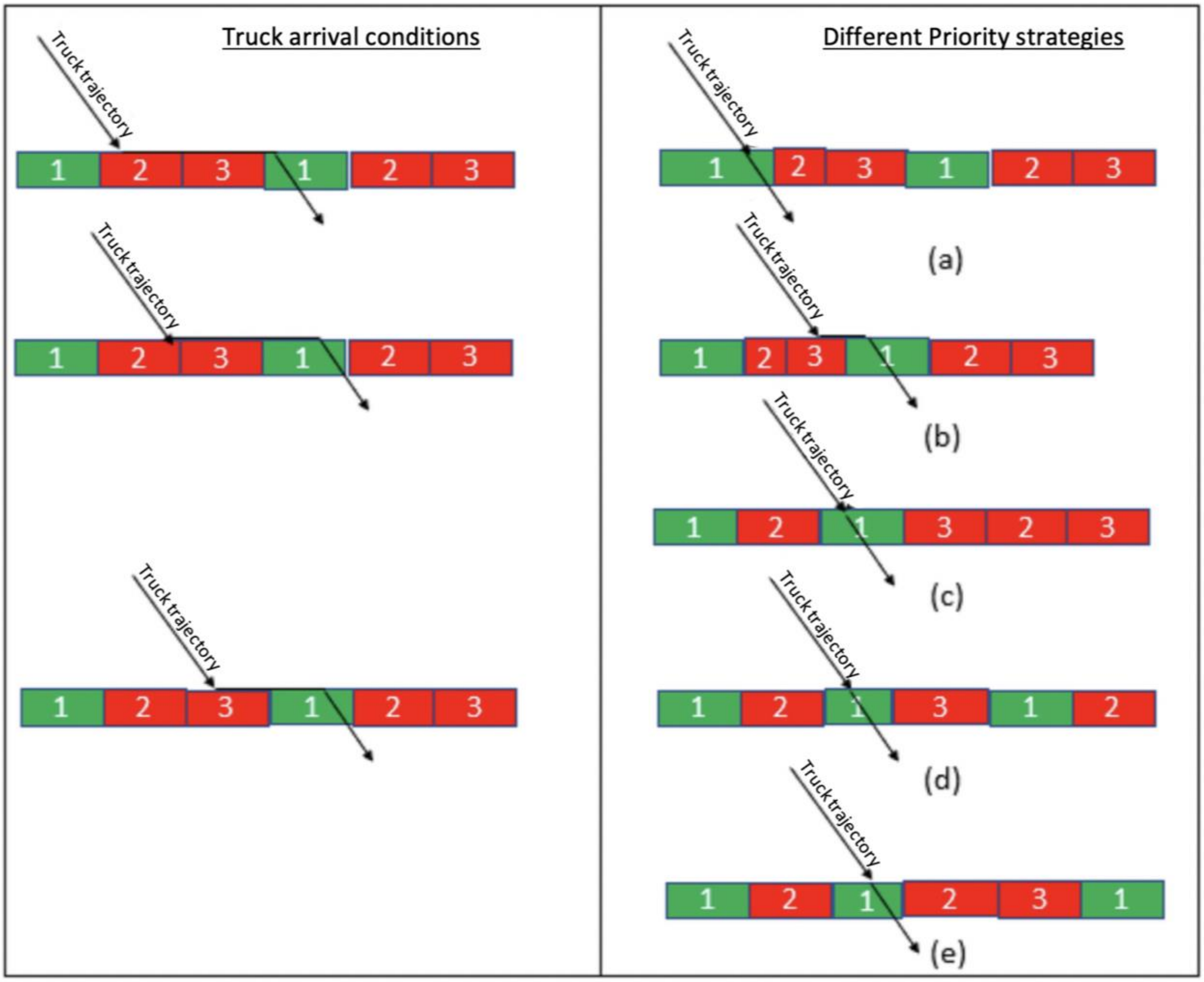


Figure 3: Priority Techniques, a) Green Extension b) Early Green/Red Truncation c) Phase Rotation d) Phase Insertion e) Phase Skipping

The other two adjustment techniques are the Phase Rotation (priority strategy ‘c’ in Figure 3) in which involves skipping of a non-priority phase to expedite the arrival of the green signal for the approaching priority vehicle. Lastly, the Phase Insertion (priority strategy ‘d’ in Figure 3) method introduces a temporary green phase exclusively designated for priority vehicles within queue jump lanes. These techniques collectively constitute foundational strategies within FSP systems, each tailored to mitigate traffic congestion and prioritize designated vehicles efficiently.

One of the major disadvantages of FSP is that it can negatively affect cross traffic, especially at intersections operating near capacity. This happens because FSP often relocates the green time from cross traffic to prioritize transit vehicles. This can lead to significant delays for cross-traffic and potentially offset the benefits of FSP, especially when an intersection is already facing heavy traffic (Al-Sahili & Taylor, 1996). In addition, the variability and uncertainty when predicting bus arrival times causes further delays for cross traffic as to compensate, longer green times may be assigned to transit phases to ensure buses pass through, even if they arrive later than expected (Hu, et al., 2014).

A new approach is Vehicle-to-everything (V2X) or Vehicle-to-Infrastructure (V2I) that enables vehicles to communicate with road infrastructure such as traffic lights and coordinate the most efficient lights, barriers, crosswalks, etc. (Chong, 2016). This technology allows for the vehicle to communicate with the signal allowing it to get real-time data based on measures such as vehicle speeds, positions, arrival rates, rates of acceleration and deceleration, queue lengths, number of passengers, and stopped time (Hu, et al., 2014). This method offers greater reliability compared to adaptive GPS-based systems. However, its adoption is limited due to the lack of vehicle-to-infrastructure (V2I) technology at many intersections. Therefore, this study focuses on widely implemented Active and Passive priority techniques to analyze prior research.

There are several studies about the usage of FSP, including various strategies and techniques. This literature review focuses on research where travel time is the primary Measure of Effectiveness (MOE), aligning with the objectives of this study. This review will also focus on signal priority systems designed for freight vehicles (FSP), exploring their role in optimizing freight movement. In addition, it will examine the interaction of signal priority with emerging concepts such as HCV platooning and left-turn movements, to study any previous research and their methodology.

In a 2020 study by Kevin Balke et al., FSP was implemented along a 2.2-mile segment of Burnet Road in Austin, Texas. This corridor, a four-lane arterial with a continuous two-way left-turn lane, included seven signalized intersections and served as a key route for freight traffic. The FSP strategy applied a 10 second green time extension for through truck movements at all seven intersections. The study analyzed travel times for passenger and freight vehicles and found minimal impact. Passenger vehicle travel times increased by 1.90%, and freight vehicle travel time increased by 0.87%, showing that during peak periods, when the signal's maximum split is already in use, a 10 second extension offers limited benefits to cycle time efficiency (Shelton, et al., 2020). This shows that while FSP can extend the green light duration for the Northbound (NB) approach, its effectiveness may be limited during peak hours when the signal cycle is already operating at its maximum capacity. The additional 10 second extension does not significantly alter the cycle time or improve traffic flow under such conditions.

However, the study compared them to a 2014 study by Mahmud at a heavily trafficked, low-speed intersection in Portland, Oregon, North Columbia Boulevard at NE Martin Luther King Jr. Boulevard. This earlier study used an 11 second green time extension for freight traffic. The results show that in the Eastbound (EB) approach only, the truck travel time was decreased by 13% to 21% (4.3 seconds to 5.3 seconds per vehicle) and overall vehicle travel time in the truck direction was decreased by 0% to 8% (0.5 second to 2.1 seconds per vehicle) (Mahmud, 2014).

The study by Kevin et al. concludes that FSP is most effective on corridors with a high percentage of truck traffic, minimal impact on cross-street traffic, close proximity to industrial areas or intermodal facilities, demonstrated operational benefits through capacity analysis or microsimulation, and locations with air quality concerns, such as non-attainment zones. This highlights that while FSP can offer localized benefits, its success depends heavily on site-specific traffic conditions and freight movement patterns (Shelton, et al., 2020).

Another study by Kaisar et al. (2018) tested FSP for transit vehicles and freight vehicles. The study was conducted on nine signalized intersections along a 7.1km (4.4 mile) corridor in Broward County, Florida. The results show that an overall reduction of 18.1 seconds in corridor travel times per vehicle, while freight signal priority contributed to a reduction of 84.2 seconds per vehicle. Notably, transit signal priority demonstrated a significant impact, reducing travel times by 251.2 seconds per transit vehicle, while freight signal priority led to a reduction of 175.3 seconds per freight vehicle. The study 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 (Kaisar, et al., 2020).

Most previous studies on TSP and FSP have focused on through movements, leaving a notable gap in research on their implementation for left-turn movements. Only one study, conducted by the U.S. States Department of Transportation, specifically addressed this scenario. Harriet et al. (1998) analyzed the eastbound left-turn movement at 54th Avenue, where buses were required to turn left to access a nearby station. To facilitate this maneuver and improve bus operations, FSP was implemented specifically for the left-turn movement at this intersection. They also had to turn left out of the terminal onto Central and proceed south to return to Cermak Road. Conventional FSP was implemented on this driveway at Central Avenue to call the Central NS green. The results showed that eastbound and westbound buses achieved an average travel time decrease of 15% (3 minutes per vehicle). The actual decrease in travel times varied between 7% and 20%, depending on the time of day (Illinois Department of Transportation and Civiltech Engineering, Inc., 1998). However, the study fails to detail the specific decrease in travel time at the intersection where FSP was implemented for left turns.

In addition, there has been only one study conducted that explored HCV platooning and FSP, a study conducted by Chowdhury et al., in 2022. It dives into the utilization of truck signal priority measures with HCV platooning. The study was conducted along a 9.2 km segment of Derry Road, Mississauga, Ontario, with 16 signalized intersections, exploring the usage of Level 4 HCV platooning, both with and without signal priority for through movements with market penetration rates of 0%, 5% and 10%. The study used a 0.6 second time headway between two HCVs in a platoon, combined with a 9 second green time extension for signal priority. Results showed that without signal priority, 5% and 10% market penetration rates increased travel time by 24 and 33 seconds per vehicle, respectively, whereas with signal priority, travel time decreased by 29 and 12 seconds per vehicle, respectively. Additionally, without signal priority, these rates led to a significant increase in the number of stops by 810 and 990 additional stops per hour, respectively. In contrast, with signal priority, the 5% market penetration rate decreased stops by 950 per hour (Chowdhury, et al., 2022). This highlights that a 5% market penetration rate of HCV platooning can assist in reducing travel times and stops for all vehicles, particularly with effective signal priority strategies.

2.2 Surface Infrastructure Improvements

Surface infrastructure improvements represent enhancements made to visible, surface-level features along roadways in transportation networks. In this study, these enhancements include features such as dual left-turn lanes, dedicated truck lanes, and optimized intersection geometries, including adjustments to turning radii and lane widths. These improvements are designed to enhance traffic flow, improve safety, and address specific operational requirements.

1) Dual Left Turn Lanes

In urban areas, intersections often experience traffic demands beyond capacity, leading to congestion and delays. One of the surface infrastructure improvements that is designed to alleviate this congestion includes dual left-turn lanes that provide additional capacity for vehicles making left turns. This approach involves upgrading a single left lane into dual left-turn lanes, allowing a greater number of vehicles to simultaneously pass through the intersection during the signal phase. Guidelines from the National Cooperative Highway Research Program Report 375 and HCM 2000 recommend considering dual left-turn lanes when left-turn volumes exceed 300 vehicles per hour (vph) (Harwood, et al., 1995; Transportation Research Board, 2000).

Saturation Flow Rate represents whether more vehicles are able to pass through the intersection when a dual left turn is implemented. According to Highway Capacity Manual (HCM), the saturation flow rate feres to the number of vehicles that pass through an intersection in one hour, assuming the traffic signal remains continuously green (Transportation Research Board, 2010). The ideal values for saturation flow rate when operational and geometric conditions are ideal are 1750 or 1900 passenger vehicles per hour of green per lane (pcphgpl) (Transportation Research Board, 2010). A study conducted by Siddiqui, studied the saturated flow rate of a dual left turn at the intersection of 19th Avenue and Main Street in Montana, United States. The saturated flow rates observed for the two left-turn lanes and the through lane in this study fall within the expected range and are actually higher than HCM’s base value, meaning that the dual left turns operate and demonstrate an effective traffic flow. In addition, Drivers in the inner left-turn lane are slightly more aggressive, with SFRs about 3% higher than those in the outer left-turn lane (Siddiqui, 2015).

The Texas Department of Transportation (TxDOT) identifies dual left-turn lanes as essential for managing high traffic volumes, seeing that they operate at approximately 1.8 times the capacity of a single left-turn lane (Yu, et al., 2007; Neuman, 1985). This allows more vehicles to pass through the intersection at the same time during the signal phase. This aids in reducing congestion by increasing the capacity for left-turning traffic. Since the Texas Department of Transportation regards the upgrade of lanes into dual left-turn lanes as a necessity for handling high traffic volumes and are an effective way to improve intersection efficiency (Yu, et al., 2007). Additionally, a study conducted in Charlotte by Shaik et al. (1996) demonstrated that upgrading a single left-turn lane to dual left-turn lanes can reduce delays by 23% (Shaik & Graham, 1996). Therefore, dual left-turn lanes are recognized as an effective measure to reduce delays.

Dual left-turn lanes are not suitable for locations with asymmetric receiving lanes or mismatched left-turn lane designs, as demonstrated in Figure 4. Since this study implements a new dual left turn lane, intersections should have adequate and aligned receiving lanes. In the study by Fitzpatrick et al. in 2014, explored the addition of a new lane shortly after the intersection left turn lane. This allowed vehicles in the outside lane to smoothly enter the new lane, improving traffic flow as the saturation flow rate increased by about 50 vehicles per lane per hour (Fitzpatrick, et al., 2014). Despite this limitation, dedicated left turn lanes remain an effective solution for alleviating congestion and improving intersection efficiency in appropriately designed settings.

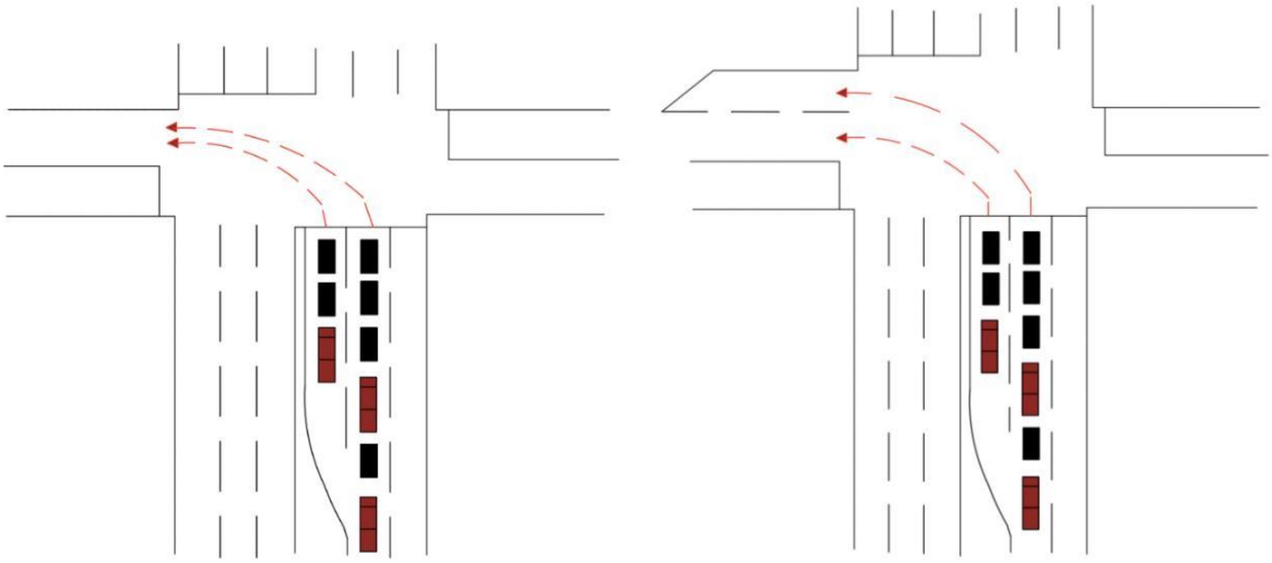


Figure 4: Insufficient Receiving Lanes for Left-Turn Movements a) and After Extra Lane Installation b)

A main problem with left turn lanes is the overflow in the storage length and unbalanced queue length, adding another reason that single left turns may be upgraded to dual left turns (Yu, et al., 2007). Overflow in the storage length occurs when the left-turn queue length exceeds the designated capacity of the left-turn lane. This can cause the vehicles to spill over into the adjacent through lanes, disrupting traffic flow and compromising the efficiency and safety at the intersection. Intersections that experience left-turn overflow problems, on average experience an increase in rear-end accidents at intersections by 35% compared to intersections without such issues (Yu, et al., 2007).

A possible solution could be increasing the storage length, however, due to considerations for roadways with two-way left-turn lane (TWLT) configuration is not feasible. In a TWLT setup, the central lane serves as the left-turn lane for both directions of traffic. Increasing the length of the storage in this scenario is impractical as it could impede the functionality of the TWLT and potentially block entrances for opposing traffic.

The second issue that occurs on dual-left turn lanes is an unbalanced queue length situation which occurs when the queue length of the left-turn vehicles is longer than that of the adjacent through lane. Usually, when the total left-turn volume is low, drivers tend to choose lanes more randomly, typically based on which lane provides the best access to their intended downstream lane. However, as the left-turn volume increases, drivers become more focused on ensuring they can clear the intersection within a single signal cycle (Kikuchi, et al., 2004). According to Wei et al., which developed driving behavior for vehicles in a two-lane arterial road, whether drivers wish to turn at the next intersection or further downstream they chose to be in the lane connecting them to their turn (Wei, et al., 2000). Therefore, if the drivers need to access to a right-turn or an exit shortly after completing a dual left turn, the drivers tend to pick outer lane of the dual left-turn lanes. This is because the outer lane provides easier access to the adjacent through lane or right-turn lane, minimizing the need for lane changes immediately after the turn. This behavior is a result of drivers planning their lane choice based on their intended downstream movements to ensure smoother transitions and avoid conflicts.

Due to the long queue length, a phenomenon called left turn queue intrusion problem occurs. This is when left turning vehicles approach the intersection from the adjacent through lane and try to squeeze into the left-turn queue from the adjacent through lane as shown in Figure 5. The shaded area represents raised medians, therefore, the left turning vehicles merging into the left-turn queue from the adjacent through lane can impede the flow of following through vehicles and create safety concerns at the intersection (Yu, et al., 2007). According to Levinson's (1989) findings, approximately 80% of the through vehicles may experience blockage in a shared left-turn lane when there are five or more left-turning vehicles in a cycle (Levinson, 1989).

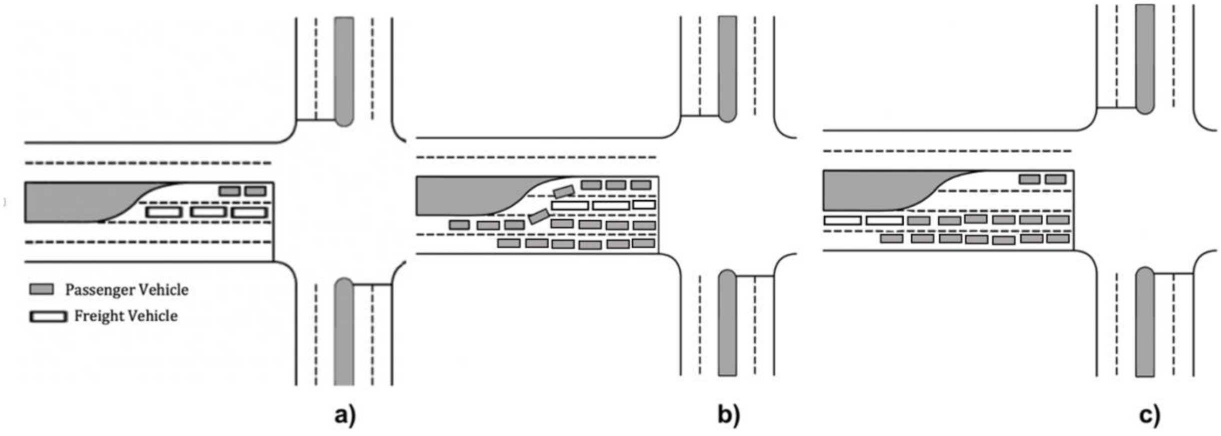


Figure 5: DLTL layout and pattern of vehicle arrivals: a) typical DLTL and arrival patterns, b) left-turn vehicles overflowing DLTL, and c) through vehicles blocking entrance of DLTL

2) Dedicated Truck Lanes

Another surface infrastructure improvement that aids in the movement of freight vehicles are dedicated truck lanes. This allows for slow-moving trucks to utilize their own lane by separating them from faster-moving general traffic, reducing congestion and increase safety. However, previous studies have mainly focused this priority measure on urban freeways, specifically for through movements. This literature review will focus on all the components needed to implement dedicated truck lanes and the different types. This includes the different types of dedicated truck lanes, such as Truck-only lanes and physically and operationally separation methods of implementation. Criteria for freeway selection and the truck lane configuration and types are also discussed, with focus on operationally separated truck-only lanes for their potential benefits will be used in this study.

There have been ways that lanes were used to separate traffic like High Occupancy Vehicle (HOV) lanes, toll lanes and the combination of them called High Occupancy Toll (HOT) lanes. HOV lanes will provide a lane for 2 or more passengers in a vehicle, this includes transit, carpool and vans (Ministry of Transportation, 2022). This encourages people to use a single vehicle to travel in congested areas to increased vehicle occupancy while decreasing the number of vehicles on congested roadways. The usage of HOV lanes is seen to reduce delay during peak hours by 20% in a Texas study conducted by Urban Mobility Report and improve travel time (Schrank & Lomax, 2005; Xu, 2005; Lipnicky & Burris, 2010). The City of Toronto assessed the changes in passenger vehicle travel time on HOV lanes and General-Purpose Lanes (GPL) on the Eglinton Avenue East during the morning (AM) and evening (PM) peak hours. For the eastbound (EB) HOV lanes, travel time experienced a decrease of 17.2% in the AM peak hours and 30.5% in the PM peak hours. Similarly, the westbound (WB) HOV lanes showed a decrease of 22.5% in travel time in the AM peak hours and a significantly smaller decrease of 3.53% in travel time in the PM peak hours. These results show the importance and effectiveness of HOV lanes in reducing congestion and improving the travel time during peak periods (City of Toronto, 2014).

These dedicated lanes do not separate traffic by vehicle of class, such as transit or freight vehicles. Therefore, they were not considered for the methodology and focused on truck lane restrictions. Truck lane restrictions designate a specific lane exclusively for truck usage, leaving the remaining lanes for general traffic. In 2014, the Transportation Association of Canada (TAC) conducted a study on the different types of truck lanes in urban areas across Canada. This research examined Truckways, Truck Bypasses, and Truck-Only Lanes (Rempel, et al., 2014). Figure 6 shows an example of truck-only lane implementation using either physical barriers or operational strategies to ensure separation from other traffic.

Figure 6: Truck-only Lane Sign

Truckway lanes gives direct access to freight vehicles to significant hub and industrial areas using dedicated lanes or corridors. While truckways are intended to be truck-exclusive, they may also accommodate other users, such as employees accessing the freight facilities. Truckways are mainly used in rail intermodal terminals, marine ports, truck staging areas, and large industrial parks. A case study at the Global Transportation Hub near Regina, Saskatchewan addressed the issue that freight vehicles coming in and out of the facility on Highway 11 caused major congestions. Therefore, an interim two-lane undivided highway with grade-separated access was constructed to alleviate the issue. This improved travel time and reliability while reducing congestion on general routes. However, the requirements for implementing a truckway do not align with the conditions in our study area, thus this was not considered (Rempel, et al., 2014).

Truck bypasses are designed to facilitate the movement of freight vehicles onto less congested roadways this helps them avoid bottlenecks such as busy interchanges, access ramps, or congested urban streets. By redirecting truck traffic, these bypasses help improve overall traffic flow, reduce delays, and enhance safety for all road users. The effectiveness of truck bypass depends on the conditions of the parallel or alternative roadways. If these roadways are already congested with general purpose traffic, freight vehicles might face the same issues they were meant to avoid, such as delays and inefficiencies (Rempel, et al., 2014).

