New Signal Priority Strategies to Improve Public Transit Operations

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ABSTRACT

New Signal Priority Strategies to Improve Public Transit Operations

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Rapid urbanization is causing severe congestion on road transport networks around the world. Improving service and attracting more travellers could be part of the solution. In urban areas, improving public transportation efficiency and reliability can reduce traffic congestion and improve transportation system performance. By facilitating public buses' movement through traffic signal-controlled intersections, a Transit Signal Priority (TSP) strategy can contribute to the reduction of queuing time at intersections. In the last decade, studies have focused on TSP systems to help public transportation organizations attract more travellers. However, the traditional TSP also has a significant downside; it is detrimental to non-prioritized movements and other transport modes.

This research proposes new TSP strategies that account for the number of passengers on board as well as the real-time adherence of buses to their present schedules. Two methods have been proposed. First, buses are prioritized based on their load and their adherence to their schedules, while in the second method, the person delay at an intersection is optimized. The optimization approach in the first method uses a specific priority for public transit, while additional parameters are considered in the second method, like residual queue and arrival rate at the intersection. One of this research's main contributions is providing insight into the benefits of these new TSP methods along a corridor and on an isolated signalized intersection. The proposed methods need real-time information on transit operations, traffic signals status and vehicular flows. The lack of readily available infrastructure to provide all these data is compensated by using a traffic simulator, VISSIM, for an isolated intersection and an arterial corridor. The study area simulation results indicated that the new TSP methods performed better than the conventional TSP. For the investigated study area, it was shown that the second method performed better in an isolated signalized intersection, while the first method reduced traffic and environmental indices when used for an arterial corridor.

Future research can investigate the effects of the proposed methodology on the urban network by using macrosimulation to see the effects of the proposed TSP on the network. Also, considering conflicting TSP requests in these methodologies could be another area for further research.

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CHAPTER 1

INTRODUCTION AND BACKGROUND

The population is growing, and the number of cars entering the transportation system is increasing, resulting in increased congestion on the streets and highways. Congestion solutions can be divided into three categories: Adding lanes to existing highways or expanding existing highways. Also, increasing the number of buses/trains, promoting a carpool-vanpool system, or managing travel demand by offering alternatives that increase vehicle occupancy can be effective methods of reducing the number of vehicles. In addition, other methods may be available for operating networks more efficiently. Due to the low infrastructure investment required, the last option may be the most cost-effective. To deal with traffic congestion, city planners have looked to improve the public transportation system as a cost-effective and smart solution.

Providing more people with access to public transportation is in the interests of all decision-makers in cities, as it frees up space on our streets, decreases our dependence on fossil fuels, and improves air quality. Transit Signal Priority (TSP) can be used to improve transit services' reliability, speed, and efficiency. It has been widely implemented in many countries worldwide and is rapidly gaining popularity in the international community. The TSP has little effect on general traffic and is inexpensive for improving transit's competitiveness with cars.

Typically, TSP facilitates the movement of transit vehicles (usually those in-service), such as buses or tramways, through traffic-signal-controlled intersections by controlling the movement of transit vehicles. Although signal priority and preemption are often used interchangeably, in effect, they are two distinct processes. Signal priority modifies the normal signal operation process to accommodate transit vehicles. On the one hand, preemption interrupts the normal signal operation process in response to a special event, such as a train approaching or a fire engine responding. In addition to reducing emergency response times, emergency vehicle preemption also improves the safety and stress levels of emergency vehicle personnel. It also reduces accident rates associated with emergency vehicles at intersections. Additionally, light rail systems are often equipped with preemption at grade crossings and intersections to minimize accidents. On the other hand, without disrupting the normal signal timing operation (like preemption, which is used for emergency vehicles), TSP aims to improve schedule adherence and transit travel time efficiency while minimizing the impact on normal traffic operations(Smith, Hemily, & Ivanovic, 2005). Figure 1 shows the difference between TSP and preemption.

In addition to improving schedule compliance and reliability, TSP can reduce bus travel times, improving transit service quality. There are likely minimal negative impacts, primarily delays for non-priority traffic. According to prior deployment experience, bus travel times are typically reduced by 15% (depending on exit signal delays) with minimal impact on overall intersection operations. Impacts and deployments, however, vary considerably in their nature and magnitude(Smith et al., 2005).

As a result of the configuration of the system, costs may be higher for signal upgrades, intersection equipment/software, vehicles, or central management systems. It is important to note that many TSP systems have been implemented without costly upgrades. However, since specific desired functionality can significantly affect costs, comparisons between TSP systems with different capabilities should be made cautiously.

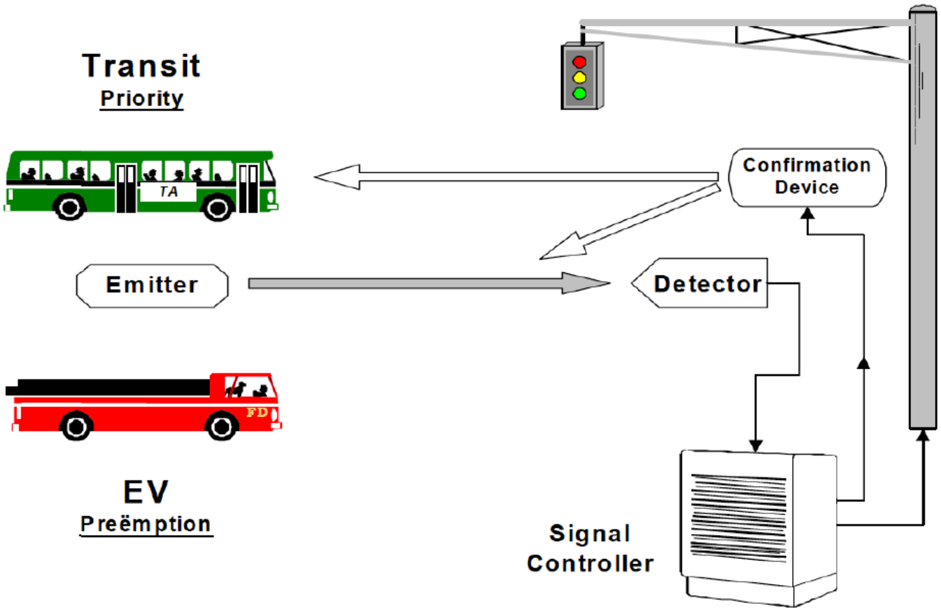

Figure 1: Difference between Preemption and Priority (Baker et al., 2004)

Here are some examples of successful implementation of TSP (Smith et al., 2005):

- TSP and signal optimization were combined in Tacoma, Washington, to reduce transit signal delays by approximately 40%.
- Using TSP, TriMet (Portland, Oregon) avoided adding one more bus to their schedule and experienced a 10% improvement in travel time, up to a 19% reduction in travel time variability. Because of improved reliability, TriMet has been able to reduce scheduled recovery times.
- PACE buses in Chicago reduced their running times between 7% and 20%, with an average of 15% (three minutes).
- Using TSP and run cutting more efficiently, the agency in Chicago has been able to save one bus per weekday while maintaining the same frequency of service.
- As a result of TSP, bus travel times in Los Angeles have been reduced by up to 25%.

There are four components of TSP: (1) a detection system which informs the TSP system of the location of the vehicle requesting signal priority. A priority request generator (2) communicates with the detection system to alert the traffic control system to the vehicle's request for priority. The software processes the request using the programmed (3) priority control strategies, which determine whether and how priority should be granted, and (4) the system is also managed by software that collects data and generates reports. The focus of this dissertation is on the third step, which is the most important one, the priority control strategies.

Many studies have been conducted in the last decade regarding TSP systems. It has been argued that TSPs have the potential to move more people in the corridors while reducing emissions, which may benefit both transit users and the agencies in the long term. As one of the methods of congestion solutions, the TSP system has the advantage that it does not require expansion in infrastructure or a reduction in vehicle numbers. Multiple parameters can directly or indirectly influence the performance of the TSP. In the next chapter, these parameters will be introduced.

There are many challenges associated with transportation networks in Quebec. For Example, the transport sector's Greenhouse Gas (GHG) emissions in Quebec rose by 14 percent in 2014 compared to 1990, representing 40 percent of total provincial emissions. The end-user demand for energy in Quebec in 2017 was 1770 petajoules. At 39 percent of total demand, the largest energy demand sector was manufacturing, followed by transportation at 30 percent. One of the main reasons for the increase in congestion is the rise in private vehicle ownership. Based on Statistics Canada, in 2019, there were 5,800,411 passenger vehicles owned by individuals on Quebec's roads, while this number was 5,459,650 in 2015. The number of passenger cars in Quebec increased at an annual pace of 1.9% from 2006 to 2013. Also, studies predicted an increase in vehicle kilometres travelled (VKT) in 2031 compared to 2008. The rise in VKT also influences the number of trips in some parts of Quebec, especially the trips made by private vehicles. The rise in the number of trips contributed to more congestion, emission, and fuel consumption (Mazaheri & Alecsandru, 2020).

An increase in the number of private's vehicles also negatively affects a very important performance measure, traffic safety. In 2019 the Société de'l'Assurance Automobile du Québec (SAAQ) reported 333 fatalities, 1,334 serious injuries, and 33,403 minor injuries across the province (Société de l'assurance automobile du Québec, 2020). It was predicted that the number of trips in Montreal would be increased by 14.8 percent in 2021 compared to 2003 (Ville De Montreal, 2008). Considering all of the mentioned challenges, other modes of transport in Quebec, especially in Montreal, a major city in the province, should be encouraged.

The Montreal Transportation Master Plan (MTMP) in 2008 indicates that private vehicle use increased dramatically between 1987 and 2003. In contrast, during the same period, public transit use declined (except in 2003) (Ville De Montreal, 2008). In order to serve more demand and mitigate traffic congestion, it is imperative to optimize public transportation efficiency by implementing transit-priority strategies like dedicating a reserved line for public transit and TSP.

Although these strategies can improve the performance of transit operations, their potential negative impacts on the competent modes raise concerns about their deployment, and a thorough validation should be conducted before their implementation. For example, one of their negative impacts is although public transit is given priority on major roads in an intersection, imposing delays on the vehicles on minor approaches. For all of the pros and cons that this system has, a systematic approach to measuring the performance of priority strategies at an isolated signalized intersection or corridor with a feasible computational cost is required to consider the effect of priority strategies on a corridor, including private and transit vehicles. All being said, bus priority strategies can significantly impact the achievement of benefits to buses and negatively affects private cars, depending on the implementation methods used, priority parameters considered policy objectives, intersection types, and network characteristics (Alrashidan, 2018).

Having said the advantages of TSP, in this research, existing bus priority methods and parameters for isolated intersections have been considered, and new important parameters like the number of passengers on board and adherence to the schedule are included to improve bus priority method's' performance in an intersection and corridor. The development of new advanced bus priority methods benefits both buses and private cars.

1.1 Research Motivation

Throughout the history of Canadian communities, public transportation has played an important role in defining residents' travel patterns (Heydari, 2019). Public transportation, in Canada, as in many other places throughout the world, has undergone a long and challenging evolution, and both public and private agencies are still struggling to provide a safe, affordable, accessible, and competitive system in today's car-dominated world. Public transportation is not only an essential aspect of achieving equality among the citizens of a city, but it also has a significant impact on the development of the local economy as it encourages employment, business activity, and property values, among other things. Transit has always had to compete against other modes of transportation to improve its service quality and reliability, such as vehicles, which may have an advantage over other modes of transportation due to their accessibility, speed, and convenience. A good quality transit service is characterized, among other parameters, by small or no travel time variability and good schedule adherence. These features can be achieved by reducing or even eliminating the travel time delay, which typically occurs due to congestion at signalized intersections (Heydari, 2019).

In a variety of ways, public transit contributes to the sustainability of urban agglomerations. For example, public transportation reduces the detrimental effects of urban sprawl and traffic congestion as an alternative to vehicles. However, the rapid rise in traffic congestion on urban roads and infrastructure growth challenges call for better operation of available transport facilities. In order to increase transit ridership, it is necessary to provide transit services that are highly competitive to private cars, at least for commuting needs. This means that transit should be convenient, comfortable, safe and efficient for passengers. It is already known that rapid transit modes with high capacities, such as buses or light rails, can satisfy most of the needs of commuters. Several factors contribute to the efficiency of these transit systems; these include low travel times, high reliability of running times, and a satisfactory adherence to schedules. These advantages can be achieved using new systems, like TSP.

The introduction of TSP can contribute significantly to reducing traffic congestion by optimizing the performance of public transportation. Many TSP strategies have been proposed to increase public transit users (Zlatkovic, 2012).

TSP is an operational strategy that facilitates transit vehicles at signalized intersections. Using this strategy, public transit is given a certain priority over other traffic, reducing the number of delays they experience and improving their travel time reliability. It is the main aim of TSP for transit vehicles to be able to pass through signalized intersections without stopping at red lights or to reduce waiting time if they are already stopped.

They also increase bus speed and reliability by prioritizing buses at signalized intersections to reduce stop time. TSP has recently been widely adopted by transportation entities in North America and worldwide. For instance, TSP is applied to more than 350 intersections in Toronto and based on a report; it led to a 46% reduction in transit control delay (Commision, 2009)

TSP aims to reduce control delay at intersections. The term“ "control delay" refers to the travel time delay due to a traffic control device (Transportation Research Board, 2016). As a result, the delay is included in the time spent by vehicles when they slow down upstream of an intersection as they approach the intersection, move up the queue, and accelerate to their desired speed. In order to reduce the number of transit delays at signalized intersections, transit agencies have used TSP, among other solutions (e.g., dedicated right of way, specific signal timing phases, etc.). The Advanced Traffic Management Systems and Advanced Public Transportation Systems Committees, both entities of Intelligent Transportation Society America (ITS America), define TSP as a strategy for moving public vehicles through intersections controlled by traffic signals, regardless of whether they are buses or tramways. Using TSPs at intersections makes it possible to reduce the delay per person at intersections, leading to a more efficient traffic flow for many road users. In contrast preemption, which is used for emergency vehicles and tends to interrupt the normal process of signal operation, TSPs modify normal signals to accommodate transit vehicles better.

1.2 **Research Objectives**

An unreliable transit service may increase transit user costs in the short term, to the dislike of both transit agencies and transit users. Over the longer term, it may lead to a reduced transit mode share and ridership, increasing urban congestion, emissions, energy consumption, and vehicle dependency. It is also important for agencies to determine the total travel time of a transit unit (bus) in the system since excessive variability in bus travel time may be responsible for adding extra slack or layover time to the existing schedules. All being said, transit agencies want to reduce bus travel time and its variability. Bus travel time is highly variable in practice due to a variety of factors such as uncertain passenger demand, traffic conditions, driver behaviour, delays caused by traffic lights and bus stops, the geometry of roads, vehicle incidents and accidents, weather conditions, and many others(Feng, 2014).

TSP has many advantages and disadvantages, as it has been proven by existing literature. The existing research contributes to the available practice by offering detailed insights into TSP, developing methods for its evaluation, and providing solutions to some ongoing problems. By providing a detailed understanding of TSP, developing methods for its evaluation and providing algorithms for different levels of TSP, different researchers try to improve the efficiency of the public transit system.

In the last decade, TSP systems have been an area of extensive study. They have been identified as potentially helping to bring more people into the corridor and minimize pollution, benefiting both transit users and the network. However, traditional TSP is not ideal because it potentially affects other traffic users. The traditional TSP induces a significant delay for the competing directions movements. Also, TSP does not effectively serve transit facilities with nearside stops due to the high uncertainties of dwell times. Moreover, although many studies investigated TSP strategies, there is limited research evaluating TSP systems based on the number of passengers. Most of the proposed methods prioritize all buses, regardless of the bus loading or its capacity. Also, most studies only focus on traffic Measures of Effectiveness (MOEs). A few researches could be found to assess the impacts of TSP on environmental factors like vehicle emissions.

Given the above-identified issues, this research develops a novel TSP strategy that considers the number of passengers on board as well as adherence to bus schedules. The developed methodology used real-time transit data to decide whether a bus should receive priority when approaching a traffic signal. This research aims to minimize the intersection's delay and evaluate delay per person and other traffic and environmental measures, like speed, number of stops, and so on, for all other approaches at the intersection. Additionally, this research evaluates the effect of proposed TSP strategies on the environment since an increase in the efficiency of public transit may result in a reduction in greenhouse gas emissions.

1.3 **Research Contribution**

Public transit saved Montréal households around $600 million in transportation costs in 2003. Based on MTMP, Montréal should have a minimum 26% increase in public transit ridership by 2021. New strategies would help increase public transit efficiency. As a result of the COVID-19 virus, according to (Abdy, 2010), bus ridership fell by 50 percent, and revenue fell by $870 million between the beginning of the pandemic and 2022. (Sargeant, 2020). Furthermore, based on the MTMP, public transit must easily and safely carry passengers along public roads to maximize public transit use. For this reason, a priority program has been launched by STM and Montréal's authorities along more than 200 km of road networks, intended to encourage people to use public transit to improve the system's parameters. Aside from this, unlike the existing TSP algorithms, the proposed algorithm does not prioritize all buses approaching an intersection. Some criteria must be met for a bus to receive priority. Another key objective of this research is to minimize delays for everyone, including passengers in private vehicles and those on buses.

Moreover, the methods which are presenting in this dissertation increase public transit efficiency, especially for the nearside bus stations, which Montreal has many of them. With this strategy, the number of stops for all the vehicles in the intersection would be decreased. This MOE increases fuel consumption and GHG emission. For this reason, this strategy could decrease the adverse environmental effects of public transit, which is aligned with the MTMP(Ville De Montreal, 2008).

1.4 **Transit Signal Priority (TSP)**

A transit signal priority is an operational strategy that allows transit vehicles in service to move through signalized intersections more efficiently. In the first year that TSP was implemented (Evans & Skiles, 1970), it was aimed at reducing transit delays at intersections, reducing transit travel times at arterials, improving transit service reliability, maximizing intersection person throughput, and increasing transit quality of service through its implementation. While signal preemption interrupts normal signal processes during special events (such as emergency vehicles or trains passing), signal priority alters the normal signal processes to allow transit vehicles to pass through more smoothly (Baker et al., 2004). In the case of a corridor, there is a greater difference between the two operating modes. The sole purpose of signal preemption is to provide right-of-way to the requesting entity immediately, without regard to the existing signal timing for coordination; there is no consideration of maintaining the existing signal timing for coordination. The signal coordination can, however, only be modified to a degree that does not significantly impede the general flow of traffic when the signal priority is in effect.

Traffic signal control strategies are generally considered to be an additional layer in the traffic signal control system. They are also independent of the type of traffic control system used. It is important to note that the types of TSP controls that can be implemented are limited by the availability of infrastructure, which is generally determined by the type of signal control system that will be used.

In general, vehicles with any form of signal emitters, such as optical emitters or radio frequency (RF) tags, can send a signal to a receiver or detector connected to the signal controller as quickly as possible. The controller processes and implements the TSP logic, and confirmation signals are optionally sent back to the vehicle as a confirmation signal. Besides being deployed alone, TSP strategies sometimes work with other preferential treatments. The addition of a queue jump lane (Allen, 2012; Zhou & Gan, 2009) is one of the strategies used most frequently in combination with the transit signal priority. Another example is that conditional TSP can be used with a bus stop holding strategy to achieve better schedule adherence (Furth & Muller, 2000).

1.4.1 Benefits

TSP system's primary goal is to minimize the transit vehicles' travel time (particularly those using the shared right of way by reducing the delay at the intersections). Given the congestion along a major arterial, it is assumed that a system such as this will significantly improve the transit vehicle's operating efficiency and ensure better compliance with the schedule. Increasing the total vehicle traffic along the corridor is another expected advantage of TSP. These facts are shown in a study in 1998 (Jones, 1998), which demonstrates that the ITS's enhanced bus priority will replace the need for guideway segregation to increase public transport operations.

Kamdar (2004) proposed that a TSP system would be particularly useful for the farside bus stops instead of those on the near side. The buses that can clear an intersection at a farside bus station and then make a pick-up/drop-off have to station just once. However, if the bus needs to make a stop, there is a reasonable chance the bus will have to stop again at the red light before the intersection to pick up passengers. Significant criteria must be specified to achieve one or more of these goals. One condition is that a bus can be identified until it enters the intersection. The signal timings can then be changed in some specified way (e.g., extending the green interval to allow the intersection to be cleared). Another condition is that only those behind schedule or within a defined period are given priority. This could avoid the bundling of buses and therefore ensure better schedule adherence.

1.4.2 Implementations

For more than two decades, various TSP strategies have been implemented and tested either in the field or through computer simulation (Garrow & Machemehl, 1999). Based on the type of priority given by the implemented TSP system, these strategies can be classified (Furth & Muller, 2000) as a full, partial, and relative priority:

1. Full Priority: Full priority tends to offer zero-delay service to transit vehicles. This form of priority is the most common implementation in many European cities.
2. Partial priority: Only the priority strategies with the least negative impact, such as green extension and early green, allow for partial priority. On extension lengths, it typically uses stringent restrictions. North American cities use this type of priority more frequently.
3. Relative Priority: Transit services compete with other traffic for the available green time and prioritize prioritized under relative priority. Transit vehicles are normally given a higher weight to account for their higher passenger loads but depending on the competing volumes of traffic and queues, requested priority may be refused.

. Based on the available literature, TSP strategies are classified into different types listed in the subsequent sections. (V. W. Ngan, 2002).

Passive Priority Strategies

A passive priority strategy uses a standardized evaluation of transit routes and demands as an input to traffic signal operation at an intersection. This technique does not require any transit vehicle control or detection system (V. W. Ngan, 2002). This aims to favour bus movements by minimizing cycle length or offering phase sequences that provide public transit vehicles with more frequent green time (Mirchandani, Knyazyan, Head, & Wu, 2001). Some passive priority techniques frequently employed are:

1. Cycle length modification: For both transit vehicles and passenger cars, shortened cycle length may decrease the stopped time delay. Even with the absence of transit buses, this technique is successful and does not penalize buses along the crossroads like other active transit signal priority modes. However, shorter cycle benefits must be weighed against arterial capacity reduction (Garrow & Machemehl, 1999).
2. Phase splitting: This method divides the signal phase of transit into several phases so that the cumulative time matches its original length. Without modifying the total intersection cycle length has the disadvantage of shortening the cycle length for transit vehicles' approach (Garrow & Machemehl, 1999).
3. Area-wide timing plans: Area-wide timing strategies offer buses with priority treatment by preferential progression, which can be done simply by designing the signal offsets using bus travel times in a synchronized signal scheme (Sunkari, Beasley, Urbanik, & Fambro, 1995).
4. Metering-Vehicles: This strategy enables buses to bypass metered signals with metered signals. It also contains specially reserved bus lanes and special signal stages to be re-routed to non-metered signals (Sunkari et al., 1995).

Active Priority Strategy

The active Priority strategy is the most commonly used and verified TSP strategy in North America. This strategy includes detecting or locating buses present or approaching a signalized intersection. In response to a transit vehicle's presence or imminent presence determined by a detector, the strategy triggers the regular signal activity to be altered (Kamdar, 2004; V. W. Ngan, 2002). Mainly 4 different types of these strategies can be found in the literature:

- Green Extension;
- Red truncation/Early Green;
- Special Bus Phase; and
- Mixed strategies.

Green extension and red truncation strategies are more widespread in practice than the others, and most literature developed models based on these two strategies. These two strategies do not require additional clearance time, so the lost cycle time does not increase. They are, however, less disruptive than the other methods or strategies for the drivers. Finally, with no adjustment in phase sequence and cycle period, green extension and early green can be implemented so that less disruption can be required in the vehicle platoons(Bagherian, 2017).

Green Extension

This TSP strategy implies the extension of the green phase along the transit route at an intersection until the normal green phase ends when a transit vehicle is identified in its proximity. In most cases, the green phase is terminated once the bus clears the intersection. Also, the extension of the green phase is limited to a pre-specified maximum duration. This max duration of the green phase extension is necessary if there is a misdetection of the bus crossing the intersection in order to terminate the unnecessarily long bus priority calls (Khasnabis & Rudraraju, 1997). The amount of maximum green extension used varies for various TSP implementations or simulations. Most green maximum extensions are between 10 and 20 seconds.

Red Truncation/Early Green

This method offers the transit route with an early green phase upon identifying a transit vehicle during the red phase. The method includes the truncation of either all or some chosen non-bus phases (skipping or shortening). However, a review of the literature reveals some drawbacks of this method, including the clearance protection of the other phases (including vehicle and pedestrian phases) and the unnecessary delay of truncated approaches when planning the early green process's overall duration. It was found that the amount of maximum early green is not the same for different implementations. All the same, the red truncation time duration is, in most cases, shorter than the green extension time. Also, the red truncation time is tightly connected to the pedestrian phase's minimum walk and the clearance times of the conflicting movements (V. W. Ngan, 2002). For example, in (Chatila & Swenson, 2001), the maximum red truncation time was set to 20 percent of the usual split duration of the opposing stages preceding the bus stage, while another study recorded that buses appeared to have less advantage from early green or red truncation than green extension (McLeod, 1998). This study assumed that early green or red truncation would cause conflicting traffic to interrupt more frequently than the green extension was not appropriate for the traffic signal settings. Another study found that phase skipping would cause an important vehicle delay because it brought the most significant disruption to the signalized intersection (Al-Sahili & Taylor, 1996).

Special Bus Phase

A particular bus phase allows the insertion into the regular cycle of a dedicated duration for buses' movements only. This method is applicable for signalized intersections with more than two phases.

Mixed Strategies

To offer priority to transit vehicles subject to the expected arrival time of a bus in a cycle, the idea of mixed transit priority strategies was developed. Green extension, early green, and particular phases can be included in these strategies (Balke, Dudek, & Urbanik, 2000).

Although active strategies are more versatile and successful than passive ones, they are much more costly than passive ones. Communication technologies and bus detection systems and their implementation complexity (which can waste the investment from a system-wide perspective without any major impact) can be identified as the main problem with these methods (Bagherian, 2017).

Types of Active Priority Strategies

Active priority may be either conditional or unconditional, depending on the bus detectors' positions and capabilities (Mirchandani et al., 2001).

Unconditional Transit Priority:

The unconditional priority strategy does not evaluate the effectiveness of serving a transit request for signal priority. In other words, it does not check whether the priority is really needed. This form of strategy prioritizes transit buses without assessing the impact on the other vehicles approaching the intersection. Another disadvantage is that it can make it harder to handle subsequent arriving transit vehicles because of possibly extraneous delays and queues. In most recent studies and procedures, conditional or selective priority is applied to resolve this deficiency and monitor the interruption to general traffic (Yagar & Han, 1994).

Conditional Transit Priority:

Based on specific predefined requirements, conditional priority assigns signal priority to a transit order. The majority of TSP projects depend on one or more of the following factors to base their conditional transit priority decisions:

1. Schedule Adherence: Only buses that are behind schedule or late will be given transit priority. For various control systems, the concept of "lateness" may vary. Some implementations consider any negative deviation from the bus schedule to be "late,"; whereas other systems consider a bus to be "late" if it arrives outside a predefined "variable window."
2. Passenger Occupancy: For buses with higher passenger occupancy, higher transit priority would be granted, and priority would not be granted to empty buses. One study (Skabardonis, 2000) pointed out that giving priority to empty buses would not be helpful. The critical elements of using this approach are the communication mechanism and data source. Among the suggested approaches is to allow the drivers to cause a TSP request (which may involve recruitment and extra attention from the driver)(Smith et al., 2005). Finally, the person-based delay approach is another strategy in which a limit on capacity or number of passengers would be given priority (E. Christofa & Skabardonis, 2011).
3. Spare Green Time: According to this criterion, the priority of transit can only be granted if, in a signal loop, there is plenty of spare green time. At intersections and along arteries, this ensures that the usual phasing sequence is maintained. (Skabardonis, 2000) mentioned that signal preemption at a signalized intersection should not result in over-saturated movements or signal coordination losses.
4. Bus Route Progression: The traffic conditions at the intersection(s) downstream are Assumed for priority provision in transit (V. W. Ngan, 2002). (Skabardonis, 2000) If

progressing the green time at an upstream signal for the buses would carry them to a queue downstream, raising their delay downstream, no bus delay advantage would be achieved.

Conditional TSP strategies are developed around more complex systems than unconditional strategies since they involve additional ITS components such as Automated Vehicle Positioning systems (AVL) and various detection and communication systems (Baker et al., 2004). The benefits of the conditional strategies are expected to be higher since they address a whole system instead of finding transit-centric solutions. Conditional TSP solutions have become more prevalent in recent years, considering their proven efficiency and providing technological and IT developments (Bagherian, 2017).

It is worth mentioning that most conditional TSP policies prioritize buses behind their schedule to boost the timetable and ongoing enforcement of transit services. However, a TSP system in which priority is provided only too late for buses were tested (Furth & Muller, 2000). The TSP logic was such that the signal promptly turned green if the bus was late and approached a red light. In Eindhoven, Holland, the authors investigated a transit service and reported improved service quality by keeping buses on schedule when conditional priority was used. It has also been found that there were fewer adverse effects on the other approaches. Besides, since the bus drivers are less concerned about adjusting their speed to stay on schedule, they claim a more straightforward operation to be achieved.

Another TSP strategy was tested by Ma and Liu (2010) to induce a previously approved delay to buses, as prescribed by the operators. It should be noted that applying TSP for a bus that is ahead of schedule will add an extra delay to the bus. The authors suggested this Coordinated and Conditional Bus Priority (CCBP) strategy by adjusting the bus travel time (i.e., decreasing or increasing its delay) to ensure that its delay is within the specified threshold.

As described above, developing a reliable communication system between vehicles and infrastructure is required to successfully implement conditional priority strategies. However, these days, more data is provided through cutting-edge technologies that can be used to develop TSP strategies. For instance, using V2I communication, real data like the number of passengers, the schedule, and their location can be used to develop strategies.

1.4.3 Bus Detection and Location Methods

A bus location/detection system approaches an intersection (K. Gardner, D’Souza, Hounsell, Shrestha, & Bretherton, 2009) and is the first requirement for identifying a bus on an approach at a traffic signal. The following general categories summarize the alternatives for this method.

Infrastructure instrumentation

With no need for on-bus facilities, these strategies include bus detection. This includes using technologies such as “long loops,” signature processing loops, or above-ground devices, like video image processing, to detect buses (Ahmed, 2016).

Bus Instrumentation

These methods allow the identification of buses exclusively from the equipment onboard the bus. Global Positioning System (GPS) can be a primary example here, which offers continuous vehicle positioning at an accuracy of usually 5–10 meters (Public Transport Priority: State of the Art Review, 2002). The bus can then be positioned relative to the traffic signals by proper onboard software

Bus and Infrastructure Instrumentation.

