A study on traffic signal patterns and performance measures accounting for pedestrian and vehicle flows

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Farzaneh Montazeri

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THIS THESIS HAS BEEN EVALUATED

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Mr. Fausto Errico, Thesis supervisor
Département de génie de la construction, École de technologie supérieure

Mr. Luc Pellecuer, Thesis Co-Supervisor
Faculty of Environment Technology, University of the West of England

Ms. Annie Levasseur, Chair, Board of Examiners
Département de génie de la construction, École de technologie supérieure

Mr. Gabriel Assaf, External Examiner
Département de génie de la construction, École de technologie supérieure

THIS THESIS WAS PRESENTED AND DEFENDED

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Une étude sur les modèles de feux de circulation et les mesures de performance tenant compte des flux de piétons et de véhicules

Farzaneh Montazeri

RÉSUMÉ

Les systèmes de contrôle de la circulation sont cruciaux pour gérer les flux de circulation. Leur fonction principale est de réduire les conflits entre utilisateurs pour des raisons de sécurité tout en minimisant les temps de voyage. L'optimisation du cycle des feux de circulation concerne principalement la détermination de la longueur du cycle et de la configuration des phases composant le cycle. Les chercheurs se concentrent souvent sur la durée du cycle, dont l'impact sur les temps de déplacement est directement mesurable. Cependant, la configuration des phases composant le cycle présente également un grand potentiel de réduction des temps de trajet et du nombre de situations accidentogènes. Ce potentiel doit encore être étudié en profondeur.

Dans ce travail, nous nous intéressons à la comparaison de différents cycles en termes de nombre de conflits potentiels et de retard pour les conducteurs et les piétons. À cette fin, nous sélectionnons d'abord trois types de cycles couramment utilisés, à savoir le phasage exclusif (EPP – Exclusive Pedestrian Phase), le phase protégé (LTI - Leading Through Interval) et le phasage concurrent (TWC - Two-Way Crossing). Nous généralisons ensuite les méthodes existantes pour mesurer le retard et la sécurité de l'utilisateur pour ces trois modèles de feux. De plus, nous étudions un cycle hybride hypothétique obtenu en adaptant dynamiquement le cycle aux données de circulation en temps réel.

La méthodologie proposée est appliquée à l'étude d'un carrefour isolé à Montréal, Canada. Nous effectuons des simulations visant à déterminer le meilleur cycle en fonction d'indicateurs de performance ad hoc et des flux d'utilisateurs.

Les résultats montrent que les cycle EPP et LTI fonctionnent généralement mieux que TWC. EPP surpasse LTI lorsqu'il s'agit de mesurer le nombre de conflits potentiels, tandis que LTI surpasse EPP lorsqu'il s'agit de prendre en compte les délais. De plus, le cycle hybride hypothétique a un impact positif mais globalement limité.

Mots-clés: Feux de circulations,piétons, Sécurité, Temps de retard

A study on traffic signal patterns and performance measures accounting for pedestrian and vehicle flows

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ABSTRACT

Traffic control systems are crucial for managing traffic flows. Their main function is to reduce interactions among users for safety reasons while minimizing travel times. Traffic signal control optimization is primarily concerned with determining the cycle length and the signal pattern. Researchers often concentrate on the cycle length, whose impact on travel times is directly measurable. However, the choice of signal pattern may also have a great potential to reduce travel times and unsafe situations. This potential is yet to be thoroughly investigated. In this work, we are interested in comparing different signal patterns in terms of the number of potential conflicts and delay time for both drivers and pedestrians. To this end, we first select three commonly adopted signal patterns, namely the Exclusive Pedestrian Phase (EPP), the Leading Through Interval (LTI), and the Two-Way Crossing (TWC). We then generalize existing methods for measuring user delay and safety for these three signal patterns. Moreover, we investigate a hypothetical hybrid pattern obtained by dynamically adapting the signal pattern to real-time data. The proposed methodology is applied to a case study considering an isolated intersection in Montreal, Canada. We perform computational experiments geared towards determining the best pattern according to ad hoc performance indicators and user flows. Results show that the EPP and LTI patterns generally perform better than TWC. EPP outperforms LTI when measuring the number of potential conflicts, while LTI outperforms EPP when considering delay times. Furthermore, the hypothetical hybrid pattern shows a positive but overall limited impact.