Truck-only lanes operate by making one of the lanes only for heavy freight vehicles. They tend to be similar to managed lanes, however, truck-only lanes focus on the movement of heavy freight vehicles as the infrastructure, maintenance and operations would change. Chrysler (2016) emphasized the potential benefits of truck-only lanes, highlighting ability to reduce congestion for both freight and non-freight vehicles (Chrysler, 2016). While truck-only lanes are rarely implemented, an earlier study found that they aid in traffic management by increasing the operational efficiency of the traffic network (He, et al., 2000). Furthermore, a study by Iowa DOT (2017) affirmed the positive impact of truck-only lanes, noting improvements in truck travel time reliability, enhanced operation for light vehicles, and the provision of supplementary facilities for emergency vehicles as needed (U.S. Department of Transportation, 2017). There are two different strategies to implement a truck-only lanes and separate them from the general traffic, physically and operationally.

Physically separated truck lanes typically require the implementation of medians or barriers, such as grass, concrete medians or grade-separated structures, to isolate trucks from general-purpose traffic, as demonstrated in Figure 7. The TAC (Transportation Association of Canada) manual identified Highway 427 as a strong case study in 2014 due to its high truck volumes and proximity to intermodal terminals (e.g., CN Brampton and CP Vaughan) (Rempel, et al., 2014). However, the construction outcome differed from the recommendations. Managed lanes and HOV lanes were implemented instead of physically separated truck-only lanes. This decision aligns with findings from the original case study, which emphasized that high truck volumes are critical for justifying such lanes. U.S. guidelines recommend at least 60,000 trucks per day and two lanes per direction for physically separated truck lanes to be viable. Highway 427, with a maximum of 20,000 trucks per day, did not meet these criteria. As a result, shared truck-HOV lanes were proposed as a more practical alternative for maintaining service levels in areas with insufficient truck or HOV volumes (Rempel, et al., 2014).

Additional challenges included the limited Right-of-Way (ROW), high construction costs, and risk of collisions. Space constraints, particularly in residential areas along Highway 427, made it difficult to add new lanes. Physically separated lanes require additional width for breakdown areas and emergency access, further complicating the design. In addition, the expense of building physical barriers or grade-separated truck lanes was deemed too high relative to the traffic volumes and available funding. In conclusion, while Highway 427 was a strong candidate for study, the practical implementation opted for managed and HOV lanes as a more feasible solution (The Miller Group, 2021). The addition of truck lanes can increase the interaction of trucks and general-purpose traffic at entry/exit points, raising the risk of collisions. To solve this issue, specific infrastructure design strategies and the implementation of clear signage are necessary.

One solution involves the use of different configurations for truck-only lanes, such as inner lanes (located next to the median) versus outer lanes (closer to the roadway shoulder). When implementing the inner lane as the truck only lane, it requires trucks to merge across multiple general-purpose lanes to access entry or exit ramps. While this setup poses challenges for freight vehicles and increases the risk of collisions during lane changes, it remains the most publicly favored and cost-effective option. On the other hand, outer lanes allow freight vehicles direct access to ramps without crossing general-purpose lanes, improving operational efficiency for trucks (Douglas, 2004; Saiyed, 2021). However, this configuration forces passenger vehicles to merge into truck-only lanes when accessing ramps, creating a hazardous environment for smaller vehicles due to increased interactions with large trucks.

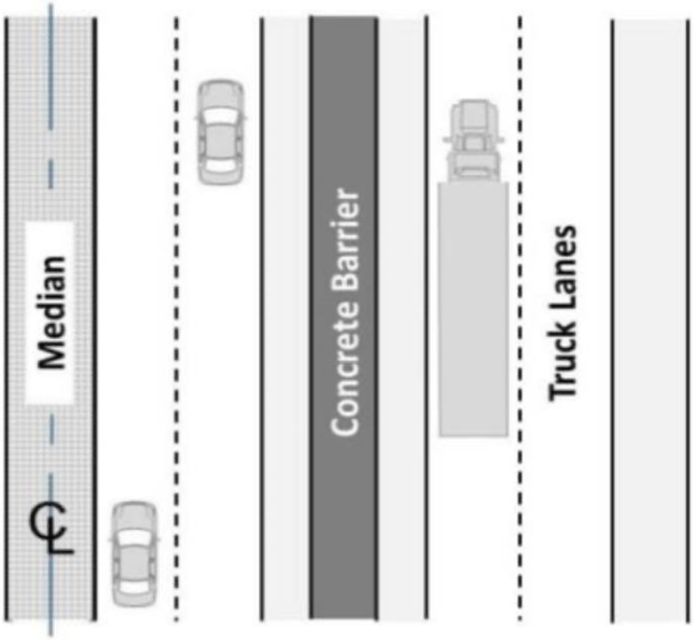


Figure 7: Physically Separated Truck-Only Lane

Most existing truck lane configurations studies focuses mainly on through movements and neglect left turning movements. However, implementing truck-only lanes for left turns requires accommodating the wider turning radius of freight vehicles. Hummer et al. (1988) stated that when trucks are provided with sufficient space in a left-turn lane, they can navigate the turn without intruding into adjacent lanes or interfering with other vehicles (Hummer, et al., 1988). Therefore, when intersections have two left-turning lanes, implementing the outermost lane to trucks provides sufficient space for their turns, reducing conflicts with passenger vehicles. This approach ensures that trucks can safely navigate left turns without intruding on adjacent lanes while enhancing traffic flow and intersection safety by addressing the specific spatial needs of freight vehicles.

Operationally separated truck lanes, shown in Figure 8, are designated lanes for freight vehicles to keep them separate from general-purpose traffic by utilizing traffic control measures such as rumble strips, painted lane markings, signage, adjusted speed limits, or the implementation of special policies (Rempel, et al., 2014). These lanes can be categorized into three types: truck friendly lanes, truck only lanes and truck lane restrictions. Truck friendly lanes are shared with other users, such as transit vehicles or temporary parking, but are designed to accommodate trucks during selected periods. While truck only lanes are exclusively utilized by specific types of trucks, often those categorized as Federal Highway Administration (FHWA) Classification 8 or higher. This classification includes single-trailer trucks with four or more axles (Federal Highway Adminstration (FHWA), 2015). Truck lane restrictions allocate two or more lanes exclusively for trucks, ensuring that other lanes remain accessible to non-truck vehicles, effectively reducing conflicts between vehicle types.

A study by Trowbridge et al. focused on strategies for designated truck lanes without physical barriers in the Seattle area. In this setup, trucks are given priority access, but passenger vehicles are still allowed to enter the lanes. The study found the following key outcomes: $10 million in annual travel time savings for trucks, with an average truck trip saving 2.5 minutes, which translates to less than an 8% improvement in travel time and $30 million in annual travel time savings for single-occupancy vehicles due to reduced congestion and more efficient traffic flow (Fischer, et al., 2003). Another example of operationally separated truck lane is the New Jersey Turnpike, where outer lanes are open to both trucks and cars, while inner lanes are designated for cars only. This configuration allows for some separation of truck and passenger vehicle traffic, though it does not involve physical barriers, offering a less strict form of lane separation but still aiming to improve safety and traffic flow (Espiritu, 2013).

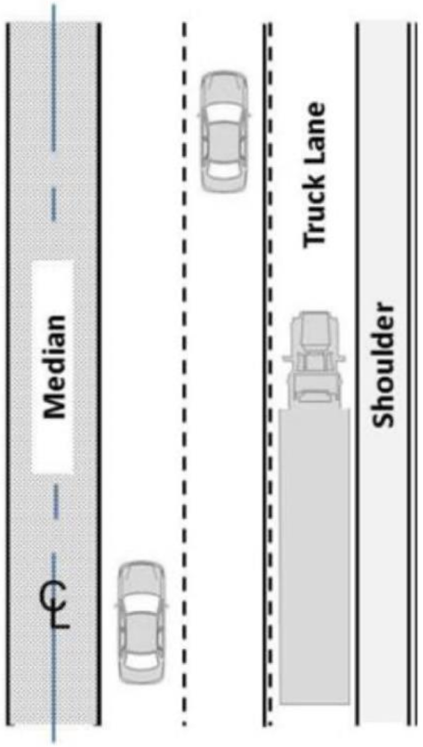


Figure 8: Operationally Separated Truck-only Lane

A study conducted by the Georgia Department of Transportation (DOT) compared the advantages and disadvantages of operationally versus physically separated truck-only lanes. Operationally separated truck lanes are relatively quick and affordable to implement, making them an attractive option for immediate improvements. These lanes can be adjusted or removed with ease if they do not generate the desired results. The clear difference between truck and car lanes helps organize traffic flow, which can improve overall efficiency. However, the downside is that drivers may ignore the lane separation, reducing its effectiveness. Additionally, the system relies heavily on pylons, signs, and markings, all of which require frequent upkeep and replacement to remain visible and functional. The Georgia DOT (2010) points out that due to the required investment, these lanes are not well-suited for use in HOT or toll systems because they lack the durability and infrastructure necessary (HNTB Corporation, 2010).

In contrast, physically separated truck lanes offer the clear benefit of enhanced safety for passenger vehicles by ensuring that trucks are completely separated from car traffic. However, these lanes come with significant drawbacks, including lengthy construction timelines and the risk of damage to vehicles if they collide with the barriers. Some drivers may also experience a sense of claustrophobia while navigating lanes bordered by concrete walls, and there is often resistance to such large-scale and costly projects, with concerns over whether such an elaborate system can actually be implemented effectively.

A study examined the road network around the Port of Miami, including highways and major streets, focusing on I-395 which is a short highway in downtown Miami that connects I-95 to the Port of Miami Tunnel and FL-A1A, leading to Miami Beach. The study assessed existing traffic conditions with the addition of dedicated truck-only lanes and lane restrictions. It then introduced HCV platooning into the existing conditions, testing both dedicated truck lanes and lane restrictions. The platoons consisted of a maximum of seven trucks, which disbanded when exiting and entering the freeway and only formed on highways (Jaya, 2023).

The results demonstrated that implementing a dedicated truck-only lane reduced travel times between 3.1% and 16.3% in the eastbound (EB) direction and between 1.05% and 8.5% in the westbound (WB) direction. The most significant reduction of 16% (EB) occurred when trucks exclusively used the dedicated lane, outperforming lane restriction strategies and shared-use lanes. HCV platooning further improved traffic efficiency, with travel time reductions ranging from 1.7% to 12.6% (EB) and up to 16.1% (WB) on the Dolphin Expressway through I-395. Even greater benefits were observed on I-95, where platooning reduced travel times by up to 17.9% (EB). HCV platoons operating within dedicated truck-only lanes demonstrated greater performance compared to scenarios where trucks shared lanes with other vehicles (Jaya, 2023).

2.3 Environmental Impacts

To assess the environmental impacts of freight traffic properly, it is essential to identify the relevant vehicle emissions to be analyzed. According to the U.S. environmental protection agency, the main greenhouse gas (GHG) emissions that are emitted make up the combined effects of carbon dioxide (CO_2), nitrogen oxide (NO_2), and methane (CH_4) emissions. CO_2 is the main contributor to the deterioration of air quality, while vehicles that use gasoline emit NO_2 and CH_4 that would hurt the environment (United States Environmental Protection Agency, 2024). In Canada, the transportation sector is a significant source of greenhouse gas emissions, contributing approximately 28% of the country's total emissions (Government of Canada, 2023). Similar to the U.S., the primary pollutants of concern are carbon dioxide (CO_2), nitrogen oxides (NO_2), and methane (CH_4), all of which contribute to air pollution and climate change. Figure 9 shows greenhouse gas (GHG) emissions from on-road freight between the years 2000 and 2018, measured in megatonnes of CO_2 equivalent (Mt CO_2e). Emissions have generally increased over time, indicating a growing environmental impact from on-road freight transport, due to increased freight demand due to economic growth.

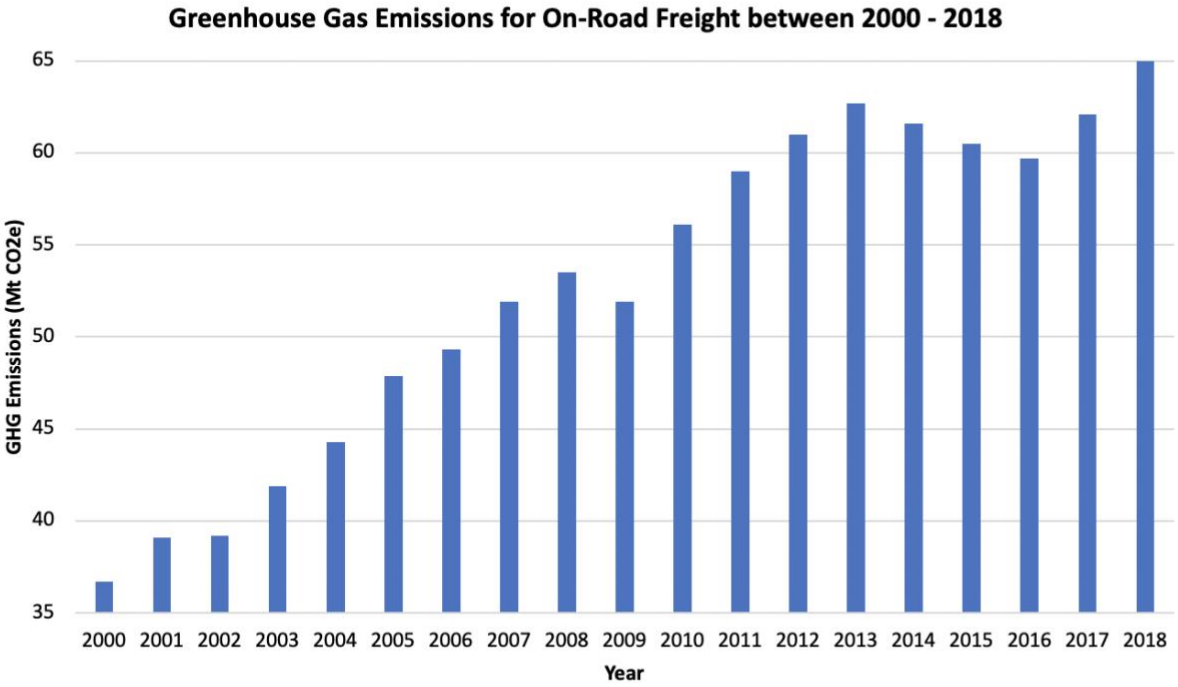


Figure 9: GHG Emissions for On-Road Freight for 2000-2018

Wijayaratna (2013) implemented FSP along a 10km stretch of El Camino Real in California, United States. The average CO_2 and N_2O emissions were seen to increase by an average of 12.3% and 14.88%, respectively during the AM peak hour when considering all vehicles. However, when accounting only for the bus emissions, CO_2 and N_2O emissions decreased by 9.13% and 10.78%, respectively during the AM peak hour (Wijayaratna, et al., 2013).

Alam and Hatzopoulou (2014) implemented FSP along a 5.1 km corridor with various slopes ranging from -17% to 8% in Montreal. The study extended transit green time by 15 seconds and the minimum green time for the non-priority phases was set at 50% of their initial fixed green time. The results show that Northbound and Southbound GHG emissions decreased by 5.91% and 13.49% respectively for the buses traveling along the corridor. However, this study does not assess the overall network GHG emissions. For the estimation of emissions analysis, all the earlier studies utilized EPA's Motor Vehicle Emission Simulator (MOVE) emission model (Alam, et al., 2010).

HCV platooning offers environmental benefits compared to HCVs and provides a practical engineering solution for addressing roadway challenges faced by long combination vehicles (LCVs). However, from an environmental perspective, LCVs outperform HCV platoons. This is because an LCV uses a single engine to pull two trailers, whereas a platoon of HCVs involves multiple engines operating. A lot of studies though focus on fuel savings as it is directly correlated to environmental benefits. As reducing fuel consumption directly lowers greenhouse gas emissions and air pollutants. The combustion of fossil fuels, particularly diesel and gasoline, releases carbon dioxide (CO2), a major contributor to climate change. By burning less fuel, CO2 emissions are proportionally reduced (Canadell, et al., 2021). LCVs have been shown to reduce fuel consumption by up to a 30%. However, no studies about LCVs dive into the specific reduction of GHG emissions, such as CO_2 and NO_x emissions.

Since HCV platoons are closely spaced tandem trucks, the distribution of pressure will influence the drag reduction. In this arrangement, the lead and trailing trucks experience varying levels of drag savings due to distinct aerodynamic effects, influenced in part by vehicle geometry. Particularly, pressure in the gap between trucks is higher than at the trailer base but lower than at the truck nose. This dynamic results in drag savings for the lead truck, which benefits from increased pressure over its trailer base (Patten, et al., 2012). Browand in 2004 conducted field tests that put model HCV platoons into wind tunnels. The results showed that both the model trucks used in wind tunnel testing and full-scale trucks experienced similar levels of drag reduction when closely spaced in tandem formation. For the trailing truck, the nose shape plays a significant role, but variations between model and full-scale trucks impact drag reduction Additionally, the engine-forward design significantly influences the actual drag reduction experienced by the trailing truck. Overall, platooning offers substantial advantages for leading vehicles, particularly regarding aerodynamic efficiency (Browand, et al., 2004). Moreover, strategies such as smoothing acceleration/deceleration peaks and applying aerodynamic add-on devices to intercity buses can further improve fuel efficiency. These strategies often focus on minimizing flow separation and optimizing underbody aerodynamics (Zabat, et al., 1995). It's important to note that air density changes resulting from temperature fluctuations, particularly in cold climates like Canada, significantly affect aerodynamic drag and fuel consumption, leading to higher fuel consumption in such conditions (Alam, et al., 2015).

Research studies by Bibeka and Shlavador show that reducing the distance between trucks minimizes wind resistance, leading to fuel savings between 4.7% and 7.7%, with closer spacing resulting in greater efficiency. Bibeka et al., the impact of HCV platooning on emission rates was evaluated for a 26-mile freeway without off-ramp and on-ramp flows. The study discovered that using a shorter time gap of 0.2 seconds resulted in larger emission reductions compared to a 0.6-second time gap (Bibeka, et al., 2019). This states that the smaller the headway, the less emissions the HCV platooning experience. An experiment conducted by PATH and Transport Canada measured maximum fuel consumption savings of 7.4% for the first follower at a gap of 17.4 meters and 11.0% for the second follower. Interestingly, the first truck, positioned at the front of the platoon, does not experience significant fuel savings, while the second truck, located in the middle of the platoon, saves between 7% and 6% of fuel consumption (Shladover, et al., 2018).

Lammert et al. (2014) examined how factors such as speed, following distance, and vehicle weight impact fuel consumption in platooning trucks. Their study tested speeds from 88.5 km/h to 112.6 km/h and following distances between 6.1 m and 22.9 m. This shows that the headway time is slightly larger than the average seen which is 0.2 seconds to 0.6 seconds equivalent to a distance gap of 5.49 and 17.37 m (Bibeka, et al.). The findings indicated fuel savings of up to 5.3% for lead trucks and 9.7% for trailing vehicles (Lammert, et al.). Similarly, Davila (2013) used aerodynamic simulations and field tests to analyze the effects of platooning, showing that a spacing of 3 to 15 m could reduce wind drag by approximately 80%, with fuel savings between 7% and 16% for gaps of 5 to 7 m .

As for studies specifically on emissions, a European study saw reduction in CO_2 emissions by 19%, if market penetration rate is 100% (Pribyl, et al., 2020). In addition, Davila and Ferrer (2014) studied two HCV platoons traveling at 85 km/h at a distance of 8m (0.34 second headway) for two 2km highways. Results show that CO_2 emissions reduce by 11% (Davila & Ferrer).

In 2019, Park et al. conducted a study on the emissions impact of connected trucks with the implementation of FSP. The study was conducted along a section of United States Route 50 in Chantilly, Virginia, including six signalized intersections equipped with FSP. While the study did not specify the level of priority given to trucks, it employed the Motor Vehicle Emissions Simulator (MOVE) emission model for analysis, consistent with previous research. The findings indicated that reductions in CO_2 and NO_x emissions for connected trucks were influenced by traffic conditions. At lower volume-to-capacity (V/C) ratios, reductions were relatively small, with CO_2 emissions decreasing by 6.6% and NO_x by 6.5%. In comparison, higher V/C ratios demonstrated significantly greater reductions of 25.3% for CO_2 and 24.3% for NO_x. As for passenger vehicles traveling along truck routes, FSP also had significant environmental benefits, with maximum reductions of 23.8% in CO_2 emissions and 17.6% in NO_x emissions. However, the implementation of FSP negatively impacted vehicles on cross streets due to reduced green signal time, leading to maximum increases of 103.2% in CO_2 emissions and 11.2% in NO_x emissions (Park, et al., 2019).

A study by Kim et. al ran a study to evaluate a proposed $2 billion project to construct 40-miles of truck-only lanes on Interstate 75 (I-75) between Atlanta and Macon, Georgia (United States). The study found that the enhanced vehicle operations with the installation of the truck-only lanes helped reduce the total fuel consumption by 2.8% to 3.7%, decreases in CO_2 (up to 3.7%), CO (up to 8.0%), and NOx (up to 3.9%). These reductions were more noticeable when truck demand increased, demonstrating the long-term sustainability benefits of truck-only lanes. Additionally, pollutant concentrations declined significantly near the highway, with CO levels dropping by up to 11.7 $\mu g/m^3$ within 0.25 miles. As truck volumes grow, dedicated lanes help mitigate air pollution by promoting smoother traffic flow, reducing acceleration and braking, and lowering vehicle-specific power demands (Kim, et al., 2018).

This study focuses on urban arterial roads; however, most existing research on GHG emission reductions examines freeway environments. This difference leads to differences in expected outcomes, as the operating conditions on freeways, such as higher, more consistent speeds and minimal interruptions, allow strategies such as HCV platooning and ITS systems to achieve more significant GHG reductions. In contrast, urban arterials are subject to frequent intersections, pedestrian activity, turning movements (particularly left turns), and variable signal timing, all of which create stop-and-go conditions that limit the potential for sustained fuel savings. While ITS strategies such as FSP and DTLL can still produce measurable benefits on urban roadways, these improvements are typically localized, such as reduced idling at bottlenecks, rather than network wide. As a result, the magnitude of GHG reductions on urban arterials is unlikely to match those reported in freeway-based studies.

2.4 Microsimulation Model

This study uses VISSIM to model traffic flow and evaluate the travel time impacts of Transit Signal Priority (FSP) and Freight Signal Priority (FSP) systems. VISSIM is a widely recognized microsimulation tool that allows for detailed, microscopic-level modeling of vehicle movement, enabling an analysis of how passenger cars, trucks, and transit vehicles interact at signalized intersections and along corridors (FHWA, 2022). Data from Synchro is used as input for the microsimulation model, which is used to gather essential traffic information, such as traffic volumes, turning movements, and signal timings, to ensure that the model accurately reflects real-world conditions.

In the context of this study, VISSIM was used to simulate how different signal priority systems, like FSP and FSP, would affect travel time, delays, and overall traffic flow. By adjusting signal timings in real time and introducing priority for specific vehicles, the tool can track how these changes improve or worsen travel times for buses, trucks, and passenger vehicles, as well as how they interact with each other.

In terms of emission modeling, this study utilized PTV VISSIM 2024, while previous studies have typically employed Motor Vehicles Emission Simulator (MOVE) as the simulation tool. MOVE, developed by the U.S. Environmental Protection Agency (EPA), is designed to estimate greenhouse gas (GHG) emissions such as CO_2, NO_x, and N_2O based on real-time data and simulated traffic conditions. However, MOVE does not account for the real-time dynamics of traffic signal priority systems (FSP/FSP), meaning it cannot directly simulate the effects of signal timing or traffic management strategies on emissions without input from a traffic simulation tool. VISSIM is crucial in this context as it generates the detailed traffic behavior data that can then be used by emission models like MOVE for more accurate environmental assessments.