These methods detect buses based on communication between on-bus equipment and the relevant field infrastructure, classified as communication between the bus and local infrastructure or central infrastructure. (Ahmed, 2016).

On-Bus and Local Infrastructure communication includes using bus transponders or "marks" and contact on the approach to each fitted junction with an inductive loop or beacon detectors. It provides accurate identification (only of fitted buses) at particular locations (Ahmed, 2016). On the other hand, communication between the bus and central infrastructure includes bus identification onboard equipment (e.g., GPS) and, generally, radio-based contact between the bus and the control center(s). Radio communications can differ from "polling" dedicated channels, where the bus position is questioned at regular intervals (e.g., every 30 seconds), to systems using General Packet Radio Services (GPRS) technology. It also consists of exception reporting' (e.g., the bus only communicates with the control center[s] if the bus does not follow the timetable by more than a pre-set amount). This alternative, which is currently expected, reduces communication costs but needs greater analysis and infrastructure on each bus (Hounsell, McLeod, & Shrestha, 2004).

1.4.4 TSP Efficiency

Many factors affect TSP efficiency. These factors could be classified as intersection geometry, signalized intersection timing, and transit network characteristics.

One of the most critical considerations for any transportation system's operation is intersection geometry since it directly determines the transportation system's capability and types of potential operations (Z. R. Abdy, 2010; Advanced Public Transportation System Committee, 2002). Among other factors, land use affects the position and number of intersections, generates traffic in the city, and determines transit stops.

The TSP system's general performance is affected by traffic demand (Rakha & Zhang, 2004). During the peak hour, intersections run with the highest volume of daily traffic and transit vehicles(Advanced Public Transportation System Committee, 2002). The volume of peak hours is usually one of the main components in deciding which plans should be used for signal timing. High demand for a non-prioritized approach can mean fewer opportunities for prioritizing green time, thus decreasing the TSP's efficiency. Transit vehicle arrivals on heavily congested approaches can benefit system-wide benefits if the conflicting systems are not congested. On the other hand, if the conflicting approaches are heavily congested, transit vehicle arrivals on slightly congested approaches can produce significant system-wide disadvantages (Rakha & Zhang, 2004).

Traffic signal service is another influencing factor. Traffic signal operation has many components: cycle length, phase number, phase sequence, green time allocation, and appropriate pedestrian clearance. If there is less green time derived from a non-prioritized approach, there is an effect on TSP performance. (Z. R. Abdy, 2010).

A proper TSP strategy consists of parameters such as the amount of green time that can be reduced from the non-prioritized method. An inappropriate selection of TSP parameters may result in increased intersection delays(Advanced Public Transportation System Committee, 2002). TSP system is highly dependent on the transit vehicles' headway. [66]. The possibility of conflicting TSP requests is also increased as bus frequency increases. Consequently, if buses arrive with smaller and smaller headways, it is expected that the efficiency of TSP will decrease (i.e., the reduction in bus delays will be less significant). This may lead to a queue blockage as the minor approach signal cannot restore the cycle in consecutive priority requests.

The level of progression is another aspect that influences TSP quality. The overall net advantage is expected if the signal timings change due to TSP control favouring the traffic progression. On the contrary, if the TSP's altered signal timing results in a disturbance to the traffic progression, a detrimental effect is expected(Z. R. Abdy, 2010).

1.4.5 TSP Algorithms

In the literature, in addition to the type of TSP methods, various types of implementations can be found. As mentioned in the previous section, the logic can be classified as passive and active, depending on the available infrastructure and budget. Active strategies usually use real data that can be extracted from GPS and detectors. On the other hand, passive strategies do not deal with real data, and they work with the bus's general characteristics, like headways, dwell time, and expected arrival time.

A priority request weighting factor for the TSP strategy was introduced (Liu, Skabardonis, & Zhang, 2003). In their analysis, by using a weighting factor (which is derived from traffic demand and queueing conditions), a bus with priority was converted to a group of vehicles. A passenger car equivalent rate will, therefore, be obtained for each approach. The signal was controlled using a new set of flow rates typically modified in favour of a TSP request approach. Setting suitable weighing factors had a primordial role in this method.

Zlatkovic, Stevanovic, Martin, and Tasic (2012) evaluated several TSP strategies to determine which one works best for a bus-rapid transit (BRT) system. This objective was accomplished by comparing four TSP options in a VISSIM. To measure effectiveness, the researchers used travel times, intersection efficiency, and network performance. The analysis used projected and scheduled traffic and transit operations for the tested network. Besides, a heuristic TSP logic was developed and compared to their analysis's standard methods. In this method, the algorithm's key feature was that none of the traffic controls phases were omitted in the defined strategies in this research. In addition, before the signal turns red, the proposed rationale ensures that the prioritized bus crosses the intersection. For BRT vehicles, each of the tested strategies brings some benefits. The results show that TSP with phase rotation and the proposed TSP strategy could also be taken into account for implementation.

Ekeila, Sayed, and Esawey (2009) proposed a dynamic traffic signal priority strategy to improve the previously established active TSP strategies, providing priority in response to real-time traffic and transit conditions. Three key elements are included in their method: automatic vehicle location (AVL), dynamic model of arrival prediction, and dynamic TSP algorithm. They modelled the AVL system in VISSIM using a distance-interval detection system. The space between detectors was 10 meters, and they controlled each phase's bus position. To forecast arrival times, a linear model was used. Upper and lower boundaries were also defined. Since the model did not work well, they used two refinement methods, Empirical Bayes (EB) and Kalman Filtering (KF). The algorithm recursively examines the bus's estimated arrival time before reaching a decision. They described several scenarios for the signal phase's arrival times and their upper and lower boundaries. According to the condition, they suggested one of three types of the mentioned TSP methods (green extension, red truncation, and cycle extension). They used the microsimulation approach to test their strategy and showed better results than the no TSP or traditional, not improved TSP strategies.

An adaptive transit signal priority control (KATC) method based on kinematic waves is proposed in another study to minimize average passenger delays at intersections. As a mixed-integer non-linear program (MINLP), the passenger delay minimization problem is formulated with two decision variables - green time and phase sequence. The adoption of the phase sequence in the optimization and not involving the commonly used simplifying assumptions in the delay models were the main contributions of the current study. A genetic algorithm has been utilized to solve the MINLP problem at 1-cycle intervals and for a decision horizon of 3 consecutive cycles using general traffic and public transportation unit delays. KATC performance was evaluated against SYNCHRO and the KATC model without phase sequence optimization, with VISSIM as the analysis tool. The results of the experiments indicate superior performance of KATC over the two other models in terms of average passenger delay and bus passenger delay, particularly at low levels of congestion. Moreover, increasing the occupancy of bus passengers can effectively contribute to a reduction in passenger delays. As compared to SYNCHRO and the KATC model without phase sequence optimization, the adverse effects on passenger vehicles are limited to an increase of 3.4% and 2.7% in general traffic delays, respectively (Behbahani & Poorjafari, 2022).

Kim and Rilett (2005) proposed an Enhanced Transit Signal Priority, prioritizing buses with nearside bus stops. They argued about traditional TSP logic's performance for the buses at an intersection with nearside stops, where their dwell time was not decisive. e. They used a weighted-least-squares (WLS) regression model to estimate dwelling time distributions to predict bus arrivals at the intersection. This prediction will enable the algorithm to change the timings so that the bus will cross the intersection without delay. Early green, green extension, phase insertion, and phase extension were the strategies they used in their logic. They mentioned less bus delay than traditional TSP logic when testing the model using microsimulation methods.

A coordinated transit priority control optimization model is presented in a study that Ma, Ni, Head conduct with the following features: (a) the control unit is identified as the collaborative intersection group between two successive bus stops; (b) buses are detected at the first intersection of the control unit after leaving the upstream stop before arriving; (c) the complex interactions of priority strategies between adjacent intersections within a control unit are modelled using a model of bus delay and an inadequate model of priority time, and (d) a linear program model is built to establish optimal priority strategies to minimize bus travel time when priority is required and to ensure that every priority treatment is applied at each intersection. Extensive experimental studies were conducted, including time-space diagram-based deterministic analysis and simulation-based analysis, and findings were compared with traditional priority transit signal strategy and scenarios of no priority. The proposed model provides impressive outcomes in control design for transit priority signals to reduce bus delay, improve bus schedule adherence, and mitigate the negative impacts on general traffic under various traffic demand patterns.

It is possible to consider customizing simple TSP techniques as a primary solution to enhance the system's performance. Considering different parameters like dwell time, space between buses and intersections and the number of requests, different logic could be added to an existing model. They will improve the method with more advanced algorithms for decision-making, representing multiple scenarios encountered at each intersection(Bagherian, 2017). However, taking into account the ad hoc existence of the traffic state as well as the necessary level of accuracy in a macro-level study, with no added benefit for the planning intentions, these approaches incur additional computational costs for the evaluation process.

1.4.6 Evaluation of TSP Methods

Regardless of the type of method proposed and/or implemented, TSP performance assessment is important. The following three methods can usually be used to determine the effects of TSP on traffic flow and transit efficiency(Z. Abdy & Hellinga, 2011):

1- Microsimulation methods
2- Analytical methods
3- Before and after studies

Microsimulation Methods

Microsimulation models have been used in most TSP modelling and research studies. This is mainly due to TSP performance sensitivity to many parameters such as intersection layout, vehicle flow speeds, bus headway, positions of bus stops, and synchronization of signals(V. Ngan, Sayed,

& Abdelfatah, 2004). A wide variety of parameters and conditions that affect TSP effectiveness can be considered by microsimulation models (Z. Abdy & Hellinga, 2011; Bagherian, 2017).

The influence of a series of traffic parameters on TSP's application's effectiveness was investigated by (V. Ngan et al., 2004). They applied TSP techniques to a corridor using the VISSIM microsimulation tool and introduced some TSP implementation guidelines. Ahn and Rakha (2006) investigated the system-wide impact of TSP service on a corridor using INTEGRATION microscopic traffic simulation software.

Microscopic simulation is the most frequently used tool for evaluating TSP strategies. Several models to simulate cars and drivers' behaviour and the ability to represent the network layout with the highest level of detail made the microsimulation approach an appropriate tool for analyzing traffic conditions. Nonetheless, their implementation has various disadvantages (Bagherian, 2017). The disadvantages of using traffic simulation include the following: (1) simulation models are sophisticated and could provide more straightforward administrative procedures; (2) simulation models should be analyzed, calibrated, and validated; (3) any shortcoming in the implementation of the latter procedures can make the results unreliable and inefficient; and (4) some users apply simulation models without being aware of its limitations and modalities(Transportation Research Board, 2016).

A recent study (Bagherian, 2017) evaluated a proposed TSP strategy at a network level. The author optimized the location of priority strategies in the network through different methods to find the optimal TSP strategies. These methods could be used in simulation-based or analytical tools at a macroscopic level using the O-D input data and propose some passenger-oriented delay metrics. However, the focus of this work was at a network level, and the accuracy of a microscopic calibration cannot be validated.

Analytical Methods

Several studies have developed an analytical approach to test the developed TSP methods. One of the early attempts to establish an analytical method for assessing the effect of TSP strategies at intersections was (Sunkari et al., 1995). They used the 1985 Highway Capacity Manual's simple delay equations for signalized intersections. In some cases, they reported an overall acceptable accuracy but overestimated delay. Although the approach was oversimplified and was not ideal for practical use (the calculation of delay for some phases was not accurate), it was an easy tool to determine the viability of implementing priority strategies.

Hongchao, Zhang, and CHENG (2008) used a queueing theory approach to evaluate shortened red and extended green effects at an intersection. They expected that a TSP deployment would not substantially alter the randomness of the traffic stream. They used deterministic arrival and departure rates to capture the effects of the TSP. They measured the increased delay for both the bus strategy and the competing movements, concentrating on early and extended green as the most prevalent TSP strategies. The delay was measured for only one period, and its influence was ignored beyond the first period.

Z. Abdy and Hellinga (2011) argued for a range of shortcomings of the previous study on the analytical evaluation of TSP impacts. Some of the shortcomings that they mentioned include the estimation of the delays for only one period and thus ignoring TSP impacts that could extend beyond the first period, deficiency in estimating the uncertainty in the oversaturated conditions, ignoring the effect of bus frequency on TSP output, calculating the delays for just one cycle and neglect the effect of TSP on the consecutive. A collection of scenarios was specified in their proposed model, depending on the TSP type (early green or green extension) and queue dissipation cases. A mathematical formulation was provided to measure the total vehicle delay and time of queue dissipation. Compared with those obtained using microscopic simulation analysis, the results calculated from the model were compared, and a close match was recorded, especially for flows with $v/c < 0.8$. This study was still focused on queueing theory and determinist arrival and service rates (i.e., $D/D/1$ models), similar to many other analytical models.

In a recent publication, a new approach to estimating the impact of TSP on control delay and the level of service of an intersection was proposed by Skabardonis and Christofa (2011). They presumed that getting priority equals the probability of reaching the average delay and service level for various modes within extended green and estimated. Their analysis model was based on the Highway Capacity Manual (HCM). In their analysis, the delay was considered to be only a function of the saturation degree (volume to capacity ratio) and the rate of green time to cycle length. Two methods applied as the TSP were green extension and RT red truncation.

Analytical methods can be seen as a feasible solution for evaluating the output of TSP in a study at the network level. The assessment process is much quicker than simulation techniques due to a collection of simplification assumptions, and the results match those obtained by microsimulation methods. Also, as (Bagherian) mentioned in his research, the cost of simulation-based methods at a network level can play an essential role in decision-making. Nevertheless, the literature shows the values of delay and travel time as the only indicators of these successful methods.

Before and After Studies

Another approach for estimating TSP impacts is to assess the effect of TSP by analyzing the data from before and after TSP deployment. After applying a strategy and evaluating its results in the field.

Wang, Hallenbeck, Zheng, and Zhang (2007) conducted a detailed analysis of an applied TSP strategy before and after collecting field data. A series of effectiveness indicators (i.e., transit time match, transit travel time, traffic queue length, signal failures, frequency of TSP calls, average person delay, and vehicle delays) were evaluated before and after TSP deployment. Data were collected from TSP logs, vehicle GPS logs, traffic controller logs, traffic video recordings, and bus driver log forms (in case of unexpected delays in transit vehicles). Their assessment indicated that the TSP had a positive effect on transit vehicles and a negative impact on other traffic delays. They suggested that the nearside stops move to the other side of the intersection. Also, they recommended that the green extension method removes from TSP logic when it comes to an intersection with a near-side bus stop.

TSP implementation's effects on operators and passengers were examined (Kimpel, Strathman, Bertini, & Callas, 2005). They measured the performance of the TSP in various performance viewpoints and indicators but drew atypical conclusions. They showed that the predicted advantages of TSP are not uniform across routes and periods, nor are they consistent over the different performance indicators. The authors concluded that the benefits of TSP could be accrued only due to comprehensive assessment and adjustment after initial deployment. An ongoing performance assessment and adjustment program should be incorporated in most cases to maximize TSP advantages. Travel time data for buses and other vehicles were collected at four intersections in an arterial corridor before and after introducing an active TSP system (Hunter-Zaworski, Kloos, & Danaher, 1995). The authors found that bus travel time decreased during peak hours after the TSP introduction but increased during off-peak hours. Also, it was found that the total person delay at the intersection had a mix of changes at various times of the day.

Koonce, Kloos, and Callas (2002) assessed a TSP system’s effect on bus travel time on another corridor. The study found that 0.4-3.2 minutes of bus travel time and the variability in travel time decreased by 2.2-19.2 percent at various periods of the day and travel directions. No difference between late buses and those that were not late has been found; however, in bus travel time savings. Following the TSP implementation on several corridors, Kimpel et al. (2005) assessed bus running times, on-time efficiency, and excess passenger waiting times. Results have shown that TSP’s advantages are not consistent across routes and periods or across different performance measures.

To evaluate the effects of TSP on bus headways on the same corridor, (Albright & Figliozzi, 2012) also used regression models. They found that a transit vehicle asking for a priority would decrease the headway between itself and the proceeding vehicle and increase the headway with the following vehicle.

However, according to the literature, since these approaches are only limited to before-after studies, field measurements cannot be applied to a decision-making process in some studies. For instance, it is hard to analyze this method at a network level. They can either predict TSP performance in similar sites or evaluate the developed strategy after its application. Considering this fact, these observations can limit the number of intersections with TSP deployment potential. In other words, from these findings, a set of guidelines can be derived to be implemented in future studies. For instance, a network could be divided into different parts, and each part analyzed separately. Then, all of them could be integrated into one network. However, the results would not be accurate since each part would be analyzed separately.

1.4.7 TSP Measure of Effectiveness

The following can be listed among the objectives for the implementation of TSP strategies (Smith et al., 2005).

1. The effects on bus and car travel times.
2. The effects of transit system variation (e.g., timetable adherence or headway preservation)
3. The impact on the reduction of air pollution and modal shifts
4. Reducing unnecessary delays for transit vehicles
5. Possible transit operating cost savings (e.g., savings by reducing the size of the fleet)
6. The effects on the study area's overall person-based throughput.
7. The effects of the changing the timing frequently on safety
8. The effects of the strategy on fuel consumption and vehicle emissions (environmental MOEs)

Many studies have suggested methods to increase transit services' reliability and have analyzed their impacts on bus travel time and service reliability. These strategies include consolidating and relocating bus stations, introducing bus rapid transit (BRT), an intelligent card payment system, and holding and expressing bus strategies. However, without a thorough cost-benefit analysis process, bus stop consolidation and relocation, BRT implementation and smart card payment system solutions are typically not simple. Bus holding strategies minimize the waiting time of individual passengers outside the vehicle but raise the waiting time of onboard passengers in the vehicle, and vice versa for strategies to express the bus (Feng, 2014).

Several researchers concentrate on assessing the impact on transit vehicles and other traffic using empirical or simulation models of the proposed TSP strategies. It was found that outcomes vary significantly. With both green extension and early green phases at an isolated intersection, Balke et al. (2000) simulated an active priority strategy. Significant decreases in bus travel time were observed at various traffic levels, with small increases in overall intersection delays at moderate traffic levels.

A person-based cooperative adaptive traffic signal control system named PACT was proposed in another study (Lee & Wang, 2022). In PACT, two separate components are involved: adaptive traffic signal control on a second basis (by Road-Side Units (RUs)), and optimal driving speed guidance on a second basis (by On-Board Units (OBUs)). Signal control models optimize signal parameters to minimize the total number of people delayed. To calculate optimal speed advisory, signal phase and timing information is sent to OBUs once optimization has been completed. Optimal speed advisory algorithms provide an advisory speed which maximizes intersection passing probability. Using a normal distribution assumption, the algorithms account for a stochastic nature of bus arrival times. Following the application of recommended speed by transit vehicles, RSUs optimize signal parameters according to the latest traffic status, and the process repeats itself. Both transit vehicles and cars can benefit from PACT's signal-vehicle cooperative control system.

The experiment results show that PACT has a strong ability to handle real-time traffic variation, reducing total person delays by up to about 28% and bus person delays by up to 60%. Furthermore, PACT-OS can generate additional benefits of up to 20% compared to PACT-No OS, suggesting that optimal speed advisory can further strengthen the benefits of delay reduction. As demonstrated by the sensitivity test for bus occupancy, passengers experiencing delays of approximately 65% reduced when the average bus occupancy exceeds 20 passengers.

Another study evaluated passive and active TSP systems' efficiency on a corridor using simulation (Furth & Muller, 2000). Results showed that both passive and active priority greatly enhanced adherence to bus schedules. However, it was demonstrated that active priority has virtually no impact on traffic delays, while passive priority has significantly increased traffic delays. Skabardonis (2000) evaluated available control strategies and extracted the parameters which affect TSP. They also evaluated and proposed passive and active strategies for a corridor consisting of 21 intersections. This study showed that TSP strategies provide buses with moderate changes without negative effects on car traffic. Bus delay was improved by 14% in the passive strategies, while active strategies reduced the delay by up to 6 seconds per intersection per bus. The performance of several active priority strategies using simulation models on an arterial corridor was assessed by Dion, Rakha, and Zhang (2004). They noticed that buses, at the expense of the overall traffic, would usually benefit from the TSP. However, the overall adverse effects can be marginal when the traffic flow on the side street is minimal.

Byrne, Koonce, Bertini, Pangilinan, and Lasky (2005) analyzed the feasibility of a conditional TSP method at a single intersection using a simulation model. Their TSP strategies depended on location. They designed four different scenarios: nearside stops without TSP, nearside stop with TSP, farside stop without TSP, and farside stop with TSP. The results showed that the signal delay was reduced by 33% in the farside TSP scenario and increased in the nearside stop case. Also, travel time was reduced by 12% in the farside TSP scenario. Moreover, some research has shown that TSP is more effective at farside bus stops because there is less variability in predicting the arrival time of a bus at an intersection (Chada & Newland, 2002).

Stevanovic, Stevanovic, Kergaye, and Martin (2011) considered the delay of private vehicles, delay per person (assuming occupancy of private and transit vehicles) and transit vehicle delay as three performance measures to test various TSP scenarios and sought to optimize specific signal timings along with TSP parameters (cycle length, offset, splits and phase sequence). Likewise, Ekeila et al. (2009) developed a priority strategy for adaptive transit signals and compared it with a conventional strategy. Two indicators were used for comparison, the buses' total travel time and the cross-street delays.

Through the use of cycle-free Nash bargaining (NB) signal control systems, another study developed an advanced decentralized transit signal priority (TSP) system (Abdelghaffar, Ahn, Rakha, & Center, 2020). By adjusting signal timing, TPS allows transit vehicles to utilize additional or alternative green time to clear intersections. It is a technology solution recognized as capable of enhancing traditional transit services. Using the developed Decentralized Nash bargaining (DNB)-TSP system, a variable phasing sequence and free cycle length were considered in determining an optimal control strategy for an isolated intersection as well as an arterial corridor. INTEGRATION – a microscopic traffic assignment and simulation software, was used to implement and evaluate the developed system. As part of the evaluation of the developed controller's performance in different scenarios, the new DNB-TSP system was compared to an optimum fixed time plan (FP) controller, an adaptive phase split controller that is centralized, a phase split and cycle length controller that is decentralized, and a DNB controller without TSP. According to the study, a four-legged isolated signalized intersection with the new DNB-TSP system demonstrated significant improvements in various margins of error. Compared to FP, PS, PSC, and DNB controllers, the new system significantly reduced average vehicle delays by 67.5%, 73.2%, 71.1%, and 3.4%, respectively. The authors showed that transit vehicles decreased their average travel times by 15.6%, passenger travel times by 15.2%, total delays by 23.3%, stopped delays by 68.3%, and fuel consumption by 6.17% when using the DNB-TSP system over the DNB controller. As part of the study, an arterial corridor was also tested for its performance and it was reported that by comparison to other traffic signal controllers, the new system reduced vehicle stops, vehicle travel time, passenger travel time, vehicle total delay, vehicle stopped delay, fuel, and greenhouse gas emissions by 14.2%, 21.3%, 18.7%, 66.5%, 82.9%, 13.1%, and 13.1%, respectively.

Ahn and Rakha (2006) examined the system-wide advantages of implementing a green extension priority policy. They suggested that TSP implementation does not usually lead to system-wide advantages, while individual transit vehicles usually benefit from it. For various TSP scenarios, total and average vehicle delays for buses and private cars, average stops per vehicle, crossing-street queue length, fuel consumption, and emissions (HC, CO, and NOx) were compared. A mathematical formulation for optimizing TSP parameter settings was proposed by (Guangwei, Albert, & Sherr, 2007). They implemented minimization as the objective feature of the average delay of the buses at the intersection.

1.4.8 TSP Limitations

TSP is a commonly accepted operational technique that adjusts the intersection signal's timing in favour of transit vehicles by minimizing their overall delay at intersections and, subsequently, reducing fuel consumption. Nevertheless, some adverse effects have been determined to occur. For example, due to the complexity of identifying the duration of the transit vehicle dwell time, a TSP cannot consistently serve the transit facilities' requests with stops upstream of the intersection. Because nearside bus stops are common in large cities, the introduction of TSP may not be well argued for many intersections. Although there are many models for predicting dwell time for stops located upstream of an intersection, TSP could still impose an additional delay to the non-prioritized approach. (Bagherian, 2017; Kim & Rilett, 2005; V. Ngan et al., 2004). This problem is discussed in the literature as the key issue of TSP implementation (E. M. Christofa & Skabardonis, 2010; Li, 2008). Prioritizing buses can cause a delay in other approaches and modes.

Consequently, it is typically restricted to moderate congestion and a suitable network configuration to implement such preferential transit strategies at intersections.

The theory of reducing individual delay was recently implemented to give each approach a reasonable share of delay, depending on the number of people experiencing a delay at intersections (E. Christofa & Skabardonis, 2011). One study by Khalighi and Christofa (2015) proposed an emission-dependent optimization signal timing approach for an isolated intersection dependent on their person-based system. This model's goal was to minimize the number of vehicle stops and their corresponding acceleration and deceleration instances, thus reducing fuel consumption. They indicated no substantial change in total bus emissions (which are associated with fuel consumption), mainly due to the dominant proportion of cars generating emissions at the intersection. In other words, the main advantage of minimizing the consumption of intersection fuel is in favour of passenger vehicles, and in this regard, there is a modest (if any) gain for transit operators (Sobh, 2015).

Growing the popularity of transit agencies' preferential strategies has caused TSP requests in a network to increase. This situation increases the likelihood that two or more buses entering an intersection will have simultaneous TSP requests. In the field of TSP implementation, addressing conflicting TSP requests is an ongoing problem, and various approaches are proposed to address them (Bagherian, 2017). A heuristic algorithm for TSP with different priority requests was proposed by He, Head, and Ding (2011); (He, Head, & Ding, 2014). In the previous formulations, they assumed some simplifications and made it a "solver-free" problem. Three assumptions that made the algorithm valid at an isolated intersection were expecting phase sequences to be set, a First in First Serve (FIFS) rule for requests in the same phase, and the ability to serve all requests in two cycles. The model's evaluation using a microsimulation approach validated its ability to perform better than the previous methods (in terms of reducing total bus delays).

It can be concluded that TSP deployments can be efficient in a transportation network. They may help reduce delays, travel time, and the number of stops. However, these solutions are difficult to generalize for any type of network. For example, careful attention should be paid to the intersections with nearside stations and conflicting requests, as they might impose an additional delay to the other approaches. In addition, other factors influencing the efficiency of the TSP deployments were not thoroughly investigated, for example, the number of passengers onboard or a thorough assessment of environmental effects. The proposed methodology will be presented in the next chapter and explain how it can bridge these gaps in the literature.

TSP allows transit vehicles to adapt the timing of their signal's plans on their respective routes when travelling on signalized roadways. Implementing this technology aims to reduce the amount of delay and improve the reliability of schedules on these routes. In order to determine the actual priority of a signal, different methods can be used, depending on the system being used. The transit vehicle carries a device that emits a "message," which is sent to the signal controller, alerting it that a transit vehicle is approaching, employing a wireless signal. Upon receiving a green signal from the controller, the existing signal-timing plan is modified to provide that vehicle with a green signal.

There are various ways in which the signal-timing plan may be altered, depending on the type of system present. When a preemption system is used, the transit vehicle receives a green signal in a manner that does not take existing phasing or coordination into account and simply receives a green signal. Green signals are provided to transit vehicles progressively in other types of TSP systems so that the phasing of the traffic signal is not drastically altered. Generally, when a transit vehicle is preempted, the timing plan is altered to accommodate it as soon as possible. In emergency vehicles, such as police cars and fire engines, this is a standard procedure that is commonly used. On the other hand, the “priority” system uses special algorithms that determine whether or not a special plan needs to be given to the transit vehicle and when it should be given, resulting in an easy transition from one signal to another.

One can invoke the transit signal priority system in several ways. Devices such as radio emitters and loop detectors are used in some systems to detect loops. As part of the TSP system that will be implemented by METRO, the TSP system will utilize a radio-frequency-based (RF) automatic vehicle identification (AVI) as a means of determining if a vehicle is behind schedule as well as a means to detect that the vehicle is behind schedule. It is a system in which a vehicle is fitted with special equipment that notifies the system when a particular signal is emitted, informing it of the particular details about the vehicle. The literature review provides information on the history of TSP application of TSPs as well as the modelling techniques and algorithm development used to simulate TSPs.

1.4.9 Important Parameters in TSP Efficiency

Using the Transit Signal Priority system, buses will be given more priority so that passengers can travel more reliably. By increasing bus ridership, emissions will be reduced, and congestion will be reduced as well. Although the TSP system is effective, it still needs to be improved. The traditional system is unsuited for handling multiple bus requests, heavy traffic conditions, or uncertain bus arrival times. To measure the effectiveness of TSP, we need to know what variables or factors are considered.(Garrow & Machemehl, 1999) Summarized the parameters that influenced the success of the TSP by dividing them into 5 components that could be measured in different ways. However, each of these components depends on a number of factors.

1- Schedule

2- Number of Passengers

3- Traffic volume,

4-Capacity of the network

5- Efficiency of Intelligent transportation systems.

The impact of these parameters on the quality of TSP needs to be carefully studied to determine their impact. It is also possible for TSP to disrupt signal coordination, which can be a negative effect. For example, if one signal along a signalized corridor has a timing change of the TSP, platoons along that corridor may be disturbed in their movements. As a result of these negative impacts of TSP, it is evident that the development of TSP systems should consider both positive and negative aspects of TSP. TSP does not only aim to minimize bus delay as different factors are also taken into account to ensure a net positive outcome or an improvement of the entire process.

Schedule

A change in bus headways can affect the bus arriving at the intersection frequency. In passive TSP systems, a change in bus headway might require reprogramming the TSP to enable bus progress. Undoubtedly, adaptive systems can work with random bus arrivals, but too frequent arrivals can adversely affect TSP performance in more ways than one. Based on the fact that every bus entering the intersection will send a request for priority passing, this is the logic behind this. (McLeod, 1998) developed a model to deal with the issue of frequent requests by prioritizing bus requests based on their headway as more buses arrive. By prioritizing bus requests based on their headway, (McLeod) tackled the issue of frequent requests. According to his "Headway Algorithm," buses are given priority according to their headway compared to their scheduled headway. Despite this, it may take away a significant amount of green time from cross streets, leading to more delay overall. As a result, TSP may harm the corridor more than good in this case.

Another variable affecting TSP is the busload factor, as the primary purpose of TSP is to grant priority to Transit vehicles. However, 1.3 car passengers experienced the same delay as 10 bus passengers, which seems unfair. It is more critical for transit vehicles carrying more passengers to have TSP than other vehicles since the person's delay will be significantly higher when more people are in the vehicle. The logical goal of TSP would be to maximize load ratios to minimize delays between passengers. Heavy-loaded buses, however, tend to make frequent stops for passengers boarding and alighting. As a result of a greater number of bus stops, bus arrivals are also more likely to vary, which could lead to the bus not reaching the progression bandwidth and requesting more green time at each intersection (Alrashidan, 2018).