Keywords: Traffic signal optimization, pedestrian, delay time, safety, Exclusive Pedestrian Phase (EPP), Leading Through Interval (LTI), Two-Way Crossing (TWC), hybrid signal pattern

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LIST OF ABBREVIATIONS

ETS	École de Technologie Supérieure
EPP	Exclusive Pedestrian Plan
LPI	Leading Pedestrian Interval
LTI	Leading Through Interval
LPI	Leading/lagging Pedestrian Interval
HCM	Highway Capacity Manual
NTOC	National Transportation Operation Coalition
SO_X	Sulfur Oxides
NO_X	Nitrogen Oxides
VOCs	Volatile Organic Compounds
CO_2	Carbon Dioxide
PM2.5	Fine Particulate matter
HSL	Herbert S. Levinson
v2p	Vehicle to Pedestrian
v2v	Vehicle to vehicle
Ds	Delay and Safety index
PC	Potential Conflict
LOS	Level Of Service
ATCS	Adaptive Traffic Control System

P	Signal Pattern
H	Hybrid Pattern

LIST OF SYMBOLS AND UNITS OF MEASUREMENTS

i	Set of arms and corresponding corners at an intersection
g_i^{veh}	Duration of green for vehicles from arm i
g_i^{ped}	Duration of green for pedestrian crossing the arm i
l_{ij_i}	Length of the crosswalk from corner i to corner j_i
s^{ped}	The average walking speed of pedestrians
α_{ik_i}	The portion of pedestrian volume from corner i to corner k_i in total pedestrian demand of corner i
t	Acceptable gap
μ_i	The flow rate of turning vehicles on the corner i
C	Cycle length
d^{ped}	Pedestrian delay at intersection
d^{sig}	Pedestrian delay due to traffic signal at the crosswalk
d^{con}	Pedestrian delay due to conflicts with turning vehicles
d^{det}	Pedestrian delay due to detour distance
v_i^{lt}	Number of left-turning vehicles on approach i during the green interval of g_q
v_i^{ot}	Number of vehicles moving in the opposite direction on approach i during the green interval of g_u
p_i^{pc}	Probability of potential left-turn conflict on approach i
v^{ped}	Pedestrian flow rate in the subject crossing (walking in both directions)
g^{ped}	Pedestrian service time

g^{veh}	vehicle service time
g^{q}	Amount of the permitted green time that is not blocked by an opposing lane
occ^{l}	Relevant conflict zone occupancy for conflicts between permitted or protected left-turning vehicles and pedestrians
v^{o}	Opposing demand flow rate
g^{pl}	Effective green time for permitted left-turn operation
t^{c}	Critical gap
V^{veh}	The total vehicle volume
V^{ped}	The total pedestrian volume
pc^{v2v}	The total expected number of vehicles with potential conflicts
pc^{v2p}	The total expected number of vehicles with potential conflicts
pc_i^{lt}	The number of left-turning vehicles with potential conflicts on approach i
pc_i^{ot}	The potential conflicts of opposing vehicles resulting from left-turn on approach i
occ^{ped-g}	The pedestrian occupancy
occ^{r}	The relevant conflict zone occupancy for conflicts between right-turning vehicles and pedestrians
g^{f}	The part of green time (g) before the first turning vehicle arrives at the intersection
g^{o}	The part of the green time while left turning vehicles stop to opposite through queue of vehicles get clear

g^u	The portion of green time that there is no potential conflict between left turning and through vehicles
v^{ped-g}	Pedestrian flow rate during the pedestrian service time
occ^{ped-u}	Pedestrian occupancy when the opposing queue is clear

INTRODUCTION

The current development of the transportation system intends to have a positive effect on travel time, safety, and environmental emissions while they provide highway, rail, air, water, transit, pipeline, freight movement, and personal mobility. How to balance this development to provide the best trade-off between these impacts is a crucial question in today's researchers' discussions. The urban transportation system includes three general components: infrastructure (roads, intersections, and bridges), users (vehicles, pedestrians, bicycles, and drivers), and operation tools (signs, traffic signals, management, and control systems). Intersections are significant components of urban transportation infrastructures since they cause interactions between different users. This interaction directly affects travel time and safety at the intersection.