2.5 Chapter Two Summary

Chapter 2 presents an in-depth analysis of existing literature on Intelligent Transportation Systems (ITS) and infrastructure enhancements, particularly focusing on technologies like Transit Signal Priority (FSP) and Freight Signal Priority (FSP), and the development of dedicated truck lanes. The chapter is divided into two main sections: Section 2.1 focuses on ITS strategies, while Section 2.2 explores infrastructure enhancements aimed at improving roadway and network efficiency.

Section 2.1 explores various ITS technologies, including LiDar, Radar, Bluetooth communications, and vehicle-to-infrastructure (V2I) technology that supports systems like HCV platooning. The section provides an overview of FSP and FSP, which prioritize the movement of transit vehicles, emergency vehicles, and trucks at signalized intersections. The chapter outlines the evolution of FSP, beginning with the early study by Salter and Shahi in 1979, which identified the trade-offs between reducing delays for buses and increasing delays for passenger vehicles. FSP systems have now been deployed in over 100 cities worldwide, demonstrating their effectiveness in improving transit operations.

The section also examines four types of signal priority strategies:

1) Passive Priority: Pre-emptive adjustments of traffic signals based on fixed schedules or conditions. It is low-cost but can cause delays for non-prioritized vehicles.
2) Active Priority: Real-time adjustments to give priority to transit vehicles only when they approach an intersection. This approach improves efficiency but can cause delays if used unnecessarily.
3) Conditional Active Priority: A more refined version of active priority, where the system grants priority based on conditions like bus lateness or traffic conditions.

4) Adaptive Priority: A dynamic approach that adjusts signal timing based on real-time conditions, offering a more responsive and efficient solution.

FSP and FSP can improve travel times but vary in effectiveness depending on traffic conditions. Studies show that FSP is most beneficial on freight-heavy corridors with minimal cross-street traffic, reducing truck travel times by up to 21%. However, its impact is limited during peak hours when signal cycles are already maximized. FSP has shown greater benefits, cutting transit travel times by over four minutes per vehicle, though it can increase delays for cross-street traffic. While most research focuses on through movements, a study on left-turn FSP found travel time reductions of 7% to 20%, but priority on left-turning movements remains underexplored.

Section 2.2 examines physical improvements to transportation networks, such as dual left lanes, dedicated truck lanes, and intersection geometry modifications. A particular focus is placed on the advantages and disadvantages of operationally and physically separated truck-only lanes. Operationally separated lanes are cost-effective and flexible, but they can lose effectiveness if drivers ignore lane separations, requiring regular maintenance. In contrast, physically separated truck lanes offer enhanced safety but are costly and time-consuming to implement. In addition, the study examined the benefits of HCV platooning on dedicated truck-only lanes. Jaya (2023) found that implementing dedicated truck-only lanes reduced travel times by 3.1% to 16.3% in the eastbound (EB) direction and 1.05% to 8.5% in the westbound (WB) direction.

Section 2.3 explores several studies on the environmental impact of ITS systems, especially the effects of FSP and FSP on greenhouse gas (GHG) emissions. Studies show mixed results:

- A study by Wijayaratna (2013) found a reduction in emissions for buses with FSP but an overall increase in CO2 and N2O during peak hours.

- Alam and Hatzopoulou (2014) observed a decrease in GHG emissions for buses in Montreal, but the study did not consider network-wide emissions.
- Park et al. (2019) highlighted the benefits of FSP in reducing CO2 and NOx emissions for connected trucks, particularly under favorable traffic conditions, though the implementation led to increased emissions on side streets due to reduced green time for cross traffic.
- A study by Kim et al. (2018) highlighted the environmental benefits of dedicated truck-only lanes (DTLL), demonstrating reductions in CO_2, NOx, and CO emissions, even as the percentage of trucks on the highway increased.

In summary, Chapter 2 presents a detailed review of signal priority systems, and infrastructure enhancements. It examines the operational advantages and limitations of truck-only lanes and priority systems while also considering their environmental effects, highlighting a need for further research to understand their full impact.

CHAPTER 3: STUDY AREA AND DATA

This chapter discusses the study area, and the data used for this study. This includes a description of the study corridor and area, as well on identifying routes suitable for LCV freight movements. Additionally, it outlines the data sourced from Peel Region, which includes traffic volume information, such as vehicle classifications, turning movements, as well as signal timing plans. This data is used to understand the freight activity in the area, including the types and volumes of vehicles.

3.1 Study Network

Regional Municipality of Peel, also known as Peel Region, is approximately 1,257 square kilometers and has a population of roughly 1.45 million according to the 2021 census (Peel Region, 2021). It is subdivided into three municipalities: The City of Mississauga, the City of Brampton, and the Town of Caledon. The region's land usage is diverse, consisting of urban, suburban, rural, agricultural, and natural landscapes. According to Metrolinx, in 2017, it became a significant freight hub in North America, as it aids in the freight movement between Southern Ontario, the rest of Canada, the United States, and other international destinations. In total handling 25% of all goods transported within Ontario, which is approximately CAD 1.8 billion of freight being transported through the region daily. This contributes 6.3% to the provincial GDP, adding a total of CAD 49 billion annually to the Peel Region's economy (Region of Peel, 2015). These roadways also connect to major transportation infrastructure, including Toronto Pearson International Airport, Canada's largest cargo airport, seven major expressways, and the two largest inland rail container terminals in the country (Region of Peel, 2012).

Figure 10 shows the general land use of Peel Region being predominantly industrial around Toronto Pearson airport. The study area, indicated by the red box, is located within this zone. This concentration of industrial land use contributes to significant freight activity in the area, making it a good study area (Peel Region, 2023).

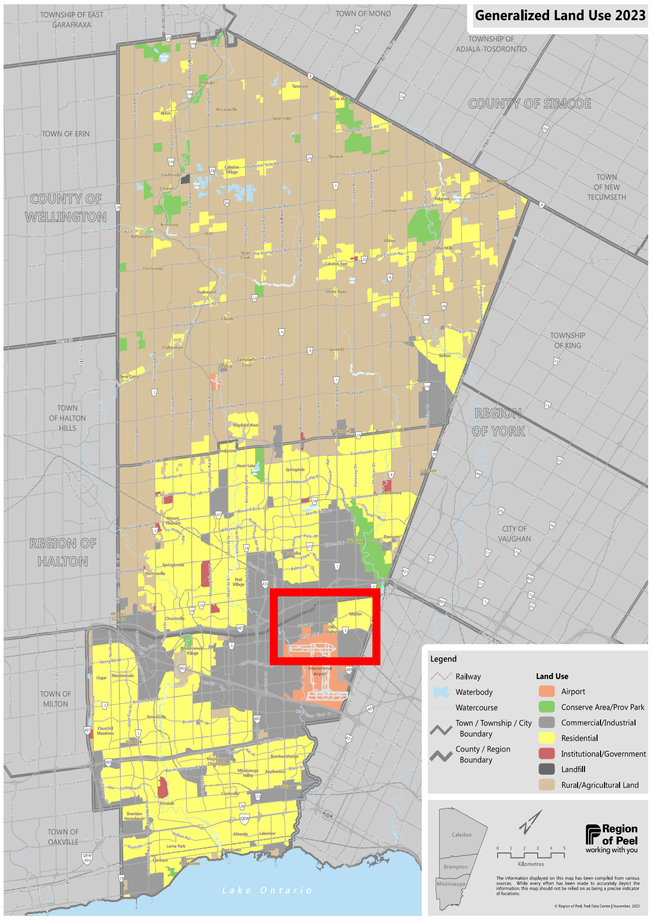


Figure 10: Peel Region Land Use

To accommodate the usage of LCVs in the area, Peel Region conducted an LCV Usage Study, which identified the appropriate roadways and intersections for LCVs based on roadway geometry as shown in Figure 11. This usage study was necessary because LCVs face challenges on urban road infrastructure, such as needing wider turn radii and larger traffic lanes, therefore, the study corridor comprised three major connected truck routes: Dixie Road, Derry Road, and

Steeles Avenue, located in Brampton, Ontario. The three roadways were specifically selected because they are designed for LCV usage (Region of Peel, 2021).

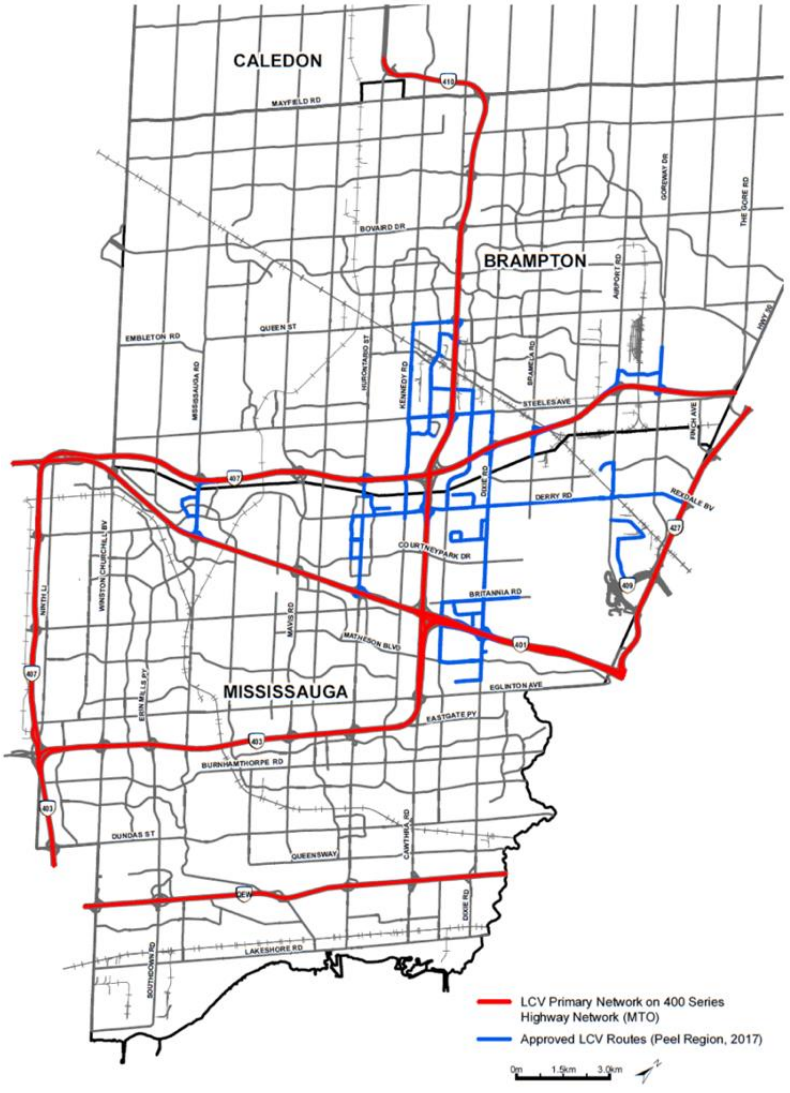


Figure 11: Approved LCV Routes

Using the approved LCV routes (Figure 11) a study corridor was chosen. The total corridor, shown in Figure 12, consists of 32 signalized intersections and five un-signalized intersections along a total of 19.2km corridor in the Region of Peel. It includes seven major intersections on Derry Road, five major intersections along Dixie Road, and four major intersections along Steeles

Avenue. The green dots represent all the identified intersections within the study network, while the blue boundary represents whether each intersection is signalized.

Figure 12: Study Network (19.2Km)

3.2 Traffic Volume Data

The traffic volume input data were collected from the 2017 fall season AM (7:15 AM to 8:15 AM) and PM (4:30 PM to 5:30 PM) peak hour Synchro files provided by the Peel Region from September to November. These files contain the traffic volume data, turning movements at all intersections, the percentage of HCVs travelling along the corridor, and signal timing details, which include signal splits, control modes (actuated vs. semi-actuated), and cycle lengths for each signalized intersection within the study corridor.

After reviewing the AM and PM data sets, the AM peak hour data set was selected for analysis. This decision was determined using two factors, average HCV percentage and the volume-to-capacity (V/C) ratio. The AM peak hour has a higher average HCV percentage of 22.5% making it more relevant for a freight focused study. The PM peak hour data showed over-saturation, with a volume-to-capacity ratio reaching 1.13 for certain movements, which could distort the simulation results by exaggerating the queuing and congestion problems. Therefore, the 2017 AM peak hour traffic volumes were selected for the study as they ensured a more balanced and reliable traffic flow for evaluating freight operations. These datasets were then used to update the traffic volumes and route movements when developing the VISSIM microsimulation model.

Table 3 shows the simulated total volume of vehicles at each intersection, as well as the number and percentage of HCVs and LCVs for each direction (Eastbound, Westbound, Northbound, and Southbound) at major signalized intersections along Dixie Road, Derry Road, and Steeles Avenue. The assumption that LCVs make up 5% of traffic in Peel Region is based on Hussain (2019), who found that 5% of LCV trips either start or end within the region. Since all LCV trips must begin or end in urban areas to access freight facilities, this percentage reasonably represents their share of traffic on Peel's roads. Therefore, using 5% as the LCV proportion in the vehicle composition appropriately reflects their presence. Since freight trips must begin or end in urban areas, this statistic reflects that freight vehicles are classified as 5% LCVs with the rest being comprised of single unit trucks. It is important to note that the HCV percentages shown in the table represent only a portion of the overall traffic. The total traffic volume is made up of HCVs, LCVs (5%), and passenger vehicles, which together adds up to 100% of the total traffic.

Cardiff and Derry Road show the highest percentage of HCVs northbound, roughly 50.3%. However, a significant portion of these trucks are right turning onto major roadways. On the other hand, Steeles Avenue and Tomken Road show high freight activity, with HCVs representing 26% of southbound traffic and 22.3% of northbound traffic. These intersections show the importance of these routes for truck movement within the study corridor as they exhibit high freight volumes.

Table 3: Base Freight Traffic Composition for Major Intersections

Intersection	Total Volume (AM Peak) 7:15 am – 8:15 am		Number and Percentage of Freight			
			EB	WB	NB	SB
Airport and Derry	5,802	HCV	250 (12%)	88 (5%)	131 (13%)	102 (10%)
		LCV	14	4	7	6
Bramalea and Derry	4,019	HCV	148 (10.3%)	116 (7%)	11 (10%)	59 (6.33%)
		LCV	8	6	0	3
Dixie and Derry	7,100	HCV	183 (11.7%)	279 (12.3%)	205 (20.3%)	153 (11.7%)
		LCV	10	14	11	8
Cardiff and Derry	3,856	HCV	170 (12.7%)	250 (22%)	64 (50.3%)	68 (40%)
		LCV	8	13	4	3
Tomken and Derry	3,799	HCV	99 (6.33%)	215 (18.7%)	70 (22.3%)	102 (17%)
		LCV	6	11	3	5
Kennedy and Derry	6,502	HCV	139 (10.3%)	213 (14%)	94 (19%)	85 (7.33%)
		LCV	8	11	5	4
Hurontario and Derry	6,502	HCV	53 (3.67%)	123 (13%)	63 (12.7%)	74 (4.33%)
		LCV	2	6	3	4
Steeles and Dixie	6,309	HCV	166 (8.67%)	265 (47%)	99 (14.7%)	64 (5.67%)
		LCV	8	14	5	4
Drew and Dixie	2,912	HCV	56 (10.3%)	65 (7%)	206 (10%)	167 (6.33%)

Intersection	Total Volume (AM Peak) 7:15 am – 8:15 am		Number and Percentage of Freight			
			EB	WB	NB	SB
		LCV	3	4	11	9
Britannia and Dixie	3,856	HCV	120 (34.3%)	84 (36.7%)	228 (14.7%)	230 (24.3%)
		LCV	7	5	11	12
Matheson and Dixie	5,906	HCV	68 (9.67%)	94 (18.7%)	117 (22.3%)	169 (17%)
		LCV	5	5	6	9
Kennedy and Steeles	6,118	HCV	110 (3.67%)	113 (7%)	39 (7%)	70 (6.33%)
		LCV	5	5	1	4
Rutherford and Steeles	5,388	HCV	98 (7.67%)	160 (9.67%)	53 (13%)	114 (12.67%)
		LCV	5	8	2	6
Tomken and Steeles	4,666	HCV	155 (7.67%)	184 (17.3%)	65 (22.3%)	116 (26%)
		LCV	8	10	4	6

Table 4 shows the simulated hourly traffic volumes in the study corridor with an assumption of 5% HCV platoons. It is important to note that the HCV percentages shown in the table represent only a portion of the overall traffic. The total traffic volume is made up of HCVs, LCVs (5%), HCV platoons (5%), and passenger vehicles, which together add up to 100% of the total traffic. The 5% of HCV platoons are taken from the total number of HCVs, not from the LCVs. In other words, the platooning vehicles are a subset of the existing HCV volume, meaning that a portion of the heavy trucks is designated as platoons, keeping the total number of heavy vehicles constant throughout the simulation.

Dixie and Derry Road show the highest total traffic volume of 7,100 vehicles, highlighting its importance and potential congestion issues. Additionally, at Britannia and Dixie, HCVs represent 34.3% of eastbound traffic, indicating high freight activity. HCV platoons are defined as two WB-20 trucks; therefore, volumes were calculated as one platoon for every two trucks counted. In addition, the number of HCV platoons was deducted from the total HCV counts. The maximum volume of HCV platoons, reaching seven, is shown at three intersections: the eastbound direction of Airport Road and Derry Road, the westbound direction of Steeles Avenue and Dixie Road, and the westbound direction of Derry Road and Dixie Road. These intersections are significant because they represent the meeting of all three study corridors, highlighting their importance in managing and assisting the truck traffic flow within the region.

Table 4: Assumed Freight Traffic Composition for Major Intersections

Intersection	**Total Volume (AM Peak) 7:15 am – 8:15 am**		**Number and Percentage of Freight**			
			EB	**WB**	**NB**	**SB**
Airport and Derry	5,802	HCV	243 (12%)	86 (5%)	128 (13%)	99 (10%)
		LCV	14	4	7	6
		HCV Platoon	7	2	4	3
Bramalea and Derry	4,019	HCV	144 (10.3%)	113 (7%)	11 (10%)	57 (6.33%)
		LCV	8	6	0	3
		HCV Platoon	4	3	0	2
Dixie and Derry	7,100	HCV	178 (11.7%)	272 (12.3%)	200 (20.3%)	149 (11.7%)
		LCV	10	14	11	8
		HCV Platoon	5	7	6	4
Cardiff and Derry	3,856	HCV	166 (12.7%)	244 (22%)	62 (50.3%)	66 (40%)
		LCV	8	13	4	3
		HCV Platoon	4	6	2	2
Tomken and Derry	3,799	HCV	96 (6.33%)	210 (18.7%)	68 (22.3%)	99 (17%)

Intersection	Total Volume (AM Peak) 7:15 am – 8:15 am		Number and Percentage of Freight			
			EB	WB	NB	SB
Tomken and Derry	3,799	LCV	6	11	3	5
		HCV Platoon	3	5	2	3
Kennedy and Derry	6,502	HCV	135 (10.3%)	208 (14%)	91 (19%)	83 (7.33%)
		LCV	8	11	5	4
		HCV Platoon	4	5	3	2
Hurontario and Derry	6,502	HCV	52 (3.67%)	120 (13%)	61 (12.7%)	72 (4.33%)
		LCV	2	6	3	4
		HCV Platoon	1	3	2	2
Steeles and Dixie	6,309	HCV	162 (8.67%)	258 (47%)	96 (14.7%)	62 (5.67%)
		LCV	8	14	5	4
		HCV Platoon	4	7	3	2
Drew and Dixie	2,912	HCV	53 (10.3%)	63 (7%)	200 (10%)	162 (6.33%)
		LCV	3	4	11	9
		HCV Platoon	2	2	6	5
Britannia and Dixie	3,856	HCV	116 (34.3%)	81 (36.7%)	222 (14.7%)	224 (24.3%)
		LCV	7	5	11	12
		HCV Platoon	4	3	6	6
Matheson and Dixie	5,906	HCV	65 (9.67%)	91 (18.7%)	114 (22.3%)	164 (17%)
		LCV	5	5	6	9
		HCV Platoon	3	3	3	5
Kennedy and Steeles	6,118	HCV	107 (3.67%)	110 (7%)	38 (7%)	68 (6.33%)
		LCV	5	5	1	4
		HCV Platoon	3	3	1	2
Rutherford and Steeles	5,388	HCV	95 (7.67%)	156 (9.67%)	52 (13%)	111 (12.67%)

Intersection	Total Volume (AM Peak) 7:15 am – 8:15 am		Number and Percentage of Freight			
			EB	**WB**	**NB**	**SB**
Rutherford and Steeles	5,388	LCV	5	8	2	6
		HCV Platoon	3	4	1	3
Tomken and Steeles	4,666	HCV	151 (7.67%)	179 (17.3%)	63 (22.3%)	113 (26%)
		LCV	8	10	4	6
		HCV Platoon	4	5	2	3

3.3 Traffic Control Data

The Synchro database provided signalized intersection input parameters for the study corridors, which are managed by the Ring Barrier Signal Control (RBC) system. The RBC system works by organizing signal phases into a continuous loop, or "ring," and placing barriers between conflicting movements to avoid simultaneous operations. This system coordinates conflicting traffic movements by either having them one after another or separating them with a barrier in the timing plan called change intervals and clearance times. RBC systems manage signal timing and coordination at intersections, especially along corridors with high traffic volumes.

The RBC (Ring Barrier Controller) input parameters incorporated a range of signal timing and phasing details essential for accurately modeling intersection operations in the VISSIM microsimulation environment. These parameters included phase numbers, movement directions (e.g., left-turn movements, through traffic, and right-turn movements), as well as pedestrian walking times, ensuring that pedestrian clearance intervals were appropriately reflected in the simulation.

Key timing aspects were also included, such as green time, amber (yellow) time, and all-red time, which together determined the total cycle time for each signalized intersection. The total cycle time is calculated as the sum of the green, amber, and all-red phases, ensuring proper clearance and safety margins for all road users.

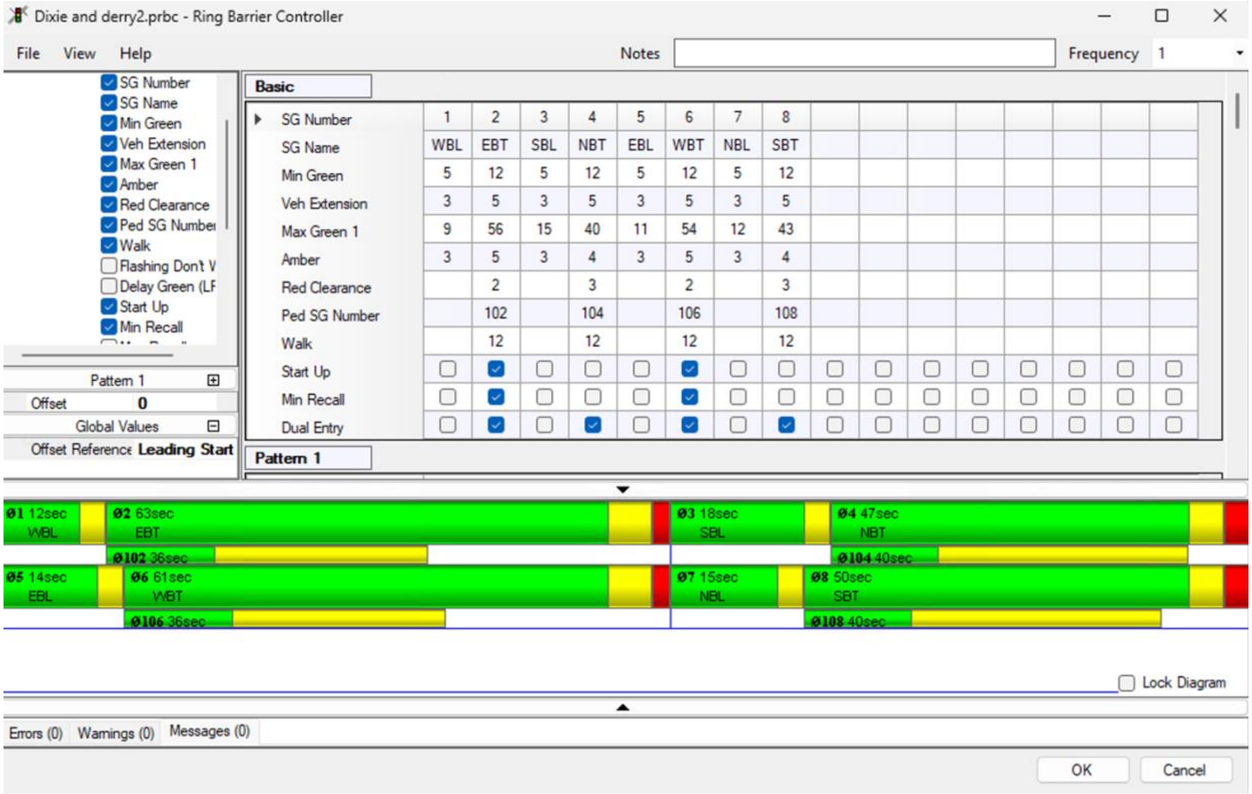
Beyond basic signal timings, additional traffic signal control parameters were incorporated to enhance the accuracy of the microsimulation. These included:

- Signal split times: the proportion of the total cycle time allocated to each movement phase.
- Cycle lengths: the duration of a complete signal cycle, varying based on intersection demand.
- Signal offsets: timing coordination between adjacent signals to optimize traffic flow and reduce stops and delays.
- Lead/lag phasing: specifying whether protected/permissive left-turn phases were implemented, allowing for better traffic progression along corridors.