The frequency of bus stops will have a significant impact on the outcome of the TSP. Commuters who travel more than 15 minutes tend to choose rapid buses since they stop much less frequently than local buses when testing at a network level. As a result of such behaviour, buses with fewer stops travel faster when travelling at a network level (long path). Additionally, dwelling times also affect the speed at which buses travel.

In the case of commuters commuting for a more extended period, they are likely to choose rapid buses because they stop less frequently than local buses during testing at a network level. This indicates that rapid buses are buses with fewer stops that travel faster when travelling over a network level (long path) because they are more likely to be chosen when travelling for a longer period. One more thing to consider when it comes to the time it takes a bus to reach its destination is the time it takes for the bus to reach its destination. Magnetic stripe readers can help speed up the boarding process for passengers. In 2000, only 5% of buses were equipped with this technology. This number increased significantly in 2009, from 5% to 40%(Alrashidan, 2018). This change will directly impact the results of many field-based TSP studies as buses will now cover longer distances due to the reduction in the time it takes to board and disembark buses. Another method is to implement systems to allow passengers to pay their bus fares more quickly.

Since some TSP models depend on bus arrival time, there should be a solution to that problem of additional uncertainty. A stochastic mixed-integer nonlinear model (SMINP) accounted for bus arrival uncertainty (Zeng, Balke, Songchitruksa, & Zhang, 2014). This model calculates green time whenever a bus arrives while considering green time, split phase, deviation from green time, and saturation flow. Compared to a standard TSP model where the bus is given the green light according to its arrival, this model showed a 30% reduction in bus delay compared to the basic model in low to medium traffic flow. In cases like several bus lines in the same intersection, the "rolling optimization scheme" was used first to control which bus needed access by implementing a rolling optimization scheme. When there is much congestion in an intersection, the model automatically gives less priority to buses, allowing the bus to operate on the standard pre-timed settings. Giving priority might result in an increased delay in the intersection.

Considering the location of bus stops is one of the most important factors that influence the effectiveness of TSPs. Most research shows that far-side bus stops can improve the likelihood of buses travelling through intersections(Smith et al., 2005; Sundstrom, 2008). When a bus approaches an intersection and a request is made, it will not be possible for the TSP system to complete its purpose by allowing the bus to travel if it stops at a nearby bus stop (before the intersection). This lack of communication between buses and TSP significantly affects TSP's performance.

Number of Passengers

Multiple variables can be indirectly related to transit occupancy. For example, transit occupancies can be affected by the time of day, the bus headway, or the amount of bus traffic flowing. Basically, the purpose of TSP is to make buses travel faster. However, if bus occupancies are low, then this may undermine the objective of shifting delays from buses to general traffic, as it is a fundamental purpose of TSP. A majority of studies (particularly recent ones) have sifted through this issue in the literature, and most studies (especially recent ones) have been conducted during peak hours in urban areas, which assumes a higher level of bus occupancy, ultimately influencing the quality of the TSP contribution.

The TSP was examined in several studies during rush hours, concluding that buses are more used than average. In that case, priority should be given to medium and high-occupancy buses. V. Ngan et al. (2004) examined the benefits and costs of adding a TSP to a particular intersection based on the results of several studies. In the table he developed, he used values from multiple studies to show the effects of passenger occupancy and bus volume on the benefit-cost ratio. Based on his table, it is evident that buses with high occupancy are the best clients for the TSP, and the more frequently the buses run, the higher the benefit-cost ratio will be.

When passenger occupancy is higher, TSP may be negatively affected in terms of buses stopping more frequently for alighting and boarding as a result. As a result of an additional passenger on board the bus, (Surprenant-Legault & El-Geneidy, 2011) found that the average travel time of the bus will be reduced by 0.3 to 2.3 seconds on average. This may be because late buses usually travel faster to catch up with the schedule (Figliozzi, Feng, Lafferriere, & Feng, 2012).

Traffic Volume

Many factors are directly related to this factor, and this factor summarizes how important TSP is. To reduce transit stops at intersections, TSP was created as a solution. Increasing transit volumes means a higher probability that transit will eventually stop at intersections, allowing traffic to flow in other directions. It is important to note that the volume of traffic affects the quality of the system, the number of transit passengers, the number of transit arrivals, and the network's capacity.

TSP is most effective when high volume-to-capacity ratios are typically higher during peak hours when streets are more congested. Most TSP systems are designed to function specifically when volume-to-capacity ratios (V/C) are higher. TSP might be effective in cases with high traffic during special occasions outside peak hours, such as a special event that might attract more traffic to a specific location than usual. According to Kimpel et al. (2005), a regression model was used to examine the effects of TSP on bus running time in general and concluded that there was a statistically significant improvement in bus running time in general. However, the benefits of TSP were primarily confined to the PM peak hour only.

A TSP implementation scenario with high congestion might be better. In high V/C cases, buses may not be able to enter the intersection due to standing queues, and congestion at intersections does not allow them to give up green time in order to minimize delays. Ultimately, this would defeat the purpose of TSP. When V/C is smaller (off-peak), transit vehicles can travel smoothly with minimal impact on cross-streets. In contrast, Garrow's thesis showed that using TSP during off-peak hours can increase delays(Alrashidan, 2018; Garrow & Machemehl, 1999).

The Capacity of the Network

Adding a reserved bus lane as part of a TSP study has yet to be reported in the literature. Adding a reserved bus lane primarily affects the capacity of a corridor or network, affecting driver behaviour and significantly impacting traffic demand. A study carried out by (Surprenant-Legault & El-Geneidy, 2011) estimated that the time savings from implementing reserved lanes ranged from 1.2% to 2.3% of total running time without any significant impact on trip time or headway variation.

As part of a study published in Transportation Science and Policy, E. Christofa and Skabardonis (2011) developed and implemented an adaptive TSP system for a single intersection in Greece.

Since the intersection serves multiple bus routes travelling in different directions, it is quite complex. According to their research, their model also successfully reduced bus and car delays. In 2003, He et al. developed a similar model with an active system, which showed similar results. Thus, TSP has the potential to be implemented at intersections where transit is travelling in either one direction or two directions at the same time.

There are many advantages to developing and monitoring one-way TSP systems. However, if there is a large network capacity, there is a high chance that buses will travel both ways. The majority of studies have only examined one-way systems. It is worth noting that (Bagherian, Mesbah, Ferreira, Charles, & Khalilikhah, 2015) study is one of the most advanced studies investigating TSP at the network level. This research tested TSP effectiveness on nine intersections (buses travelling in North-South and West-East and East bounds). With the help of VISSIM and a C++ program to optimize the TSP, they could simulate bus and automobile travel times with TSP (Green extension, red truncation). A total of five objective functions were generated. The one that led to the most significant reduction in bus travel time was minimizing total travel time, which resulted in a 4.7% reduction.

Regarding car travel time, TSP at a network level has a small impact, a little bit +0.6% and -0.3% in the best—and worst-case scenarios, respectively. The results could have been more impressive in this study, but their model was not built on a realistic scenario. Kimpel et al. (2005) Found that the likelihood of having nine intersections with bus routes is exceptionally slim. He found that TSP showed significant improvement on the route level; however, when the system network level was evaluated, it could have shown a considerable improvement. There could be a reason for this since TSP in one direction tends to have less variation in both positive and negative impacts. As the results of TSP can be significantly affected by the direction of travel, having two-directional TSP can increase the variability of bus arrivals. The TSP can also affect the results due to the variability of delays on both sides of the travel.

The Efficiency of Intelligent Transportation Systems

The quality of detectors greatly influences TSP performance. Loop detectors are currently the most commonly used detectors. There are, however, multiple reasons why loop detectors can fail, including reading a truck as a bus, or reading a slow-moving bus entering the interest zone but not leaving, leading the TSP to make false assumptions about bus movements.

It is important to coordinate signals in passive TSP systems and active and adaptive systems. In connected intersections, platoon progression, which travels through multiple intersections without stopping, is significant. It is also possible to minimize the conflict of screening and processing buses at each intersection by coordinating with single or numerous buses. The better the coordination, the better the TSP quality.

Some early studies in developing TSP systems focused on isolated intersections so that they could optimize the movement of buses at those intersections. As a result, TSP could not be applied to these models due to the lack of coordination among several intersections. However, this problem is addressed uniquely by (Duerr, 2000)) through developing a TSP system. As part of his system, signal timings are dynamically adjusted to maintain progression coordination. It is possible to adjust and modify connected intersections mathematically using his model. This approach can be applied to coordinate multiple signals on a single corridor more significantly. It has been shown that dynamic traffic assignments can cope with the dynamic nature of network-based problems. Chang and Ziliaskopoulos (2003) explored how dynamic traffic assignments can be applied to TSP systems. As they pointed out, applying DTA models in smaller networks is sufficient to validate the algorithm's effectiveness in solving TSP problems, whereas using these algorithms in an extensive network will have significant outcomes.

As a result of the lack of large network data sets, most of these impacts will not be captured in the validation process. VISTA and ROUTESIM (simulator used to assign vehicles to the shortest routes) were used by (Chang & Ziliaskopoulos, 2003) for their model, which used datasets for forecasting purposes and that caused problems with signal timings and/or locations in their model. To improve the quality of their model, 2115 signal data nodes were added to increase the model's accuracy. This study successfully captured the impact of the TSP at a network level, including highways and a few major roads in the Chicago area, by analyzing the data. The study's effects were limited to only the traffic flow changes resulting from the TSP implementation. However, one major drawback was the effect on cross streets. A lack of detailed turning movement counts made them decide not to include minor streets in their studies.

1.4.10 Applications Review

There have been a variety of applications for TSP over the years. Many urban and suburban arterial roads have been implemented with TSP. In the past, there have been bus routes that accommodated both express and local buses. In the United States, the earliest projects implementing transit signal priority began in the 1970s as demonstration projects. Generally, these were called "preemptions," in which phasing was automatically given to accommodate the transit approach to avoid any delay. Some reasons led to the abandonment of these systems. However, a critical one was that the urban roadway infrastructure was becoming inundated with vehicles, resulting in various operational and political obstacles that needed to be overcome. Recently, TSP has become more widespread in Europe, where transit services are routinely given priority over private vehicles, where TSP has become more widespread recently. The following section of the study covers cases that have been implemented in North America and Europe concerning transit signal priority applications.

North America

In 1970, Los Angeles was the first city to experiment with signal priority for buses. These were preemption systems. Demonstration projects in the 1970s proved that preemption was an effective way of reducing delays associated with transit. Although the system had its advantages, other issues existed with it as well, especially with traffic progression along arterials. Cross-Street queueing problems were also common on streets undergoing the preemption program. A motion was made to eliminate the use of preemption systems due to the rapid increase in vehicle demand in urban traffic systems and the problems associated with progression and queueing. During the 1970s, politics changed transportation policy to favour a more efficient movement for all vehicles rather than focusing on transit vehicles(Hunter, 2000).

During the early 1990s, technological advancements led to the return of transit signal priority systems. As a result of dramatic improvements in computer processing power and better communication capabilities, traffic controllers were able to make more effective adjustments to timing plans. Charlotte, North Carolina; Bremerton, Washington; Anne Arundel County, Maryland; Portland, Oregon; and Pierce County, Washington, have all reported success with their transit signal priority systems in recent years. There is little difference between these systems and those used in the 1970s, but they are more efficient due to the greater computer processing capability. Using signal priority on their express bus routes in Charlotte's primary northern travel corridor reduced travel times by 50% for most routes. Al-Sahili and Taylor (1996)) found that the Bremerton system reduced overall travel time by 10% for buses. Maryland State Highway Administration found that express buses on Route MD 2 in Anne Arundel County, Maryland reduced travel times by 13%-18%. The Portland project reduced bus travel time by 5% to 12%, but other vehicles' travel times did not differ significantly(Kohan, 2001). Most signal operations changes in these tests were limited to changes in phases within the prescribed cycle length.

In contrast, the Portland project also included the construction and use of a queue jump. In Pierce County, WA, TSP was successfully demonstrated in 1996 (Funkhouser, Nelson, & Semple, 1996), which showed travel time savings of 5% to 8%. On average, additional delays of 1–4 seconds per vehicle were reported on cross-streets.

Pierce County's test indicated that some routes increased travel time. This was counterintuitive, especially for a transit approach that was given priority signalling. Before the priority signalization strategy (LOS F (HCM standard)), the intersection approach that resulted in increased travel time for the route always worked severely. It should also be noted that the segments on which the TSP was tested were concise, only less than a mile in length, which resulted in the impact of the TSP being felt immediately rather than that expected over a longer period for a more general travel delay distribution.

At 11 intersections along the South, 19th Street corridor in Tacoma, Washington, Pierce Transit(Funkhouser et al., 1996) demonstrated the installation and testing of signal priority equipment along this corridor, as well as on 15 Pierce Transit buses, in Tacoma, Washington. As part of the bus detection and priority systems, all intersections were equipped with these devices.

Green extension and green extension and/or shortening of opposing green phases were some of the control strategies that were used. It was the strategy that featured the green extension that allowed the traffic signal facing the bus to be extended beyond the normal phase length for the green signal. The strategy consisted of shortening the opposing green phase, which was opposed to the movement of the bus approach, for example, the left turn phase or the cross-street phase. As a result of the extension of the green phase and the shortening of the opposing green phase, both of these signal control strategies worked effectively. There were two bus routes travelling on South 19th Street during the day. They both travelled in both directions.

Europe

London, England, has several projects that study transit signal priority, including Priority and Informatics in Public Transport (PROMPT). PROMPT has been actively involved in developing, implementing, and evaluating real-time public transport priority systems within Urban Traffic Control (UTC) systems. In London, England, Split Cycle Offset Optimization Technique (SCOOT) controls the real-time UTC system in real-time. It has been proposed to introduce transit priority into SCOOT by developing and implementing new logic for providing green time extensions or recalls following the spare green time available during non-priority phases. In order to achieve this logic, a user-defined target saturation level on intersection approaches can be used to determine the relative effect that buses and other traffic should have on each intersection approach. This target saturation level can then be adjusted according to the desired effect. When transit vehicles emit a signal, and an inductive loop detector detects a vehicle's presence, transit priority is activated by using transponders in every transit vehicle that emits a signal. SCOOT can initiate priority extension facilities by detecting transit vehicles either centrally or locally by a set of detectors located between 70 and 100 meters upstream of the intersection. As a result, local extensions avoid the 4 to 5 seconds of delays when timing plan decisions are centralized, a common issue with SCOOT. Furthermore, SCOOT has been developed to accept other vehicle detection techniques, such as AVI technology, into the system(Hunter, 2000).

There is also a system whereby unemployment compensation is administered in Turin, Italy. Traffic Optimization by Integrated Automation (UTOPIA) traffic control systems are used to control traffic in the area. In UTOPIA, local intersection control operates within a reference plan determined by the central control system, which is a traffic-responsive UTC system based on a hierarchical concept. It is based on the basic idea of UTOPIA to provide absolute priority to transit vehicles while optimizing the movement of all vehicles at a particular intersection. As part of the control system, there is communication between intersections and a rolling horizon control algorithm, which ensures that signal decisions consider traffic predictions for the next two minutes when making signal decisions. It is designed to incorporate transit signal priority into this predictive control system so that traffic signals are adjusted based on predicted travel times two minutes away from a particular intersection for transit vehicles. In order to accomplish this, the city uses the city's Automatic Vehicle Monitoring (AVM) system, which holds the city's transit schedules for all tram and bus routes, in addition to algorithms developed to determine priority requirements in terms of "following schedule" or "headway variability." The AVM system then passes selected priority requests to the central control system at UTC for implementation at the appropriate intersections as soon as possible. The PROMPT organization has worked closely with Turin to enhance the existing priority system, notably its algorithm for predicting travel times, and to develop new techniques for integrating priority features into overall fleet management within the PROMPT organization's work(Hunter, 2000).

The use of transit priority schemes on Uxbridge Road reportedly reduced bus journey times by more than four minutes (7%) between 1992 and 1995, with a maximum saving of 13% achieved (L. Gardner, 1999).

1.4.11 Using V2X communication

New possibilities have been created for intelligent transportation systems with the implementation of connected vehicle (CV) technology, which is known as vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication. Over the past few years, much interest has been shown in using V2I connectivity in transportation operations.

Vehicles can communicate with surrounding entities via V2X to share their current status. This information may then be used for safety and efficiency applications. Their surroundings may include other vehicles, infrastructure units, networks (manufacturer, operator, or cellular), and VRUs. V2X communication, as mentioned earlier, is divided into three main categories; V2I and V2V and Vehicles to Network (V2N).

A vehicle's status can be broadcast up to 10 times per second (10 Hz periodicity) through Vehicle-to-Vehicle (V2V) communication. In addition to broadcasting its status up to 10 times per second (10 Hz periodicity), it uses a special message called a beacon. The process of periodically transmitting safety messages is also known as beaconing. By doing so, they enhance their visibility, predict their trajectory, and reduce the risk of a collision. The vehicle can broadcast its braking status to the following vehicles, who will then decide to brake based on the stopping distance when the vehicle brakes. Communication between vehicles requires each vehicle to have an Onboard Unit (OBU).

In order to improve safety and efficiency, vehicles and infrastructure nodes share information through Vehicle-to-Infrastructure (V2I) communication. An infrastructure node, also called a Roadside Unit (RSU), is a fixed node deployed along the roadside. RSUs may be used for various purposes, including safety and efficiency. By broadcasting the current phase of a traffic light to the surrounding vehicles, an RSU can improve traffic efficiency because it helps them determine the appropriate speed. As well as being equipped with cellular and Wi-Fi communication technologies, RSUs may also be able to gather information from various stakeholders and forward it to vehicles. Smart infrastructure may be developed in part through the deployment of RSUs. Over the last few years, V2I connectivity has received great attention and has been implemented to improve transportation operations. Data is transmitted between the signal control systems and the approaching buses using V2I technology. Thanks to modern technology, the control center can provide more accurate data, like the fleet's real-time location, the number of passengers on board, and the approaching time. This differs from traditional signal controllers, which use loop detectors to collect data from the vehicle. In various studies, such versatility is harnessed in signal control systems (Bagherian, 2017).

For efficiency, vehicle-to-Network communication (V2N) involves exchanging information over a cellular network between a vehicle and the cloud of a manufacturer or fleet operator. Several types of non-critical information may be sent by the vehicle, including its current location, vehicle to improve operational efficiency, diagnostic information, data gathered during travel, etc., to the back end.

In one study (Cvijovic, Zlatkovic, Stevanovic, & Song, 2022), Connected Vehicles (CV)-based algorithms are developed to trigger TSP, based on transit vehicle speed and estimated arrival time at intersections. Depending on the traffic conditions of the intersection, a transit vehicle's current distance from the intersection, and queue conditions, this information is updated every second. To calculate the time required for the vehicle to reach the stop line, the algorithm takes into account the actual speed of the transit vehicle and its latitude/longitude coordinates. As it uses world coordinates, it can be easily implemented in the field, as it has been tested on a real-world network using VISSIM traffic simulation. They used upgrade the algorithm which they had used in the previous study. Based on the previous TSP29 model, the TSP29CV was upgraded with CV technologies in already implemented TSPs. This model was limited to buses with CV technologies. In CV TSP, the algorithm takes into consideration the time it takes for a vehicle to reach an intersection, as well as the queue conditions as it approaches an intersection. To be considered by the algorithm, the time that a vehicle needs to reach the intersection must not be more than the green extension time. Using the TSP29CV Model upgraded algorithm, a future bus rapid transit (BRT) scenario was explored, and different levels of conditional TSP were implemented based on three combined factors: the time it takes a transit vehicle to reach the stop line, the number of passengers aboard, and the amount of lateness experienced by the transit vehicle. In order to construct a model, ten signalized intersections along State Street in Salt Lake City were used as test cases. It shows that using CV algorithms in conjunction with TSP delays are reduced by 33% and 12%, for regular buses and BRTs, respectively.

There are three major types of V2X applications. Below are descriptions of each type.

Improve Traffic Safety

In V2X safety applications, critical information is disseminated in real-time to reduce crashes. The vehicles broadcast safety messages containing information about their current status to their surrounding entities. These elements include speed, location, brake status, route history, and path prediction, which are then utilized by other vehicles and infrastructure nodes in various ways. Hazard warnings, cooperative collision warnings, and emergency brake warnings are examples of such applications. It is possible to use such communication for coordinated driving in the case of self-driving vehicles in order to predict crash situations and warn the driver. The delivery of critical information in real-time is a major component of safety applications, which have stringent requirements regarding latency, packet delivery reliability, safety message frequency, and communication range. Among all categories of V2X communication, safety-critical information delivery is given the highest priority.

Improve Traffic Operations

V2X efficiency applications aim to improve traffic management. As a result, road congestion is reduced, travel times are reduced, and drivers are less fatigued due to improved noncritical information sharing. Additionally, efficient traffic management reduces the impact on the environment by improving the fuel economy of vehicles. A few examples of V2X efficiency applications include in-vehicle signage for road signs, Green Light Optimal Speed Advisory (GLOSA), and traffic light phase notifications. Because these applications are not safety-critical, V2X efficiency applications fall into the category of utility applications. Their information has lower priority as compared to safety applications. However, this information is still time sensitive and should be delivered within the defined duration.

Transition Soft News

Information delivery for these applications is the lowest priority among all V2X application categories. They may provide targeted information, such as point-of-interest information, local product advertisements, parking information, etc. They aim to improve passengers' experiences (Sewalkar, 2021).

Automated Fare Collections

Transit agencies have relied heavily on traveller surveys and manual counts to plan their services and operations. In today's world, many agencies can enhance their planning toolbox with data obtained from Automated Fare Collection (AFC) technologies. In addition to enhancing their analytical capabilities, transit agencies can answer some planning questions previously unachievable. Even though transit agencies could gather a good picture of existing transit demand through surveys and manual counts, accurate AFC data should give planners a detailed, continuous and accurate picture of customers' travel behaviour at a fraction of the cost previously.

A fare collection system provides an inexpensive, fast, secure, and user-friendly platform to collect passenger fares and control access to the service. As a result, AFC systems are increasingly being used to replace traditional fare collection platforms. Transit agencies can reduce their operational expenses by automating fare collection or shifting ticketing staff to more productive tasks with automation. As a result of minimizing human intervention, they can also enhance revenue protection and develop a broader range of fare products to cater to a wide range of needs (Pincus, 2014).

Over the past couple of years, the availability of vast and disaggregated passenger transaction data for transit planning and operational purposes has increased substantially due to using the smart card to collect revenues. Depending on the fare collection scheme, invaluable data sources for travellers such as departure and arrival times, origin and destination of passengers, selected transit routes and transfer information are available. Also, the number of passengers could be collected through this system.

1.5 The Gap in the Literature and Research Gap

The literature review found that many TSP strategies have been proposed to improve the city's public transit system. However, they have some drawbacks. Some of them are listed below:

1- Most of the available TSP strategies prioritize the public transit fleets regardless of their occupancy. When a bus is detected near a signalized intersection, the timing is adjusted in favour of the bus. Even if the bus is without passengers, it receives priority, which negatively affects the signalized intersection control delay and imposes a delay on the other approaches. Although some researchers considered passengers in their analysis (for example, (Bagherian, 2017) for their journey), they did not consider the number onboard for giving priority at an intersection.

2- Most of the strategies do not consider the bus schedule in their logic. It means that regardless of the schedule, the fleets get priority. However, logic must give weight to the public transit schedule.

3- A few kinds of research focused on the environmental impacts of TSP. However, environmental factors are so important and should be considered. The number of stops in a traffic network is highly related to emissions and fuel consumption.

Thus, this research aims to propose passenger-based TSP strategies based on traffic and environmental indices for increasing the efficiency of the public transit system in Quebec. While this methodology used data from the Quebec network, its applicability is suitable for any public transit network.

CHAPTER 2
TSP AND VISSIM: METHODOLOGY, SETUP AND CALIBRATION

Conventional TSP strategies have some limitations, as we previously discussed. For instance, in most implemented systems, buses receive priority regardless of the number of passengers on board. As a result, it imposes delays to vehicles waiting at other approaches. To overcome this problem, this dissertation proposes a novel methodology based on the number of passengers on board as well as adherence to schedules. This means the bus will receive priority only if the pre-defined criteria are met. Moreover, this section proposes another method to minimize the person's delay (including public and private transportation). As a result, the bus receives priority if the person's delay in the entire intersection is minimized.

A total of four scenarios are presented. In the first scenario, existing conditions (without TSP) are tested. In the second scenario, a conventional TSP has been installed at all signalized intersections along the corridor. As part of the third scenario, the TSP method based on the number of passengers and compliance with the schedule will be evaluated. As part of the final scenario, the method to minimize delays throughout the intersection will be evaluated.

Additionally, three different traffic regimes are evaluated to evaluate the effectiveness of the proposed methodologies in various traffic conditions. In all scenarios, the existing traffic condition, an undersaturated traffic condition (70% of the existing traffic volume), and an oversaturated traffic condition (130% of the existing traffic volume) are all tested.

As a further step toward evaluating the effectiveness of the proposed methods, the system is tested both at a single intersection and along a corridor to determine whether the proposed solutions are effective in both situations (single intersections and multiple intersections in a network).

2.1 **Method of analysis**

Today, transportation professionals are increasingly turning to traffic microsimulation for traffic analysis. A number of state and federal transportation authorities have adopted microsimulation calibration standards to demonstrate the importance of accurately calibrating these traffic simulations, most of which are similar to those established by the Federal Highway Administration in 2004 (Richard Dowling, Skabardonis, & Alexiadis, 2004). Among the three steps in a recommended calibration strategy by FHWA, capacity calibration is considered one of the first. Although the recommended calibration process is not detailed in the paper, the information presented here will significantly impact the recommended calibration process. Using lower-level parameters to calibrate a high-level measurement, like roadway capacity, may not provide an optimal global solution, as stated in the FHWA guidelines. In many cases, it is possible to have more than one parameter configuration optimal for one location in the simulation or a particular set of parameter values optimal for one road location, producing unrealistic results at another location.

During the calibration of roadway capacity, a better understanding of the parameters influencing the simulation's output will help address situations where it is possible to combine multiple parameters to produce optimal solutions and in which such optimal solutions are location specific. Users of simulations should understand the calibration problem in detail in order to determine whether to address calibration issues directly or to select optimization tools that take into account and utilize both the calibration problem and the optimization methodology chosen.

In recent years, VISSIM, a discrete, stochastic, time-step-based microscopic traffic flow simulation platform, has grown in popularity worldwide. Using the car-following model that Wiedemann (1974, 1991) developed, VISSIM has been used to model freeway travel, as described by (Panwai & Dia, 2005). The behaviour of simulated vehicles can be modified by changing ten specific parameters (CC0, CC1, …, CC9) of the car-following model used to control vehicles' movements under four distinct driving modes: free driving, approaching, following, and braking. In a study conducted by (Nicholas & Randy, 2006), individual components of the Dallas, Texas, metropolitan area were examined for their impact on simulation capacity. Several of the driver behaviour parameters can have a significant impact on the individual road capacity. Details of these parameters will be discussed in the following sections.

In order to validate the theory of car-following models for use in Germany and abroad, (Fellendorf & Vortisch, 2001) analyzed the car-following model empirically in American and German contexts. There was, however, no intention in their research to examine the impact of the car-following model on the simulated capacity. It was intended to validate the car-following model as such. Gomes, May, and Horowitz (2004)Investigated the relative effects of several driver behaviour parameters on the performance of a congested freeway by developing and calibrating the VISSIM model. Based on the study's findings, the authors examine how tuning parameters affect the calibration of the simulation model. These tuning parameters include a number of parameters relating to driver behaviour that are studied in this research. As well as Moen, Fitts, Carter, and Ouyang (2000), Bloomberg and Dale (2000), and Tian, Urbanik, Engelbrecht, and Balke (2002), several other studies have examined the performance of VISSIM when compared with other popular traffic microsimulation packages. In another study, N. Lownes and R. Machemehl (2006) compared VISSIM to the popular traffic microsimulation CORSIM that has been extensively studied for the past thirty years by FHWA, and they found that VISSIM performed similarly to CORSIM. In addition to the car-following model, previous studies have provided a better understanding of how VISSIM compares to other microsimulations and how individual driver behaviour parameters impact simulation performance.

In order to be able to understand how VISSIM works, one must first examine how these driver behaviour parameters interact and how their relationship affects the simulation capability (N. E. Lownes & R. B. Machemehl, 2006).

2.2 **Traffic simulator setup**

As previously mentioned, VISSIM is a microscopic traffic simulation platform based on time steps and behaviour developed in the early 1970s at the University of Karlsruhe, Germany. The German company PTV Transworld AG started commercial distribution of VISSIM in 1993 and maintained the software up to this day. It consists of two main components: a traffic simulator and a generator for signal status. The main components of VISSIM are a psycho-physical car following model, a longitudinal vehicle movement model, and a lateral movement rule-based lane change algorithm. This model states, “The basic concept of this model is that the driver of a faster-moving vehicle starts to decelerate as he reaches his perception threshold to a slower-moving vehicle. Since he cannot exactly determine the vehicle’s speed, his speed will fall below that vehicle’s speed until he starts to accelerate slightly again after reaching another perception threshold. The results in an iterative acceleration and deceleration process” (Mishra, 2016). This car-following model is introduced by Widemann in 1974 for arterial networks and urban traffic. The following parameters are considered among the most important parameters for the driver behaviour model in VISSIM.

CC 0 — Stopped Condition Distance

CC0 is the distance (or the clear space) that a driver wishes to maintain behind a stopped vehicle on a freeway if he wishes to maintain a safe distance. It has been shown that the CC0 parameter is very important for capacity calculations as it is used in conjunction with the CC1 parameter to calculate the safety distance maintained by drivers in accordance with the following equation, as determined by the VISSIM User’s Manual (PTV 2004). The CC0 value is set to 4.92 feet by default.

CC 1 — Headway Time

The above equation shows the speed-dependent portion of the safety distance desired by drivers, which CC1 controls. Since CC1 directly affects the headways maintained by drivers (or at least the mean of the headways), it is expected to impact roadway capacity significantly. Its default value is 0.90 seconds.

CC 2 — “Following” Variation

As a result of CC2, vehicles do not oscillate longitudinally in the simulation. It is the distance an individual will allow between vehicles beyond the safe distance (dx_safe) before moving closer to the vehicle he is following. 13.12 feet is the default distance.

CC 4 and CC 5 — “Following” Thresholds

According to the driver behaviour model, CC4 and CC5 are parameters that determine the upper and lower following thresholds (sensitivity to the acceleration and deceleration of the preceding car), respectively. In general, drivers’ reaction to accelerations and decelerations of the preceding car is more sensitive when the absolute values for CC4 and CC5 are smaller (PTV 2004). As a result, the vehicles are more tightly coupled as they move throughout the simulation when the sizes of CC4 (the negative value) and CC5 (the positive value) are more diminutive. As a result, these values are typically around +/- 0.35.