The main components of an intersection related to traffic management are control tools (hardware and software), geometry, and users that determine the traffic characteristics of the intersection (such as delay time, capacity, and level of service). The development and enhancement of control tools can improve the performance of the intersection.

Traffic signal control features different approaches in terms of methods, technologies (hardware and software), and objectives to regulate traffic flows in urban areas. (Li, Alhajyaseen & Nakamura, 2010). The traffic signal's most common objectives are to maximize vehicle throughput and intersection safety while minimizing travel time. The inability of the traffic signal to respond to current traffic flows can cause congestion at an intersection.

Traffic signal control is a complex process since it involves many interrelated factors such as safety, capacity, delay time, queue length, intersection geometries, heterogeneous users, and uncertain environmental conditions. Two main features of the traffic signal operation are the cycle length (the time a traffic signal requires to complete the sequence of signal phases) and signal pattern (the set of user movements allowed at each phase of the signal cycle). Most traffic agencies are nowadays interested in the concept of an adaptive control system that applies real-time traffic data to operate dynamic modifications of the cycle length and phase sequences (Transportation Research Board, 2016). Moreover, connected vehicle technologies, such as mobile data platforms enabling real-time data exchange among vehicles and between vehicles and infrastructure, facilitate the employment of adaptive traffic control systems to respond to real-time traffic data (Jing, Huang & Chen, 2017).

In the literature, only simple forms of traffic signal phase sequences and patterns have been studied (such as a two-phase traffic signal). Even those researchers who simulated optimal cycle length models for different signal patterns (Ishaque & Noland, 2007; Li & Sun, 2019a; Zhang & Su, 2018) have simplified the intersection conditions by assuming a fixed traffic flow or one-way streets (Ma, Liao, Liu & Lo, 2015; Zhang & Su, 2018), while, in the real world, traffic flow or intersection movements are complex. Similarly, one specific signal pattern is typically applied for the whole day while traffic flows largely change during the day, with a potential increase of delay time and travel times at the intersection (Zhang & Su, 2018).

Traffic signal control optimization is mainly geared towards optimizing the cycle length and improving other dependent measures, such as traffic capacity, travel time, system throughput, vehicle-to-vehicle conflict, and vehicle emissions which mainly quantify vehicle-related performances (Stevanovic, Stevanovic, So & Ostojic, 2015; Jia, Lin, Luo, Li & Miao, 2019; Builenko, Pakhomova & Pakhomov, 2018; Chen, Osorio & Santos, 2019; Li, Shahidehpour, Bahramirad & Khodaei, 2017; Li & Sun, 2019a). Some researchers have also studied pedestrian-related performance indicators (Wong & Wong, 2003; Ishaque & Noland, 2007; Builenko *et al.*, 2018). However, they have not explicitly considered interactions between pedestrians and vehicles.

Urban transportation management systems aim to control and improve the quality of travel experience for motorized and non-motorized users. However, due to the fact that collecting real-time pedestrian data is costly or time-consuming (Transportation Research Board, 2016), even Intelligent Transportation Services (ITS) tools such as an adaptive traffic control system are mostly overlooked the non-motorized users. This issue can affect pedestrian travel time, or increasing pedestrian disobedience will reduce intersection safety.

The most common signal patterns that explicitly consider interactions between motorized and non-motorized users are the two-way crossing phase (TWC), exclusive pedestrian plan (EPP), leading pedestrian interval (LPI), and leading through interval (LTI).