Furthermore, the database distinguished between actuated, semi-actuated, and coordinated signal operations, ensuring that each intersection's control type was properly represented in the microsimulation. Actuated signals respond dynamically to traffic demand via vehicle detection systems, while semi-actuated signals operate with fixed phases but adjust timings based on side-street demand. Coordinated signals, often used along arterial corridors, were also accounted for by incorporating signal coordination strategies, helping to maintain progression and minimize delays at consecutive intersections.

All these data inputs were integrated into VISSIM through RBC files, which were generated to accurately replicate real-world signal timing plans at each intersection. The RBC files, derived from Synchro outputs provided by Peel Region, included detailed intersection control settings for both signalized and unsignalized intersections. These files contained key signal phase parameters such as green times, cycle lengths, and amber/red clearance intervals, ensuring that the microsimulation closely mirrored real-world traffic operations.

As shown in Figure 13, the Synchro data was imported into VISSIM and developed into a fully functional microsimulation model.



Frequency 1

☑ SG Number
☑ SG Name
☑ Min Green
☑ Veh Extension
☑ Max Green 1
☑ Amber
☑ Red Clearance
☑ Ped SG Numbe
☑ Walk
☐ Flashing Don't V
☐ Delay Green (LF
☑ Start Up
☑ Min Recall

Pattern 1
Offset 0
Global Values
Offset Reference Leading Start

SG Number	1	2	3	4	5	6	7	8								
SG Name	WBL	EBT	SBL	NBT	EBL	WBT	NBL	SBT								
Min Green	5	12	5	12	5	12	5	12								
Veh Extension	3	5	3	5	3	5	3	5								
Max Green 1	9	56	15	40	11	54	12	43								
Amber	3	5	3	4	3	5	3	4								
Red Clearance		2		3		2		3								
Ped SG Number		102		104		106		108								
Walk		12		12		12		12								
Start Up	☐	☑	☐	☐	☐	☑	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Min Recall	☐	☑	☐	☐	☐	☑	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Dual Entry	☐	☑	☐	☑	☐	☑	☐	☑	☐	☐	☐	☐	☐	☐	☐	☐

Errors (0) Warnings (0) Messages (0)

Figure 13: Ring Barrier Controller modelled in VISSIM

3.4 Chapter Three Summary

Chapter 3 of this research provides a detailed overview of the study area, and the data used for the analysis. The study area is in the Peel Region, Ontario, a major freight hub in North America, handling a significant portion of Canada's freight traffic. The region's infrastructure, which includes key roadways, intersections, and connections to major transportation networks, is crucial for freight movement. The study specifically focuses on identifying Long Combination

Vehicle (LCV) routes suitable for freight transport in urban areas. Three major truck routes, Dixie Road, Derry Road, and Steeles Avenue were selected for the study, with each designed to accommodate LCVs based on road geometry and turning radii. The total study corridor spans 19.2 km and includes 32 signalized intersections and five unsignalized intersections.

The chapter also discusses the traffic data used for the analysis, which was sourced from Peel Region's Synchro database. This data includes traffic volumes, turning movements, vehicle classifications, and signal timing details, gathered during peak AM and PM hours. After evaluating the data, the AM peak hour data was selected for analysis due to its suitability and lower risk of oversaturation compared to PM data. The collected traffic data provides insights into the volume of HCVs and LCVs along key intersections, highlighting critical freight routes and their importance in the study corridor. The following intersections stand out for their high truck volumes and freight percentages:

- Dixie Road and Derry Road: The highest total traffic volume (7,100 vehicles) and substantial freight activity, with HCVs making up 11.7% to 20.3% of the traffic, indicating a significant truck presence along this route.
- Britannia and Dixie: 34.3% of eastbound traffic consists of HCVs, highlighting the high freight activity at this intersection.
- Tomken and Derry: Notable for 22.3% of northbound traffic being HCVs, which shows the importance of this route for freight movement.
- Steeles and Dixie: A critical intersection with high freight traffic, especially in the westbound direction where 47% of the traffic is HCVs.

These intersections, along with others in the corridor, highlight the importance of Dixie Road, Derry Road, and Steeles Avenue in supporting freight traffic within the Peel Region. These routes are essential for managing truck movements and improving transportation efficiency in the region.

The traffic control data is also examined, focusing on the Ring Barrier Signal Control (RBC) system used to manage signalized intersections in the region. The RBC system coordinates traffic signal phases to improve flow and reduce conflicts between different traffic movements. The chapter concludes with an explanation of how this data was incorporated into the VISSIM microsimulation model, ensuring an accurate representation of traffic conditions and signal operations along the study corridor. This comprehensive dataset provides a solid foundation for analyzing the impacts of Transit Signal Priority (FSP) and Freight Signal Priority (FSP) systems on traffic flow and freight movement in the Peel Region.

CHAPTER 4: METHODOLOGY

This Chapter discusses the decision-making process used to determine which signalized intersections in the study area will implement the truck priority measure techniques. The chapter highlights the lack of standardized criteria for prioritizing specific movements at intersections and, in response, develops a methodology to guide this selection process effectively.

4.1 Identifying Process for Freight Priority Measures

Previous studies offered limited detail on the methodology used to select intersections for truck priority measures. In most cases, the criteria were vague, often citing general areas with high truck volumes without specifying a clear selection process (Ardalan, 2020). The development of Figure 14 represents a critical step in identifying which intersections are most suitable for truck priority implementation. This section outlines the operational and cost-based criteria used in the evaluation, as well as the number of intersections excluded at each stage of the process.

4.1.1 Operational Criteria

When compiling FSP guidelines from previous studies, primary factors such as slack time, major and minor street designations, Average Annual Daily Traffic (AADT), and the percentage of heavy vehicles were considered as key criteria used in the methodology of this study (Ardalan, 2020)

1) Slack Time

One of the main focuses that is addressed in the methodology is slack time. This criterion was introduced by a FSP checklist by Ardalan in 2020 and previously identified in 2018 study by Kaiser et al. also focused on FSP implementation guidelines. Slack time refers to the portion of the green phase at a signalized intersection that can be reallocated or extended for priority vehicles, such as freight trucks or transit, without adversely affecting cross traffic or pedestrian phases. Essentially, it is unused green time that can be safely shifted to extend the priority vehicle's green interval without causing significant delay or safety concerns for other road users (FHWA, 2021). Slack time in this study was calculated as the difference between the total signal cycle time and the sum of all minimum pedestrian clearance intervals and minimum green times allocated for left-turn movements (Ardalan, 2020).

Even though the study area is represented as a predominantly industrial area, it's essential to recognize the urban movement patterns within the region. Since the implementation of FSP in this study involves extending the green time for the applied movement, there is a potential concern for the reduction of green time for cross traffic movements. Therefore, this criterion was vital in the methodology as it reflects the flexibility within the traffic signal cycle without affecting the flow of cross traffic or pedestrian movements and ensures that FSP implementations are effective and smoother for the applied signalized intersections.

2) Importance of intersection

Next, minor streets were identified as locations where LCVs are restricted from making left-turning movements by utilizing the LCV usage study provided by Peel Region. In addition, it was identified that minor streets typically do not require priority measures, as their traffic volume is generally lower than major streets, therefore, resulting in fewer freight vehicles needing priority. In addition, providing priority measures on minor roads could negatively impact the flow of major roads as it may slow down traffic leading to inefficiencies and congestion. To prioritize maximum green time for the major streets, detectors on minor roads are set to semi-actuated mode, this means the green phase for minor roads is activated only when a vehicle is detected waiting (Smith, et al., 2005). Therefore, adding freight priority measures on minor roadways may impede major roadways traffic flow and no additional priority will be given regardless of truck percentages.

The main factor in evaluating whether a signalized intersection will receive priority is the percentage of trucks against the guidelines of the Transportation Association of Canada (TAC) manual, which recommends a truck traffic percentage range of 14% to 30% for effective implementation of traffic management strategies (Transportation Association of Canada, 2014).

For urban environments, a 14% truck traffic threshold is selected based on the percentage range recommended by the TAC manual for truck-only lanes is on the higher end because the study was done on freeways, where trucks travel more frequently than on urban roadways (Transportation Association of Canada, 2014).

The second factor considered the total traffic volume per day. According to the turning movement data counts from the Synchro data files, which have already surpassed the 20,000 vehicle per peak hour from 7:15 am to 8:15 am threshold. This suggests that the traffic volume meets the criteria for analysis, as the peak hour counts are often used as an indicator of the overall demand on the intersection.

3) Type of priority needed

Since the TAC manual's operational separation guidelines for trucks helps with the implementation of dedicated truck only lanes (DTLL), the criteria are used to verify that the intersection data aligns with these standards. This verification includes assessing factors such as intermodal terminals, level of service (LOS), collision statistics, and the number of lanes at the intersection to ensure compliance with the TAC manual's standards for managing truck traffic.

Intermodal terminals are facilities where different modes of transportation, i.e. truck, train, ships, and airplanes interconnect, this allows for the efficient transfer of goods between them. TAC manual states that the freeway is important enough to receive truck lane priority if the lane is less than 3 kilometres away from an intermodal terminal. The study area is surrounded by the biggest cargo airport in Ontario, Toronto Pearson airport, which is an intermodal terminal.

The next decision input is level of service (LOS). The LOS describes the quality of traffic flow and the effectiveness of transportation infrastructure, particularly roads, highways, and intersections. Usually, the primary consideration for the quality of traffic flow is density which is related to the flow rates and traffic volumes; however, for signalized intersections like the study area, control delay and volume-to-capacity ratio are the primary performance measures considered. Control delay refers to the additional time a vehicle experiences at a traffic signal or stop-controlled intersection beyond what it would take to pass through if no control (like a traffic light or stop sign) was present.

LOS scored range from A to F, A indicating free-flowing traffic with no delays while F is when traffic is at a complete stop and congestion is severe. TAC manual indicates that a lane requires priority when the LOS grade is E or worse. Level E represents frequent delays and slow speeds, and traffic is near capacity, indicating the need for better maneuvering (Transportation Research Board, 2016). Table 5 represents the LOS grades in terms of control delay and volume-to-capacity ratios.

Table 5: LOS Grades for Signalized Intersections

	LOS by Volume-to-capacity Ratio	
Control Delay (sec/veh)	**≤1.0**	**>1.0**
≤ 10	A	F
$> 10 - 20$	B	F
$> 20 - 30$	C	F
$> 35 - 55$	D	F
$> 55 - 80$	E	F
> 80	F	F

The TAC manual identifies intersections with truck collision rates above the national average as priority locations for priority measures. Collision statistics are a critical component in prioritizing and improving safety in areas with high truck traffic ensuring that the safety of the area is a priority. While no specific data is available for the number of truck related collisions in the Region of Peel, Ontario reported a truck collision rate at 5.4 per 100 million Vehicle Kilometres Traveled (VKT) for 2021, which is higher than the national average for truck crashes in Canada. Nationally, Canada had a truck collision rate of about 4.2 per 100 million VKT for 2021 (Transport Canada, 2021; Ministry of Transportation, 2021). These figures highlight the need to consider collision risk as a key measure when selecting intersections for truck priority measures.

The number of lanes at in the TAC manual specifies that the freeway must have four or more lanes in each direction to accommodate truck priority measures. This requirement does not typically apply to intersections as having four through lanes is unconventional. At the intersections, the number of lanes counted is with the addition of left and right turning lanes. When evaluating a dedicated left-turn lane, the receiving lanes must have enough capacity to accommodate at least two left turn lanes.

Studies conducted by Ardalan and Kaisar et al. (2020) examined criteria for implementing freight and transit signal priority, with both emphasizing the importance of Volume-to-Capacity (V/C) ratios. Specifically, when the V/C ratio exceeded 0.85, the studies recommended the implementation of freight signal priority to improve traffic flow efficiency. This study found that the criteria for DTLL were also applicable to the implementation of FSP, as they are equally important to assess. Therefore, the truck priority criteria are combined in the flow chart.

Assessing the availability of sufficient space is essential for both applications. This ensures that the well-studied base plan of intersections aligns with regulatory guidelines and stakeholders' needs. These plans include existing and proposed elements such as pavement edges, islands, sidewalks, right-of-way, and pavement limitations. Depending on the type of priority, whether FSP or DTLL, implementation measures like integrating check-in/check-out detectors and adding a new left-turn lane must be examined to avoid negative impacts on utilities and stormwater systems. The feasibility of adequate space for DTLL installation is a critical factor. If space constraints hinder DTLL implementation, FSP must be explored as an alternative, and vice versa.

4) Feasibility

To assess the feasibility of implementing truck priority measures, a microsimulation tool like VISSIM is essential for evaluation. It was assumed that a 5% decrease in travel time would be sufficient, as this threshold was verified through a benefit-cost analysis for the truck priority measures individually (Victoria Transport Policy Institute, 2023). This assumption stems from previous studies and experience with similar transportation measures. A 5% reduction in travel time has often been observed as a typical benefit from truck priority measures or Traffic Signal

Priority (FSP) systems (Kaisar, et al., 2021; Rakha, 2006), where the goal is to minimize delays for freight traffic.

5) GHG Emissions

If this threshold is not met, the combination of FSP and DTLL is considered for further evaluation. For the second performance measure, greenhouse (GHG) gas emissions are assessed by comparing the lowest alternative against each alternative, rather than aiming for a specific reduction. Figure 14 shows the strategic methodology of selecting ITS techniques for intersections performance improvements using the criteria stated above.

4.1.2 Cost Criterion

The payback period for implementing and construction of transportation engineering projects can vary significantly based on the scale of the project. Larger projects, like highway expansions or major urban truck lanes, often require substantial investment and might take 10 to 20 years to pay back the costs. For instance, projects like the Highway 407 ETR in Ontario, a major toll highway with significant infrastructure and technological upgrades, have a longer break-even timeline due to the higher capital costs involved and the broader scale of the improvement.

On the other hand, smaller projects, such as intersection upgrades or localized truck priority systems, can pay off much quicker. These projects typically focus on improving traffic flow at specific intersections or corridors, which have lower upfront costs and can provide quicker benefits. In these cases, the payback period is often much shorter, ranging from 1 to 5 years, depending on factors such as traffic volume, the scale of the improvements, and the level of congestion in the area.

The cost of implementing FSP can vary depending on whether existing equipment can be reused or if new equipment is required. If existing equipment can be leveraged, the cost per intersection typically ranges from $4,000 to $7,000. This lower cost is possible because the necessary infrastructure (such as signal control systems and traffic detectors) is already in place, and only minor modifications or upgrades are needed (Translink, 2020).

While travel time savings is a primary benefit, it is important to note that FSP systems also contribute to several other benefits, which enhance their overall value. Reduced emissions are another key benefit of FSP, as trucks can spend less time idling or waiting at intersections, which leads to lower fuel consumption and fewer emissions. In addition, reducing delays for trucks also helps to alleviate congestion, making the road network more efficient for all vehicles, not just freight. Trucks typically occupy more road space, accelerate slower, and have longer stopping distances than passenger vehicles which disrupts traffic flow, especially in urban settings where passenger vehicles cannot overtake trucks. Given these additional benefits, the 5% reduction in travel time considered in this analysis is a conservative estimate that accounts solely for the travel time savings.

However, if the existing equipment is outdated or incompatible with the truck priority measures, the cost to replace equipment may range from $25,000 to $40,000 per intersection. This higher cost accounts for the complete installation of new systems, including upgraded signals, detectors, and potentially new traffic management software. The need for new infrastructure could also include work like new wiring, installation of communication systems, or other technical requirements to enable the priority measures to function effectively (Translink, 2020).

The 5% travel time evaluation threshold for dedicated left-turn lanes are expected to have minimal construction costs, as most intersections already feature two left-turn lanes. Converting one of these into a truck-only left-turn lane would primarily involve operational separation measures, rather than major structural modifications. Since a raised median cannot be considered for separation, the primary costs would be limited to signage and pavement markings to clearly designate the lane for truck use.

For truck-only lanes, special pavement markings, such as diamond symbols or truck lane identifiers, must be incorporated into the cost analysis. Previous projects provide useful cost benchmarks: the pavement widening on Lakeshore Rd West and the realignment of Clarkson Road North estimated the cost of pavement markings and signage at $5 per meter (City of Mississauga, 2022). Additionally, data from the Town of Innisfil suggests that permanent roadway signage costs approximately $265 per sign (Town of Innisfil, 2022).

Material durability is also a key factor in cost considerations. Ontario Traffic Manual stated that hot-applied thermoplastic markings, while more expensive upfront, can last three to fifteen times longer than standard painted markings. Thermoplastic is also highly resistant to de-icing chemicals and sand, making it a cost-effective alternative for high-wear truck lanes where longevity and visibility are critical (Ministry of Transportation, 2000). Therefore, the maintenance costs associated with pavement markings and signage would be deferred further into the project's lifespan, as the use of durable materials would reduce the frequency of required reapplications. This contributes to long-term cost efficiency, minimizing ongoing upkeep expenses compared to conventional painted markings.

4.2 Decision Tree Flowchart

The total study network includes 32 signalized intersections; however, after excluding those involving minor roads, only 13 intersections are classified as major to major. These intersections account for 33 individual left turning movements (e.g. westbound left, eastbound left, northbound left, southbound left). Applying the initial criteria, slack time, did not eliminate any intersections. Truck percentage criteria appeared to be more concise as it narrowed down the selection to 10 intersections, covering 16 individual left turning movements, roughly half the number of left turning movements initially considered.

Applying the truck priority criteria, reduced the number of intersections to 9 intersections and 14 left turning movements. Particularly, all intersections that qualified for FSP also met the requirements of DTLL. Following the microsimulation analysis, the travel time savings threshold did not eliminate any additional intersections. As a result, the total was 9 intersections and 14 turning movements that meet all levels of the decision tree criterion.

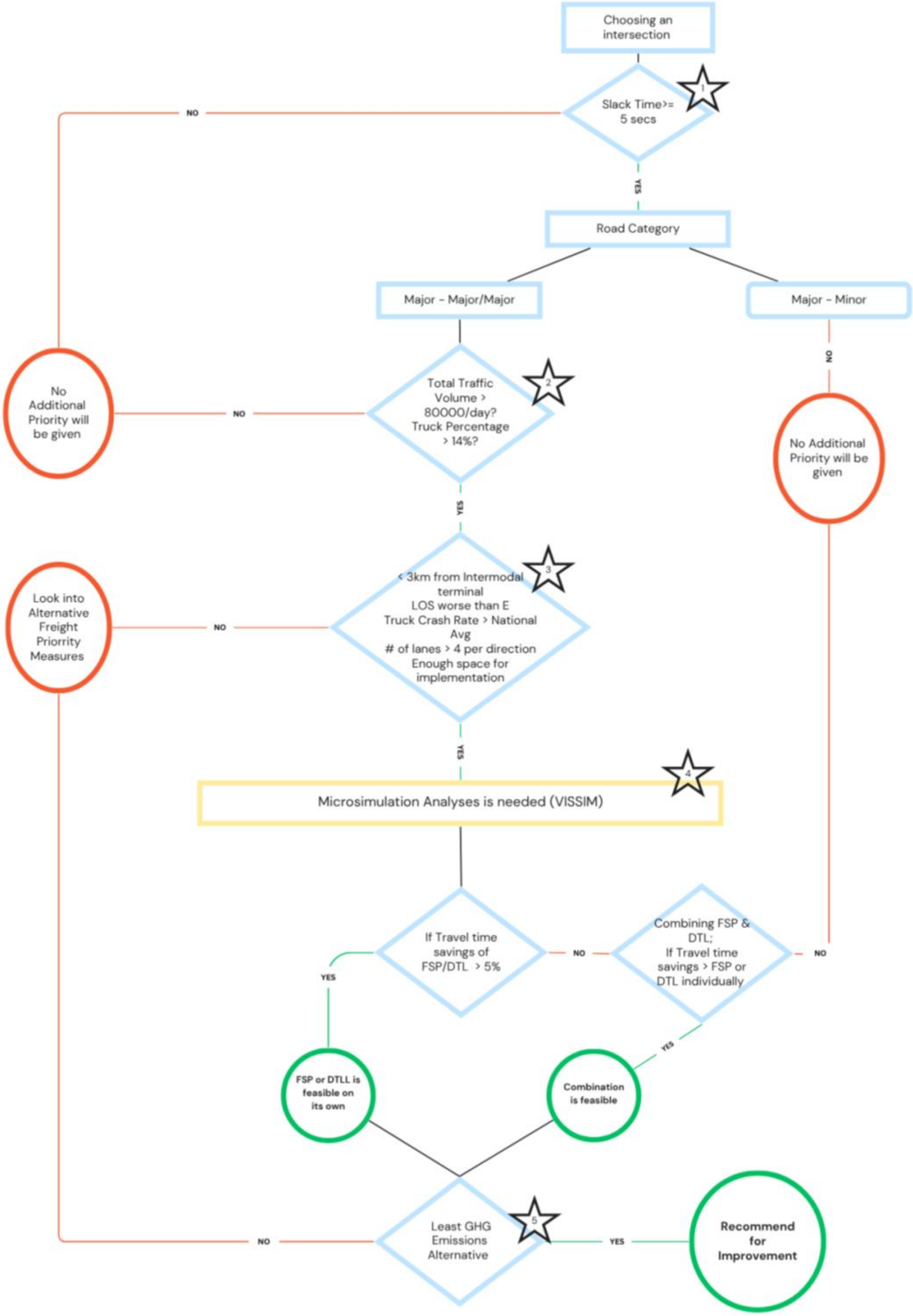


Figure 14: Strategic Methodology of Selecting Truck Priority measures for Intersections

4.3 Updated Study Network

Since the decision tree refined which signalized intersections require truck priority measures within the study network, the study network was updated to reflect these changes. The following Table 6 represents the final list of intersections and corresponding left turning movements that were also identified through the decision tree criteria, and visually shown into Figure 15.

Table 6: Intersections and Movements that Received Priority

Intersection	Movement
Steeles Ave E. and Dixie Rd.	NBL
Derry Rd. and Dixie Rd.	EBL
	NBL
Matheson Blvd E. and Dixie Rd.	EBL
Britania Rd E. and Dixie Rd.	EBL
	WBL
	SBL
Tomken Rd. and Derry Rd.	NBL
Kennedy Rd S. and Derry Rd	WBL
	NBL
Airport Rd. and Derry Rd E.	EBL
Cardiff Blvd. and Derry Rd.	EBL
Tomken Rd. and Steeles Ave E.	WBL
	NBL

Figure 15 shows the total study network that spans 19.2 km and includes 32 signalized intersections and five unsignalized intersections, with seven major intersections on Derry Road, five major intersections along Dixie Road, and four major intersections along Steeles Avenue. The blue boundary around the dots represent the signalized intersections, the green dots identify unanalyzed intersections along the corridor, while the red dots show the identified intersections that will receive the different types of truck priority along the study network.

In addition, the map indicates that many warehouses are located near intersections prioritized through the study's decision tree methodology. This arrangement suggests that the decision tree effectively identifies key logistical hubs, enhancing transportation efficiency and accessibility for freight movement.