CC 8 — Stopped Condition Acceleration

The CC8 parameters affect acceleration when a vehicle is stopped and is necessarily bounded by the maximum and minimum acceleration values defined as data functions within VISSIM. The simulation will be run with the maximum theoretical acceleration if CC8 assigns acceleration values above those defined as maximums for a vehicle. By default, 11.48 ft/s2 is used, which corresponds to the maximum acceleration for a passenger car.

Three fundamental variables describe traffic flow: flow, speed, and density. Greenshields, Bibbins, Channing, & Miller developed a linear relationship between speed and density when evaluating traffic flow(Hall, Zhang, Kuhne, & Michalopoulos, 1996). According to Drake, Schofer, and May (1965), there is a very complex relationship between these traffic stream characteristics. Even though the speed-flow of some models could more accurately predict the density relationship observed in empirical data, none of the models presented a perfect fit to the data. This finding raised two questions: the first, regarding the amount and derivation of empirical data used to describe these fundamental relationships, and the second, regarding the car-following models that were used to generate synthetic data points. As a result, the primary issue that is raised is whether the input data can adequately describe real-life traffic conditions or not based on their ability or inability to do so(Esmaeeli, 2021)

A long-standing interest in traffic flow research has been generated by two fundamental driving behaviours, Car-Following and Lane-Changing, which describe vehicle longitudinal and lateral interactions, respectively. For many years, some Car-Following models have been developed to depict Car-Following behaviour from various perspectives, including engineering and human perspectives (Zhang, Sun, Qi, & Sun, 2019).

Many classifications or types can be derived based on the logic used in car-following models. Several model families are the most studied, including the Gazis-Herman-Rothery (GHR) family. The GHR model is sometimes referred to as the general car-following model. In 1958, the GHR model was developed, and several enhanced versions were developed. The GHR model only controls the actual behaviour of a follower. In this instance, lead and follower vehicles are linked in a stimulus-response manner. According to the GHR model, the acceleration of the follower is a function of the follower's speed, the difference between the follower's speed and the leader's speed, and the distance travelled between the follower and the leader.

Other car-following models are based on safety distances or collision avoidance methods. Based on these models, the driver of the following vehicle is assumed to maintain a safe distance from the vehicle in front. There is a rule for following another vehicle at a safe distance known as the Pipes Rule. According to Hoogendoorn and Bovy (2001), a safety distance model is to allow oneself at least the length of a car between you and the vehicle ahead for every ten miles per hour of speed. In most cases, the safe distance is measured by modifying Newton's equations of motion to specify the safe distance. It is important to note that in some models, this distance is calculated similarly to that required to avoid a collision if the leader decelerates heavily. Kometani and Sasaki presented the first model of this type in 1959(Brackstone & McDonald, 1999). Gipps' enhancements to the original model were presented in 1981. According to Gipps, a follower will not collide with a leader if the time gap between the follower and its leader exceeds or equals 3T/2, where T represents the reaction time, and if the follower estimates the leader's deceleration to be greater than or equal to the leader's actual acceleration.

Michaels introduced a new approach to car-following modelling in 1963(Brackstone & McDonald, 1999). This approach to car-following modelling is called psycho-physical or action point models. GHR models are based on the assumption that a follower reacts to an arbitrarily small change in the vehicle's speed. A GHR model also assumes that even though the follower is far from their leader, it still reacts to their leader's actions and that once the relative speed is zero, the follower's response disappears. In order to correct this problem, either the GHR model can be extended with different regimes, such as free driving and emergency deceleration, or a psycho-physical model can be applied. A psychological model uses thresholds as action points where the driver changes their behaviour. When these thresholds are reached, drivers can react to changes in spacing or relative velocity(Leutzbach, 1988).

For the microsimulation tool VISSIM, Wiedemann developed another psycho-physical model. Based on the results of this model, a decision-action-point car-following model was developed (Rainer Wiedemann, 1974). This was essentially a psycho-physical model that contained certain thresholds for the relative speed and distance behind a lagging vehicle before a driver could take action (Rainer Wiedemann, 1974). When a vehicle approaches a slower leading vehicle, the driver recognizes that certain action points can be used to make conscious decisions. Wiedemann defines discrete driving as a combination of four regimes: free flow, approaching a slower leader vehicle, following in near steady-state equilibrium, and braking at critical speeds. As a result of the use of different acceleration functions for following the vehicle and five boundaries' regimes according to the zeroes of the following functions, the following regimes were determined. Equations (1) to (7) show the car's basic concept following the model in VISSIM.

$$AX = L_{n-1} + AX_{add} + RND1 \times AX_{mult} \tag{1}$$

$$ABX = AX + BX \tag{2}$$

$$SDX = AX + EX \times BX \tag{3}$$

$$SDV = \left(\frac{\Delta x - L_{n-1} - AX}{CX}\right)^2 \tag{4}$$

$$OPDV = CLDV \times (-OPDV_{add} - OPDV_{mult} \times NRND) \tag{5}$$

$$BX = (BX_{add} + BX_{mult} \times RND1)\sqrt{u} \tag{6}$$

$$EX = EX_{add} + EX_{mult} \times (NRND - RND2) \tag{7}$$

Where:

AX is the desired distance between vehicles in standstill situations,

L_{n-1} is the physical length of the lead vehicle,

ABX represents the desired minimum following distance at low-speed differences between vehicles,

SDX is the perception threshold for modelling the maximum following distance between 1.5 to 2.5 times ABX;

SDV is the approaching point where a driver becomes aware of a slower leader;

$CLDV$ is the reduction of the relative speed differences at short and decreasing distances; and

$OPDV$ is the increase in the relative speed difference when a driver acknowledges the current travelling speed slower than the speed of the leading vehicle.

$AX_{add}, AX_{mult}, BX_{add}, BX_{mult}, EX_{add}, EX_{mult}, OPDV_{add}, OPDV_{mult}, RND1$,

$RND2, RND3, RND4, NRND$ are additional dependent parameters for the model. CX is assumed to be 40.

As with the Fritzsche model, this model comprises thresholds that form regimes. Figure 2 displays these thresholds in a relative speed relative position space(Olstam & Tapani, 2004).

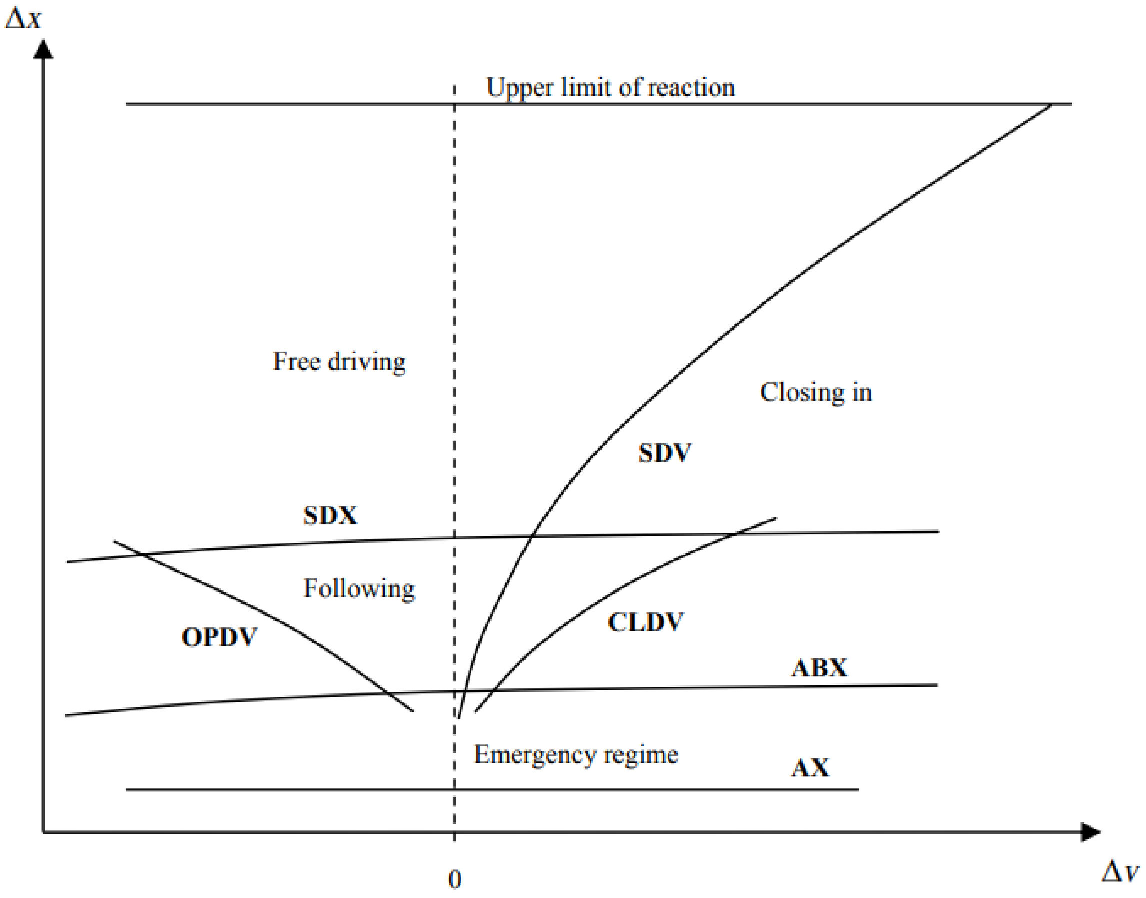

Figure 2: Wiedemann car-following model thresholds and regimes (Olstam & Tapani, 2004).

As a result of the inexact handling of the throttle, the following thresholds are considered: SDV, SDX, OPDV and ABX. For this reason, it is assumed that the vehicle's acceleration rate is always separated from zero to compensate for the inexact handling of the throttle. In the following regime, when a vehicle passes either the threshold of the SDV or the ABX, it receives the acceleration rate $-b_{null}$. When it passes either the threshold of OPDV or SDX, it receives the acceleration rate b_{null}. These parameters can be calculated using Equations (8) to (11).

$$b_{null} = BNULL_{mult} \times (RND4 + NRND) \tag{8}$$

$$b_{max} = BMAX_{mult} \times (u_{max} - u \times FAKTORV) \tag{9}$$

$$Maximum\ acceleration = 3.5 - \frac{3.5}{40}u \tag{10}$$

$$Maximum\ deceleration = -20 + \frac{1.5}{60}u \tag{11}$$

Where:

$BNULL_{mult}$ is a calibration parameter

$BMAX_{mult}$ and $FAKTORV$: Model constants

u_{max} : Maximum desired speed.

A decade later, Wiedemann developed the W99 model, a car-following model for freeways. He developed the model to reduce the level of uncertainty associated with random variables). The W99 model was developed to incorporate logic for autonomous vehicles. The subject driver begins to decelerate until an individual threshold is reached, which is a function of acceptable speed difference and spacing. In this model, the driver that reaches the driving behaviour thresholds for different maneuvers will continue to drive at or below the current speed of the leader (Esmaeeli, 2021). Figure 3 shows the W99 car following the model according to VISSIM 11 Manual.

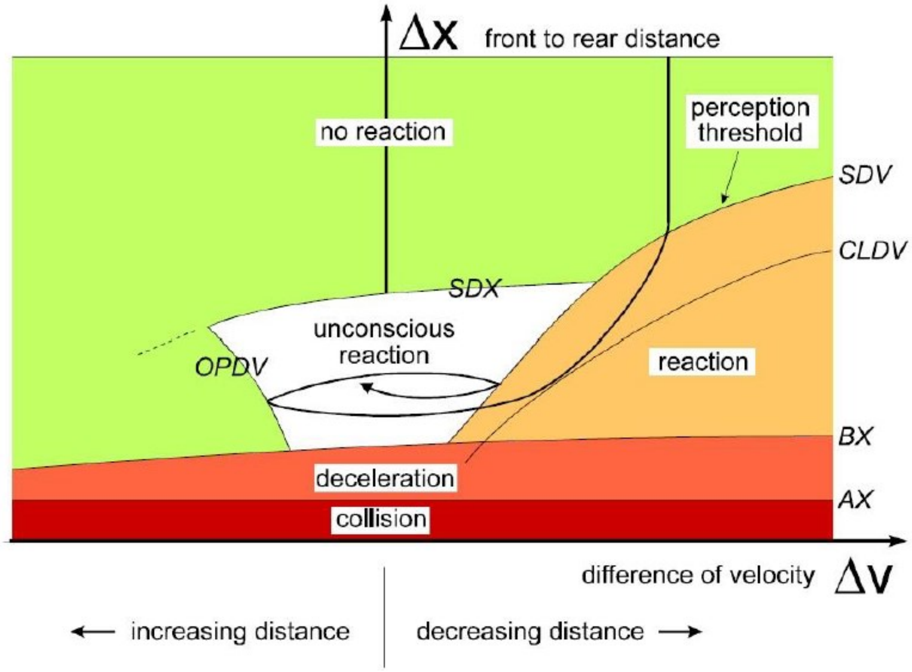

Figure 3: Car-Following model for VISSIM (PTV Group, 2019)

Parameters in Figure 3 are calculated using Equations (12) to (17):

$$AX = L + CC0 \tag{12}$$

$$BX = AX + v \times CC1 \tag{13}$$

where,

AX is the collision threshold [$meter$]

BX is the deceleration threshold [$meter$]

L is the length of the lead vehicle [$meter$]

v is the velocity of the vehicle, which has a lower speed in each pair of vehicle interactions [m/s]

$CC0$ is the average standstill distance between vehicles [$meter$]

$CC1$ is the headway time for measuring the average following distance [$seconds$]

$$CLDV = \frac{CC6}{17000} \times (\Delta x - L)^2 - CC4 \tag{14}$$

$$SDV = -\frac{\Delta x - BX - CC2}{CC3} - CC4 \tag{15}$$

$$SDX = BX + CC2 \tag{16}$$

$$OPDV = -\frac{CC6}{17000} \times (\Delta x - L)^2 - \delta \times CC5 \tag{17}$$

where,

Δx is the spacing between the subject vehicle and its leader [$meter$]

δ is a dummy variable that is 1 when the speed is greater than CC5 and 0 otherwise,

$CC2$ is the allowed safe following distance to surpass before the following vehicle accelerates within maximum link speeds [$meter$]

$CC3$ is the time taken to reach the safe following distance when the leader is slower [*seconds*]

$CC4$ is the sensitivity of the vehicle to the negative change in the leader’s speed [m/s]

$CC5$ is the sensitivity of the vehicle to the positive change in the leader’s speed [m/s]

$CC6$ is the influence of distance on speed oscillations [$m.s$]

Car-following models utilized in applications requiring microscopic output data must be able to emulate driving behaviours very similar to real-life observations. Simulation of surrounding traffic in a driving simulator or simulation used to estimate exhaust pollution can be examples of such simulations. Both require detailed information about a vehicle's driving course. However, it is important to remember that the calibration of models that produce microscopic outputs is considerably time-consuming and harder than the calibration of models that produce macroscopic outputs. This is due to the fact that in the microscopic simulation, the interaction between vehicles is taken into account, so it is important to reflect the existing network conditions in the simulation..(Olstam & Tapani, 2004).

2.2.1 Vehicle-Actuated Programming, a module for developing a TSP logic

The intersection signal timing should be considered when simulating a corridor or network in microsimulation.

Several interfaces for signal setting development are available to develop TSP strategies in the microsimulation, depending on the simulation software. Vissig, VisVAP, text editors and programming tools are created to describe the desired logic using the VISSIM microsimulation framework to conduct experiments.

The Vissig package is implemented to specify the signal structure. Using the Vissig graphical interface, the number of phases, the description of interstate phase times and future changes can be initialized. A Vehicle Actuated Programming file is required to create the signal timing layout to establish the signal controller's logic and custom functions. The PUA file needs to contain at least the following information(PTV Group, 2019):

1. Description of all groups of signals
2. Description of all phases
3. Description of beginning stages
4. All interstate descriptions.

Figure 4 illustrates the criteria for using the microsimulation model of VISSIM to test various signal timing scenarios, including TSP strategies. Notice that *. sig and *. vv are the default interface formats for Vissig and VisVAP, respectively.

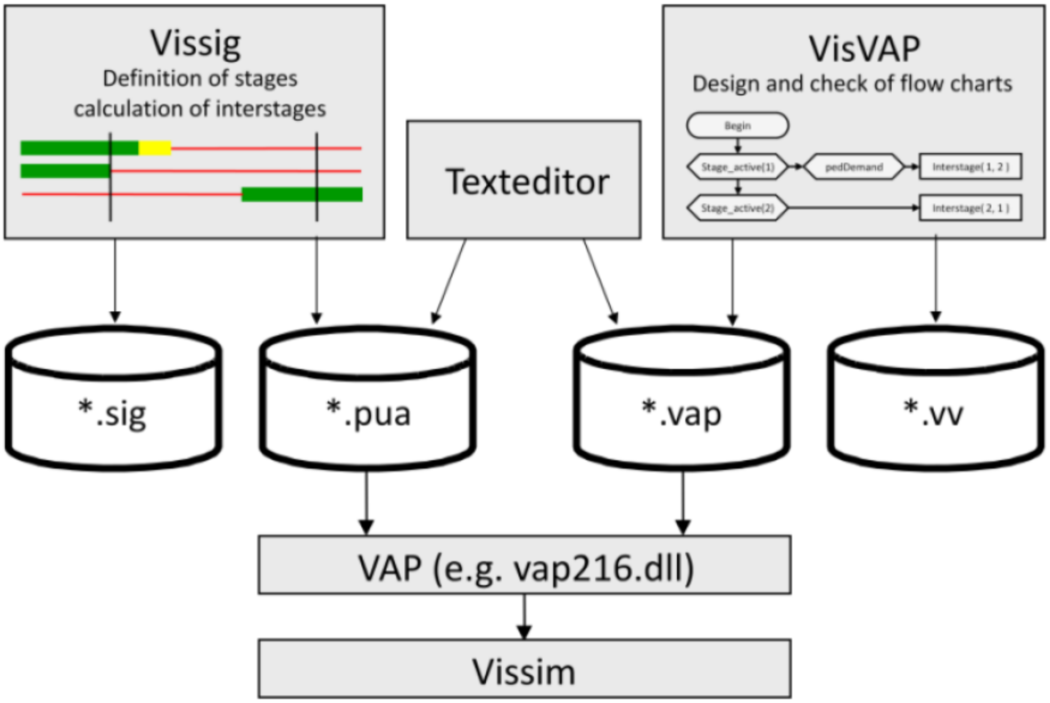

Figure 4: Using VISVAP for devolving a TSP strategy (PTV Group, 2019) (Bagherian, 2017)

Besides the Signal Timing Layout (. PUA), a Vehicle Actuated Programing (. VAP) file is required to define the signal controller's logic. In this microsimulation model, VAP allows for customizing the signal timing logic. In each simulation step, VISSIM processes the coded VAP logic as an input. The logic was initialized as VAP files using VisVAP, a tool for creating flowcharts. Programmable editing of. vap and. pua files allow automatic adjustment of signal timing parameters. The flexibility of VAP allowed for the development of customized signal logic, but occasionally models had to be developed using VISSIM COM libraries in Python.

2.2.2 Traffic simulator automation

Based on the Component Object Model, binary elements in different programs interact. Various programming languages, including Python, MATLAB, C++, etc., can be used for this interface. Python, which satisfies the research's needs, is used for this interface. It receives data from VISSIM and links VISSIM and VisVAP.

Since the proposed methodology needs real-time data to decide when a priority strategy should be employed, an algorithm was coded in Python to retrieve and analyze the data from VISSIM at each simulation step (0.1 seconds). The proposed algorithm takes all vehicle information, including the type of vehicle, occupancy, vehicle ID, etc. Also, it checks whether the detector receives a request from the bus driver. If the detector receives a request, the vehicle ID is taken, and it checks if that particular ID has more than the required number of passengers. In this case, the system would send a command to the control device (visVAP) to give the vehicle priority.

2.2.3 Number of Simulation Runs (Replications)

In order to reduce stochastic variability, multiple runs of the network in VISSIM are required for each scenario, and for each run, the average performance measure and the standard deviation are to be recorded. All VISSIM models should initially start with at least ten simulation runs with different random seed numbers (Oregon Department of Transportation, 2011). The random seed value generates a random sequence of numbers different for each run. This sequence is used to draw instances of parameter values from their predefined distributions (e.g., vehicle headways, vehicle speeds, gap acceptance values, deceleration rates, the order of different vehicle types entering the network, etc.). This is the principle of stochastic modelling used in any simulator, not only in VISSIM" (Park, Won, & Perfater, 2006). These ten replications provided an initial data set to help find the minimum number of simulation runs needed for a 95 percent confidence interval using Equation (18) (Oregon Department of Transportation, 2011).

$$N = \left(2t_{0.025}N - 1\frac{S}{R}\right)^2 \tag{18}$$

Where:

R: is the 95% confidence for the widely used value

$t_{0.025}$: student's t-statistics for a two-sided error of 2.5 percent with N-1 freedom's degrees.

N: number of required replications

S: Standard Deviation about the mean, which is calculated as Equation (19):

$$S^2 = \frac{\sum(x - \bar{x})^2}{N - 1} \tag{19}$$

Where:

x: is the output value for each replication.

$\bar{x}$: Average value for all replications

2.2.4 The calibration process of the microsimulation model

Different variables in the simulation models are used to characterize traffic flow features (for example, driver behaviour and traffic control operations). Although these parameters give these microscopic simulation models default values, simulation under default values produces unreliable outcomes. Users must also calibrate these values so that actual case studies can accurately reflect real-world traffic conditions. Model calibration aims to minimize the discrepancies between the simulation results and corresponding field measurements, such as traffic volumes, speed, and travel time.

Important microscopic traffic simulation model parameters must be calibrated to match the observed and simulated traffic measurements. The calibration process can be time-consuming and complex since many unknown parameters are involved. Consequently, such a calibration method has been formulated as an optimization model. Calibrating a microscopic traffic simulation model is intended to fine-tune the model parameters' values. Ideally, the difference between the field data and those generated by the simulation model should be minimized to calibrate a microsimulation model properly. An optimization formulation can be used for this purpose. The general optimization system is formulated as Equations (20) and (21) (Yu & Fan, 2017):

$$\min f(M^{obs}, M^{sin}) \tag{20}$$

Subject to:

$$l_{\theta_i} \leq \theta_i \leq u_{\theta_i} \ , i = 1, \dots, n \tag{21}$$

Where:

θ_i: The vectors of model parameters to be calibrated.

$f(.)$: Objective function

M^{obs}, M^{sin}: Observed and simulated traffic indices

l_{θ_i}, u_{θ_i} : lower and upper boundaries for the parameter θ_i

n : number of variables

Different algorithms can be used for optimizing the calibration of traffic simulation models. Generic Algorithms (GA) and Simultaneous Perturbation Stochastic Approximation (SPSA) were commonly used in previous calibration experiments. Other algorithms such as OptQuest / Multi start Algorithm (OQMA), non-linear programming techniques, Particle Swarm (PS), and Trial-and-Error Process (IA) were also used to decrease computational complexity and to increase the efficiency of the solution (Yu & Fan, 2017).

The biological evolution concept inspires GA-based optimization models. Similar to genetic behaviour, given a population of diverse and numerous solutions, one can use selection, crossover, and mutation to search for a suitable candidate solution. Selection is implemented so that better solutions are more likely to be used to create new populations (solutions). In order to produce new ones, crossover and mutation are applied to approaches. The GA begins from a random population set and tests each generation of candidate solutions. In the microscopic traffic simulation models, the GA was shown to obtain near-global optima when calibrating parameters (Yu & Fan, 2017).

Recently, other studies used Particle Swarm Optimization (PSO) algorithm to calibrate microscopic parameters. Particle swarm optimization is an evolutionary algorithms model inspired by bird flocking and fish schooling's social conduct. PSO conducts a swarm-based search using particles to represent possible solutions within the search space, first proposed by Kennedy and Eberhart (1997). Each particle is distinguished by its location, speed, and a record of its past results. In the simple PSO algorithm, the position (x) and speed (v) of each particle in the swarm can be modified at every repetition using Equations(22) and (23).

$$x(t+1) = x(t) = v(t+1) \tag{22}$$

$$v(t+1) = v(t) + C_1 r_1(t)[g(t) - x(t)] + C_2 r_2(t)[p(t) - x(t)] \tag{23}$$

Where the accelerator constants are C_1, C_2, r_1 and r_2 are randomized numbers that are uniformly distributed in the [0, 1] interval, $g(t)$ is the best answer to that point found by the population, and $p(t)$ is the best answer found by each particle (Bagherian, 2017).

In order to make the microsimulation results more accurate, a target parameter should be chosen carefully. There is a significant variance in the number of parameters (from 2 to 15) being calibrated in the previous studies, but most parameters are relevant to driving behaviour. This study will use driving behaviour parameters as the target parameters.

In the calibration process for the base scenario, the deviation between the simulation outputs and the field data is determined by the objective function. Equation (*24*) represents the objective function of the longitudinal movement of vehicles in a network to reflect the driving behaviour of vehicles in the real world.

$$\boldsymbol{Obj} = Minimize\left\{\frac{\mathbf{1}}{\boldsymbol{n}}\sum_{\boldsymbol{i=1}}^{\boldsymbol{n}}\frac{\mathbf{1}}{\boldsymbol{m}}\sum_{\boldsymbol{j=1}}^{\boldsymbol{m}}\frac{\left|\boldsymbol{h_{ij}^{obs}} - \boldsymbol{h_{ij}^{sim}}\right|}{\boldsymbol{h_{ij}^{obs}}}\right\} \tag{24}$$

Where,

i: the random seed of the given simulation run

j: a given calibrating parameter set

h_{ij}^{obs} and h_{ij}^{sim}: the observed and simulated measure of effectiveness, respectively, corresponding to the simulation run i and parameter set j.

A sensitivity analysis is conducted to test the possibility of combining model parameters within a specific boundary. In VISSIM, the Wiedemann car-following model needs to be adjusted for the perception-sensitive parameters: Average Standstill Distance ($CC0$), Gap time distribution ($CC1$), and additional desired safety distance ($CC2$). According to the Wiedemann car-following model, each parameter's lower (l) and upper (u) bounds are defined as $CC0_l = 1.22m, CC0_u = 1.67m, CC1_l = 0.7sec, CC1_u = 3sec, CC2_l = 2m, CC2_u = 7m, MTD_l = -3.6m/s^2$, and $MTD_u = -2.43m/s^2$.

By applying stochastic optimization algorithms, the calibration time can be significantly reduced. A single objective function can be considered when longitudinal movement is the dominant movement in urban roadways. Prior studies (Aghabayk, Sarvi, Young, & Kautzsch, 2013; Seliman, Sadek, & He, 2020)have successfully calibrated the simulation model parameters sensitive to longitudinal movements using the PSO optimization method.

The PSO evaluates each set of parameter values to estimate the objective function value derived from simulation runs. The calibration algorithm runs VISSIM using different traffic behaviour parameters and estimates the objective function. In order to reduce the objective's value, the optimization algorithm evaluates the error of the objective function and proposes another set of parameters closer to the global optimum.

Every time a new set of parameters is tested, the optimization algorithm chooses a new set for the next iteration based on the testing results. For modelling conventional vehicles, the microscopic simulator uses the final set of parameter values that yield the minimum objective function.

In order to make the microsimulation results more accurate, a target parameter should be chosen carefully. There is a significant variance in the number of parameters (from 2 to 15) being calibrated in the previous studies, but most parameters are relevant to driving behaviour. Hence, as mentioned earlier, driving parameters were used for calibration. The results of the calibration are mentioned in the following chapters.

2.3 **TSP Deployment Setup**

Four different scenarios have been proposed to evaluate the proposed methodologies' effectiveness. Based on microscopic simulations and statistical analysis, the developed methodologies evaluate the effectiveness of TSP strategies. This methodology can be applied to any corridor to understand how TSP affects traffic performance. Each scenario is described in the following subsections.

2.3.1 Scenario 1: Current Conditions

In this scenario evaluates the current traffic condition without any TSP. The data represent existing conditions, including traffic volumes, existing transit line setup with observed field data (e.g., the number of passengers alighting and boarding in each station and bus frequency) and signalized timing.

2.3.2 Scenario 2: Conventional TSP

This scenario used the conventional TSP, meaning that any bus approaching a signalized intersection is treated with a priority strategy (e.g., the green phase may be extended, the red phase shortened, etc.) to minimize its signal control delay.

2.3.3 Scenario 3: Transit Unit Load-based TSP

For this scenario, a TSP strategy is used to account for the number of passengers on board and the bus schedule. This study considers giving priority to buses only when the benefits outweigh the negative consequences of cross-traffic delays, as previously mentioned. If more people use public transportation than cars, the positive effects outweigh the negative ones. When the bus is empty or has only a few passengers, giving priority to the bus is not justified, as the delay per passenger will be more significant due to the crossroad traffic.

The first objective of this logic is to minimize the average delay per person in an intersection. The mathematical model of the total delay per person in the intersection is shown in Equations (25) to (29).

$$\psi = Minimize\ \left[(\sum (D_v\ \times NP_v) + \sum (D_b \times NP_b)\right] \tag{25}$$

Subject to:

$$g_{min} < g_{TSP} < g_{max} \tag{26}$$

$$D_v = d_{vt} \times c_{itsp} \tag{27}$$

$$D_b = \alpha \times d_{bc} \times c_i \tag{28}$$

$$d_{vt} = d_1 + d_2 + d_3 \tag{29}$$

Where:

D_v: Delay for a passenger car vehicle [sec]

NP_v : Number of Passenger inside the private vehicle

D_b: Delay for a bus in a cycle [sec]

NP_b: Number of bus passengers onboard

d_{vt}: Total delay for a vehicle, [sec]

g_{min}: Minimum green time [sec]

g_{max}: Maximum green time [sec]

g_{TSP}: Extension of a green time generated from the TSP strategy [sec]

d_1: Average delay per vehicle for uniform arrivals in seconds [sec]

d_2: Average delay per vehicle for the stochastic arrivals [sec]

d_3: Average delay per vehicle for the residual vehicle from the previous cycle [sec]

As seen in the model above, a coefficient is considered when considering the delay's effect on the transit vehicle. Three conditions are determined in the schedule range. If the bus is on schedule, α will be 1. If a bus is behind schedule between 0–10 minutes, α=1.5 and if the bus is behind schedule for more than 10 minutes, α is considered 2. In this case, more weight is given to public transit as an objective of this dissertation.