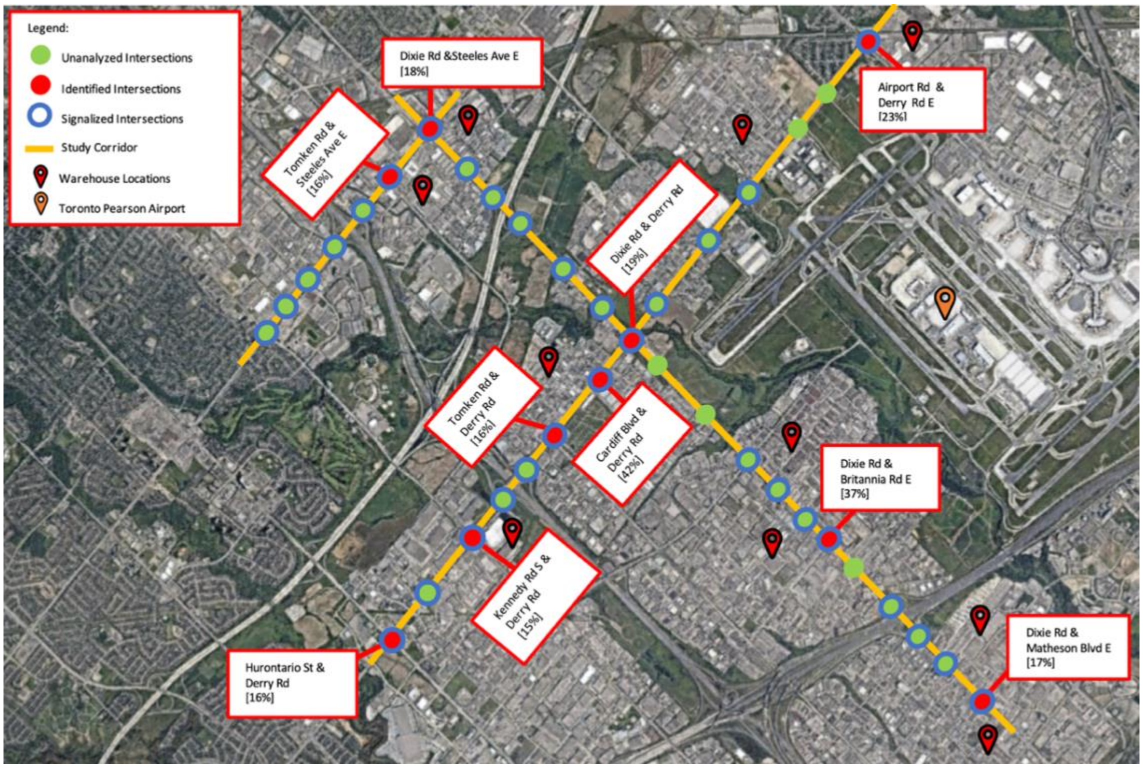


Figure 15: Study Network with Identified Intersections

4.4 Methodology Discussion

To evaluate the operational and environmental impacts of the proposed freight priorities measures, the study utilized PTV VISSIM 2024 to conduct microsimulation-based analysis of travel time and GHG emissions from the implementation of 5% HCV platooning, DTLL, and FSP across the study network. VISSIM was chosen over other microsimulation platforms such as

Aimsun due to its flexibility in customizing vehicle dynamics and signal control behavior. It allows detailed, vehicle-level modeling, making it ideal for analyzing the interactions between passenger vehicles, HCVs, LCVs, and HCV platooning at signalized intersections. Key driving behaviors such as car-following and lane-changing were modelled using Wiedemann 74 and Wiedemann 99 parameters. This allows for the calibration of different vehicle classes, specifically important when simulating freight-specific characteristics like LCVs and HCV platoons, which are not standard vehicle types in VISSIM and required custom parameter adjustments.

The simulation process began with the development of a base network in PTV VISSIM 2024, which involved inputting essential traffic data including traffic volumes, vehicle classifications, turning movement counts, signal phasing, and signal timing plans. These inputs were sourced from Synchro files provided by the Region of Peel. The model was calibrated and validated using the GEH statistic, ensuring that simulated traffic flows closely matched observed conditions.

In order to evaluate the operational and environmental performance of the proposed scenarios, this study defines a set of Measures of Effectiveness (MOE), including travel time and greenhouse gas (GHG) emissions. These MOEs are critical indicators for assessing the impacts of freight priority strategies and vehicle technologies on corridor efficiency and sustainability. Travel time, in particular, was chosen based on its common use in previous studies analyzing the effects of signal priority measures (Kaisar, et al., 2021). A more detailed breakdown and discussion of these metrics, including separate analyses for heavy commercial vehicles (HCVs), long combination vehicles (LCVs), and HCV platooning scenarios, is presented in the results chapter.

CHAPTER 5: SIMULATION MODEL DEVELOPMENT

This chapter discusses the setup, calibration, and simulation of traffic scenarios using PTV VISSIM 2024 to replicate real-world traffic conditions on study corridors. Key driving behaviors such as car-following and lane-changing are modeled using Wiedemann 74 and 99 parameters and the differences between them. The chapter explains adjustments made to simulate LCVs and HCV platoons, as these are not standard VISSIM vehicle types. Input data for traffic volumes, vehicle types, signal phases, and intersection controls were gathered from sources like Google Maps and Synchro files from Peel Region.

The chapter also discusses how model calibration and validation were done using the GEH statistic, ensuring that the simulated scenarios closely reflected real-world traffic patterns.

In addition, it discusses the development of various simulated scenarios, including the base case scenario with LCVs, the base case with the addition of HCV platooning, freight signal priority (FSP), and a dedicated truck left-turn lane (DTLL).

5.1 VISSIM Model Parameters

To simulate traffic along the study corridor, PTV VISSIM 2024 was used due to its ability to mimic real-world traffic conditions effectively through its car-following and lane-changing behaviors. While the Wiedemann 74 (W74) model is commonly used for urban arterials because of its accuracy in representing typical traffic flow, the Wiedemann 99 (W99) model is more suitable for simulating HCV platoons and autonomous driving behavior. The PTV group recommends the use of W99 for vehicles with adaptive cruise control and autonomous technology, as it offers 7 additional parameters compared to W74. These additional parameters enable more advanced control over vehicle interactions, including time headways and interaction with surrounding objects and vehicles, which are both critical when simulating HCV platoons (Sukennik, 2018). Since LCVs and HCVs share similar characteristics aside from vehicle length, LCV driving behavior was modeled based on HCV driving behavior (AASHTO, 2018; TAC, 2017). A comparison between the parameters of these models, included the look-ahead and back distance, interaction objects, standstill distance, time headway, and safety distance reduction, as seen in Table 7.

Table 7: Driving Behavior Input Parameters

Input Parameters	**Wiedemann 74**		**Wiedemann 99**		
	Default	HCV	Default	HCV/LCV	HCV
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	2	1	3
Number of interaction vehicles	99	1	99	1	2
Average standstill distance (m) for a following car	2.0	3.77	NA	3.77	3.77
Average standstill distance (m) for a following HCV	2.0	3.37	NA	3.37	3.37
Standstill distance (m) for a following HCV platoon	NA	NA	1.5	NA	1.00
Time headway (s)	NA	NA	0.9	NA	0.6
Maximum deceleration for cooperative braking (m/s^2)	-3	-1.62	-3	-1.62	-1.62
Safety distance reduction factor (m)	0.6	0.6	0.6	0.6	1

In the W99 model, the look ahead and back distance for HCV platoons is set to 300 meters, this follows the NHTSA's recommendations for the communication range needed by autonomous vehicles. W74 limits the number of interaction objects, the number of vehicles or infrastructure a vehicle can respond to simultaneously, to one for conventional HCVs. Since human drivers typically interact with traffic signals or nearby vehicles. On the other hand, W99 allows HCV platoons to interact with multiple objects simultaneously. The interactable objects refer to several leading vehicles in a platoon, merging vehicles, surrounding traffic, and even infrastructure like traffic signals or road signs. Due to the vehicle-to-everything (V2X) technology equipped in autonomous vehicles and HCV platoons, which improves operational efficiency.

Standstill distance refers to the minimum gap maintained between a leading and a following vehicle when both are stopped (Ahmed, et al., 2021). In W74 has no specific standstill distance defined for following HCV platoons, but W99 introduces a distance of 1.00 meter to avoid collisions within the platoon. Studies on time headways between two HCVs in platoons on highways have studied various ranges, between 0.6 and 1.2 seconds. The shorter interval of 0.6 seconds is more appropriate for urban areas, where slower traffic speeds allow the vehicles in a platoon to maintain closer spacing and better coordination. According to Shladover et al., cooperative adaptive cruise control which is enabled by vehicle-to-vehicle communication, allows the 0.6 second headway to be feasible. Chowdhury et al. (2019) also supported the use of 0.6 second headway on urban arterial roads when examining two HCV platoons. Therefore, this study set the headway time as 0.6 seconds.

Vehicle speeds were assigned according to posted limits for cars and trucks, with reduced speed zones implemented for right and left turns. To ensure that the simulation model accurately reflected the real-world traffic conditions, input parameters such as lane configurations, tapered lanes, and road geometry were gathered using Google Maps.

VISSIM's standard vehicle types do not include LCVs, so for this study, LCVs were defined as being 25 meters in length. Also, HCV platoons were not part of VISSIM's default settings. The parameters for an HCV platoon can vary based on the number of HCVs, the length of each vehicle, and the headway between them. For this study, platoons were defined as consisting of two HCVs, as this represents the minimum viable configuration, with most operations anticipated to begin with vehicle pairs. Considering challenges associated with turning movements at intersections along urban arterials, testing platoons with more than two HCVs is deemed not urgent at this stage as difficulties encountered by two HCV platoons in maneuvering urban intersections will suggest that testing with three or more HCVs may not necessarily. In this study, the HCVs were defined as WB-20 vehicles, the longest standard single-trailer HCVs available in North America, measuring 22.70 meters in length. This decision was made so that the platoon length is representative of typical HCV configurations used in North America (Transportation Association of Canada, 2017; AASHTO, 2018).

An important factor influencing the simulation of freight vehicle behavior in the VISSIM model is the vehicle turning envelope, which affects lane usage and turning maneuvers at intersections. The turning envelope refers to the area a vehicle sweeps while making a turn. HCVs have larger turning envelopes than passenger vehicles due to their greater length, wider tracking, and off-tracking behavior, which can create conflicts with curbs, medians, and adjacent lanes (AASHTO, 2011). LCVs share most handling characteristics with HCVs but require even more space because of their increased overall length. Peel Region highlighted that when creating the LCV usage map, the internal roadways and driveways serving LCV supported facilities should be designed to accommodate the swept path and minimum turning radius requirements of LCVs (Hussain, 2019). In a 2024 study by Marchesan, the swept path analysis of existing roads showed mixed results. Under current intersection designs, LCVs cannot safely complete turns when restricted to a single lane on both the origin and destination roads. However, when permitted to encroach on a second lane on the destination road, the intersection geometry can accommodate these vehicles, as turnpike doubles are able to complete the turn without conflict in most situations (Marchesan, 2024). Therefore, this study assumed that in the DTLL scenarios the freight vehicles would utilize the outer left turn lanes.

Finally, the simulation was run for an 8,000 second period, beginning with a 3,600 second warm up phase at half traffic volumes, followed by a 3,600 second data collection period, and concluding with a 200 second cool down phase. PTV group suggests a warm-up period before the main analysis begins to let traffic build up and avoid unrealistic free-flow conditions at the start (PTV Group, 2025). Wisconsin DOT suggests a warm up phase of maximum 3600 seconds if traffic counts are high (Wisconsin DOT, 2019). A short cool down phase allows vehicles already in motion to exit the network without affecting the collected data set, Washington DOT suggests setting this to 200 seconds (Washington State Department of Transportation, 2014).

5.2 Model Calibration and Validation

The study used the GEH (Geoffrey E. Harver) statistic to ensure that the base case scenario closely mirrored real-world traffic conditions, which helps to validate the test scenario results. The GEH statistic shown in Equation 1, compares simulated and observed AM peak-hour traffic. A GEH value of less than 5 indicates a well-calibrated model, values between 5 and 10 are considered decent, and values greater than 10 suggest poor calibration (Doustmohammadi, 2017; Dowling, 2004).

$$GEH = \sqrt{\frac{2(m-c)^2}{m+c}} \qquad \textbf{(1)}$$

Where:

m = simulated AM peak traffic volume for an hour; and

c = observed AM peak traffic volume for an hour.

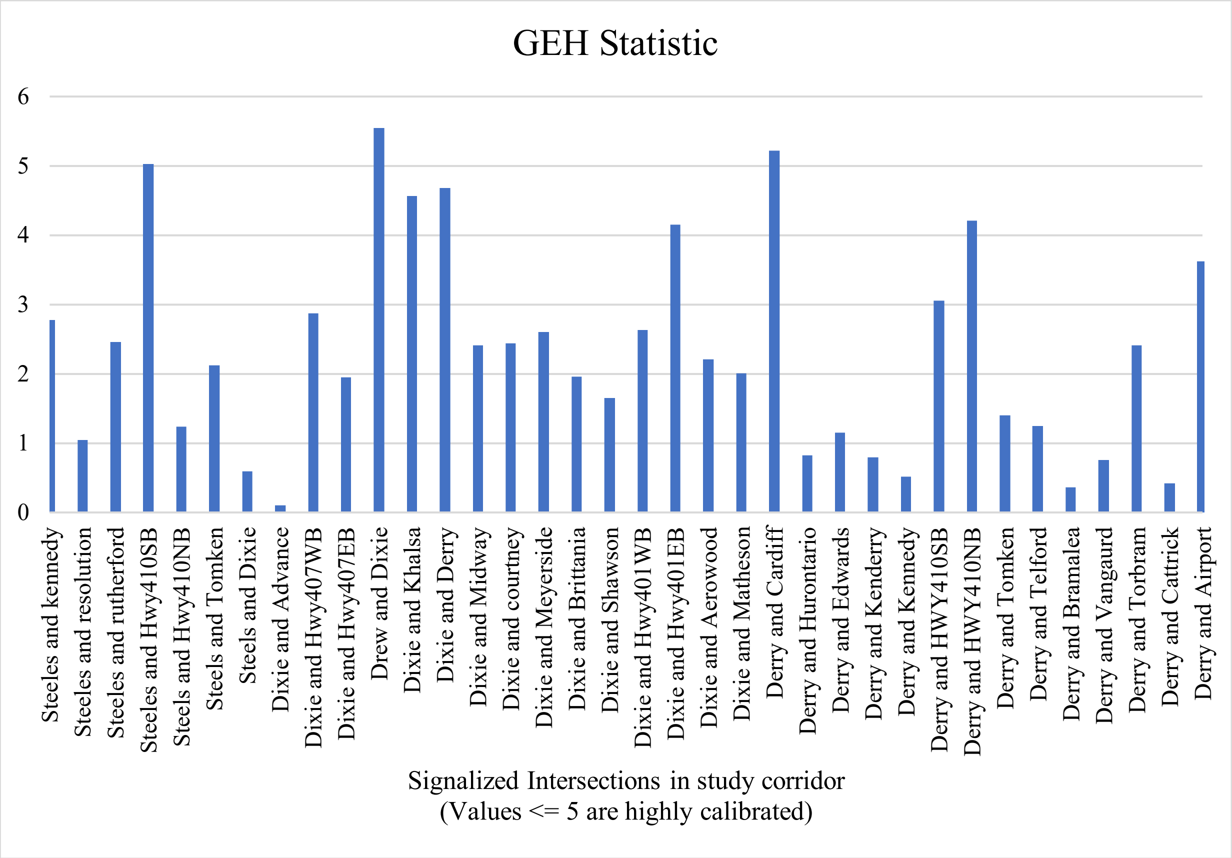


Figure 16: GEH Result of Study Corridor

According to Fries et al., a well calibrated model should be simulated 10 times and achieve a GEH value below 5 for 85% of the network. While GEH values between 5 and 10 remain within an acceptable range. Figure 16 shows a GEH graph showing a 92% compliance rate, although some intersections in the simulated scenarios exhibit value higher than 5. The highest GEH value of 5.5 corresponding to Drew Rd. and Dixie Rd. intersection which is within the acceptable range. These results suggest that the base model is properly calibrated to simulate real-world traffic.

5.3 Simulation Scenarios

To evaluate the operational and environmental impact of 5% market penetration rates of Level 4 HCV platooning on urban arterials, both with existing traffic conditions and with the addition of FSP, DTLL and their combination.

The study consists of eight simulation scenarios divided into two groups. The first group (Models 1–4) simulates current traffic conditions with 5% LCVs, while the second group (Models 5–8) introduces a 5% market penetration of Level 4 HCV platooning. Each group follows the same set of alternative solutions: a baseline do-nothing scenario (Models 1 and 5), the application of Freight Signal Priority (FSP) at left-turning movements (Models 2 and 6), the implementation of Dedicated Truck Left-Turn Lanes (DTLL) (Models 3 and 7), and a combined scenario using both FSP and DTLL (Models 4 and 8).

The first four represent the base model with alternative solutions:

1. Model 1: Do-nothing scenario (base traffic) with an assumption of 5% LCV;
2. Model 2: Base traffic with FSP on the Left Turning Lane;
3. Model 3: Base traffic with the dedicated Truck Left Turning Lane;
4. Model 4: Base traffic with FSP as well as the dedicated Truck Left Turning Lane;

The next four models simulate base scenario with 5% HCV platooning assumption and alternative solutions:

5. Model 5: 5% HCV platooning with base traffic;
6. Model 6: 5% HCV platooning with FSP on the Left Turning Lane;
7. Model 7: 5% HCV platooning with the dedicated Truck Left Turning Lane;
8. Model 8: 5% HCV platooning with FSP as well as the dedicated Truck Left Turning Lane;

Model 1 represents the do-nothing scenario with 5% LCV assumption, but no HCV platooning applied. The road network was modelled using Google Earth, this included link length, road width, and length of tapered turning lanes. Vehicle composition included both passenger vehicles and freight vehicles, within the freight vehicles 5% were classified as LCVs and the remainder were single unit trucks. According to Hussain (2019), which examines LCV usage in the Peel Region, 5% of LCV trips either originate from or have a destination within Peel Region. Therefore, in this study, the freight vehicles are classified as 5% LCVs with the rest being comprised of single unit trucks.

Heavy vehicle percentages and signal timings at intersections were determined using Synchro data provided by Peel Region, which provided data on green time, red and amber time, cycle lengths, position signal heads, detectors at intersections, and whether signals were fully or semi-actuated. Reduced travel speeds for turning movements were applied at intersections for turning movements and unsignalized intersections were modeled as stop-controlled.

In addition, vehicle volumes, including truck percentages, were obtained from Synchro data. The Synchro dataset provides traffic volumes at individual intersections only, resulting in inconsistent traffic volumes between adjacent intersections. This is because vehicles may enter or exit from parking areas, plazas, and/or other destinations located along the links between intersections. To address this, traffic volume balancing tasks are performed to align link volumes with the in-and-out traffics to street-side destinations in order to ensure consistency in traffic volumes in adjacent intersections. Figure 17 demonstrates how street layout, such as the number of lanes, turning lanes, and other details, gathered from Google maps for an intersection has been integrated into VISSIM network. The maximum desired speed was determined to be equal to the posted speed limit for both cars and trucks. At intersections, the yellow strips represent reduced travel speed during right and left turning movements were considered to be reduced-speed zones. Cars making right turns were determined to do them at a speed of 15 km/h, while left turning cars were set at a speed of 25 km/h. while trucks, the right-turning speed was set to be 12 km/h, and the left-turning speed was set to be 20 km/h (City of Toronto, 2016; Hendriks, 2015). The blue boxes represent the detectors placed for a semi-actuated signal control.

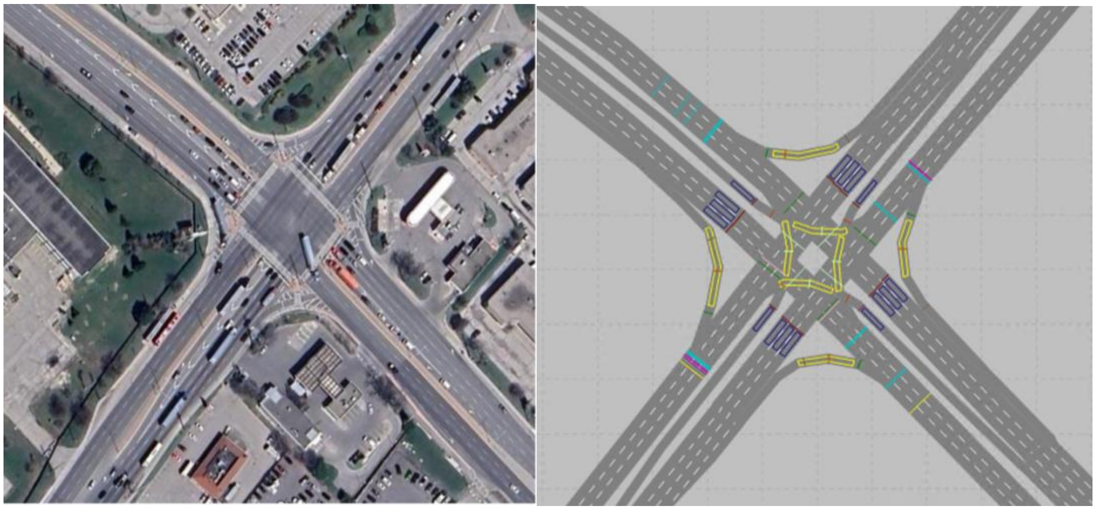


Figure 17: Google Maps Translated to VISSIM

Since models 2 and 6 implement the Transit Signal Priority (FSP) scenario, this study will discuss them together. Model 2 represents base traffic with 5% LCVs, and Model 6 includes 5% LCVs along with 5% HCV platooning. This scenario focuses on extending the green time phase at intersections to prioritize left turning freight vehicles. This extension was equipped with FSP detectors (shown in the red box in Figure 18) to identify HCVs, LCVs, and HCV platoons and was applied at nine intersections, which amounts to thirteen left turn movements across the study corridor.

Zhou et al. (2006) reported the effectiveness of FSP through a VISSIM microsimulation which identified optimal bus detector locations. The results showed that queue jump lanes should be placed approximately 130 to 170 meters before intersections, depending on traffic volumes. Kaisar et al. (2018) recommended positioning check-in loop detectors based on the Minimum Stopping Sight Distance (MSSD) for through movements as defined by AASHTO. For this study, detectors were placed beyond the left-turn lanes, starting at the connector, which enhances safety and improves the effectiveness for left turning movements. This placement was adjusted through trial and error because, when detectors were positioned according to AASHTO standards, they detected the trucks too early. This caused the green light extension to expire before the truck could complete its turn, as trucks tend to slow down significantly during left turns.

Following the guideline stated by Ioannou et al. (2015), the green time for left turning movements was extended by 8 seconds. While FSP typically extends the green time by 8 to 15 seconds for through movements, a more conservative approach was chosen for left turns, providing an 8 second extension to ensure smoother traffic flow for freight vehicles.

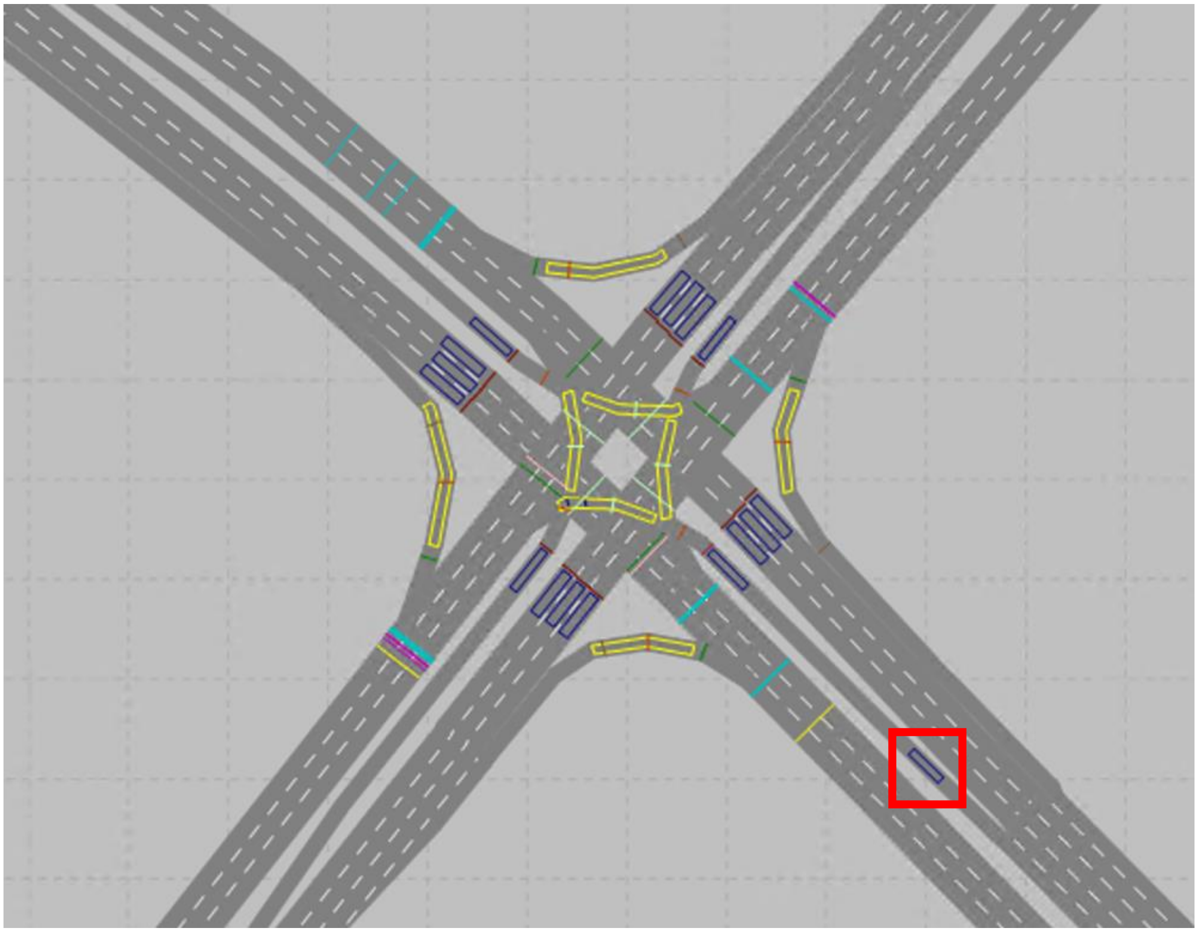


Figure 18: Application of FSP in Models 2 and 6 at Steeles Ave. and Dixie Rd.

Since Models 3 and 7 introduces a dedicated truck left lane (DTLL), this study will discuss these models together. Model 3 assuming 5% LCV and Model 7 assuming 5% LCV, with 5% HCV platooning. The truck only lane restricts trucks to using the outermost left lane, as highlighted in the literature review. Figure 19 shows the addition of a left turn lane at the original intersection, the red box shows the additional left lane added.

Certain intersections, such as Cardiff Blvd. and Derry Rd., have only one left turn lane. Despite this intersection being a significant freight hub, there are not enough physical space to implement a truck only lane. Therefore, to accommodate truck only lane design, the expansion of the single left lane to dual left lanes is necessary. The design of the new left lane was started at the existing left turn taper as this reduces confusion for last minute merging of passenger vehicles. In addition, the new left lanes were designed to mirror the length and taper of the original lane. This ensures a smooth transition for vehicles moving from the existing left lane to the new left lane taper, reducing potential confusion and enhancing overall traffic operations. Before introducing the second left lane, factors such as existing or new edges of pavement, islands, sidewalks, right-of-way, and pavement geometry outlined in the intersection plan need to be considered. It is important to ensure that this surface improvement does not negatively impact utilities and stormwater drainage systems, therefore, an assessment of space requirements before implementation is required.

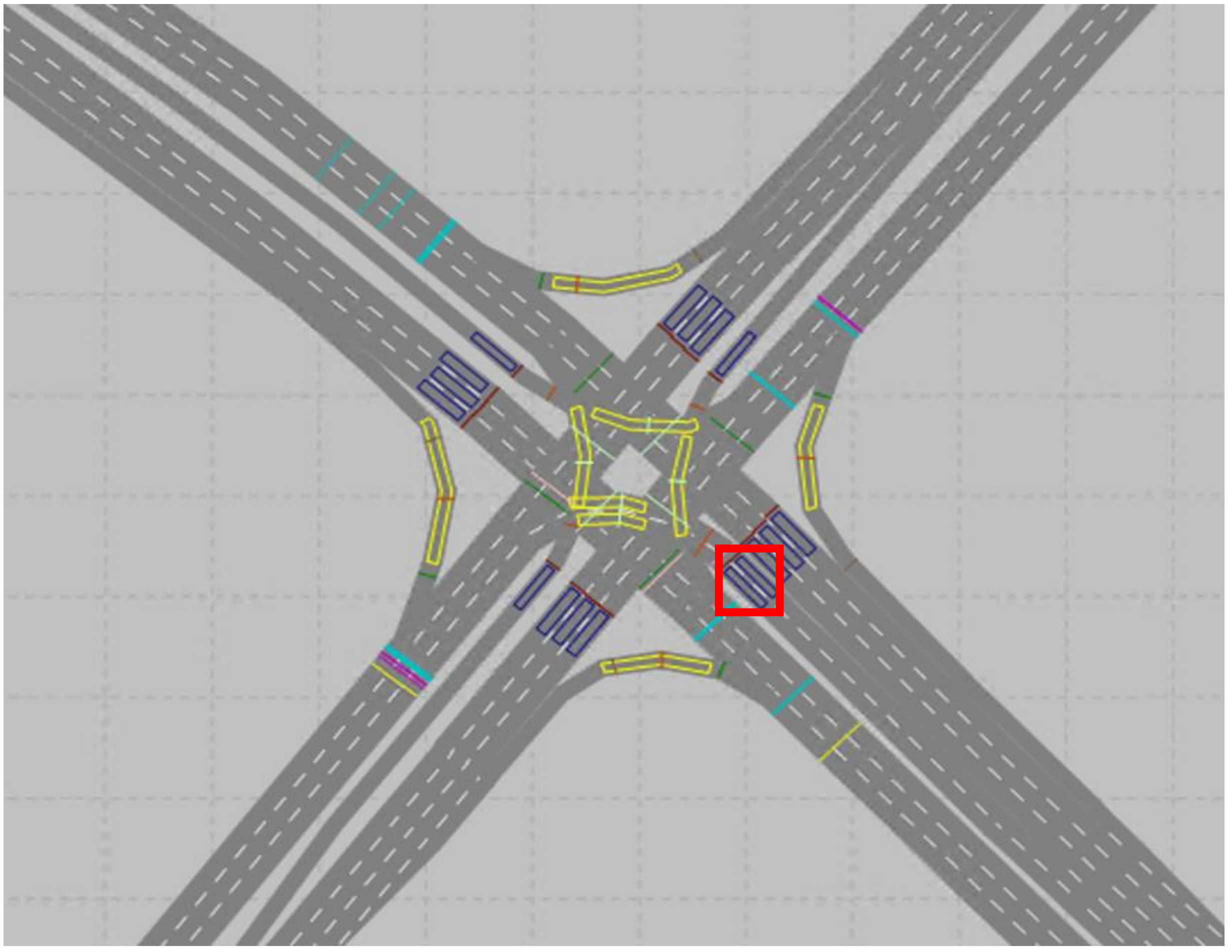


Figure 19: Application of DTLL in Models 3 and 7 at Steeles Ave. and Dixie Rd.

Models 4 and 8 incorporate both FSP and DTLL features to improve traffic operations, therefore, these two models will be explained together. Model 4 reflects base traffic conditions with an assumption of 5% LCVs, while Model 8 includes 5% of vehicles representing 2-HCV platooning with the same percentage of LCVs. As discussed in Models 3 and 7 where DTLL is implemented, an additional left lane is introduced, specifically designed to accommodate heavy vehicles. In Models 4 and 8, this new lane is equipped with check-in and check-out detectors that support the FSP functionality, Figure 20 shows that with the addition of the new left turn lane, an FSP detector was installed, as highlighted in the red box, two detectors are now placed.

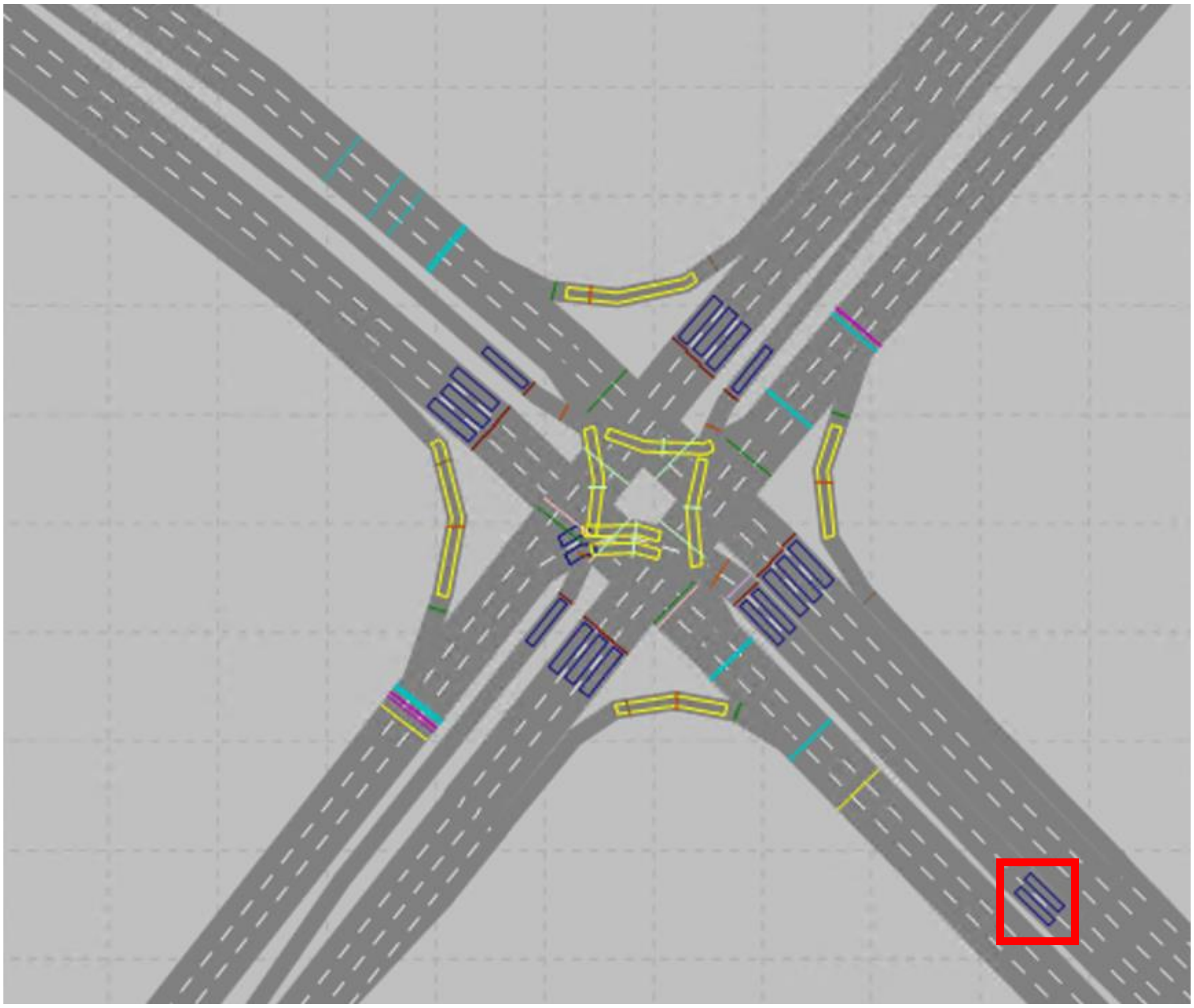


Figure 20: Application of FSP+DTLL in Models 4 and 8 at Steeles Ave. and Dixie Rd.

CHAPTER 6: ANALYSIS RESULTS

This chapter discusses the study results conducted for each of the eight models. The measure of effectiveness (MOE) used in this study includes travel time and Greenhouse gas (GHG) emissions for all transportation modes, such as passenger and freight vehicles. The MOEs for freight vehicles include analyzing HCVs, LCVs and HCV platooning results and discussing them separately.

6.1 Travel Time Analysis

The results for each model show varied impacts on travel time across the 19.2 km study corridor with 32 signalized intersections, with some models demonstrating more effective time reductions. In this study, the term all vehicles include passenger cars, and freight vehicles. Although the ITS strategies examined are primarily aimed at improving freight mobility, their positive effects extend to the overall traffic network. Freight vehicles tend to accelerate more slowly, require larger gaps for turning movements, and occupy more road space, which can create delays impacting all road users. By enhancing the efficiency and reducing delays for these slower, heavier vehicles, traffic flow improves for passenger vehicles and others sharing the road. On the other hand, prioritizing only passenger vehicles would not address freight-related congestion, restricting improvements to passenger traffic and limiting overall network performance gains.

Figure 21 presents the average travel time results for all vehicles. Figure 21a shows Models 1 to 4, while Figure 21b shows Models 5 to 8, which includes the implementation of HCV platooning. It is important to note that Figures 21 a and b use different y axis scales, reflecting the variations in travel time results between the two sets of scenarios.

Model 4, which combines FSP and DTLL, results in the highest reduction in travel time, reducing 5.77 minutes (3.17%) per vehicle compared with the base scenario (Model 1). Model 3, which includes DTLL only, comes close with a reduction of 5.35 minutes (2.94%) per vehicle, while Model 2, which includes only FSP, provides the lowest reduction of 1.30 minutes (0.70%) per vehicle. Model 4 also results in an overall journey time reduction of 50 hours (1.61%) across the network, while Model 3 and Model 2 achieve reductions of 35 hours (1.13%) and 6 hours (0.18%), respectively.

When HCV platooning is introduced in the existing traffic conditions (Model 5), a significant increase in travel time occurs, totalling an additional 13.09 minutes (6.84%) per vehicle, this leads to an overall journey time increase of 862 hours (24.08%) for a total of 6091 vehicles along the corridor. This increase highlights the challenges posed by HCV platooning under existing conditions.

Contrary to the results in scenarios without platooning, DTLL alone (Model 7) performs worse than FSP (Model 6) when subjected to 5% HCV platooning. Model 6 (FSP with platooning) reduces travel time by 1.82 minutes (0.92%) per vehicle, while Model 7 (DTLL with platooning) achieves only a slight reduction of 0.60 minutes (0.30%) per vehicle compared with Model 5. The DTLL model (Model 7) had around half the number of vehicles in the network than Model 6 and Model 5. This difference highlights how platooning can reduce the effectiveness of DTLL, as the convoy structure of the platoons can block passenger vehicles from entering the storage lane, creating additional delays in the adjacent through lanes as discussed in Figure 5.

The results for the combination of FSP and DTLL under the 5% HCV platooning assumption in Model 8 show a significant decrease in travel time across the corridor. Compared to the scenario with HCV platooning under existing conditions (Model 5), Model 8 reduces travel time per vehicle by 5.28 minutes (2.71%). Compared with the base scenario (Model 1), Model 8 shows an increase of 7.80 minutes (4.14%) per vehicle. While the percentage increase may seem big, this change indicates that the combination of FSP and DTLL can still reduce the total travel time by 118 hours along the study corridor compared with the new conditions of 5% HCV platooning.

Overall, the results demonstrate the effectiveness of the methodology employed in this study. The observed changes in travel time across the models align closely with expectations, indicating that the approach provides a reliable representation of real-world conditions. This consistency between methodology and outcomes reinforces the credibility of the findings and highlights their relevance for enhancing urban freight mobility.

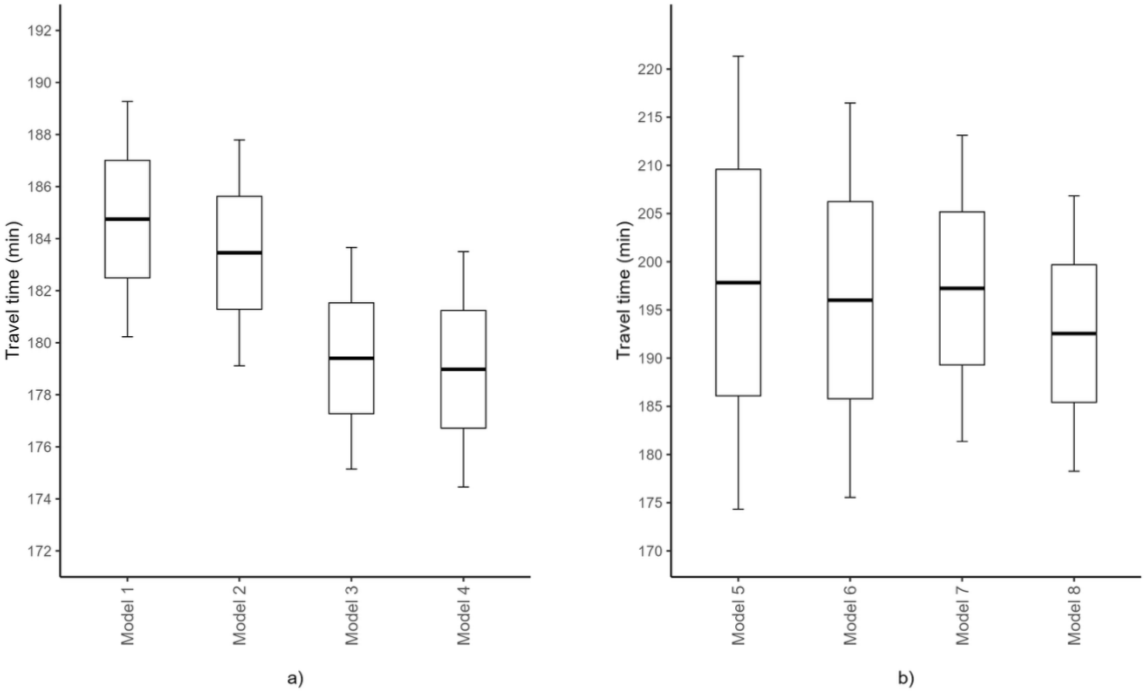


Figure 21: Average Travel Time for All Vehicles a) Models 1 to 4 b) Models 5 to 8

The average travel time per passenger vehicle vary across different models. Figure 22 shows the average travel time per passenger vehicle, with Figure 22a showing results of Models 1 to 4, and Figure 22b presents the results of Models 5 to 8, which implements 5% HCV platooning. It is important to note that Figure 22 a and b have different y-axis scale. Under existing conditions, the implementation of FSP in Model 2 reduces travel time by 0.66 minutes (0.38%) per vehicle, while DTLL in Model 3 shows a bigger reduction of 4.71 minutes (2.76%) per vehicle. This is thought to occur because passenger vehicles experience fewer delays when separated from freight vehicles, as they no longer need to wait behind slower-moving trucks or navigate around large platoons in the DTLL model. The combined strategies in Model 4 achieve the highest decrease, reducing travel time by 5.13 minutes (3.01%) per vehicle. In terms of total journey time savings for all passenger vehicles across the network, Model 2 (FSP) shows a reduction of 2 hours (0.08%), Model 3 (DTLL) results in a decrease of 31 hours (1.12%), and Model 4 (FSP + DTLL) reduces travel time by 42 hours (1.53%).

With the introduction of 5% HCV platooning in Model 5, travel time for passenger vehicles under existing conditions increases by 7.77 minutes (4.40%) per vehicle, leading to a total journey time increase of 749 hours (23.9%) for all passenger vehicles in the network. Truck priorities in Models 6 and 7 do not reduce travel time for passenger vehicles, as the length of HCV platoons blocks taper and shoulder areas during FSP and DTLL, hindering passenger vehicle flow in adjacent lanes.

However, the combination of FSP and DTLL with 5% HCV platooning in Model 8 shows an improvement over Model 5, reducing travel time by 3.95 minutes (2.21%) per vehicle, with a total decrease of 225 hours for all passenger vehicles. Although Model 8 still results in a slight increase from the base case scenario (Model 1), with a travel time increase of 3.81 minutes (2.18%) per vehicle, it performs significantly better than Model 5, which had a 7.77 minute (4.40%) increase. Overall, Model 8 shows an increase of 105 hours (3.73%) for all passenger vehicles compared to the base model, which is far less than the 749 hour (23.9%) increase seen in Model 5.

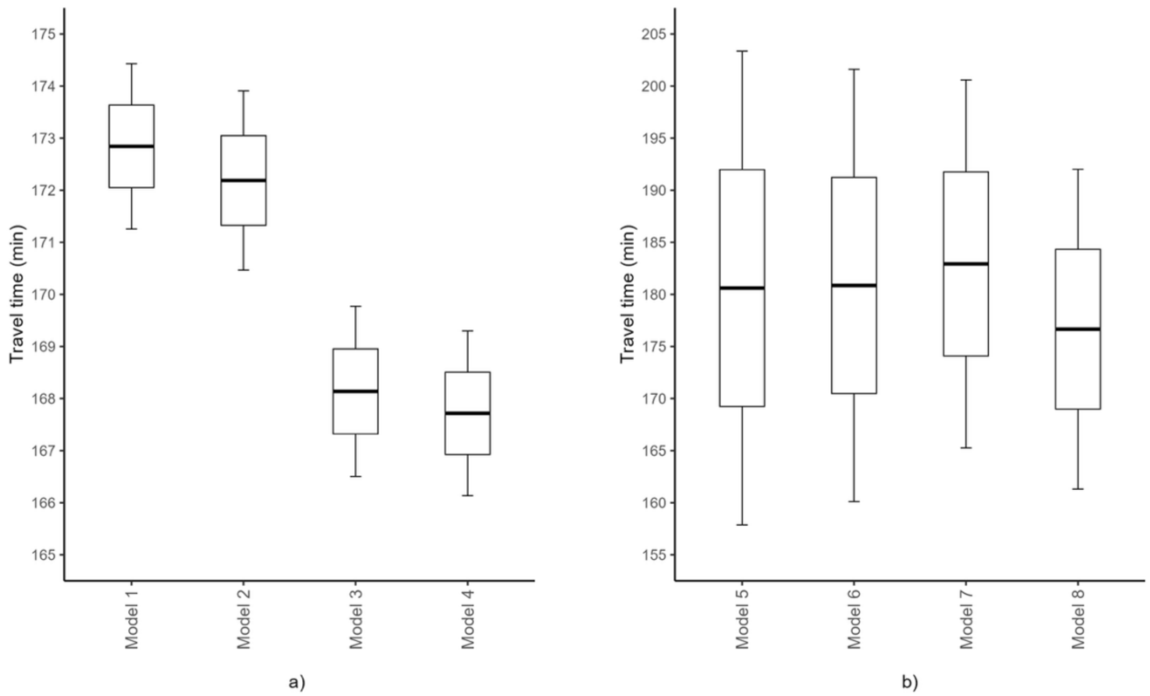


Figure 22: Average Travel Time per Passenger Vehicle a) Models 1 to 4 b) Models 5 to 8

Figure 23 represents the average travel time per HCV across all models. Figure 23a shows results for Models 1 to 4, while Figure 23b focuses on Models 5 to 8, which include HCV platooning. Different y-axis scales are used to capture the variation in travel times specific to HCVs. The travel time per HCV shows reductions under existing conditions in Models 2, 3, and 4, with decreases of 1.08 minutes (0.58%), 5.77 minutes (3.12%), and 5.96 minutes (3.22%) per vehicle, respectively. This transforms to overall HCV journey time reductions of 3 hours (0.92%) in Model 2, 4 hours (1.20%) in Model 3, and 8 hours (2.19%) in Model 4.

When HCV platooning is introduced in Model 5, travel time per HCV increases by 7.78 minutes (4.06%) compared to existing conditions, resulting in a total journey time increase of 75 hours (18.2%). Under the 5% HCV platooning assumption, FSP (Model 6) emerges as a more efficient truck priority measure, reducing travel time by 0.96 minutes (0.49%) compared to Model 5, although it shows an increase of 6.82 minutes (3.57%) relative to Model 1. Overall, HCV journey time is reduced by 20 hours (4.54%) in Model 6 compared to Model 5 but increases by 55 hours (14.4%) when compared to Model 1. DTLL (Model 7) shows a slight increase in travel time relative to Model 5, as discussed that raised medians and long truck combinations block the left turning movement entrance for vehicles.