Also, as the proposed methodology works based on the number of passengers, the system should define this value to decide whether the bus should receive priority. However, as previously mentioned, one of the adverse effects of TSP is that when the delay is reduced in the major street, more delay will be imposed on the vehicles waiting behind the signalized intersection on the cross street. As a first step to eliminating this impact and determining the necessary number of passengers onboard, intersection delays are calculated using Equations (30) to (32)), where by $\sum$ we denote all of the vehicles in each cycle for each intersection.

$$D_i = D_m + D_c \tag{30}$$

$$D_m = \left[(\sum (D_v \times NP_v) + \sum (D_b \times NP_b)\right] \tag{31}$$

$$D_c = \sum D_{vc} \times NP_{vc} \tag{32}$$

Where:

D_i: Total delay for the intersection [sec]

D_m: Delay for the major street [sec]

D_c: Delay for the crossing street [sec]

D_{vc}: Delay for a passenger car vehicle on the crossing street [sec]

NP_{vc}: Number of passengers on the crossing street

If these two equations mentioned above equate, the delay will be equally distributed, and the required number of passengers will be calculated. As mentioned earlier, the approaching bus may be on time or behind schedule, and this condition can be accounted for in the model.

In the case of a bus that is on time, equating (31) and (32) yields the minimum number of passengers to receive priority (NP_{b-os}) . This value can be calculated using Equation (33) .

$$NP_{b-os} = \frac{(\sum D_{vc} \times NP_{vc}) - (\sum(D_v \ \times NP_v)}{\sum D_{vc}} \tag{33}$$

Where:

NP_{b-bs} : Minimum number of the required passengers onboard to receive priority in case the bus is behind schedule

D_{vc}: Delay for a passenger car vehicle on the crossing street [sec]

NP_{vc}: Number of vehicles on the crossing street

If the bus is behind schedule, the waiting time for the passenger waiting at the downstream bus stop should be accounted for in the cross-street delay. For this reason, the delay equation for the major street can be written as Equations (34) to (36).

$$D_{ibs} = D_{mbs} + D_{cbs} \tag{34}$$

$$D_{mbs} = \left[\sum (D_v \ \times NP_v) + \sum (D_b \times NP_b)\right] \tag{35}$$

$$D_{cbs} = \sum D_{vc} \times NP_{vc} + N_w T_{bs} \tag{36}$$

The minimum number of required passengers necessary to trigger priority signalling for the approaching bus is shown in Equation (37), using Equations (35) and (36)

$$NP_{b-bs} = \frac{(\sum D_{vc} \times NP_{vc} + N_w T_{bs}) - (\sum(D_v \ \times NP_v)}{\sum D_{vc}} \tag{37}$$

Where:

d_{tijk}: Total delay time during a phase [sec]

α: coefficient for estimating the weight of transit vehicle b's schedule delay in cycle T at an intersection

D_{ibs}: Total delay for the intersection [sec]

D_{mbs}: Delay for the major street [sec]

D_{cbs}: Delay for the crossing street [sec]

N_w: Number of passengers who are waiting at the bus stop after the intersection [sec]

T_{bs}: Time difference between the actual schedule and the real schedule [sec]

The logic of the proposed methodology is shown in Figure 5, and it is deployed via VAP into the VISSIM simulation platform through its COM interface.

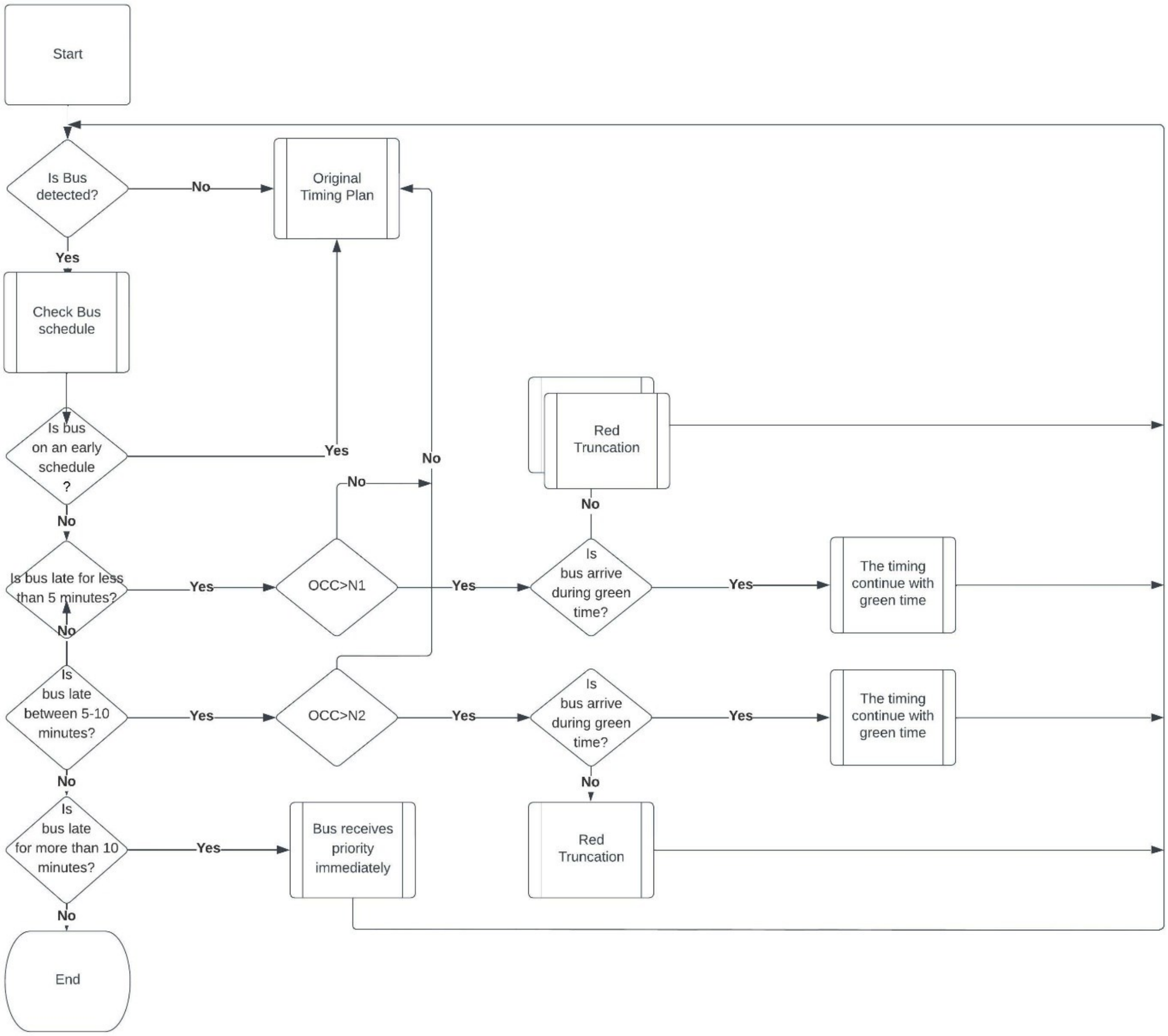

Figure 5: Travel time-based (Scenario 3) logic as implemented with VisVap

2.3.4 Scenario 4: Average person delay-based TSP

In this scenario, a mathematical program is developed to determine the optimal signal settings for all intersections to minimize the overall delay caused by the system. As a result of the model, total person delay is minimized by weighting delays for private and transit vehicles according to their respective passenger occupancies. Transit vehicle schedule delays refer to the time a bus is behind schedule when it arrives at a given intersection. As a result, transit vehicles that are further behind schedule or carry more passengers receive higher priority than others. Consequently, a higher priority is given to transit vehicles that are further behind schedule or carry more passengers than others.

This mathematical model assumes that perfect information about vehicle arrivals, traffic demand, passenger occupancy, and lane capacity at intersections is always available. A deterministic vehicle arrival pattern is assumed during the analysis period, and all signalized intersections are considered to have a constant cycle length. In addition, the sequence of phases and the phase design are predetermined and fixed. It is also assumed that the capacity for each approach at intersections is fixed and that traffic operations will not affect the capacity of each approach at intersections, which means that the saturation flow for each lane group 1 will remain constant. As a final step, we formulate the model assuming that transit vehicles ride in mixed-use traffic lanes alongside autos and treat queues at stop lines like vertical queues.

As part of the proposed algorithm, residual queues will be considered at the intersection when there are at least two-lane groups. In other words, the equation below applies to lane groups j, which can be served by phase i at intersections and whose vehicles arrive at an arriving rate of qj; T and are served at an arrival rate of sj during a cycle.

Transit vehicles are assumed to arrive at the intersection in real time. Transit vehicles also travel on mixed traffic lanes. The objective of this scenario is to find the optimum number of passengers on board based on Equations(38) and (39):

$$\min \left[\sum_{v=1}^{V} OCC_v d_v + \sum_{b=1}^{B} OCC_b d_b \right] \tag{38}$$

Subject to

$$g_{min} < g_{TSP} < g_{max} \tag{39}$$

OCC_v : Passenger occupancy of vehicle v

d_v: Control delay of vehicle v $[sec]$

OCC_b: Passenger onboard a transit vehicle b

d_b: Control delay of the transit vehicle b $[sec]$

g_{min}: Minimum green time (sec)

g_{max}: Maximum green time

g_{TSP}: Extension of a green time generated from the TSP strategy

A person's delay based on private vehicles is the sum of two terms in the objective function - 1) the delay experienced by the vehicles at the intersection during the current cycle, T, 2) the Estimated delay for those who will be serviced during cycle T+1. In this methodology, the number of vehicles in the residual queue for lane group j, as well as the arrival rate for lane group j, are considered. In addition, three different cycle times are considered, including the design cycle (T), a cycle before to account for residual queue effects (T-1), and a cycle after to account for the delay incurred by vehicles that cannot be served within the design cycle period. These equations are intended to calculate the delay for private vehicles in mixed traffic conditions. Considering the impact of the signal timing in cycle T on the delay of T + 1, the delay estimate is incorporated into the objective function. The optimized signal timings for the design cycle would provide the minimum green times for all phases apart from the last one, resulting in a substantial increase in auto delay in the next cycle if the expected delay measure was not included. In order to estimate the delay experienced by private vehicles, the number of vehicles in the residual queues for each lane group must be determined. This value can be calculated using Equations (40) to (42).

$$N_{j,T} = N_{j,T-1} + q_{j,T-1}\sum_{i}^{Z} G_{i,T-1} + q_{j,T}\sum_{i}^{Z} G_{i,T} - s_j \sum_{i} G_{i,T} \tag{40}$$

$$D_T = \sum_{j=1}^{J} D_{j.T} \tag{41}$$

$$D_{j.T} = \frac{1}{2}\,(2N_{j,T-1} + q_{j,T-1}\sum_{i}^{\emptyset} G_{i,T-1})\sum_{i}^{\emptyset} G_{i,T-1}$$

$$+\frac{1}{2}\left(2N_{j,T-1} + 2q_{j,T-1}\sum_{i}^{\emptyset} G_{i,T-1} + q_{j,T}\sum_{i=1}^{\emptyset} G_{i,T}\right)\sum_{i=1}^{\emptyset} G_{i,T} + \tag{42}$$

$$\left(N_{j,T-1} + q_{j,T-1}\sum_{i=i+1}^{Z} G_{i,T-1} + q_{j,T}\sum_{i=1}^{p-1} G_{i,T}\right)\sum_{i\in 1}^{p-1} G_{i,T} +$$
$$\frac{1}{2}\left(q_{j,T}\sum_{i\in 1} G_{i,T} - s_j \sum_{i\in 1} G_{i,T}\right)\sum_{i\in 1} G_{i,T}$$

$N_{j,T}$: Number of vehicles in the residual queue of lane group j at the end of the previous phase, which serves the same lane group in cycle T

$q_{j,T}$: Vehicle's arrival rate in lane group j during cycle $[\frac{veh}{sec}]$

s_j: Saturation flow rate for the autos in lane group j $[\frac{veh}{sec}]$

$D_{j.T}$: The total amount of time spent by vehicles in lane group j during cycle T [veh − sec]

j: Total number of lane groups at the intersection

$G_{i,T}$: Green time in the Cycle T for phase i [sec]

$\emptyset$: The first phase in the cycle T, serving lane group j

z = The first phase in a cycle that can serve lane group j

p = Total number of phases in a cycle

As a result of oversaturated traffic conditions, transit vehicle delays consist of the sum of two terms: 1) the person's delay experienced by transit vehicles at the intersection before the end of their respective green times during the design cycle T, and 2) the person delay experienced by transit vehicles that arrive before the end of the design cycle T, but cannot be served during the design cycle T. Consequently, transit vehicles arriving during cycle $T + 1$ are not considered, as information regarding transit vehicle location and arrival times are assumed to be available only for the design cycle.

Transit vehicles travel in mixed traffic lanes with automobiles, which means that the delay of a transit vehicle that arrives in the queue of its lane group at the time t_b is the same as the delay of an automobile which arrives in the queue at the same time, t_b. For example, suppose oversaturated conditions prevail during some cycles. In that case, the estimation of the transit delay used in the optimization of cycle T will depend on the actual arrival time of the transit vehicle, t_b, and whether or not it is served during the cycle.

Suppose a transit vehicle belonging to lane group j arrives after the end of the last phase that could serve j in the previous cycle, $T - 1$, but before the end of the respective current phases, T. The delay here is calculated using Equation (43):

$$d_{b,T} = \begin{cases} E_{j,T} - t_b & if\ n_{b,T+1} > 0 \\ (T-1)C + \sum_{i=1}^{p_{j-1}} G_{i,T} + \frac{n_{b,T-1}}{s_j} - t_b & if\ n_{b,T+1} < 0 \end{cases} \tag{43}$$

$E_{j,T}$: End of the green phase in the cycle T

$d_{b,T}$: Bus delay at cycle T

i: Index of the phase

$n_{b,T-1}$: Bus position in the queue after the end of the phase that serves the lane group j in cycle $T-1$, which can be calculated as Equation (44).

$$n_{b,T-1} = n_{b,T-2} - S_j \sum\nolimits_{i \in I_j} G_{i,T-1} \tag{44}$$

$n_{b,T}$: Bus position in the queue after the end of the phase that serves the lane group j in cycle T, which can be calculated as Equation (45).

$$n_{b,T} = \begin{cases} N_{j,T-1} + q_{j,T-1}\left(t_b - (T-2)C - \sum\limits_{i=i}^{i_j} G_{i,T-1}\right) & if\ t_b < (T-1)C \\ N_{j,T-1} + q_{j,T-1} \sum\limits_{i=i_j+1}^{z} G_{i,T-1} + q_{j,T}\left(t_b - (T-1)C\right) & if\ t_b \geq (T-1)C \end{cases} \tag{45}$$

$N_{j,T-1}$: Vehicle’s number in the residual queue at the end of the last phase in cycle $T-1$

T: Cycle Index

$t_{b.n}$: Real-time arrival time of the bus on route n at the end of the queue [sec]

C: Cycle length [sec]

When a transit vehicle belonging to lane group j has arrived in the previous cycle after the end of the green time when it can serve lane group j, and it is still present during cycle T, its delay for cycle T is as Equation (46):

$$d_{b,T} = \begin{cases} \sum\limits_{i=i_j+1}^{z} G_{i,T-1} + \sum\limits_{i=1}^{i_j} G_{i,T} & if\ n_{b,T} > 0 \\ \sum\limits_{i=i_j+1}^{z} G_{i,T-1} + \sum\limits_{i=1}^{p_{j-1}} G_{i,T} + \dfrac{n_{b,T-1}}{S_j} & if\ n_{b,T} < 0 \end{cases} \tag{46}$$

Where $n_{b,T}$ can be calculated using Equation (47):

$$n_{b,T} = n_{b,T-1} - S_j \sum\nolimits_{i \in I_j} G_{i,T} \tag{47}$$

It is possible for a vehicle to reach a lane group before the end of the last phase in cycle T and not be able to serve that group or to reach a lane group after the end of the previous phase. However, before the end of the cycle, according to the following two scenarios: In one possibility, extended phases will allow the transit vehicle to be served during the current cycle, T, or in the second possibility, the transit vehicle will be served during the following cycle (T+1). This objective function includes estimating how long such a bus would experience if the green time of the phase in which it can be served were not extended.

Similar to Equation (46), calculating the delay for a transit vehicle that cannot be served during cycle T depends on the vehicle's arrival time, t_b, and whether or not the vehicle can be served during the next cycle, $T + 1$. As indicated below, the delay experienced during the next cycle $T + 1$ is estimated by examining one of the two cases presented below.

When a bus travelling on lane group j arrives at some time before the end of the green time for cycle T that can serve j in the cycle T but cannot pass the light during that cycle, then its delay for cycle T can be calculated using Equation (48):

$$d_{eb,T+1} = \begin{cases} \displaystyle\sum_{i=i_j+1}^{z} G_{i,T} + \sum_{i=1}^{i_j} G_{iProch} & if\ n_{b,T+2} > 0 \\ \displaystyle\sum_{i=i_j+1}^{z} G_{i,T} + \sum_{i=1}^{p_j-1} G_{iProch} + \frac{n_{b,T+1}}{s_j} & if\ n_{b,T+2} < 0 \end{cases} \tag{48}$$

$d_{eb,T+1}$: Bus delay in cycle $T + 1$[sec]

G_{iProch}: Green time for the next phase in cycle $T + 1$ [sec]

And $n_{b,T+2}$, which is the position of bus b in cycle T after the completion of phases serving its lane group j , can be calculated using Equation (49).

$$n_{b,T+2} = n_{b,T+1} - s_j \sum\nolimits_{i \in I_j} G_{iProch} \tag{49}$$

In cycle $T + 1$, if a bus in lane group j has arrived after the last phase that can serve the lane group j in and the green time cannot be extended, the bus's delay can be estimated using Equation (50).

$$d_{eb,T+1} = \begin{cases} TC \sum_{i=i_j+1}^{z} G_{i,T} + \sum_{i=1}^{i_j} G_{iProch} - t_b & if\ n_{b,T+2} > 0 \\ \sum_{i=i_j+1}^{z} G_{i,T} + \sum_{i=1}^{p_j-1} G_{iProch} + \frac{n_{b,T+1}}{S_j} - t_b & if\ n_{b,T+2} < 0 \end{cases} \tag{50}$$

Where $n_{b,T+2}$ can be calculated using Equation (51).

$$n_{b,T+2} = N_{j,T} + q_{j,T}E_{j,T} - s_j \sum\nolimits_{i \in I_j} G_{iproch} \tag{51}$$

2.4 **Concluding Remarks**

As part of this section, analysis methods for assessing the effectiveness of TSP were discussed, and scenarios were presented. The mathematical equations for two proposed methodologies were explained in detail to identify the minimum number of bus passengers to receive priority at an intersection and minimize the person's delay.

Moreover, the VISSIM microsimulation and Wiedemann 74 car-following model were introduced, and parameters for driving behaviour were discussed. It also explained how to calibrate the simulation model and reduce the difference between field observations and simulation results.

CHAPTER 3
DEPLOYMENT THROUGH A REAL-WORLD STUDY AREA

3.1 <u>Input Data</u>

A case study is considered to measure the proposed methodology's effectiveness. For this purpose, Boulevard Saint Raymond in Gatineau is selected. This network has 12 intersections in total, 6 signalized and 6 unsignalized intersections. So, there were enough intersections along the corridor to evaluate the efficiency of the methods. Figure 6 shows the aerial photo of the network from Google Earth®.

Figure 6: Selected Network for analysis

VISSIM requires three sets of information, namely geometric design, traffic data, and transit data, in order to create the network. The geometric design was completed using Google maps and a GIS file. Information about traffic volume (for different transportation modes), turning movement at each intersection, travel time, headway, and vehicle type were provided. All the traffic and transit data were gathered using video recording in 2019 for a whole day, and images were processed by image processing technique (Miovision) every 5-minute intervals. Additionally, La Société de transport de l'Outaouais (STO) provided transit data, such as the number of passengers ascended and descended, the number of passengers on board, and information about the different transit lines in the corridor. Figure 7 and Figure 8 show a sample of data that were available for the study,

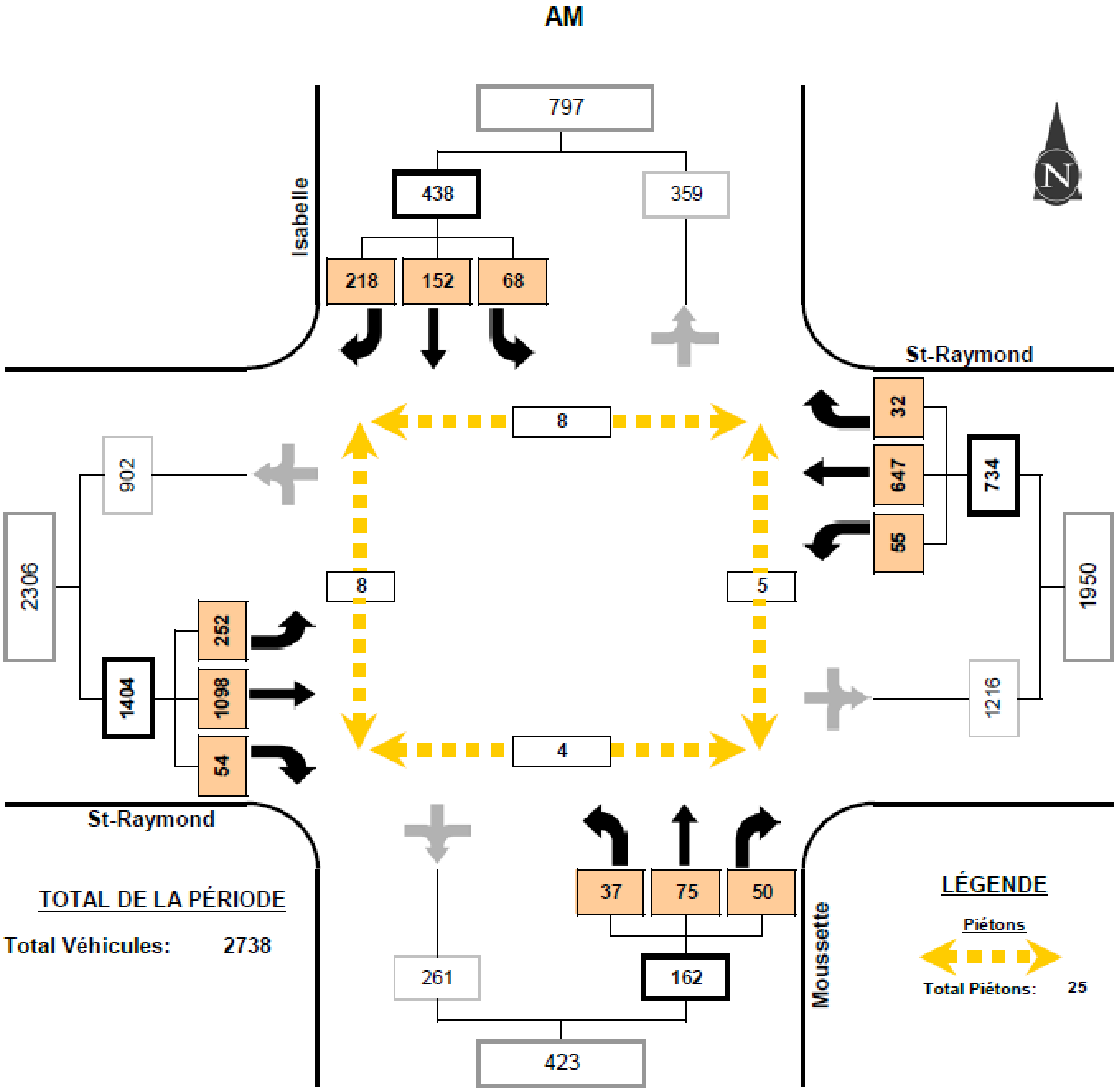

Figure 7: Traffic movements for St-Raymond & Moussette Intersection (AM period)

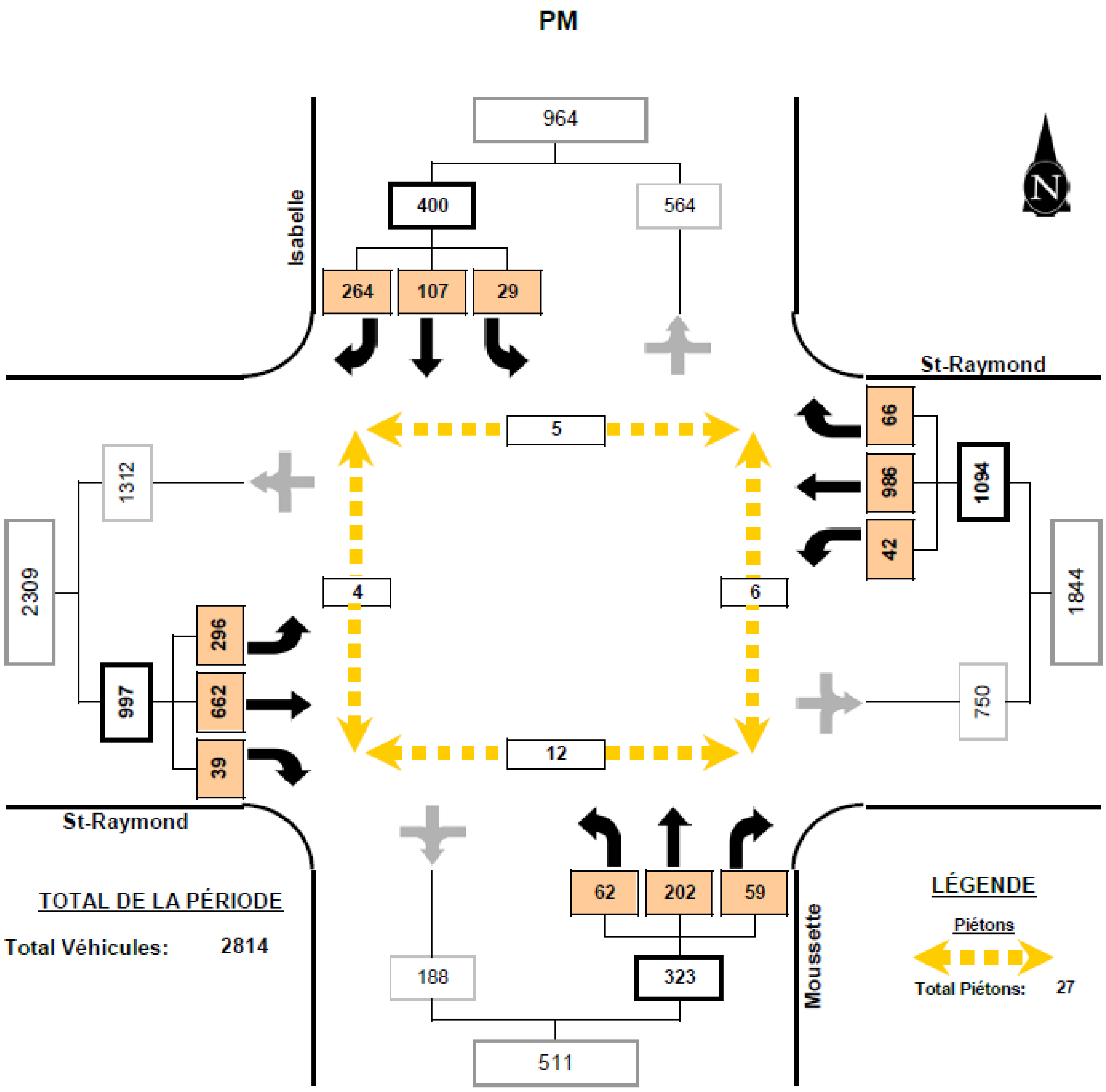

Figure 8: Traffic movements for St-Raymond & Caserne Pompier Intersection (AM period)

3.1.1 Passenger Data

As mentioned earlier, public transit data was provided by STO. Based on the provided information, eight bus stations along St-Raymond Boulevard are placed evenly between the northbound and southbound directions. According to the provided data, 14 transit lines with different headways pass along the corridor and stop at the bus stations. The public transit dataset was processed to extract the actual bus headways instead of the theoretical scheduled transit headway. A sample of the STO public transit plan with the transit lines along the corridor is shown in Figure 9.

Also, the number of boarding, alighting, and average boarding passengers were extracted during the morning peak hour. Furthermore, their observed arrival times to each stop were used in the VISSIM. The information about passenger load on the studied transit line is shown in Table 1 and Table 2.

Table 1: Passenger data along the route for all lines-Northbound

Station	Total Boarding	Total Alighting	Average on Board	Distance from the previous Station (m)
Station 1	58	32	25	0
Station 2	14	8	21	1240
Station 3	35	58	29	970
Station 4	28	24	27	1140

Table 2: Passenger data along the route for all lines-Southbound

Station	Total Boarding	Total Alighting	Average on Board	Distance from the previous Station (m)
Station 5	19	25	19	0
Station 6	6	19	27	1350
Station 7	42	29	24	840
Station 8	42	61	21	1260

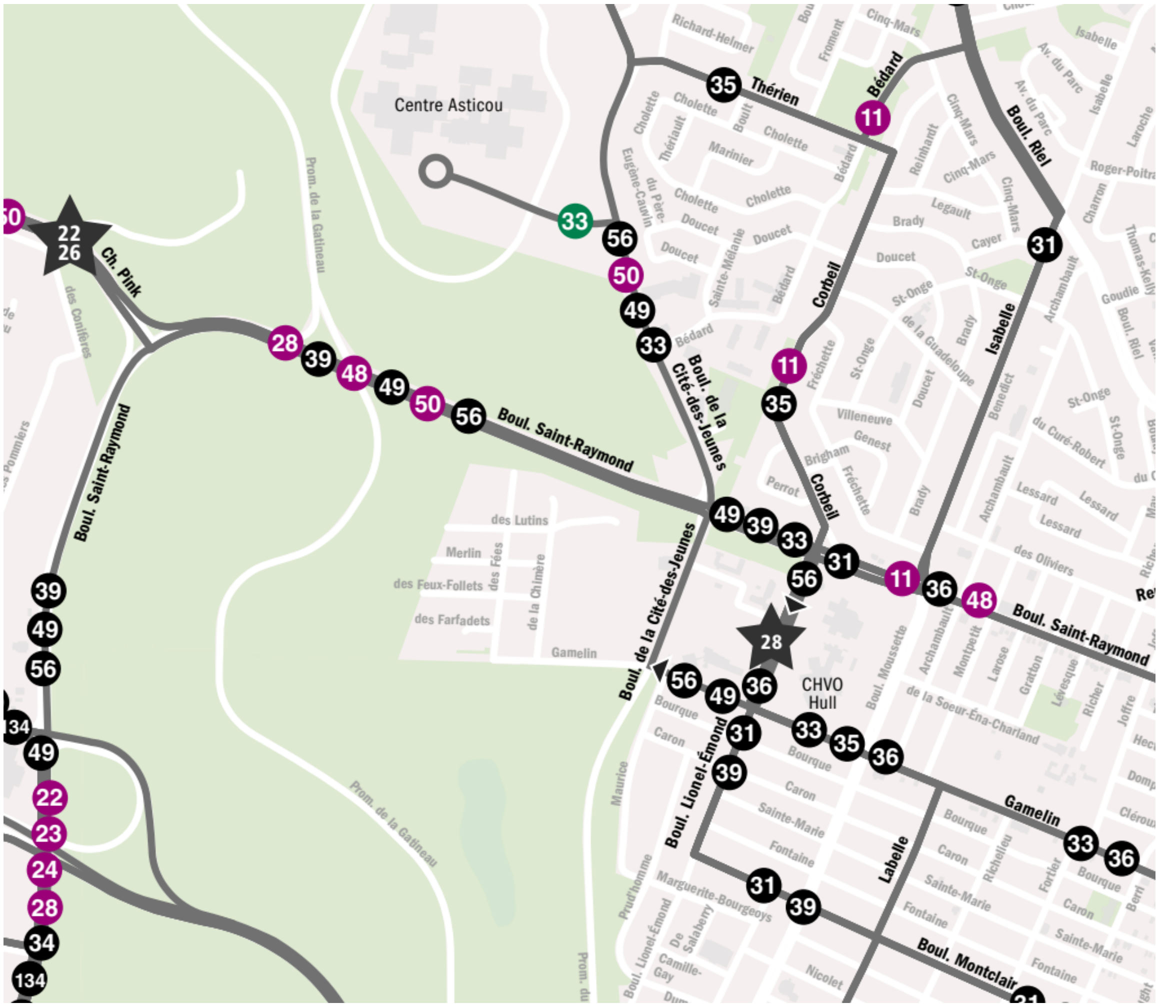

Figure 9: A Part of the STO transit plan near the study area

3.1.2 Geometric Design and Signal Control Characteristics:

As mentioned earlier, Google Maps®, AutoCAD and GIS layout of the network were used to create the network and geometric design of the corridor in VISSIM. The sources provided information on intersections and links within the corridor, such as the number of lanes per approach, the width of the lanes, grade, curvature, and bus stop locations.