The combination of FSP and DTLL in Model 8 proves to be the most effective approach as it decreases travel time by 5.29 minutes (2.04%) compared to Model 5. However, Model 8 shows a slight increase in travel time of 2.49 minutes (1.32%) when compared to Model 1. Overall, this combined approach reduces total HCV travel time by 15 hours (4.23%) relative to Model 1 and by 90 hours (22.37%) relative to Model 5, suggesting that the combined strategy outperforms the individual application of FSP or DTLL.

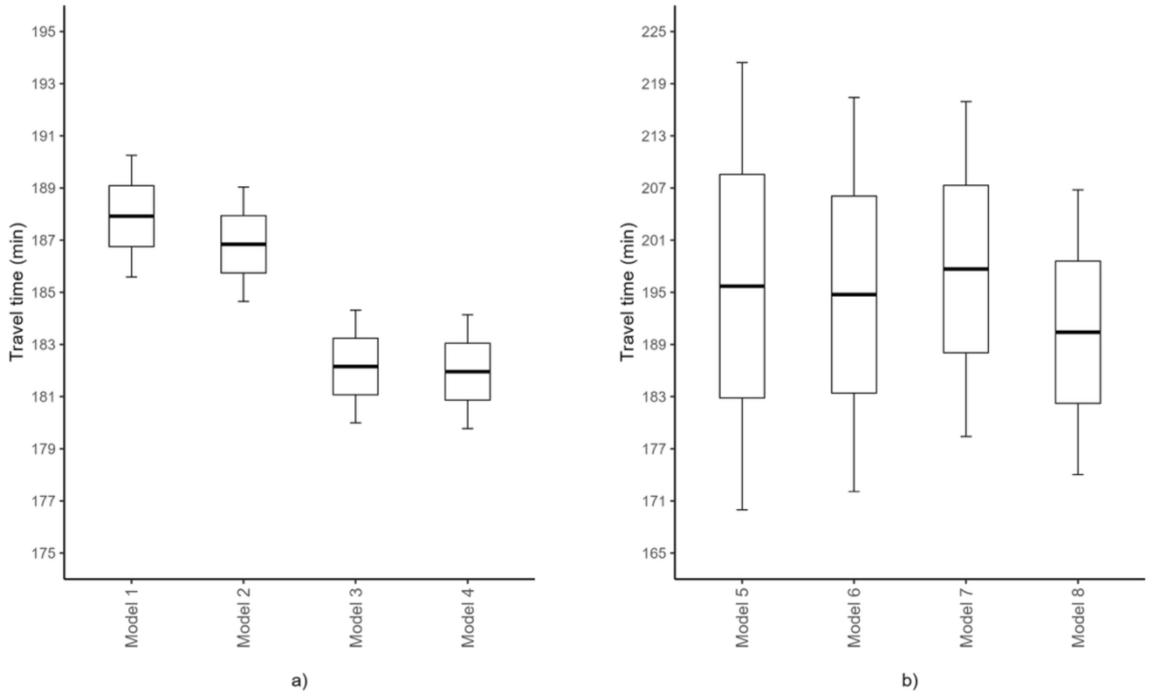


Figure 23: Average Travel Time per HCV a) Models 1 to 4 b) Models 5 to 8

The travel time results for LCVs is presented in Figure 24, with Figure 24a showing results for Models 1 to 4, while Figure 24b includes models 5 to 8, which include HCV platooning. As with the previous figures, differing y-axis scales are used. The results reflect similar patterns as those observed for HCVs, supporting a consistent analysis of the findings. In Model 2, the implementation of FSP results in a reduction in LCV travel time by 2.15 minutes (1.12%), while DTLL in Model 3 shows a more significant decrease of 5.57 minutes (2.94%). The combined application of FSP and DTLL in Model 4 leads to a significant reduction in LCV travel time by 6.22 minutes (3.17%). These reductions in travel time translate to total LCV journey time savings of 0.1 hours (0.51%) for Model 2, 0.22 hours (1.09%) for Model 3, and 0.16 hours (0.79%) for Model 4.

With the introduction of 5% HCV platooning in existing conditions (Model 5), LCV travel time increases by 7.96 minutes (4.03%), resulting in a total journey time increase of 3 hours in the corridor. The addition of FSP in Model 6 causes a slight increase in travel time compared to Model 5, while DTLL in Model 7 reduces travel time by 0.85 minutes (0.42%) relative to Model 5. In terms of total LCV travel time, this decrease is minimal compared to Model 5, totaling to a 20-minute reduction. In Model 8, which combines FSP and DTLL under 5% HCV platooning, LCV travel time increases by 3.88 minutes (1.99%) relative to Model 1 but decreases by 4.07 minutes (2.04%) compared to Model 5. Overall, Model 8 shows that total LCV travel time increased by 1.7 hours (8.14%) compared to Model 1, while it decreased by 5 hours (19.1%) compared to Model 5, indicating that combined truck priorities are the most effective approach.

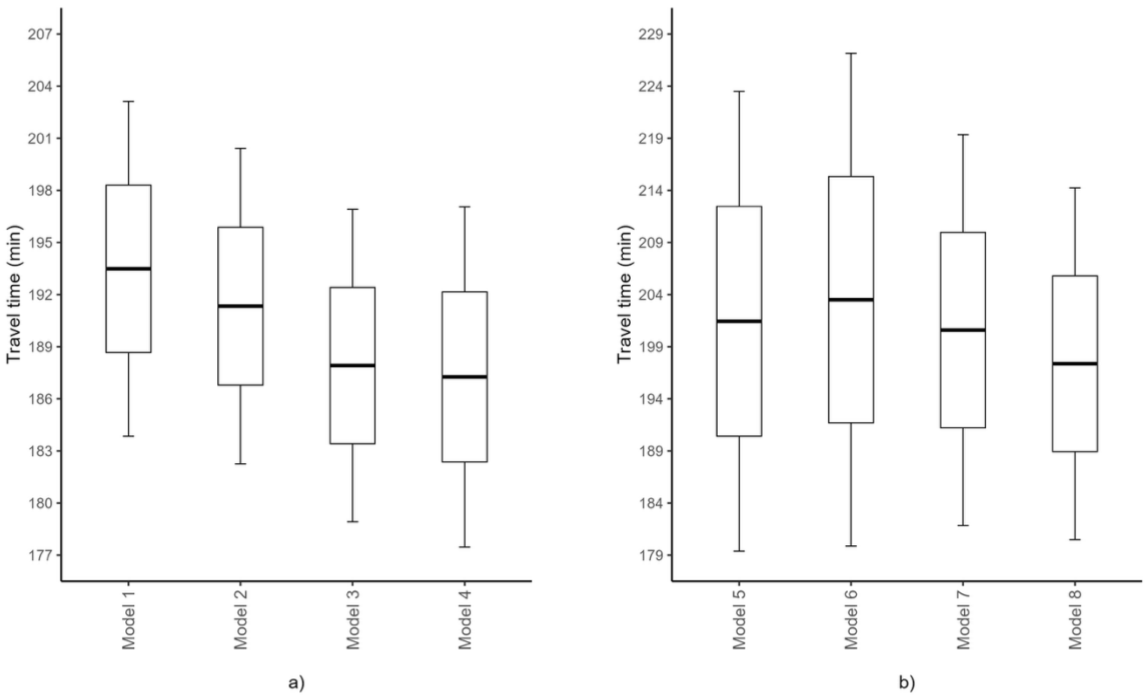


Figure 24: Average Travel Time per LCV a) Models 1 to 4 b) Models 5 to 8

Figure 25 summarizes the travel time results for HCV platoons under existing conditions versus with truck priorities (FSP, DTLL, and FSP+DTLL) implemented. Given the introduction of HCV platooning in Model 5, data for Models 1, 2, 3, and 4 is unavailable. However, Model 6 (FSP) shows a significant reduction in travel time of 8.63 minutes (4.13%) per HCV platoon. Similarly, Model 7 (DTLL) achieves a slightly smaller decrease in travel time of 5.83 minutes (2.77%). The combination of FSP and DTLL in Model 8 still achieves a significant reduction in travel time of 7.82 minutes (3.73%) per HCV platoon. Despite the low penetration rate of HCV platoons, Models 6, 7, and 8 demonstrate overall journey time reductions of 2.35 hours (7.48%), 4.4 hours (14.4%), and 4.42 hours (14.5%) for HCV platoons in the network, making this combined approach a significant improvement in overall travel time reduction.

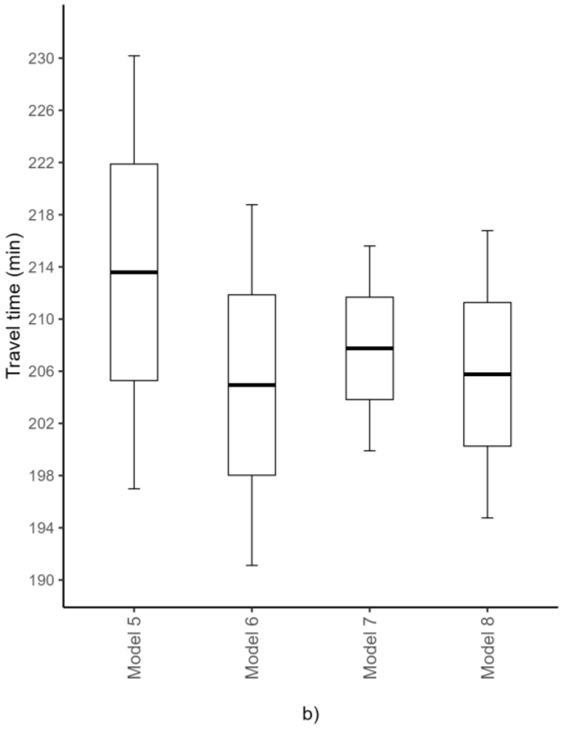


Figure 25: Average Travel Time per HCV Platoon for Models 5 to 8

6.2 Greenhouse Gas Emission Summary

Figure 26 presents GHG emissions along the 19.2 km corridor area for all vehicles, Figure 26a represents 5% LCV scenarios, while Figure 26b shows 5% HCV platooning scenarios. It is important to note that Figures 26 a and b have different y-axis scales. In this study, GHG emissions are shown as a combined total of nitrous oxide (N_2O), methane (CH_4), and carbon dioxide (CO_2) emissions.

The results indicate that the combined implementation of FSP and DTLL in Model 4 achieves a 1.61% reduction in GHG emissions, while FSP in Model 2 and DTLL in Model 3 results in a decrease of 0.18% and 1.13%, respectively. This demonstrates that DTLL is more effective in reducing emissions compared to FSP. These findings are consistent with previous studies, where reductions in GHG emissions were observed with FSP applications (Wijayaranta, 2013; Alam and

Hatzopoulou, 2014). This trend also aligns with travel time reductions observed before HCV platooning was introduced, suggesting that fewer stops may reduce emissions for all vehicles.

With the introduction of 5% HCV platooning in Model 5, GHG emissions increase substantially by 24.1%, highlighting the need for truck-friendly measures. When truck priority measures are introduced, FSP in Model 6 leads to an 18% increase in emissions compared to Model 1, showing a moderate improvement relative to the 24% increase seen in Model 5. DTLL in Model 7 results in a 5.61% increase in emissions, while the combined FSP and DTLL approach in Model 8 results in the smallest emissions increase of 3.7% compared to Model 1. When these scenarios are compared to Model 5, Model 6 (FSP) decreases emissions by 6.17%, Model 7 (DTLL) by 18.6%, and the combined FSP and DTLL approach in Model 8 shows a significant emissions reduction of 20.4% relative to Model 5. Additionally, when assessing each GHG component individually, each gas exhibits a reduction consistent with the overall GHG emission decrease across all three components.

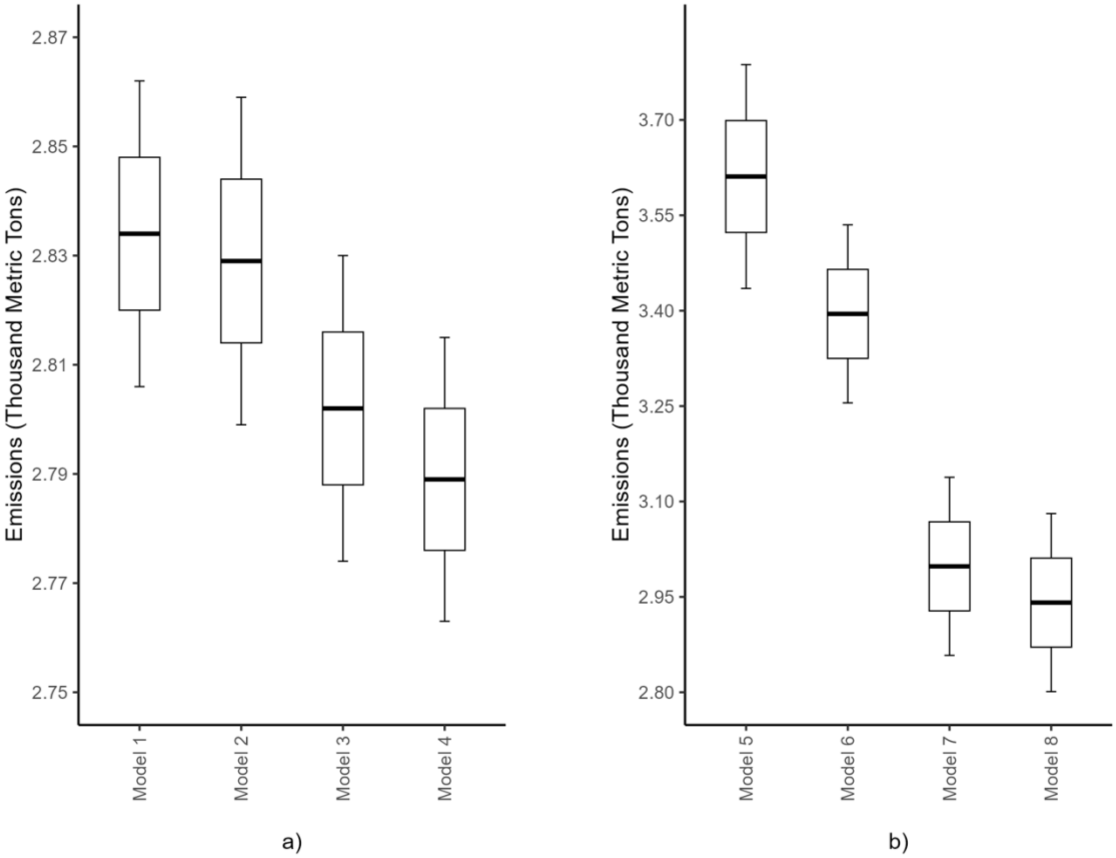


Figure 26: Total Greenhouse Gas (GHG) Emissions a) Models 1 to 4 b) Models 5 to 8

6.3 Chapter Six Summary

This study evaluated the effectiveness of various traffic management models on travel time and greenhouse gas (GHG). The results from the analysis highlighted several key findings regarding travel time and emissions across different models.

6.3.1 Travel Time Analysis Summary

Among all the models, Model 4 (FSP + DTLL) showed the highest efficiency, reducing overall travel time by 5.07 minutes (3.17%) per vehicle compared to existing conditions. In contrast, Model 3 (DTLL) resulted in a 5.34 minute (2.94%) reduction, and Model 2 (FSP) resulted in a smaller reduction of 1.29 minute (0.70%) compared to the do-nothing condition.

The Introduction of HCV Platooning (Model 5) led to an increase in overall travel time for each vehicle by 13.09 minutes (2.15%) compared to Model 1, highlighting the challenges presented by current traffic conditions. Models 6 (FSP) and 7 (DTLL) under 5% HCV platooning showed increases in overall travel time of 11.26 minutes (5.92%) and 12.49 minutes (6.54%), respectively, when compared to Model 1. However, both models offered slight reductions in travel time, 1.82 minutes (0.92%) and 0.60 minutes (0.30%), respectively compared to Model 5. While Model 8 emerged as the most effective approach, resulted in a decrease in overall travel time of 5.28 minutes (2.71%) compared to Model 5 and only increasing travel time slightly compared to Model 1, highlighting its effectiveness over individual strategies.

For LCVs, Model 4 achieved the greatest improvement with a reduction of 6.22 minutes (3.27%). In contrast, Model 8 showed a 3.88 minute (1.99%) increase compared to the baseline but remained more efficient than Model 5 with a 4.07 minute (2.04%) reduction.

For HCV platoons, Model 8 was the most effective, reducing travel time by 7.81 minutes (3.70%) compared to Model 5. Models 6 and 7 also yielded moderate improvements, showing the importance of signal priority strategies in managing platooning effects.

6.3.2 GHG Emissions Result Summary

In terms of Emissions, Model 4 (FSP + DTLL) achieved the highest reduction in GHG emissions, lowering emissions by 1.61% relative to the baseline. Models 2 (FSP) and 3 (DTLL) exhibited reductions of 0.18% and 1.13%, respectively.

The introduction of HCV Platooning on Emissions (Model 5) led to a significant increase in GHG emissions by 24.1%, showing the need for more truck-friendly measures. Model 6 (FSP) showed an 18% increase in emissions compared to the baseline, which was particularly less than the 24% increase in Model 5. Model 7 (DTLL) recorded a 5.61% increase in emissions, while Model 8 (FSP + DTLL) demonstrated the smallest increase at 3.7%.

When comparing Model 6 (FSP) to Model 5, emissions decreased by 6.17%; Model 7 (DTLL) achieved an 18.6% reduction, and Model 8 (FSP + DTLL) presented a substantial decrease in emissions by 20.4%. An individual evaluation of the gases comprising GHG emissions (N_2O, CH_4, CO_2) showed proportional decreases that aligned with the total GHG emissions across all three components.

CHAPTER 7: CONCLUSION AND RECOMMENDATION

This chapter provides an overview of the study, summarizing its key elements, including the background, methodology, and significant research findings. In addition, the chapter highlights the study's major contributions, highlighting its value in advancing knowledge. It also critically examines the study's limitations, identifying areas where improvements could be made, or further exploration is needed. Finally, the chapter concludes with detailed recommendations for future research, offering guidance on potential directions to build upon the findings and address the identified gaps.

7.1 Research Summary

The efficient movement of freight vehicles is critical to economic vitality, particularly on roadway network with high freight traffics. This intense truck activity inevitably contributes to congestion on urban roadways, along with significant environmental challenges, including greenhouse gas (GHG) emissions to the area, such as the Region of Peel. Addressing these dual challenges requires innovative approaches to improve mobility and reduce environmental impacts while maintaining economic growth.

This study investigated that heavy commercial vehicle (HCV) platooning as a possible solution for enhancing freight travel efficiency. As HCV platooning improves aerodynamics and reduces fuel consumption without the geometric constraints of long combination vehicles (LCVs), allowing for comparable freight capacity. However, while effective on freeways, HCV platooning presents unique challenges on urban arterial roads, particularly during last-mile trips. These trips often involve left-turn movements at signalized intersections, where geometric design limitations, such as inadequate storage length and insufficient signal phases exacerbate congestion, delay, and emissions.

To address these challenges, this study explores the implementation of Intelligent Transportation Systems (ITS) measures, such as Freight Signal Priority (FSP) and Dedicated Truck Left-turn Lanes (DTLL). These strategies aim to optimize traffic flow, reduce vehicle delays, and mitigate environmental impacts, particularly for left-turning freight vehicles. However, previous studies lack discussions about criteria for prioritizing signalized intersections requiring truck priority, this research fills a critical gap by introducing criteria for focused signalized intersections.

Using PTV VISSIM microsimulation, the study evaluates the operational and environmental impacts of FSP and DTLL under varying conditions, including scenarios with a 5% market penetration of HCV platooning. In total there were Key performance measures include average travel time and GHG emissions across different vehicle categories: passenger vehicles, freight trucks, LCVs and HCV platoons. Results show that the combined implementation of FSP and DTLL in Model 4 demonstrated the highest effectiveness, reducing travel time by 5.77 minutes (3.17%) per vehicle, an overall journey time in the network reduction of 50 hours and achieving the largest GHG emissions reduction of 1.61% compared to baseline conditions. While individual strategies such as FSP and DTLL provided moderate improvements, their combined application consistently outperformed individual measures.

The introduction of 5% HCV platooning in Model 5 posed significant challenges, leading to increased travel times and emissions, emphasizing the need for infrastructure enhancements. Models integrating FSP and DTLL with HCV platooning in Model 8 proved to be the most effective in mitigating these impacts, an overall journey time in the network reduction of 19 hours and a substantial 20.4% decrease in emissions relative to Model 5.

This finding highlights the importance of combining advanced traffic management strategies. By reducing delays and emissions, these measures enhance the reliability of freight shipments and contribute to sustainable urban mobility.

Overall, this study provides a foundational framework for integrating ITS measures into urban freight networks. The results demonstrate that FSP and DTLL, particularly when implemented together, significantly enhance mobility and environmental performance on urban arterial roadways. These findings offer valuable insights for policymakers and transportation planners seeking to balance economic growth with environmental sustainability and operational efficiency in freight transportation. Future research should build upon these results by exploring higher market penetration rates for HCV platooning and assessing impacts across entire freight journeys, including both freeways and urban corridors.

7.2 Major Findings

The study makes several contributions to the field of freight transportation. First, it introduces a strategic methodology for selecting intersections that require freight priority measures, filling a critical gap in existing literature. The research highlights the effectiveness of integrating FSP and DTLL to enhance traffic flow and reduce environmental impacts. Additionally, it provides a framework for using an ITS technology to support urban freight movement, particularly during first- and last-mile trips, where operational inefficiencies are most pronounced. These findings offer valuable insights for transportation planners and policymakers, emphasizing the importance of targeted infrastructure improvements for sustainable urban mobility.

7.3 Study Limitations

This study acknowledges several limitations that may influence the generalizability and depth of its findings. One of the primary limitations is the reliance on travel time as the sole performance metric. While travel time is an important indicator of the efficiency of Freight Signal Priority (FSP) and Dedicated Truck Lanes (DTLL), it does not comprehensively capture the broader implications of these strategies on urban road networks. A more complete evaluation would require the inclusion of additional metrics such as number of stops, fuel consumption, and safety outcomes. These factors are crucial for understanding the environmental and safety impacts of FSP and DTLL, as well as their potential to reduce congestion and improve traffic flow for all vehicle types.

The study also does not fully address the economic feasibility of implementing these systems. A benefit-cost analysis would be invaluable in assessing the financial viability of infrastructure improvements. It would be important to include direct costs, such as installation of traffic control devices (signage, pavement markings, signal system adjustments), as well as ongoing maintenance costs for these systems. The study did not fully consider network-wide infrastructure improvements, like converting single left-turn lanes to dual left-turn lanes, which could involve substantial construction costs. These factors should be addressed in future planning to better evaluate the overall economic implications of such projects.

A major assumption, and therefore a limitation, is the focus on a 5% market penetration rate for HCV platooning. While this assumption addresses the most imminent market need, it may require additional analysis beyond the 5% penetration rate to broaden our understanding of the impacts of platooning on FSP and DTLL effectiveness.

7.4 Recommendations for future work

Building upon the limitations identified in this study, there are several key areas for future research that could provide a more comprehensive understanding of the effectiveness and feasibility of Freight Signal Priority (FSP) and Dedicated Truck Lanes (DTLL).

Future studies should expand the scope of performance metrics beyond travel time. Incorporating indicators such as delay, number of stops, fuel consumption, and safety factors. This will offer a well-rounded perspective on the impacts of FSP and DTLL.

In addition, they could include a benefit-cost analysis to assess the economic viability of implementing FSP and DTLL systems. This analysis should encompass both direct and indirect costs, including the installation of traffic control devices and ongoing maintenance. Additionally, larger-scale infrastructure changes, such as the conversion of left-turn lanes, should be explored to evaluate how such modifications might improve traffic flow for freight vehicles while considering associated construction and operational costs.