Moreover, data about the timing scheme for the signalized intersections were provided by the Ville de Gatineau. The timing scheme provided information about the phasing, cycle length, green time, extension time and other relevant information.

3.2 **Calibration of Scenario 1 (Current Conditions)**

There are many areas where micro-traffic simulations are used in the field of transportation engineering because of their cost effectiveness, risk-free nature, and high-speed benefits, including transportation system design, traffic operations, and management alternatives evaluation. However, even though simulation models are well-known and widely used, their credibility is questioned. When model parameters are incorrect, simulation models cannot accurately mimic field conditions, limiting their ability to assist decision-makers. In order to fine-tune each model that the user is using, the user needs to pay more attention to calibrating the parameters contained within each model as well. In conclusion, calibration can be defined as an adjustment of model parameters so that the model's output closely resembles the field conditions.

The calibration procedure is a repetitive process of comparing field data with the simulation model outputs to make them close as much as possible. For instance, if travel time is selected as an index of comparison, then both field data and simulation output data will need to be collected to make an accurate comparison. The first step in a calibration procedure is to collect data from the field so that the simulation model output can be compared to it. The difference between the field-measured travel time data and the simulation model output taken for each run of the simulation model after the target data, or the field-measured travel time data, is recorded and compared. Depending on the parameters set, if the difference between the output and field values is not close enough (to be within a specific range), the simulation run will involve fine-tuning the calibration parameters until the difference is within a predetermined error range, resulting in the best calibration parameters being selected. Simulation models could generally have significantly different output values from the field values. One of the reasons is that each simulation run is based on a randomly generated seed number. Using random seeds allows for stochastic variations of traffic arrivals in VISSIM, which helps account for variations in real-world traffic conditions. If two or more simulation runs in the same VISSIM network, each using different random seeds, the stochastic functions in VISSIM will be assigned a different value sequence in each simulation run. This consequently changes the network's traffic flow and operational attributes (e.g., speed, travel time, delay) from seed to seed. A given network will, therefore, have a certain distribution of output data based on the number of runs with it.

Furthermore, each microscopic simulation model requires several inputs, referred to as calibration parameters. Users can use these inputs to fine-tune simulation models to match real-life traffic conditions, including driver behaviour and vehicle performance parameters. A number of additional calibration parameter categories are available in VISSIM, including car following, lane changing, priority rule, and desired speed distribution parameters. Table 3 summarizes the calibration parameters for VISSIM. (Park et al., 2006).

Table 3: Calibration Parameter in VISSIM

No	Parameter Type	Parameter Name
1	**Car Following Parameter**	Maximum Look Ahead Distance
2		Average Standstill Distance
3		Additive Part of Safety Distance
4		Multiple Parts of Safety Distance
5		CC0, Average Standstill Distance
6		CC1, Headway Time
7		CC2, “Following” Variation
8		CC3, Threshold for Entering “Following”
9		CC4, Negative “Following” Threshold
10		CC5, Positive “Following” Threshold
11		CC6, Speed Dependency of Oscillation
12		CC7, Oscillation Acceleration
13		CC8, Standstill Acceleration
14		CC9, Acceleration at 80km/h
15	**Lane Change Parameter**	Maximum Deceleration
16		Reduction Rate (-1m/s^2 per Distance)
17		Accepted Deceleration
18		Waiting Time Before Diffusion
19		Minimum Headway
20	**Desired Speed Distribution**	Minimum Gap Time
21		Minimum Headway

It is also possible to determine the most relevant calibration parameters using a statistical method known as the Analysis of Variance (ANOVA). This test is commonly used to test hypotheses relating to the differences between three or more means of calibration. ANOVA test outcomes contain different parameters, but only the relevant parameters should be particularly interesting to the user. In the analysis of variance (ANOVA), the variations between- and within groups in terms of their respective mean squares (MS) are studied. These values are calculated by dividing each sum of squares by its associated degrees of freedom. Although a mean square, the result is a measure of variance, which is the squared standard deviation. By dividing MS (between) by MS (within), one can obtain the F-ratio. The F-ratio may be substantially larger than 1.0 even if the population means are all equal, simply due to sampling error causing a large variation between samples (groups). An F-value of this magnitude may be even greater than the F-critical value as a result of the F-probability distribution corresponding to the two MS and at a set significant Type I (alpha-) level of error associated with the two MS. The probability of observing an F-ratio as large as your calculation can be determined by referring to the distribution of F-ratios with different degrees of freedom, even if the populations have identical mean values. If the null hypothesis that the group means is not different, a P-value represents the probability that the F-ratio will be large or larger than the observed one. This p-value must be less than .05 to reject the ANOV"s null hypothesis and conclude that there has been a statistically significant difference between the means of the three groups.

For example, if a user determined that the confidence level was 95% (95% is the most commonly applied confidence level), the user would have found that the redetermine confidence level would be 0.05 (finding the redetermine confidence level by subtracting 0.95 from 1.00). The user can consider the minimum gap as a key parameter by applying this confidence level to Table 15 since the p-value (0.003) is smaller than the confidence level (0.05) when that confidence level applies. In the case where the p-value exceeds the confidence level, it should not be included in the list of the most relevant calibration parameters.

It is worth mentioning that a number of calibration parameters are provided by VISSIM and can be modified, and these parameters are classified into different categories based on their characteristics. In order to fine-tune the model, some of the VISSIM parameters were selected to select the most relevant calibration parameters for the study area.: Four main parameters are used to calibrate this model: the basic calibration parameters, which affect the whole network and are necessary to its operation. VISSIM uses the Wiedemann model in their following model for cars. It was developed by Rainer Wiedemann in 1974 (Wiedemann 74) and revised in 1999 (Wiedemann 99) to consider the driver" psychological and physical aspects. There are some differences between the 74 and 99 models in that some thresholds have been defined differently in the 99 models in order to better model freeway traffic. As a result, VISSIM"s Driving Behavior is set to 99 for freeway driving and 74 for urban driving. Therefore, all three parameters of the Wiedemann 74 model are considered in this study.

Furthermore, there is a priority rule at this intersection because, as stated previously, left turns are permitted, which means that to consider the parameters of this priority rule. Lastly, as for the desired speed distributions: there is a speed limit for this intersection, but not all the vehicles behave like this, and the desired speed for each driver depends on the vehicle's characteristics. Within the initial parameter ranges, two hundred combinations were generated. For every 200 cases, five random seeded runs were conducted in VISSIM. VISSIM output is typically narrower than other simulation models, so only five runs were made for calibration. For every 1000 runs, the average travel time and headway were recorded. In order to represent each of the 200 parameter sets of the model, the results from each of the five multiple runs were averaged together. Through statistical analysis, it is more rigorous to identify the critical parameters. ANOVA cannot analyze continuous values, so the values of each parameter were categorized into several groups and indexes. ANOVA results are presented in Table 4, including p-values. The parameters were identified as the most relevant factor for the calibration of the based scenario parameter as the p-value for them was 0.05 or less. In addition, if some parameters do not show a significant difference under statistical analysis, the joint effect with another key parameter is also important. Based on Table 4, it can be seen that minimum gap time and desired speed distribution have values less than 0.05 and can be considered to be the most relevant parameters.

Table 4: ANOVA Results for the VISSIM parameters in the base scenario

Parameters	Significance value (p-value)
Simulation Resolution	0.871
Number of Preceding Vehicles	0.512
Average Standstill Distance	0.206
Saturation Flow	0.854
Minimum Headway (meter)	0.065
Minimum Gap Time (sec)	0.023
Desired Speed Distribution	0.042

As a result of a number of factors, the observed speed in the field was lower than the posted speed limit of 50 km/h., such as poor sight distance, allowed left turns, narrow intersections, and other factors, such as the upstream bus station of the westbound approach to the intersection. Using the average field speed rather than the desired speed of the vehicle is more reasonable. Upon reviewing the available data, the average speed was approximately 37.5 km/h, while the minimum and maximum observed speeds were 20 and 50 km/h, respectively. As a result, the speed distribution was defined as 30–50 km/h, 32.5-37.5 km/h, and 27.5-42.5 km/h.

After determining the most appropriate calibration parameters, a Particle Swarm Optimization (PSO) algorithm was used to fine-tune the Wiedemann 74 car-following model. The PSO algorithm was used along with VISSIM COM scripting to minimize the objective function for calibration purposes. 200 iterations, 1000 simulation runs, and five random seeds were used to ensure a successful calibration. The objective was adjusted accordingly based on the difference between headway and travel time in simulation and observed data. There are multiple iterations in which the algorithm runs the simulation model multiple times and chooses a new set of values for the parameters in the following iteration. The simulation runs continue until the objective function is as close to the real-world value as possible. The parameter values for each set are listed in Table 5.

Table 5: Default and Calibrated VISSIM parameters for the study area

Parameters	Default	Calibrated
Simulation Resolution	5	6.3
Number of observed preceding vehicles	2	3
Maximum look ahead distance (meter)	250	223
Average standstill distance (meter)	1.5	3.28
Additive part of the desired safe distance	3	4.8
Multiple parts of desired safe distance	3	5.1
Priority rules — minimum headway (meter)	5	7.1
Priority rules — minimum headway (Seconds)	0.9	3.14
Priority rules — minimum gap time (second)	3	4.7
Desired speed distribution (km/h)	40–50	22.5-47.5
Ave. travel time (second)	502.1	723.4

Also, many studies used traffic volumes to compare microsimulation output and field observation. The GEH formula developed in the 1970s (Alomari, 2015) is a frequently used criterion to validate a simulation model's calibration. It compares the simulated traffic volumes with the real-world ones, and its formulation is shown in Equation (52):

$$GEH\ Statistics = \sqrt{\frac{2 \times (m - c)^2}{m + c}} \tag{52}$$

Where,

m is the traffic volume from the microsimulation model,

c is the traffic volume based on field observation.

Table 6 displays the GEH statistical parameters for individual traffic flow in the model and the model.

Table 6: GEH criteria for traffic flows

GEH for individual traffic volume	
GEH less than 5	Good fit
GEH between 5 and 10	The model probably has an error or bad input
GEH greater than 10	With a higher chance, modelling has a problem
GEH for the model as a whole	
GEH less than 5	At least 75% of the intersection turn volumes

As for validation, the model was run with the calibrated values to check whether the GEH value was satisfied. Figure 10 shows the results of the validation.

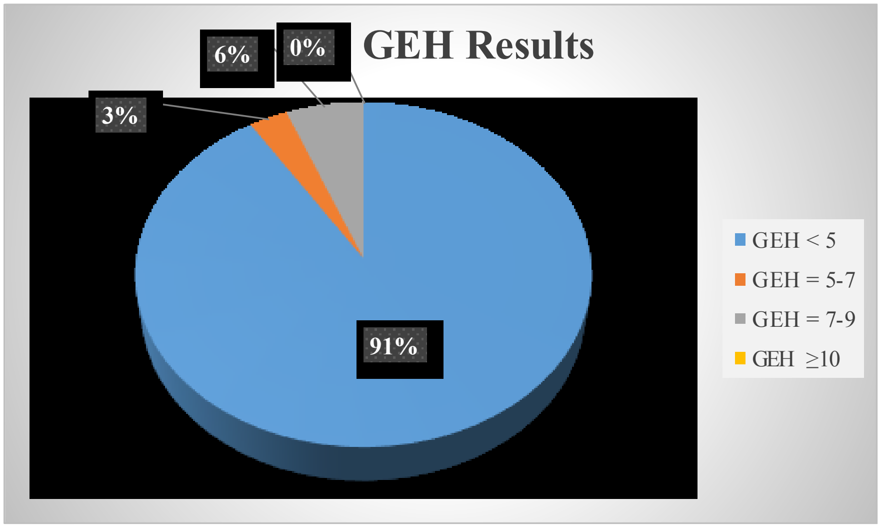

Figure 10: GEH Results for the Validation

GEH 5.0 for at least 75% of intersections, turning volumes is the model's overall acceptance criterion (Wisconsin Department of Transportation's, 2019). GEH 10.0 is also the acceptance criterion for individual traffic flows. The generated VISSIM model had GEH 5.0 for 91% of the intersection's volumes, and GEH less than 10.0 for each individual traffic flow was zero.

3.3 Analysis of Current Conditions (status-quo)

After calibrating the network in VISSIM, the Status quo was analyzed to evaluate the existing measure of effectiveness. In order to evaluate the efficiency of the proposed methods, two types of existing conditions were considered: in the first step, an isolated signalized intersection with different traffic conditions (existing, oversaturated, and undersaturated) was analyzed. In the second step, the whole corridor, including six signalized intersections and six unsignalized intersections, was analyzed in VISSIM to evaluate the measure of effectiveness in the present situation with different traffic volumes. A total of 55 replications were performed for each scenario, and the average result was considered for each MOE.

3.3.1 Isolated intersection without TSP

First, an intersection located at the crossing between Boulevard St-Raymond and Boulevard Moussette, in the City of Gatineau, QC, was selected to be evaluated in VISSIM. The network and the traffic, geometric and transit data were created in VISSIM and analyzed. The microscopic simulation model updates the network performance at every time step. The data for all vehicle classes are entered together by default. It is possible to separate the data for certain vehicle classes. In this study, 5 different MOEs are considered. Each MOE is defined below, according to the VISSIM Manual (PTV Group, 2019):

Speed: A weighted average of the speed of all vehicles is calculated using the respective travel time of each vehicle. In this case, vehicles with a short travel time will have a smaller impact on the result attribute than vehicles with longer travel times.

Travel Time: Amount of time that vehicles have traveled within the network or have already left the network (it can be extracted for different vehicle classes)

Total delay per vehicle: "delay of all vehicles in the network or of those that have already exited it. The delay of a vehicle in a time step is the part of the time step that must also be used because the actual speed is less than the desired speed. For the calculation, the quotient is obtained by subtracting the actual distance traveled in this time step and desired speed from the duration of the time step. Delay, for instance, includes stop times at stop signs." Then this amount of time is divided to the number of vehicles within the network or which have already left the network to calculate delay per vehicles.

Delay Per Person: Total delay divided by occupants of the private vehicles and public transit unit's passengers.

Stop per vehicle: calculated as *Total stops* / (*Number of vehicles in network* + *number of vehicles that have exited network*). According to the existing literature, this MOE is analyzed in order to determine the fuel and air pollution savings that can be achieved through improvements in signal timing at individual facilities (R Dowling, 2007).

In the current condition, TSP is not applied. Table 7 shows the Measure of Effectiveness for the Status quo situation for an isolated intersection. Also, Figure 11 to Figure 13 show these results graphically.

Table 7: MOEs for the Existing Scenario (No TSP) for St-Raymond & Moussette Intersection

	Traffic Condition	**Bus Travel Time (sec)**	**Total Delay per vehicle (sec)**	**Speed (km/h)**	**Delay Per Person (sec)**	**Stop per vehicle**
Scenario 1	Low (70%)	32.5	18.2	36.3	9.1	5.1
	Actual	34.5	19.3	32.4	11.2	6.2
	High (130%)	50.87	40.57	27.8	21.3	6.8

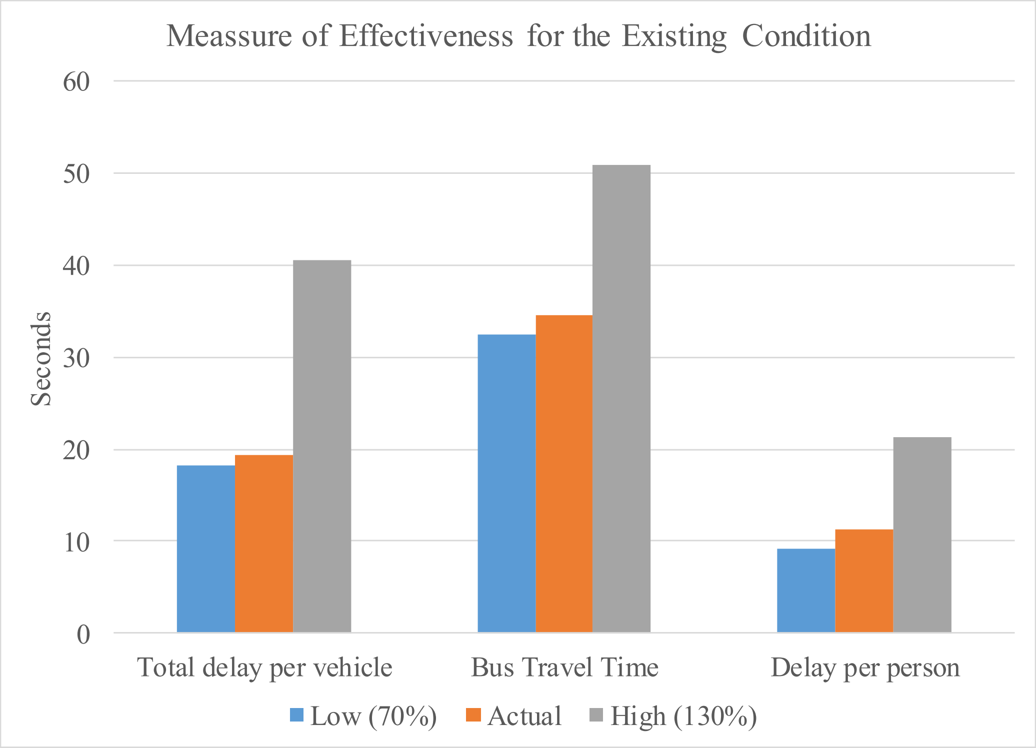

Figure 11: Total Delay Per Vehicle, Bus Travel Time and Delay Per Person for the Existing Condition (AM period) for St-Raymond & Moussette Intersection

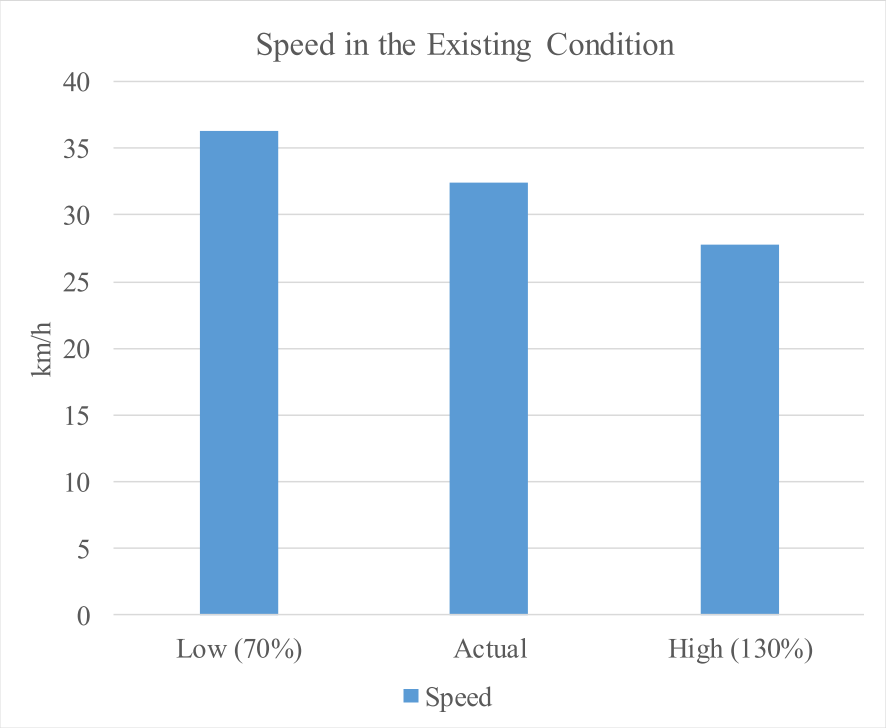

Figure 12: Speed for the Existing Condition (AM period) for St-Raymond & Moussette Intersection

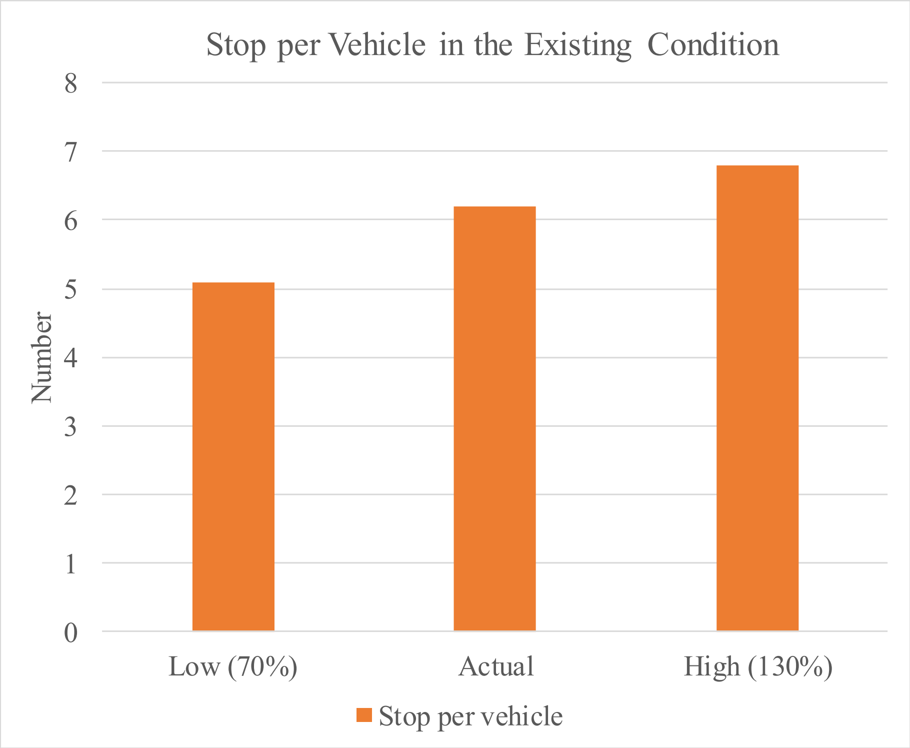

Figure 13: Stop per Vehicle for the Existing Condition (AM period) for St-Raymond & Moussette Intersection

3.3.2 Arterial Corridor without TSP

As mentioned earlier, the 4.4 km corridor was evaluated in VISSIM to know the traffic indices along the corridor for the Status quo condition. Table 8 shows the results along the corridor. Also, Figure 14 to Figure 17 show the same results graphically.

Table 8: MOEs for the Existing Scenario (No TSP) for the corridor

	Traffic Condition	Bus Travel Time (sec)	Total Delay per vehicle (sec)	Speed (km/h)	Delay Per Person (sec)	Stop per vehicle
Scenario 1	Low (70%)	769	319	16.3	28.3	17.6
	Actual	814	351	14.2	32.4	22.8
	High (130%)	892	390	12.45	45.1	37.3

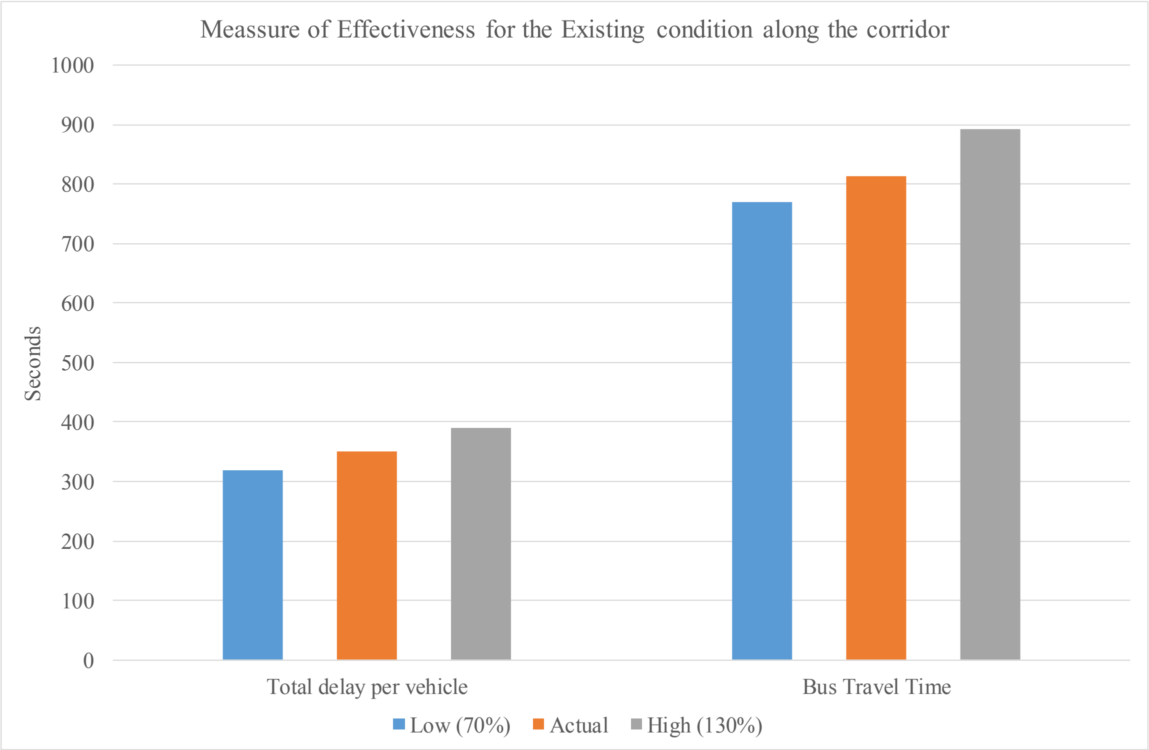

Figure 14: Total Delay Per Vehicle and Bus Travel Time for the Existing Condition (AM period) for the corridor

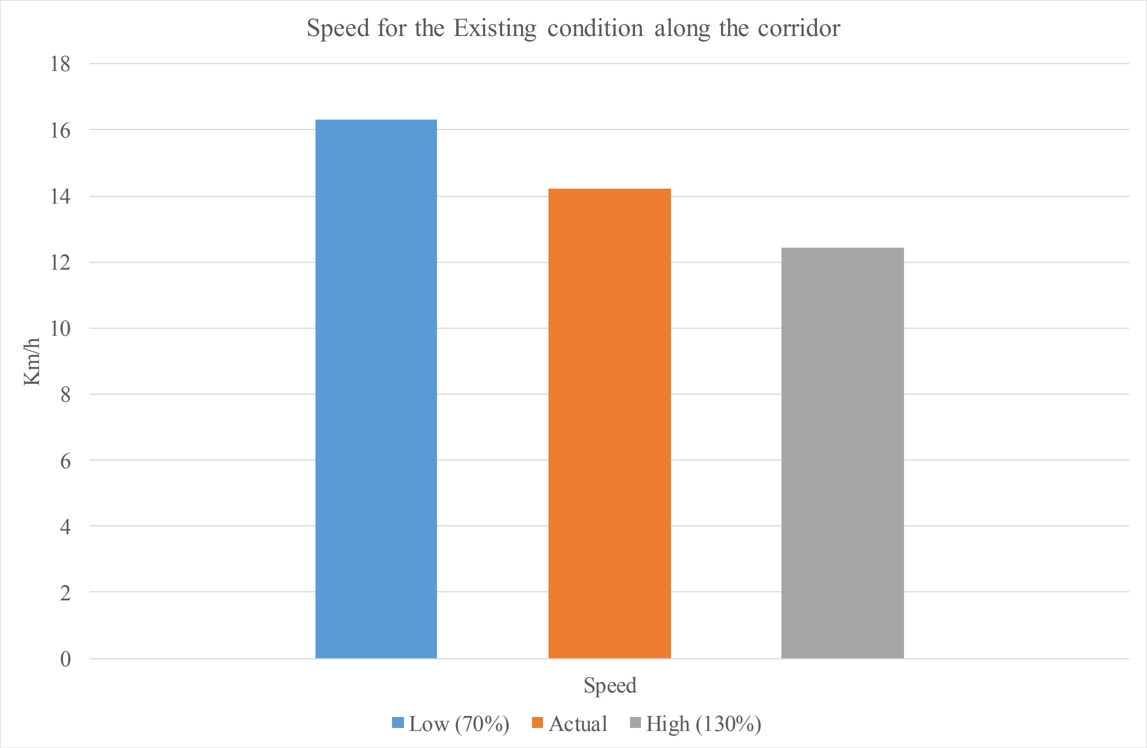

Figure 15: Network's Speed for the Existing Condition (AM period) for the corridor