The study analyzed HCV platooning based on a 5% market penetration rate only. Future research should explore higher penetration rates, such as 10% or 20%, to better understand the performance of FSP and DTLL under more widespread adoption. This could reveal how such systems handle increased traffic volumes, and whether they continue to mitigate the negative impacts of platooning while also addressing challenges related to infrastructure capacity, traffic flow, and safety. Higher penetration rates could yield more significant reductions in fuel consumption, greenhouse gas emissions, and travel time, but they may also introduce new challenges, such as increased infrastructure capacity requirements and safety considerations.

Future research should investigate the impact of FSP and DTLL systems on vehicle safety. While these strategies aim to improve traffic flow, they could also alter driver behavior, collision rates, and overall safety conditions. It may be beneficial to conduct safety risk analysis to assess how changes in signal timing or lane allocation might affect traffic safety. By addressing these safety concerns, future research can help to ensure that the implementation of FSP and DTLL systems does not introduce unintended negative consequences for road users.

In conclusion, addressing these research gaps would enable a more thorough and nuanced understanding of FSP and DTLL, ultimately leading to more effective decision-making in their design and implementation. By incorporating broader performance metrics, conducting detailed economic analyses, and exploring the impacts of higher platooning rates and safety factors, future studies can contribute significantly to improving urban road network efficiency and sustainability.

REFERENCES

AASHTO, 2011. *A Policy on Geometric Design of Highways and Streets.* 6 ed. s.l.:s.n.

AASHTO, 2018. *A policy on Geometric Design of Highways and Streets.* 7 ed. s.l.: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,* Washington, DC: s.n.

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,* Issue 4, p. 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,* pp. 306-311.

Alam, A. 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,* 19-22 September.

Alam, A. et al., 2015. Heavy-Duty Vehicle Platooning for Sustainable Freight Transportation: A Cooperative Method to Enhance Safety and Efficiency. *IEEE Control Systems Magazine,* 06 November, 35(6), pp. 34-56.

Alam, A. et al., 2015. Heavy-Duty Vehicle Platooning for Sustainable Freight Transportation: A Cooperative Method to Enhance Safety and Efficiency.. *IEEE Control System Magazine,* 35(6), pp. 34-56.

Al-Sahili, K. A. & Taylor, W. C., 1996. Evaluation of Bus Priority Signal Strategies in Ann Arbor, Michigan. *Journal of the Transportation Research Board,* 01, 1554(1), pp. 74-79.

Altaf, H., 2019. *Long Combination Vehicle (LCV) Usage Study,* s.l.: Region of Peel.

Ardalan, T., 2020. *Development of guidelines for implementation of freight and transit signal priorities to enhance road traffic sustainability.* s.l.:Florida Atlantic University.

Asaduzzaman, M., Thapa, R. & Codjoe, J. A., 2022. Safety and Operational Effectiveness of Protected Only Versus Protected/Permitted Left-Turn Signal Phase.. *Journal of the Transportation Research Board,* 12 04, 2676(9), pp. 347-356.

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

Bishop, R., 2020. *New Moves, New Markets For Truck Platooning Revealed At AVS2020,* s.l.: s.n.

Browand, F., McArthur, J. & Radovich, C., 2004. *Fuel Saving Achieved in the Field Test of Two Tandem Trucks,* California: University of Southern California, Berkley.

Browand, F., McArthur, J. & Radovich, C., 2004. *Fuel Saving Achieved in the Field Test of Two Tandem Trucks.,* California: California PATH Program.

Butler, C., 2019. *Demographic Tsunami'' Is About to Make Canada's Trucker Shortage Even Worse..* [Online].

Canadell, J. et al., 2021. *2021: Global Carbon and other Biogeochemical Cycles and Feedbacks,* Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA: s.n.

Canadian Council of Motor Transport Administrators, 2016. *Automated Vehicles in Canada,* Ottawa: s.n.

Central Phoenix Transportation Framework Study, 2011. *Review of transportation improvement concept,* s.l.: s.n.

Chiu, Y.-C., Zhou, X. & Hernandez, J., 2007. Evaluating Urban Downtown One-Way to Two-Way Street Conversion Using Multiple Resolution Simulation and Assignment Approach. *JOURNAL OF URBAN PLANNING AND DEVELOPMENT,* 133(4), pp. 222-232.

Chong, J., 2016. *Automated and Connected Vehicles: Status of the Technology and Key Policy Issues for Canadian Governments..* Ottawa: Liberty of Parliament .

Chowdhury, T., Park, P. & Gingerich, K., 2022. Operational Impact of the Through-Traffic Signal Prioritization for Heavy Commercial Vehicle Platooning on Urban Arterials. *Journal of the Transportation Research Board,* 4 11, 2677(2), pp. 62-77.

Chowdhury, T., Park, Y. P. & Gingerich, K., 2022. Operational impact of the through-traffic signal prioritization for heavy commercial vehicle platooning on urban arterials. *Transportation Research Record: Journal of the Transportation Research Board,* 2677(2), pp. 62-77.

Chrysler, S., 2016. *Preferential Lane use for Heavy Trucks,* s.l.: Texas A&M Transportation Institute.

City of Calgary, 2021. *16 Avenue North V2I Test Bed,* Calgary: s.n.

City of Mississauga, 2022. *Appendix T: Preliminary Cost Estimates,* Mississauga: s.n.

City of Toronto, 2014. *Staff report for action on Eglinton Avenue East HOV Lanes,* Toronto, Ontario: s.n.

City of Toronto, 2016. *Guidelines For Using Synchro 9 (Including SimTraffic 9),* s.l.: Traffic Management Center.

City of Toronto, 2020. *High Occupancy Vehicle Lanes (HOV lanes) - diamond lanes.* s.l.:s.n.

City of Toronto, 2020. *MoveTO 2021-25: Congestion Management Interim Action Plan and Non-Competitive Contract for Smart Signals,* Toronto: s.n.

Costello, B., 2019. *Truck Driver Shortage Analysis,* s.l.: American Trucking Associations.

Davila, A. & Ferrer, A., 2014. Tackling Three Critical Issues of Transportation: Environment, Safety and Congestion Via Semi-autonomous Platooning. *SAE Technical Paper.*

Douglas, J., 2004. *Handbook for planning truck facilities on urban highways.* s.l.:s.n.

Espiritu, C. J., 2013. *Identifying Potential Freeway Segments for Dedicated Truck Lanes.* s.l.:San Jose State University.

Federal Highway Adminstration (FHWA), 2015. *Verification, refinement, and applicability of long-term Pavement Performance Vehicle Classification Rules.,* s.l.: s.n.

FHWA, 2021. *Traffic Signal Timing Manual.* [Online] Available at: https://ops.fhwa.dot.gov/publications/fhwahop08024/chapter6.htm

FHWA, 2022. *Freight and congestion.* [Online]
Available at: https://ops.fhwa.dot.gov/freight/freight_analysis/freight_story/congestion.html

Fischer, M. J., Ahanotu, D. N. & Waliszewski, J. M., 2003. Planning Truck-Only Lanes Emerging Lessons from the Southern California Experience. *Transportation Research Record,* 1833(1).

Fitzpatrick, K. et al., 2014. Effects of Geometric and Traffic Variables on Double Left-Turn Lane Operations. *Journal of the Transportation Research Board,* p. 32–42.

Geuy, B. L., 1989. An industry perspective on longer combination vehicle operations in the Western USA. *Transportation Planning and Technology,* 14(2), pp. 101-115.

Government of Canada, 2020. *Transportation in Canada 2020 - Overview Report.* [Online]
Available at: https://tc.canada.ca/en/corporate-services/transparency/corporate-management-reporting/transportation-canada-annual-reports/green-transportation

Government of Canada, 2023. *Canadians' commutes: Still car-heavy, but some lighter footprints.* [Online]
Available at: https://www.statcan.gc.ca/o1/en/plus/3798-canadians-commutes-still-car-heavy-some-lighter-footprints#

Gray, B., 2025. *Supplementary Report: Congestion Management Plan - 2025 Update,* s.l.: City of Toronto.

Harwood, D. W., Pietrusha, M. T., Wooldridge, M. D. & Brydia, R. E., 1995. *NCHRP Report 375: Median Intersection Design,* Washington, D.C.: TRB, National Research Council.

Hendriks, J., 2015. *Validation of traffic models using PTV VISSIM 7.* s.l.:Department of Mechanical Engineering Manufacturing Networks Research Group.

He, R., Ran, B. & Choi, K., 2000. Decision Support System for Value Pricing Strategies on I-394 Corridor Network. *9th Annual Meeting of the Transportation Research Board.*

HNTB Corporation, 2010. *Barrier versus Buffer Managed Lanes.* Atlanta, GA: Georgia Department of Transportation.

Hu, J., Park, B. (. & Parkany, A. E., 2014. Transit Signal Priority with Connected Vehicle Technology. *Transportation Research Record: Journal of the Transportation Research Board,* 01 01.2418(1).

Hu, J., Park, B. B. & Lee, Y.-J., 2015. Coordinated transit signal priority supporting transit progression under Connected Vehicle Technology. *Transportation Research Part C: Emerging Technologies,* 06, Volume 55, pp. 393-408.

Hummer, J. E., Zeeger, C. v. & Hanscom, F. R., 1988. Effects of Turns by Larger Trucks at Urban Intersections. *TRANSPORTA TION RESEARCH RECORD 1195.*

Hussain, A., 2019. *Long Combination Vehicles (LCV) Usage Study,* s.l.: Peel Region.

Illinois Department of Transportation and Civiltech Engineering, Inc., 1998. *The Cermak Road Bus Priority Project Final Report,* Chicago, IL: s.n.

Imran, N. T., Vanajakshi, L. & Girijan, A., 2021. A Review on Bus Signal Priority Systems. *Transportation in Developing Economies,* 29 10.8(2).

Jaya, J. D., 2023. *Improving the Efficiency of Heavy Truck Flow Outside Intermodal Facilities while Considering Transportation Operations and Environmental Impacts: A Proof of Concept.* Boca Raton(Florida): Florida Atlantic 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,* Boca Raton: Florida Atlantic University.

Kaisar, E. I., Hadi, M., Ardalan, T. & Iqbal, M. S., 2021. *Evaluation of Freight and Transit Signal Priority Strategies in Multi-Modal Corridor for Improving Transit Service Reliability and Efficiency,* s.l.: Produced by Freight Mobility Research Institute for Florida DOT.

Kikuchi, S., Kii, M. & Chakroborty, P., 2004. Lengths of Double or Dual Left-Turn Lanes. *Journal of the Transportation Research Board,* January, 1881(1), p. 72–78.

Kim, D., Guin, A., Rodgers, M. O. & Guensler, R., 2018. *Energy and Air Quality Impacts of Truck-Only Lanes: A Case Study of Interstate 75 Between Macon and McDonough, Georgia,* Georgia: National Centre for Sustainable Transportation.

Kuhn, B. et al., 2017. *Commercial Truck Platooning Demonstration in Texas – Level 2 Automation,* Texas: Texas Department of Transportation.

Kurri, J., Sirkiä, A. & Mikola, J., 2000. Value of Time in Freight Transport in Finland.. *Journal of the Transportation Research Board,* January.1725(1).

Lammert, M. P. et al., 2014. Effect of Platooning on Fuel Consumption of Class 8 Vehicles Over a Range of Speeds, Following Distances, and Mass. *SAE International Journal.*

Levinson, H. S., 1989. The Capacity of Shared Left Turn Lanes—A Simplified Approach. *Transportation Research Record: Journal of the Transportation Research Board,* Volume 1225, p. 45–52.

Liao, C.-F. & Davis, G., 2007. Simulation Study of Bus Signal Priority Strategy Taking Advantage of Global Positioning System, Automated Vehicle Location System, and Wireless Communications.. *Transportation Research Record: Journal of the Transportation Research Board,* 12, Volume 2034, pp. 82-91.

Lindsey, R., 2007. Congestion relief: Assessing the case for road tolls in Canada.. *Commentary-CD Howe Institute.*

Lipnicky, K. & Burris, M., 2010. Influence of HOV lane access on HOV lane utilization. *Journal of Transportation Engineering,* 136(11), p. 1030 – 1038.

Mahmud, M., 2014. *Evaluation of Truck Signal Priority at N Columbia Blvd and Martin Luther King Jr. Blvd Intersection: VISSIM Micro Simulation Analysis of Truck Signal Priority,* Portland, Oregon: Civil and Environmental Engineering Master's Project Reports.

Mallik, S., 2014. Intelligent Transportation System. *International Journal of Civil Engineering Research,* 5(4), pp. 367-372.

Manitoba Transportation and Infrastructure Department, 2022. *Moto Carriers-Permits.* [Online] Available at: https://www.gov.mb.ca/mit/mcd/permits/overlength.html

Marchesan, L., 2024. *A Safety Analysis of Left-Turning Maneuvers for Long-Combination Vehicles,* s.l.: York University.

Milakis, D., Arem, B. v. & Wee, B. v., 2017. Policy and society related implications of automated driving: A review of literature and directions for future research. *Journal of Intelligent Transportation Systems,* 16 03, 21(4), pp. 324-348.

Ministry of Highways - Government of Saskatchewan, 2022. *Vehicle Weight and Dimension Regulations, 2010, H-3.01 Reg 8.* [Online]
Available at: https://publications.saskatchewan.ca/#/products/31363

Ministry of Transportation of Ontario, 2020. *CAV Readiness Plan,* s.l.: s.n.

Ministry of Transportation, 2000. *Ontario Traffic Manual - Pavement, Hazard and Delineation Markings - Book 11,* s.l.: s.n.

Ministry of Transportation, 2011. [Online]
Available at: http://www.mto.gov.on.ca/english/trucks/lcv/program- conditions/questions-and-answers.shtml
[Accessed 10 2024].

Ministry of Transportation, 2021. [Online]
Available at: http://www.mto.gov.on.ca/english/trucks/long-combination-vehicles-program-conditions.shtml#program-overview-and-principles.

Ministry of Transportation, 2021. *Commercial Vehicle Collisions.* [Online]
Available at: https://tc.canada.ca/en/road-transportation/statistics-data/commercial-vehicle-collisions-canada-2012-2021

Ministry of Transportation, 2021. *Driving and roads.* [Online]
Available at: https://www.ontario.ca/page/long-combination-vehicle-program-conditions#:~:text=The%20Program%20currently%20allows%203,trailers%20up%20to%2014.65%20metres.

Ministry of Transportation, 2022. [Online]
Available at: https://www.ontario.ca/page/high-occupancy-vehicle-hov-lanes

Ministry of Transportation, 2023. [Online]
Available at: https://tts2023.ca/en/

Ministry of Transportation, 2024. [Online]
Available at: https://www.ontario.ca/page/high-occupancy-toll-hot-lanes

National Academies of Sciences, Engineering, and Medicine, 2020. *Transit Signal Priority: Current State of the Practice.* Washington, DC: The National Academies Press.

Neuman, T., 1985. *NCHRP Report 279: Intersection Channelization Design Guide,* Washington, D.C.: Transportation Research Board of the National Academies.

Organisation for Economic Co-operation and Development (OECD), 2017. *Managing the Transition to Driverless Road Freight Transport,* s.l.: International Transport Forum (ITF).

Parker, J., 2008. *Costs of Road Congestion on the Greater Toronto and Hamilton Area: Impact and Cost Benefit Analysis of the Metrolinx Draft Regional Transportation Plan,* s.l.: s.n.

Park, S., Ahn, K. & Rakha, H. A., 2019. Environmental Impact of Freight Signal Priority with Connected Trucks. *Sustainability,* 11(6819).

Parsons, 2019. *Long Combination Vehicles (LCV) Usage Study, Region of Peel,* Region of Peel: s.n.

Patten, J., McAuliffe, B., Mayda, W. & Tanguay, B., 2012. *Review of Aerodynamic Drag Reduction Devices for Heavy Trucks and Buses,* Ottawa: National Research Council Canada.

Peel Region, 2021. *Data Portal.* [Online]
Available at: https://data.peelregion.ca

Peel Region, 2021. *Peel Region Data Portal.* [Online]
Available at: https://data.peelregion.ca

Penny, S., n.d. [Online]
Available at: https://www.smatstraffic.com/2021/07/26/level-of-service/

Pribyl, O., Blokpoel, R. & Matowicki, M., 2020. Addressing EU climate targets: Reducing CO2 emissions using cooperative and automated vehicles.. *Transportation Research Part D: Transport and Environment.*

PTV Group, 2025. *Do I have to consider a warm-up period for my simulation?.* [Online]
Available at: https://support.ptvgroup.com/en-us/knowledgebase/article/KA-04927

Rakha, H. A. K. P. M. A. M. C. C., 2006. *Transit signal priority project, phase II : field and simulation evaluation results.* s.l.:Charlottesville, Va. : Virginia Transportation Research Council.

Region of Peel, 2012. *Freight Transportation Demand Management Study,* s.l.: s.n.

Region of Peel, 2015. *Peel Region Goods Movement Economic Impact Analysis Study,* Region of Peel: s.n.

Region of Peel, 2021. [Online]
Available at: https://www.peelregion.ca/pw/transportation/business/long-combination-vehicle-program.asp

Rempel, G. et al., 2014. *Truck Lanes in Canadian Urban Areas,* s.l.: Transportation Association of Canada.

Roh, C.-G., Park, B.-J. & Kim, J., 2017. Impact of Heavy Vehicles on Highway Traffic Flows: Case Study in the Seoul Metropolitan Area. *Journal of Transportation Engineering, Part A: Systems,* 09.143(9).

SAE International Standard, 2016. Automated Driving: Levels of Driving Automation.. *Society of Automotive Engineers International.*

Saha, U., 2021. *A Swept Path Analysis of Intersection Designs for Long Combination Vehicles.* s.l.:York University.

Saiyed, S. S., 2021. *Intelligent Lane Utilisation to Improve Freight Transportation Mobility on Arterials.* Toronto: York University.

Schrank, D. & Lomax, T., 2005. *The 2005 Urban Mobility Report,* s.l.: Texas Transportation Institute, The Texas A&M University System.

Shaik, R. A. & Graham, J. R., 1996. Efficiency of Dual Left Turn Lane Intersections in Charlotte, A Study Using TRAF-NETSIM. *ITE Journal,* pp. 26-33.

Shalaby, A. et al., 2006. Development, Evaluation, and Selection of Advanced Transit Signal Priority Concept Directions. *Journal of Public Transportation,* 12, 9(5), pp. 97-120.

Shelton, J. et al., 2020. *Strategies for Managing Freight Traffic through Urban Areas: Technical Report,* Austin, Texas: Texas A&M Transportation Institute.

Shladover, S. et al., 2018. *Cooperative Adaptive Cruise Control (CACC) For Partially Automated Truck Platooning:Final Report,* s.l.: s.n.

Siddiqui, S., 2015. *Investigating Saturation Flow Rate of Dual Left-Turn Lanes at Intersection Approaches,* s.l.: s.n.

Smith, H. R., Hemily, B. & Ivanovic, M., 2005. *Transit Signal Priority (TSP): A Planning and Implementation Handbook,* s.l.: s.n.

Smith, J. G., 2020. *Canada's Truck Drivers to Require 103.5 Hours of Training.* [Online] Available at: https://www.trucknews.com/transportation/canadas-truck-drivers-to-require-103-5-hours-of-training/1003136596/

Statistics Canada, 2020. *Vehicle registrations, by type of vehicle.* [Online] Available at: https://doi.org/https://doi.org/10.25318/2310006701-eng

Sukennik, P., 2018. *Micro-simulation guide for automated vehicles,* s.l.: PTV Group.

Sureshan, S., 2009. *Impact of Intercity Trucking on Urban Environment Greater Toronto and Hamilton Area Case Study.* Vancouver: Urban Freight and Movement and Trade Gateways Session of the 2009 Annual Conference of the Transportation Association of Canada.

TAC, 2017. *Geometric guide for Canadian Roads.* s.l.:s.n.

TDM Encyclopedia, 2019. *Road Pricing: Congestion Pricing, Toll Roads and HOT Lanes.* s.l.:Victoria Transport Policy Institute.

Texas Department of Transportation (TxDOT), 2021. *201 value of delay time and road user costs.* [Online]
Available at: https://ftp.txdot.gov/pub/txdot-info/cst/ruc2021.pdf

The Miller Group, 2021. *Our Projects.* [Online]
Available at: https://www.millergroup.ca/projects/427-link

ThinkInsure, 2023. [Online]
Available at: https://www.thinkinsure.ca/insurance-help-centre/hov-lane-ontario.html

Town of Innisfil, 2022. *Active Transportation Facilities - Preliminary Construction Cost Estimate(Sep 2022) - Full Corridor,* s.l.: s.n.

Translink, 2020. *Transit Priority Toolkit,* s.l.: s.n.

Transport Canada, 2021. [Online]
Available at: https://tc.canada.ca/en/road-transportation/statistics-data/commercial-vehicle-collisions-canada-2012-2021

Transportation Association of Canada, 2014. *Primer on Truck Lanes in Canadian Urban Areas,* s.l.: s.n.

Transportation Association of Canada, 2017. *Geometric Design Guide for Canadian Roads,* Ottawa, ON: s.n.

Transportation Research Board, 2000. *Highway Capacity Manual.* Washington, D.C.: National Research Council.

Transportation Research Board, 2010. *Highway Capacity Manual 2010.* Washington, DC: National Research Council.

Transportation Research Board, 2016. *Highway Capacity Manual 6th Edition: A Guide for Multimodal Mobility Analysis..* Washington, DC: The National Academies Press.

U.S. Department of Transportation, 2017. *Managed Lanes: A Primer.* s.l.:Federal Highway Administration.

U.S. Department of Transportation, 2018. *Automated Vehicles: Truck Platooning: Its Benefits, Costs, and Lessons Learned: 2018 Update Report.,* s.l.: s.n.

United States Department of Transportation, 2024. *Saving Lives with Connectivity: A Plan to Accelerate V2X Deployment,* s.l.: United States Department of Transportation.

United States Environmental Protection Agency, 2024. *Vehicles, Greenhouse Gases & Smog.* [Online]
Available at: https://www.epa.gov/greenvehicles/greenhouse-gas-emissions-typical-passenger-vehicle#:~:text=In%20addition%20to%20carbon%20dioxide,HFC)%20from%20leaking%20air%20conditioners.

USDOT, 2020. *Truck Profile. Bureau of Transportation Statistics..* [Online]
Available at: http://www.bts.gov/content/truck-profile

Utah Department of Transportation, 2024. [Online]
Available at: https://www.udot.utah.gov/connect/2024/06/20/udot-to-connect-the-west-with-major-federal-grant/

Victoria Transport Policy Institute, 2023. *Transportation Cost and Benefit Analysis II – Travel Time Costs,* s.l.: s.n.

Vincent, R., Coope, B. R. & Wood, K., 1978. Bus-actuated signal control at isolated intersections.. *Transportation and Road Research Laboratory..*

Washington State Department of Transportation, 2014. *Protocol for VISSIM Simulation,* s.l.: s.n.

Wei, H., Lee, J., Li, Q. & Li, C. J., 2000. Observation-based Lane-vehicle-assignment Hierarchy for Microscopic Simulation on an Urban Street Network. *Journal of the Transportation Research Board,* January, 1710(1), pp. 96-103.

Wijayaratna, K., Dixit, V., Mao, T. & Waller, S. T., 2013. Emissions Impacts of Transit Signal Prioritisation. *36th Australasian Transport Research Forum,* October.

Wisconsin DOT, 2019. *Traffic Engineering, Operations & Safety Manual,* s.l.: s.n.

Wood, S. & Regehr, J. D., 2017. Regulations governing the operation of longer combination vehicles in Canada. *Canadian Journal of Civil Engineering,* 26 06, Volume 44, p. 838–849.

Woudsma, C., 2001. Understanding the Movement of Goods, Not People: Issues, Evidence and Potential. *SageJournal,* 38(13), pp. 2439-2455.

Xu, L., 2005. *Potential single-occupancy vehicle demand for the Katy Freeway and Northwest Freeway high-occupancy vehicle lanes.* s.l.:Texas A&M University.

Yu, L. et al., 2007. *Left-Turn Lane Design and Operation,* s.l.: TxDOT Department of Transportation.

Zabat, M., Stabile, N., Farascaroli, S. & Browand., F., 1995. *The Aerodynamic Performance of Platoons: A Final Report,* Berkeley: California PATH Program.

Appendix

Turning Movements and Volume Balancing