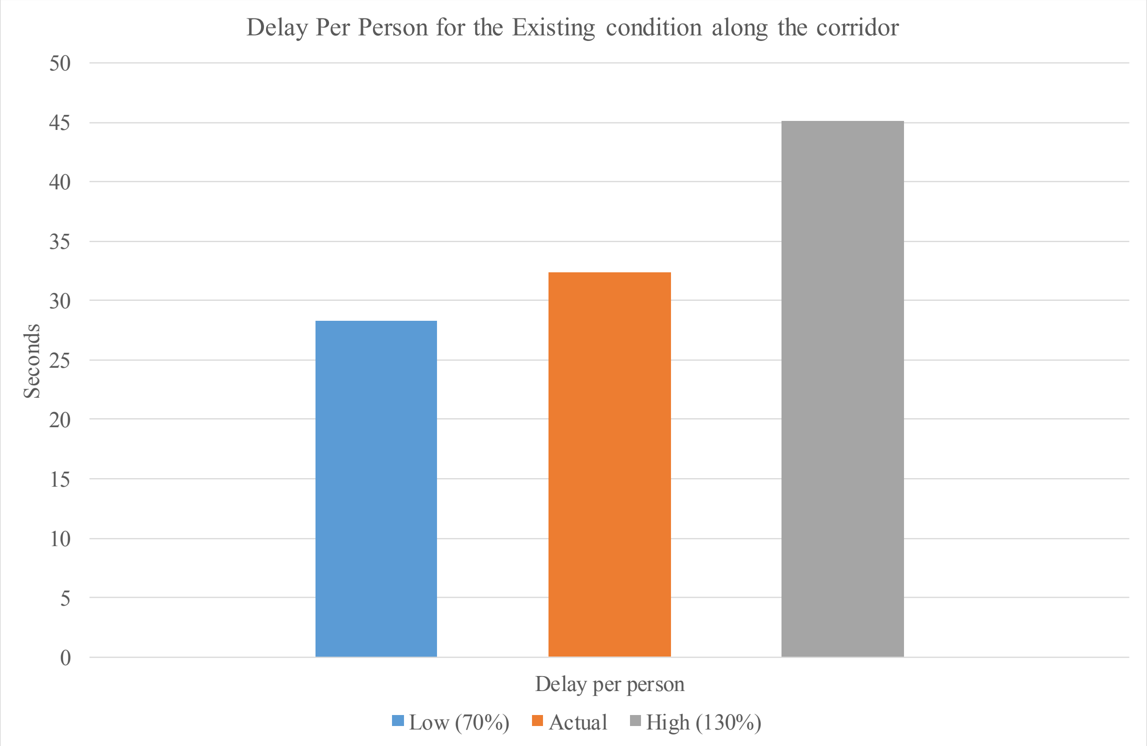

Figure 16: Delay Per Person for the Existing Condition (AM period) for the corridor

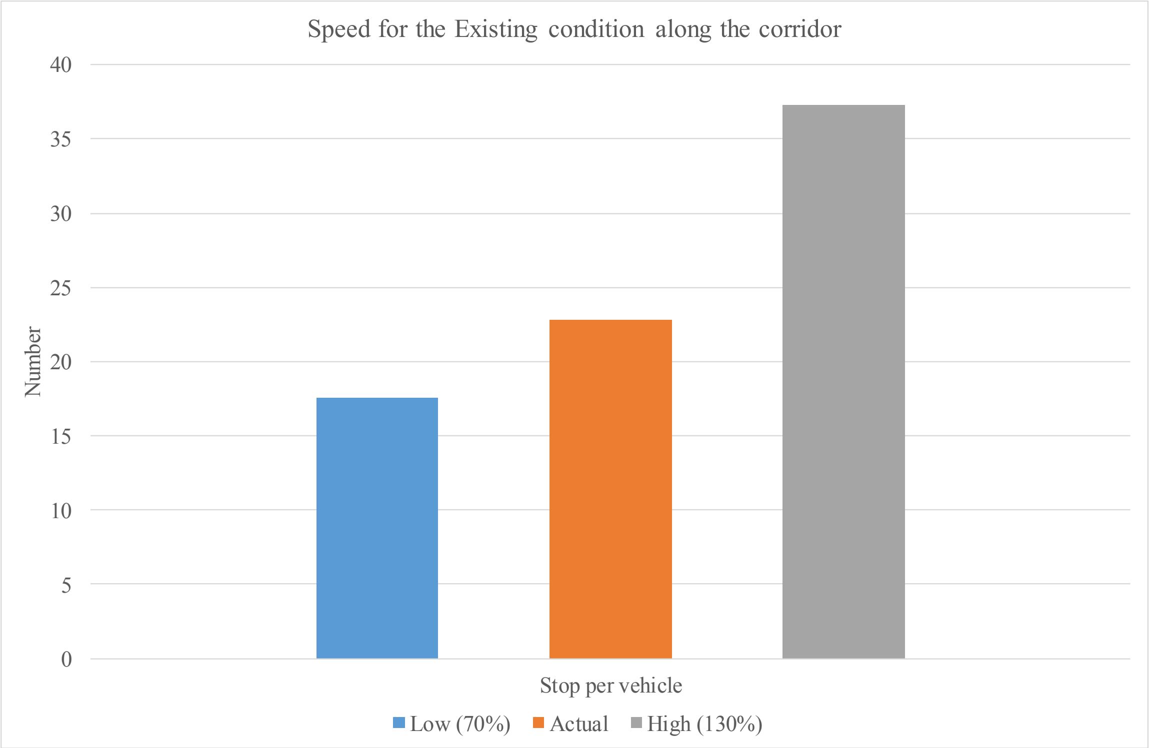

Figure 17: Stop per Vehicle for the Existing Condition (AM period) for the corridor

3.4 Concluding remarks

This chapter presented the study area for evaluating the effectiveness of the proposed methodologies in a particular field. In addition, it included information about the available data (i.e., geometric design details, traffic and transit data, etc.). VISSIM was used to create the base scenario (i.e., the status quo). In order to calibrate the simulation outputs, the most relevant parameter that caused the differences between simulation outputs and field data was identified using the ANOVA test. Afterwards, the parameters were adjusted using a PSO algorithm to minimize the differences as much as possible. The GEH test was also applied to the model as a Validation Method to ensure that the calibration was successful. The results yielded a GEH value of less than 5 for 91% of cases, which indicates that the traffic flow simulation was sufficiently accurate.

Next, both status-quo scenarios were simulated using three different traffic flow demands: existing, undersaturated (70% of existing traffic conditions), and oversaturated (130% of existing traffic conditions).

Furthermore, an isolated intersection and the corridor were simulated to understand the efficacy of the proposed methodologies better. Each scenario was replicated 55 times, and the average MOEs were reported in the tables.

CHAPTER 4
ASSESSMENT OF THE TEST CASES

All the scenarios were simulated 55 times with different random numbers of seeds considering a 95 percent confidence interval. To evaluate the effectiveness under different traffic conditions, each scenario was simulated using different traffic conditions: low traffic (70% of the observed traffic volume), observed (status-quo) traffic, and high traffic demand (130% of the existing traffic volume). The proposed strategies to ameliorate transit operation were tested using an isolated intersection as we as one arterial corridor that embeds the same intersection. Various measures of effectiveness (MOEs) are calculated for each scenario using the three traffic demand levels, as described above.

In this section, the MOEs for both one intersection and the arterial corridor are presented. This section presents the results for the intersection between St-Raymond Blvd. and & Moussette Blvd., as well as the passing through the arterial corridor along St. Raymond Blvd.

4.1 An Isolated Intersection

In this step and as in scenario 2, the conventional TSP was used. This TSP strategy gives a default priority to any approaching bus at the intersection, regardless of the transit unit load, schedule or prevailing traffic conditions at the intersection. Table 9 shows the results of this simulation setup.

Table 9: MOEs for Scenario 2 (Conventional TSP) for St-Raymond & Moussette

	Traffic Condition	Bus Travel Time (sec)	Total Delay per vehicle (sec)	Speed (km/h)	Delay Per Person (sec)	Stop per vehicle
Scenario 2	Low (70%)	27.4	16.1	36.8	7.2	4.7
	Status-quo	29.2	17.2	35.2	14.3	5.5
	High (130%)	39.5	32.17	31.7	23.6	5.9

Second, the new TSP strategy – which accounts for the number of passengers on board and the bus schedule, was tested on the same isolated intersection. As mentioned in section 2.3.3, this algorithm checks the eligibility of each approaching bus rather than providing priority indiscriminately as the normal TSP does. Table 10 shows the results from the simulation for this scenario.

Table 10: MOEs for Scenario 3 (Transit Unit Load-based TSP) for St-Raymond & Moussette

	Traffic Condition	Bus Travel Time (sec)	Total Delay per vehicle (sec)	Speed (km/h)	Delay Per Person (sec)	Stop per vehicle
Scenario 3	Low (70%)	25.2	15.27	36.98	7.18	4.7
	Status-quo	26.1	16.8	36.1	13.58	5.8
	High (130%)	31.7	25.42	34.28	20.17	6.8

Finally, the same approach of an isolated intersection was simulated using the proposed TSP that optimizes the person's delay in an intersection (considering all transportation modes). Table 11 shows the simulation outputs for this scenario at the same intersection as the previous two scenarios.

Table 11: MOEs for Scenario 4 (Average person delay-based TSP) for St-Raymond & Moussette

	Traffic Condition	Bus Travel Time (sec)	Total Delay per vehicle (sec)	Speed (km/h)	Delay Per Person (sec)	Stop per vehicle
Scenario 4	Low (70%)	23.17	14.74	37.12	7.12	4.5
	Status-quo	25.87	15.17	36.8	12.14	5.1
	High (130%)	28.24	21.87	35.8	18.09	5.7

In the case of an isolated intersection, it is apparent that the results for scenario 4 were better in all of the MOEs compared to the other scenarios and in all types of traffic conditions compared to the other scenarios.

When comparing scenario 4 to scenario 1, the bus travel time could be observed to have decreased by 58 percent in the high traffic condition compared to scenario 1. This decrease could also be observed to have decreased by 33 and 28 percent, respectively, when comparing scenario 4 to scenario 1.

Among the four different scenarios, scenario 4 also performed the best among all of them in terms of total delay per vehicle. In comparison with scenario 1, there was a 21 percent drop observed, followed by 24 and 60 percent for the actual and high traffic conditions, respectively.

The results for scenario 4 also showed an improvement with regard to speed. However, the effect of the proposed methodology in congested situations was more apparent, with a 25 percent increase in speed as compared to scenario 1. There is only a 2 percent improvement between the two aforementioned scenarios when it comes to low-traffic conditions.

During low traffic conditions, all three scenarios experienced the same drop in delays per person, hovering around 24 percent for all three scenarios. However, under actual traffic conditions, all three scenarios showed a higher value than scenario 1, but scenario 4 had the lowest increase compared to the other three scenarios. The high traffic condition has once again returned to normal, and a decrease of 16 percent has been observed as a result of that trend returning to normal.

Considering that stop per vehicle is a criterion in the environmental analysis, scenario 4 achieved a better result than the other scenarios in terms of environmental analysis. It is estimated that the value decreased by 20 percent in the actual traffic condition, while it decreased by 13 percent in the low-traffic situation and 18 percent in the high-traffic situation. Figure 18 to Figure 22 show the results from the simulation models for all scenarios.

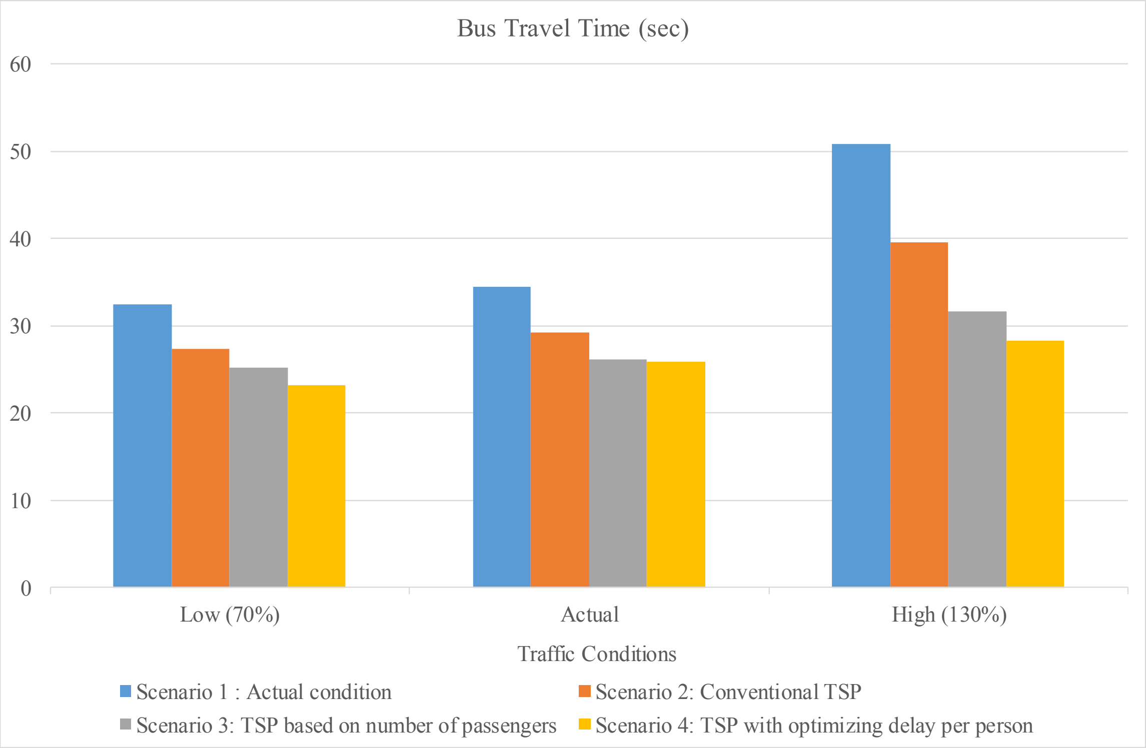

Figure 18: Bus travel time for all scenarios (AM period) for St-Raymond & Moussette

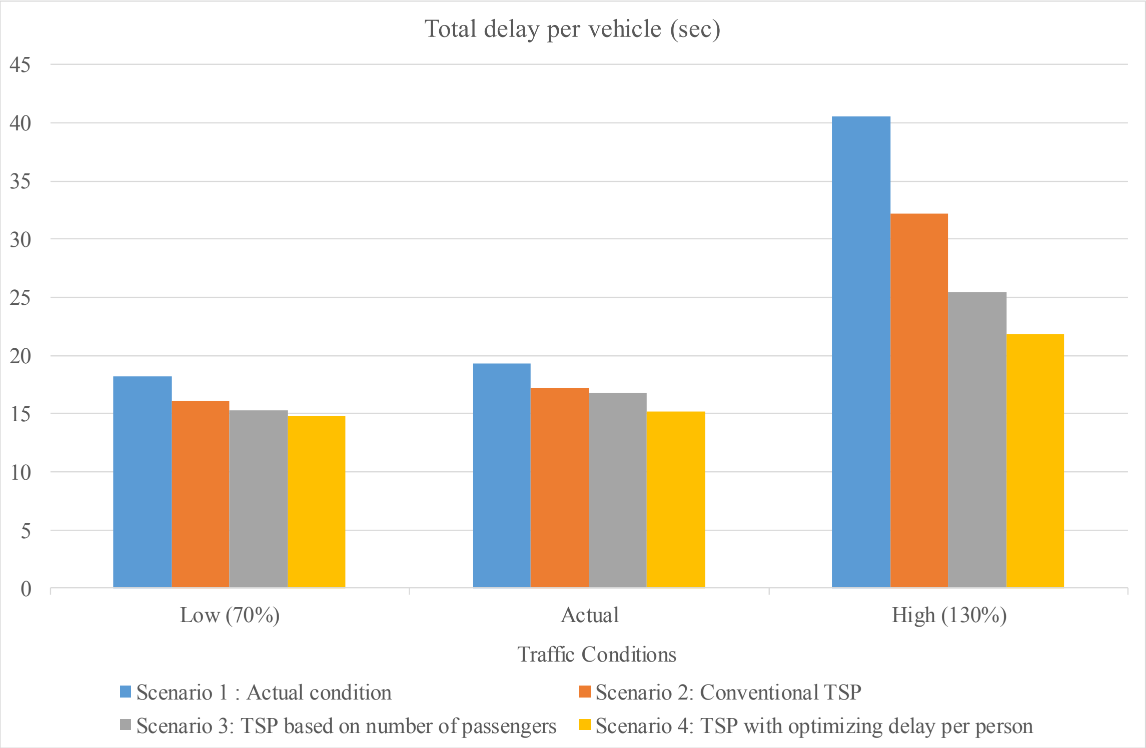

Figure 19: Total delay per vehicle for all scenarios (AM period) for St-Raymond & Moussette

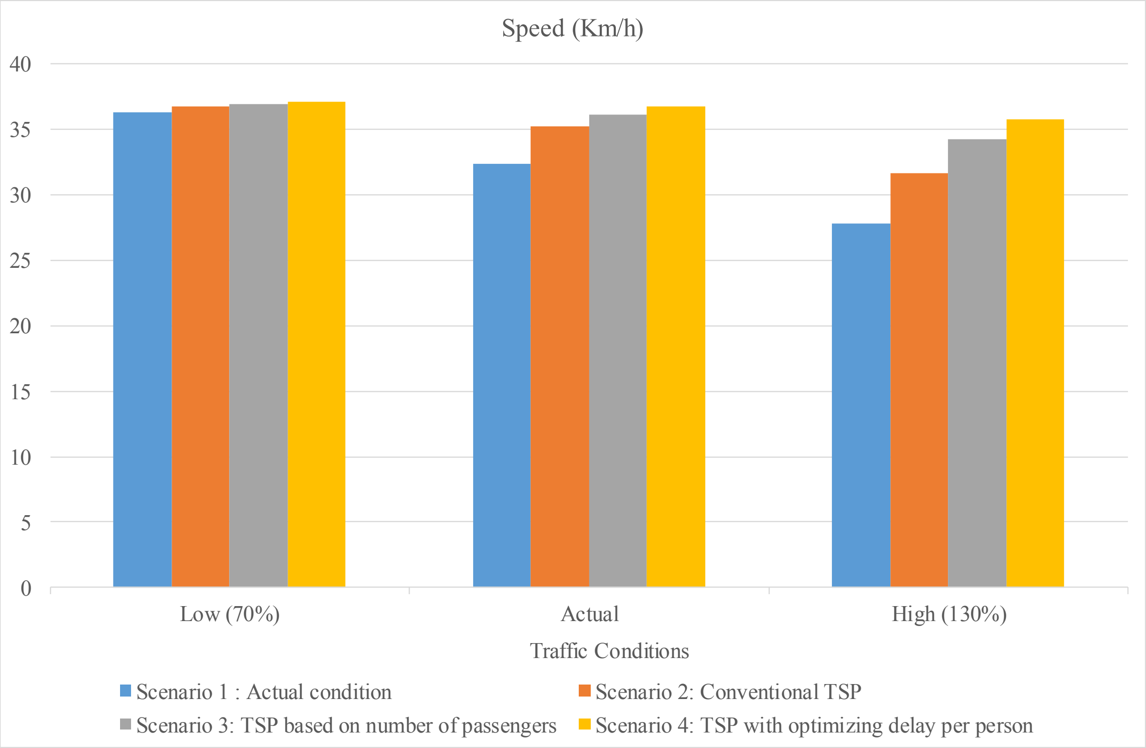

Figure 20: Speed for all scenarios (AM period) for St-Raymond & Moussette

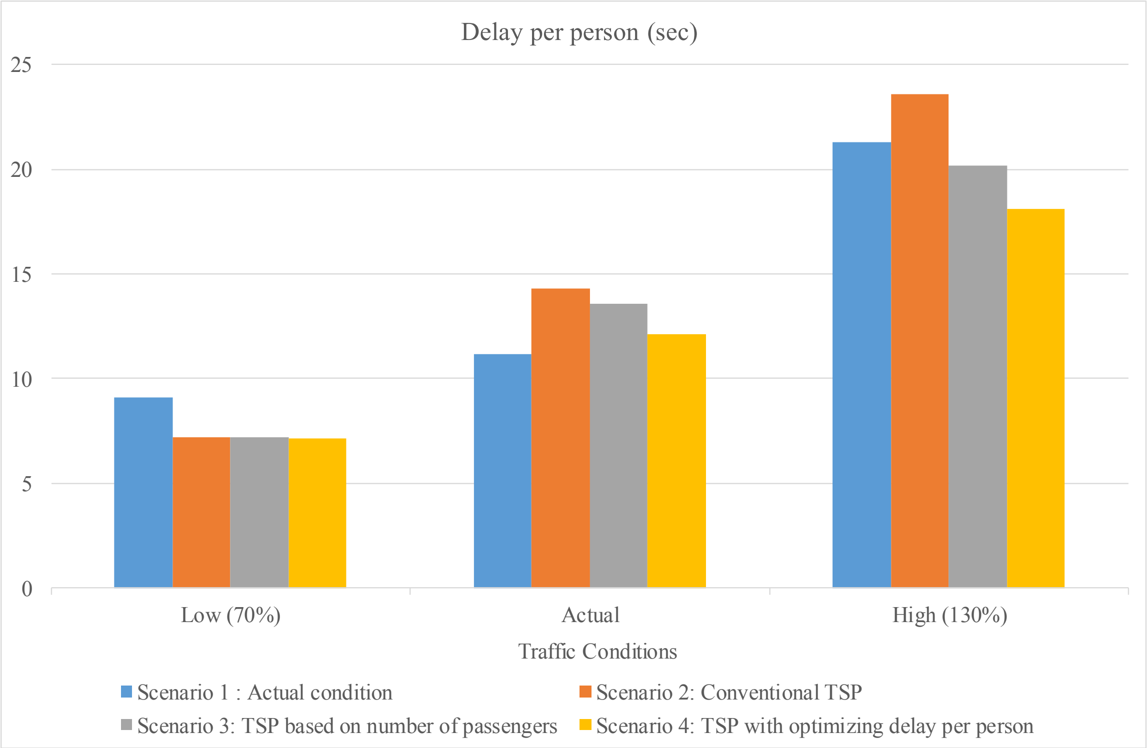

Figure 21: Delay per person (AM period) for St-Raymond & Moussette

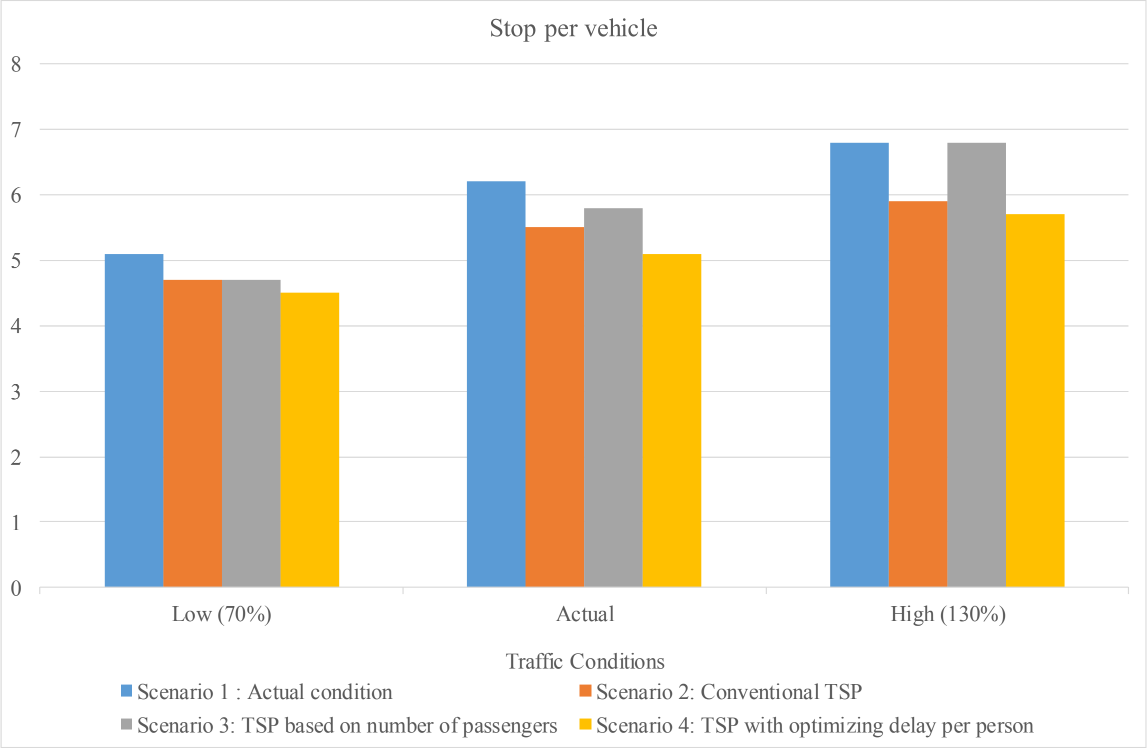

Figure 22: Stop per vehicle (AM period) for St-Raymond & Moussette

In order to assess the robustness of findings or conclusions based on primary data analysis, sensitivity analysis was carried out on the measure of effectiveness to determine whether different traffic volumes have a significant impact. Statistical analysis is done using a two-tailed test if the estimated value is greater or lower than a defined range of values, such as whether a test taker may score higher or lower than a specified range of scores. Using this method, the null hypothesis is tested, and the alternative hypothesis is accepted over the null hypothesis if the estimated value exists in the critical areas. It was hypothesized that the measures of effectiveness under different traffic conditions are similar. The alternative hypothesis was that the measures of effectiveness differ under different traffic conditions.

In this study, three MOEs from scenario 4 were evaluated: delay per person, bus travel time, and speed. Based on Levene's rejection, the t-test should be applied to the second row of each result since the MOEs did not have equal variance. According to Table 12 to Table 14, a significant 2-tailed value of less than 0.05 indicated that the null hypothesis had been rejected while the alternative hypothesis had passed.

Table 12: The results of sensitivity analysis for speed

Traffic condition		**Levene's Test**		**t-test for Equality of Means**				
		F- value	σ	T	Df	σ (2-tailed)	Mean Difference	Std.Error Difference
Low demand	Equal variances assumed	4.514	0.082	-3.15	30	0.041	-6.21	2.054
	Equal variances not assumed			-3.15	37.12	0.038	-6.21	2.054
Actual	Equal variances assumed	4.698	0.062	-2.92	30	0.022	-5.39	2.368
	Equal variances not assumed			-2.92	36.8	0.047	-5.39	2.368
High Demand	Equal variances assumed	3.928	0.076	-2.88	30	0.039	-4.12	1.487
	Equal variances not assumed			-2.92	35.8	0.045	-4.12	1.487

Table 13: The results of sensitivity analysis for Bus travel time

Traffic condition		**Levene's Test**		**t-test for Equality of Means**				
		F	Sig.	T	Df	Sig.(2tailed)	Mean Difference	Std.Error Difference
Low demand	Equal variances assumed	8.92	0.14	-12.3	400	0.021	-32.58	21.54
	Equal variances not assumed			-12.3	410	0.025	-32.58	21.54
Actual	Equal variances assumed	7.96	0.075	-15.9	400	0.019	-29.14	19.36
	Equal variances not assumed			-15.9	449	0.018	-29.14	19.36
High Demand	Equal variances assumed	9.25	0.098	-17.2	400	0.027	-28.14	17.21
	Equal variances not assumed			-17.2	510	0.032	--28.14	17.21

Table 14: The results of sensitivity analysis for Delay per person

Traffic condition		**Levene's Test**		**t-test for Equality of Means**				
		F	Sig.	T	Df	Sig.(2tailed)	Mean Difference	Std.Error Difference
Low demand	Equal variances assumed	3.21	0.081	-3.51	20	0.048	-2.54	1.02
	Equal variances not assumed			-3.51	20.7	0.023	-2.54	1.02
Actual	Equal variances assumed	2.57	0.092	-2.98	20	0.041	-3.087	1.158
	Equal variances not assumed			-2.98	28.4	0.034	-3.087	1.158
High Demand	Equal variances assumed	4.05	0.101	-3.97	20	0.038	-2.185	1.087
	Equal variances not assumed			-3.97	37.5	0.047	-2.185	1.087

Also, Table 15 to Table 19, show the difference in MOEs between the base scenario (Status quo) and all other scenarios. It is worth mentioning the negative sign means deduction, and the positive sign means an increase in the MOEs.

Table 15: The difference between Bus travel time among scenarios (compared to scenario 1) in an isolated intersection

Traffic Condition	Scenario 2 Conventional TSP	Scenario 3 Transit Unit Load-based TSP	Scenario 4 Average person delay-based TSP
Low (70%)	**-17.03%**	**-25.30%**	**-33.52%**
Status-quo	**-16.64%**	**-27.72%**	**-28.59%**
High (130%)	**-25.16%**	**-46.43%**	**-57.21%**

Table 16: The difference between total delay per vehicle among scenarios (compared to scenario 1) in an isolated intersection

Traffic Condition	Scenario 2 Conventional TSP	Scenario 3 Transit Unit Load-based TSP	Scenario 4 Average person delay-based TSP
Low (70%)	**-12.24%**	**-17.51%**	**-21.01%**
Status-quo	**-11.51%**	**-13.85%**	**-23.96%**
High (130%)	**-23.10%**	**-45.92%**	**-59.90%**

Table 17: The difference between speed among scenarios (compared to scenario 1) in an isolated intersection

Traffic Condition	Scenario 2 Conventional TSP	Scenario 3 Transit Unit Load-based TSP	Scenario 4 Average person delay-based TSP
Low (70%)	**1.37%**	**1.86%**	**2.23%**
Status-quo	**8.28%**	**10.80%**	**12.72%**
High (130%)	**13.11%**	**20.88%**	**25.16%**

Table 18: The difference between total delay per person among scenarios (compared to scenario 1) in an isolated intersection

Traffic Condition	Scenario 2 Conventional TSP	Scenario 3 Transit Unit Load-based TSP	Scenario 4 Average person delay-based TSP
Low (70%)	**-23.31%**	**-23.59%**	**-24.41%**
Status-quo	**24.31%**	**19.21%**	**8.05%**
High (130%)	**10.24%**	**-5.45%**	**-16.30%**

Table 19: The difference between stop per vehicle among scenarios (compared to scenario 1) in an isolated intersection

Traffic Condition	Scenario 2 Conventional TSP	Scenario 3 Transit Unit Load-based TSP	Scenario 4 Average person delay-based TSP
Low (70%)	**-8.16%**	**-8.16%**	**-12.50%**
Status-quo	**-11.97%**	**-6.67%**	**-19.47%**
High (130%)	**-14.17%**	**0.00%**	**-17.60%**

4.2 An Arterial Corridor

As mentioned in the previous sub-section, the proposed TSP strategies were also tested for an arterial corridor that includes signalized and unsignalized intersections, and the results are shown in Table 20 to Table 22.

Table 20 shows the results for scenario 2, using a conventional TSP, along the corridor. As a reminder, this scenario assumes that any approaching bus is given a traffic signal priority, regardless of the values of any other transit operations parameters (e.g., schedule status, passenger loading, etc.).

Table 20: MOEs for Scenario 2 (Conventional TSP) for the corridor

	Traffic Condition	Bus Travel Time (sec)	Total Delay per vehicle (sec)	Speed (km/h)	Delay Per Person (sec)	Stop per vehicle
Scenario 2	Low (70%)	617	299	15.8	26.2	17.2
	Status-quo	682	348	14.1	31.7	22.4
	High (130%)	751	420	11.2	46.5	37.9

Similar to the isolated intersection, the proposed strategy to utilize information about the transit unit load in deciding the priority signal for the approaching bus was deployed on an arterial corridor. Table 21 shows the results of these simulations under the same three levels of traffic demand.

Table 21: MOEs for Scenario 3 Transit Unit Load-based TSP) for the corridor

	Traffic Condition	Bus Travel Time (sec)	Total Delay per vehicle (sec)	Speed (km/h)	Delay Per Person (sec)	Stop per vehicle
Scenario 3	Low (70%)	382	141	14.77	19.4	12.87
	Status-quo	426	198	17.54	27.5	16.23
	High (130%)	475	251	19.7	35.24	21.87

Finally, Table 22 shows the results for the proposed TSP optimization strategy that accounts for the average delay of users on all modes travelling along the corridor.

Table 22: MOEs for Scenario 4 (Average person delay-based TSP) for the corridor

	Traffic Condition	Bus Travel Time (sec)	Total Delay per vehicle (sec)	Speed (km/h)	Delay Per Person (sec)	Stop per vehicle
Scenario 4	Low (70%)	410	160	18.2	20.7	13.1
	Status-quo	449	217	15.2	28.4	18.24
	High (130%)	510	310	14.51	37.3	24.12

Figure 23 to Figure 27 show the results graphically.

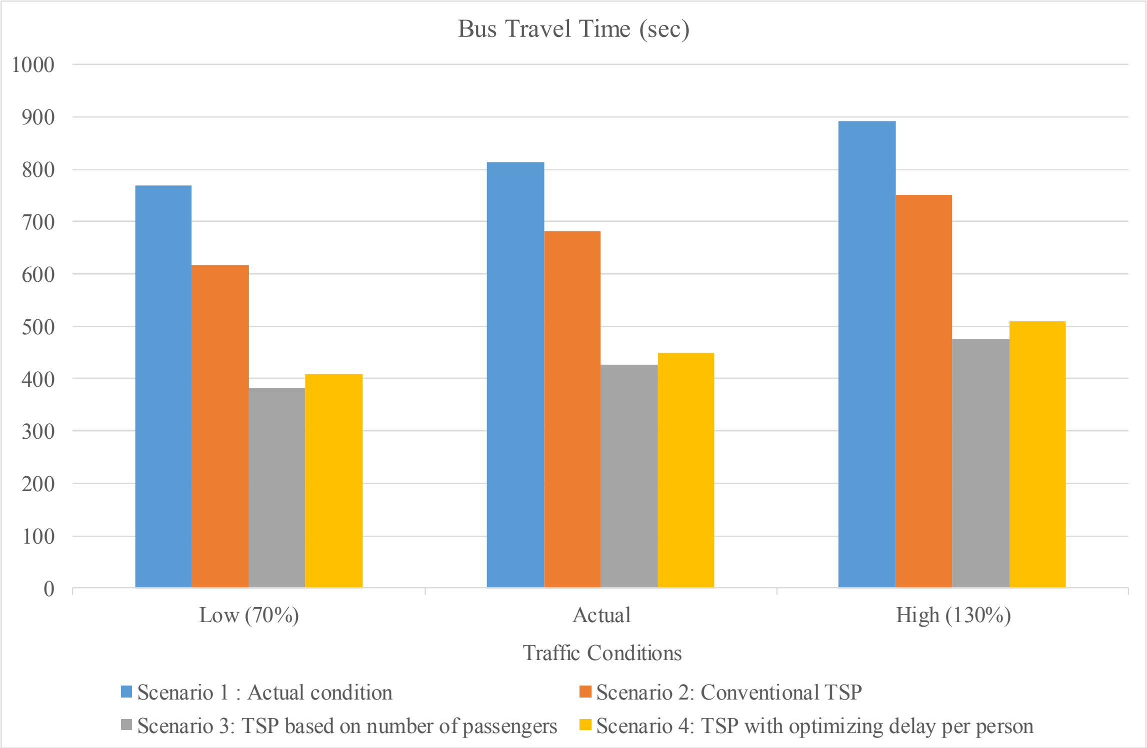

Figure 23: Bus travel time for all scenarios (AM period) for the corridor

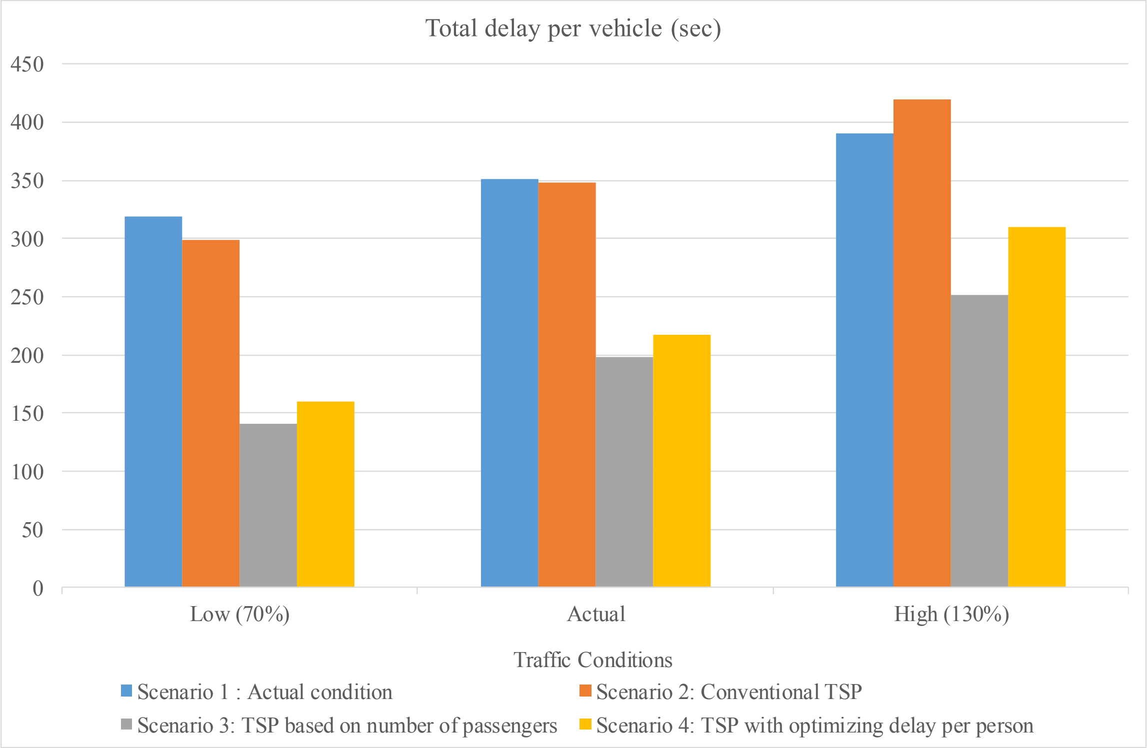

Figure 24: Total delay per vehicle for all scenarios (AM period) for the corridor

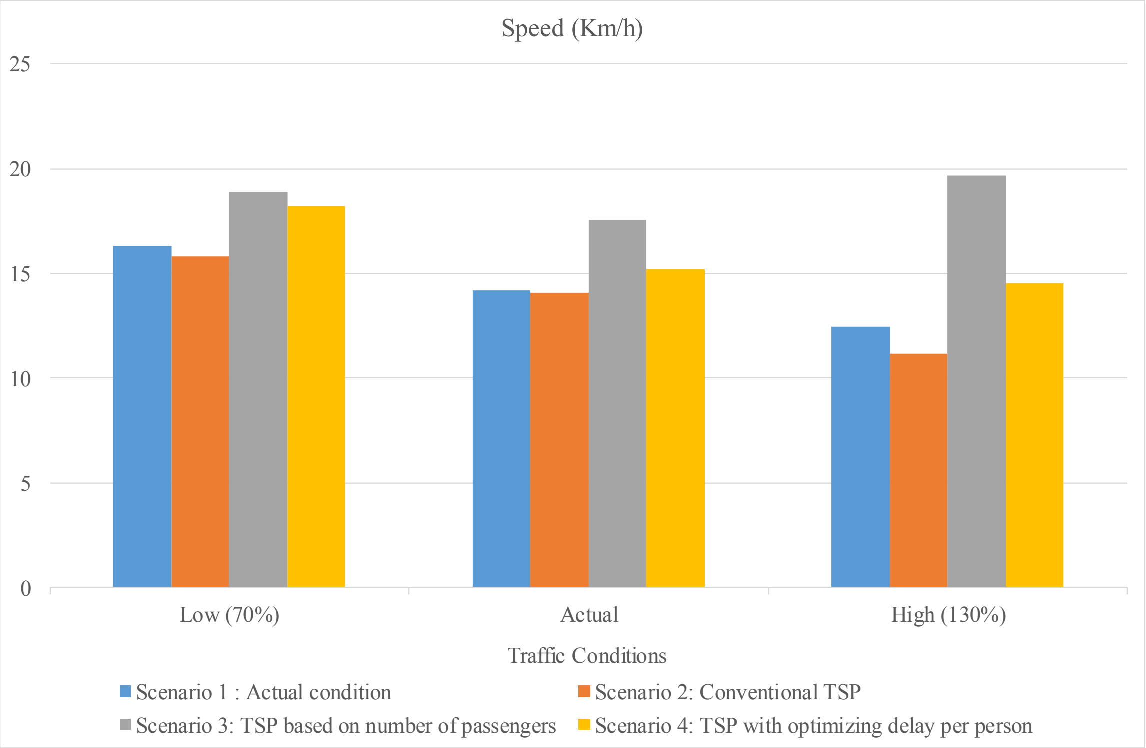

Figure 25: Speed for all scenarios (AM period) for the corridor

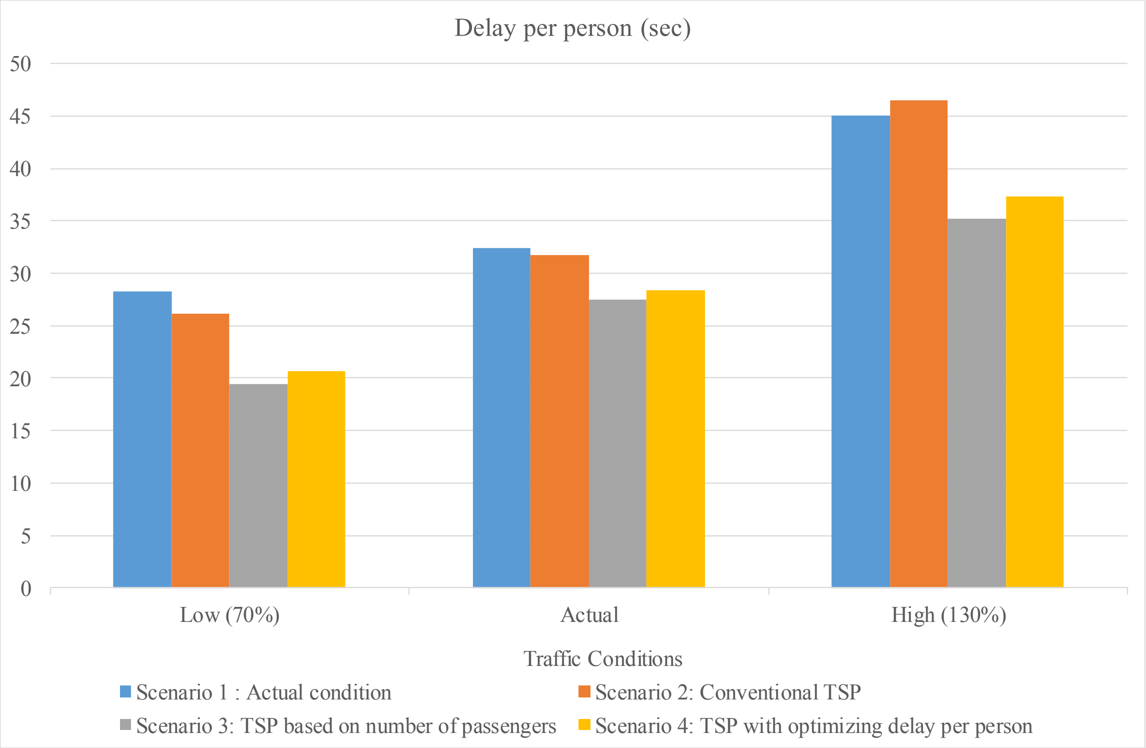

Figure 26: Delay per person (AM period) for the corridor

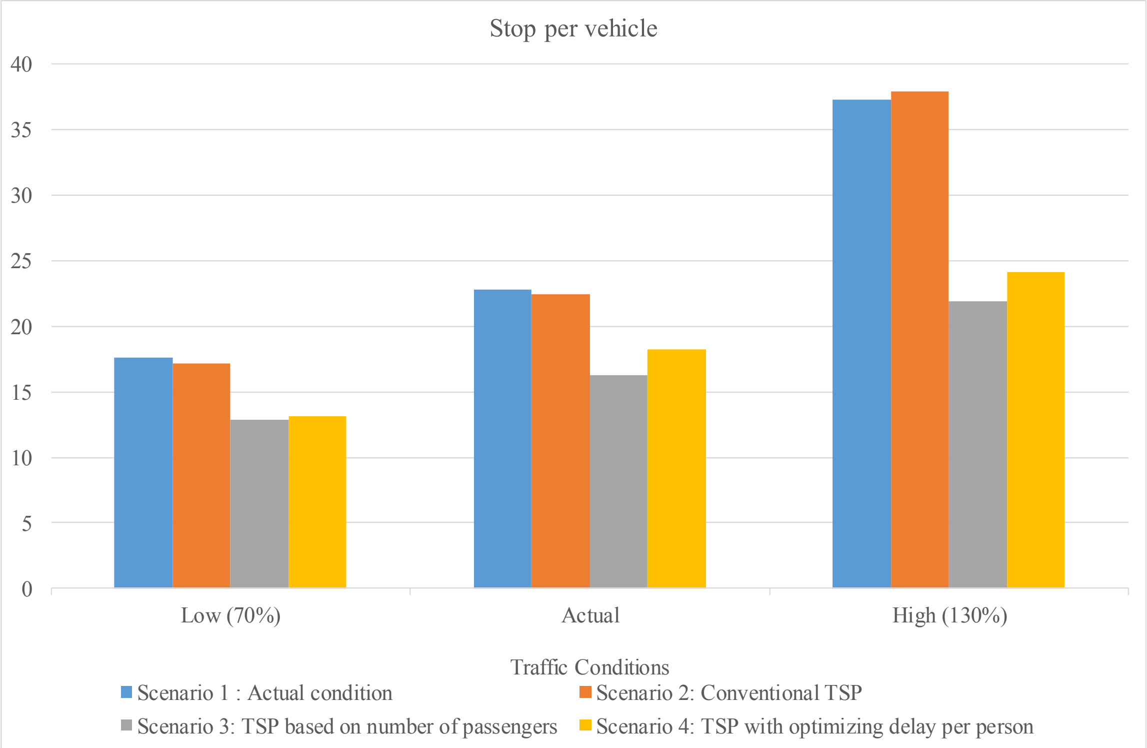

Figure 27: Stop per vehicle (AM period) for the corridor

To assess the benefits of the proposed transit operations amelioration strategies, a comparison showing the difference in the traffic indices results from VISSIM for the Status quo and all of the scenarios. , Table 23 to Table 27 show the difference between the current condition and different scenarios.

Table 23: The difference between Bus travel time among scenarios (compared to scenario 1) in the corridor

Traffic Condition	**Scenario 2** **Conventional TSP**	**Scenario 3** **Transit Unit Load-based TSP**	**Scenario 4** **Average person delay-based TSP**
Low (70%)	**-21.93%**	**-67.25%**	**-60.90%**
Status-quo	**-17.65%**	**-62.58%**	**-57.80%**
High (130%)	**-17.16%**	**-61.01%**	**-54.49%**

Table 24: The difference between total delay per vehicle among scenarios (compared to scenario 1) in the corridor

Traffic Condition	Scenario 2 Conventional TSP	Scenario 3 Transit Unit Load-based TSP	Scenario 4 Average person delay-based TSP
Low (70%)	**-6.47%**	**-77.39%**	**-66.39%**
Status-quo	**-0.86%**	**-55.74%**	**-47.18%**
High (130%)	**7.41%**	**-43.37%**	**-22.86%**

Table 25: The difference between speed among scenarios (compared to scenario 1) in the corridor

Traffic Condition	Scenario 2 Conventional TSP	Scenario 3 Transit Unit Load-based TSP	Scenario 4 Average person delay-based TSP
Low (70%)	**-3.12%**	**18.89%**	**11.01%**
Status-quo	**-0.71%**	**21.05%**	**6.80%**
High (130%)	**-10.57%**	**30.03%**	**15.28%**

Table 26: The difference between total delay per person among scenarios (compared to scenario 1) in the corridor

Traffic Condition	Scenario 2 Conventional TSP	Scenario 3 Transit Unit Load-based TSP	Scenario 4 Average person delay-based TSP
Low (70%)	**-7.71%**	**-37.32%**	**-31.02%**
Status-quo	**-2.18%**	**-16.36%**	**-13.16%**
High (130%)	**3.06%**	**-24.55%**	**-18.93%**

Table 27: The difference between stop per vehicle among scenarios (compared to scenario 1) in the corridor

Traffic Condition	Scenario 2 Conventional TSP	Scenario 3 Transit Unit Load-based TSP	Scenario 4 Average person delay-based TSP
Low (70%)	**-2.30%**	**-31.05%**	**-29.32%**
Status-quo	**-1.77%**	**-33.67%**	**-22.22%**
High (130%)	**1.60%**	**-52.15%**	**-42.92%**

According to the results of the corridor analysis, scenario 3 performed best compared to the other scenarios. For example, the bus travel time was significantly reduced compared to scenario 1. For example, it can be seen that the transit unit load TSP strategy led to the largest improvement in travel time. As such, Table 23 shows a reduction in bus travel time of 67% for low traffic demand and 61% for high-traffic demand, respectively

The total delay per person decreased in all traffic conditions in scenario 3. For example, this value dropped by 78 percent under the low traffic condition, whereas under the high traffic condition, this value fell by 43 percent. Similarly, if this novel TSP strategy is applied to the current traffic demand a travel time reduction of 55% is expected.

As shown in the obtained results, scenario 3 performed better in congested traffic conditions, with the person's delays decreasing by 45 percent in comparison to scenario 1.

Moreover, in comparison with scenario 1, scenario 3 for low traffic showed a 37 percent decrease in the delay per person. In normal traffic conditions, the delay per person decreased by 16 percent, while in congested traffic conditions, it decreased by 25 percent. According to these results, if traffic demand is high, more cars are on the network, and the delays along the corridors are divided by the number of passengers using both private and public transportation. For the stop per vehicle, as the results indicate, both scenario 4 and scenario 3 performed better in high traffic conditions. For scenario 3, the decrease was 52 percent compared to scenario 1, while for scenario 4, it was 43 percent. Nevertheless, in scenario 3, the decrease was 31 percent in low traffic demand, whereas in scenario 4, it was 22 percent.

CHAPTER 5
SUMMARY AND FINDINGS

Throughout history, public transit has played a critical role in shaping Canadian communities and the way that its inhabitants move about. As with other countries around the world, the evolution of public transportation in Canada has been a long and difficult journey, with both public and private agencies continuing to strive to provide a safe, affordable, accessible, and competitive system that can thrive in today's automobile-dominated era. The importance of public transit in a city is not only due to the fact that it is a crucial means of providing equity among citizens, but it has a significant impact on the economic development of the community by facilitating employment, business activity, and property values, which are all great economic benefits.

It goes uncontested that public transit vehicles using the same roadway infrastructure as passenger cars provide a significantly bigger passenger throughput. It is well known that public transit improves urban mobility and reduces congestion. However, as the need for the public transportation system increase, there remains a limited amount of roadway infrastructure and other facilities available. In view of this, public transportation agencies wish to prioritize the movement of buses and other forms of public transportation. With this strategy, bus delays can be reduced, and service reliability can be increased without needing any modifications to the infrastructure of the buses.

It is important to keep in mind that buses, one of the most common vehicles in use for transit service, are constantly competing for quality of service and, more specifically, reliability, which is a major factor in the popularity of buses and transit in general. The transit system has always had to compete with other modes of transportation, such as cars, to improve its service quality and reliability. On the other hand, cars provide better accessibility, are often faster, and are seen are more convenient modes of transportation than transit. In addition to reducing the number of per-person delays at intersections, TSPs can also improve the travel time of many road users by decreasing the number of per-person delays at intersections. In contrast to preemption, which is used for emergency vehicles that cause interference with the normal process of signal operation, TSPs modify the normal process of signal operation to better accommodate transit vehicle operations.

By considering the delays experienced by passengers on the crossing street and also by minimizing a person’s delay in an intersection, this dissertation is intended to develop two different conditional priority systems for public transit. It has been established the conventional TSP provides priority even when the bus is empty, resulting in unnecessary delays at the intersection. It has been shown that the conditional priority developed in this research reduces excessive delays resulting from crossing street traffic, and buses provide early green or red truncation according to both number of passengers on board and adherence to the schedule.

This dissertation begins with a review of the available literature to identify gaps in existing practices on transit priority strategies. Following the review of TSP logic, performance metrics, design and optimization strategies, further research gaps were identified. A performance measure that simultaneously reflected the value and reliability of bus and car travel times was identified as one of the identified gaps that required improvement on the existing logic of the TSP. Developing efficient methods for analyzing and designing priority schemes was also necessary, along with integrating TSP with the intersection in micro-level analysis. In accordance with the literature available, the main gap was that all of the approaches were not considered, which resulted in a delay in the minor approach based on the available literature. In many studies, the focus was also limited to minimizing the delays of people who use public transportation.

There are two novel methodologies proposed in this dissertation to address the aforementioned gap. In the first proposed methodology, the bus is given priority only if it meets certain criteria. Those requirements include adhering to the schedule and the number of passengers on board. As part of this method, the number of passengers waiting at the next bus stop is also taken into consideration to reduce delays. Also, an introduction to TSP logic followed by validation of a set of V2I-based logic was also developed to reduce person delays and increase public transit efficiency.

In the second proposed methodology, the goal of logic was to minimize a person's delay in each intersection. This methodology takes into account all transportation users (both public and private). A bus is only given priority if a certain number of passengers are present to optimize the person's delay in the intersection.

In order to evaluate the efficiency of the proposed methodologies, four scenarios were developed, namely status quo (scenario 1), conventional TSP (scenario 2), transit unit load-based TSP (scenario 3) and average person's delay-based TSP (scenario 4).

Subsequently, this dissertation presents a detailed discussion of the calibration method was provided. The number of runs and parameters for calibration and validation were presented. For calibration purposes, a statistical test was conducted to determine which driving behaviours are most relevant for this simulation model. As a result of the test, the desired speed distribution and minimum gap time were the most important parameters that affected the results. As a result of the available field data, the model was fine-tuned using the PSO algorithm, and the calibration was validated using GEH criteria.

Based on simulation-based approaches, these scenarios were developed to assess the performance of the aforementioned methodologies. This is why simulation-based methods are based on disaggregated vehicle data and can reflect changes in travel times, speed, delays per person, and overall delays. Simulation-based tools for evaluating transit priority were used.

This dissertation focused both on major arterial roads and minor arterial roads, whereas the majority of the publications only addressed the major arterial approach. As part of this research, the bus schedule was also taken into consideration, whereas in other studies, the measure of giving priority was only the approach to the intersection.

Moreover, this dissertation considered all motorized vehicles as shown in the fourth strategy, and the algorithm optimized the delay for both minor and major approaches for the both transit units and private vehicles passengers. In addition, proposed strategies, namely Transit Unit Load-based TSP and Average Person Delay-Based TSP were evaluated in three different traffic regimes, such as undersaturated, saturated, and oversaturated traffic conditions. Moreover, in the forth strategy (Average Person Delay-Based TSP) , different arrival types and residual queues were examined for each intersection. In addition, the proposed methodologies were evaluated on a single intersection as well as a corridor containing 12 intersections. In addition, considering the level of confidence and standard deviation of the mean of each MOE, the necessary number of runs in VISSIM was calculated. The results indicate that each scenario should be replicated 55 times with different seed numbers within VISSIM.

Three different traffic conditions have been evaluated in order to determine how congestion affects the efficiency of the proposed methods. The existing traffic volume as a normal condition, the high traffic demand (130% of the existing volume) and the low traffic demand (70% of the existing conditions).

Additionally, all of the developed scenarios were applied both to an isolated intersection and to a 4.4 km long corridor with six signalized and six unsignalized intersections in order to assess the effectiveness of the proposed methods.

Compared to the base and conventional TSP systems, both proposed methodologies were generally better performing. The average person's delay-based strategy (scenario 4), however, performed better at an isolated intersection, while the Transit unit load-based strategy (scenario 3) improved the measure of effectiveness along the corridor better.

In the case of isolated intersections, scenario 4 improved bus travel time, total delay per vehicle, and speed. Although this scenario improved all of the MOEs in all traffic conditions, it was remarkable in congested traffic. For example, the proposed methodology decreased the bus travel time by 22% in high traffic demand. Furthermore, compared to conventional TSP, the proposed methodology reduced the bus travel time by 33% in heavy traffic demand. As a result of scenario 4, intersections were optimized as isolated intersections with different characteristics, such as arrival rate, residual queue, and saturation rate flow.

Additionally, scenario 3 did better along the corridor. As an example, the transit unit load-based TSP reduced total delays per vehicle by 61 percent in low traffic demand and 46 percent in normal traffic demand. With this methodology, the stop per vehicle index, which is related to emissions and the environment, was reduced by 44 percent for heavy traffic demand and 27 percent for low traffic demand, as compared to the conventional TSP day. Also, along the corridor, this methodology improved the speed along the corridor in high traffic demand by 25 percent, compared to the conventional TSP. The reason for this is that this scenario also takes into account the number of passengers awaiting downstream the intersection and the fact that a bus that is on time is not given priority. In light traffic conditions, this scenario had a higher impact on improving bus travel time, total delays per vehicle, and per person. As a result of this scenario, speed and stop per vehicle were improved, given the high demand traffic situation

For improving the traffic indices in a network, this dissertation proposes two different methods (one based on the transit load unit and another based on minimizing the average person's delay at intersections). The proposed methods in this dissertation were proven to significantly improve the traffic MOEs for both intersections and corridors. As a result, public transit will become more reliable and attract more passengers, as opposed to individuals driving their own vehicles.

5.1 Limitations

Since this study focused solely on the effects of TSPs on vehicular traffic, some factors were not taken into account. For example, in this dissertation, the effect of the proposed methodologies on intersection safety was not evaluated. The change of split in each cycle may be confusing to the driver and affect their safety. However, this effect was not considered.

Based on the availability of real-time information about traffic conditions, transit vehicle arrivals, and passenger occupancy, the methodologies based on the number of passengers are proposed. To provide the necessary information, surveillance and communication technologies are currently deployed in urban networks throughout the world. As a result of malfunctioning communication systems in the buses or the unavailability of passenger data, the proposed methodologies may not work as expected.

Also, the proposed methodologies did not consider the effect of conflicting TSP requests (a situation that two or more buses (from one or more directions) approaching an intersection and sending priority requests) at the intersections of the TSP systems. This is an effect that should be investigated in future research studies.

The study focused primarily on motorized vehicles without considering other non-motorized transportation, such as pedestrians and cyclists.

In addition, the benefit-cost ratio of the proposed methodologies has not been evaluated. The system requires modern technology such as automated controllers for intersections and buses.

Moreover, this dissertation assumes that the saturation flow (i.e., capacity) of a link remains constant regardless of the interactions between multiple modes of transportation, which may not be realistic in many cases.

5.2 Future research

Several areas of future research can be suggested to expand this work as it has provided a detailed methodology for modelling, evaluating, and designing priority schemes in a network.

This dissertation provides a detailed methodology for modelling, evaluating, and designing priority schemes. In the future, future research can be directed at improving the performance of V2I treatments. First and foremost, connected vehicle technology will provide a better estimate of traffic state and arrival times. Additionally, this method can be extended to consider other parameters, such as the speed at which a bus travels and the potential savings. Also, the developed integrated V2I-TSP treatment can be extended to improve service performance measures such as service variability with marginal negative impacts on non-prioritized approaches and improve service performance measures like service variability. Finally, the developed method only focused on the portion of total bus fuel consumption at the intersections. To minimize fuel consumption throughout a route, the methods can be scaled down to the level of corridors or a small grid network. The models can also be extended further and include additional costs and benefits into the model to further enhance these measures. Research on the impact of transit priority schemes on urban texture and safety indexes can be up-and-coming. Moreover, a detailed analysis of the actual project costs and benefits can be used to determine the appropriate weighting parameters for the objective functions that have been developed. By implementing passenger-oriented reliability metrics, transit services can be managed from planning to operating in a paradigm shift.

When service providers introduce incentives based on passenger reliability metrics (instead of vehicle performance metrics), they will have a better opportunity to focus on remedies such as preferential treatment, rescheduling of services, and coordination of transfer points where and when they are most needed in terms of their impacts on passengers. In addition to being able to steer operations toward passengers' experiences, real-time monitoring of passenger reliability can be beneficial. It will be possible to differentiate between journey components and account for their contribution to the overall passenger experience by analyzing their perception of reliability as a result of the research into passengers' perceptions of service reliability, which will allow us to distinguish between journey components. Further research will enable the strategy to produce improved reports and visualizations in the future and improve future reports and visualizations. It is possible to analyze performance evolution and compare them with peers by comparing different networks and transit services based on past performance and benchmarking with peers. This will allow one to compare their performance to the performance of their peer networks. Future research may improve the framework's implementation. For example, a reduction in the computational cost of the evaluation model to optimize and tune the simulation parameters could be one of the future research directions.

The proposed models can be further improved to accurately estimate TSP effectiveness in various conditions, such as varying transit facility characteristics. A generalized function reflecting the effects of TSP on service variability can be proposed by considering the effects of TSP on service variability. A comprehensive survey of parameters for different cases is the next step to expand this study. Finally, real-time data from different TSPs and TPL applications can provide more realistic adjustment factors for different network layouts. Since the computational cost of performing network-wide optimization processes was a major concern of the developed models, improving the performance of the process can provide the opportunity to test larger networks since the computational cost is reduced. It is recommended to create an independent simulation-based core model to enhance the capabilities of both simulation-based and analytical tools. The performance of the search algorithms can also be further improved by examining other metaheuristics and optimization techniques. It is also possible to further investigate the effects of the proposed methodology on the urban network by using macrosimulation to see the effects of the proposed TSP on the network.

Furthermore, conflicting requests could be considered in the proposed methodologies to determine their effectiveness for the simulated case studies. Similarly, future studies could assess the impact of the proposed TSP approaches on non-motorized transportation modes.

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