In the literature, a trade-off between safety and delay (the difference in travel times through the intersection with and without conflicting movement) has been considered to measure each signal pattern's efficiency (Ma *et al.*, 2015). Generally, to investigate intersection safety, the literature considered as a measure of the number of accidents or predicted crash data (Alavi, Charlton & Newstead, 2013; Torbic *et al.*, 2010; Sayed & Zein, 1999; Li, Yan, Li & Wang, 2012; Frankish, Green, Ratner, Chomik & Larsen, 2001); also, to estimate the intersection delay, several researchers have used Highway Capacity Manual (HCM) delay model. However, their delay and safety models usually fail to consider the effect of signal patterns or pedestrian data.

This research aims to improve traffic safety and decrease traffic delays at urban intersections by allowing traffic signals to dynamically control pedestrians and vehicles.

The rest of the study is organized as follows. Chapter 1 reviews the literature to identify the relevant signal patterns and performance indicator models. Chapter 3 reports the scientific manuscript that has been recently published in the journal *Sustainability*, where we develop pedestrian-sensitive performance indicators and generate the delay and potential conflict models for each signal pattern of the study. Then, an experimental setting is applied to a case study for a specific intersection in Montreal, to verify the hybrid signal pattern's impact on the level of service at the intersection. Finally, the research is concluded in the last section.

CHAPTER 1

LITERATURE REVIEW

1.1 Introduction

This part of the study identifies the traffic characteristic parameters and performance indicators related to current research and investigates how the literature deals with these performances. It also describes a variety of signal patterns and their performances. Finally, it investigates how the literature compares performance indicators of signal patterns. The current development of the transportation system intends to have a positive effect on time (such as travel time), safety (such as crash frequency and intensity), and environmental impact (such as emissions). At the same time, they provide highway, rail, air, water, transit, pipeline, freight movement, and personal mobility. Combining this development to provide the best trade-off between these impacts is crucial in today's researchers' discussions. Most transportation research has focused on safety, travel time, and air pollutants as primary objectives.

Transportation Research Board (2016) defines the traffic condition, roadway condition, and signalization condition to perform the significant parameter and performances to analyze the intersection level of service. Traffic conditions include volumes on each approach, the distribution of vehicles by movement (left, through, and right), the vehicle type distribution within each movement, the location and use of bus stops within the intersection area, pedestrian crossing flows, and parking movements on approaches to the intersection. Roadway conditions include the basic geometric of the intersection, including the number and width of lanes, grades, and lane use allocations (including parking lanes). Signalization conditions include a full definition of the signal phasing, timing, and type of control, and an evaluation of signal progression for each lane group.

According to the National Transportation Operations Coalition (NTOC) (2012), delay time at a traffic signal is estimated to amount to 295 million vehicles-hour or 10 percent of all traffic waiting time. This amount of lost time causes an increase in social costs and adversely affects emissions and road safety. The 2011 Urban Mobility Report studied the effect of traffic signal coordination on reduced travel time and this report leads to the idea of improving travel time by optimizing the traffic signal plan. (National Transportation Operations Coalition, 2012)

The emissions of air pollutants such as SO_X (Sulfur oxides), NO_X (nitrogen oxides), $VOCs$ (volatile organic compounds), CO_2 (carbon dioxide), and $PM2.5$ (fine particulate matter) that are produced by vehicles are major contributors to climate change and air pollution. Li & Shimamoto (2011) investigates the direct relation between waiting time at traffic signals and emissions produced by vehicles.

La Société de l'assurance automobile du Québec in 2015 reported 55% of accidents with at least one pedestrian victim occurring at intersections (less than 5 meters from an intersection), which is due to the frequent interaction of pedestrians and motorists at these locations (Société de l'assurance automobile du Québec, 2017).

In urban transportation, the intersection is a significant part of the infrastructure and the performance and efficiency of this part are directly related to transportation missions (saving time, increasing safety, and decreasing emissions).

The development and enhancement of controlling tools such as traffic signals can improve the performance of the intersection, while the modification of some other components is generally not possible or costly and time-consuming. For example, it is not easy to change the driver's behavior at the intersection. Similarly, changing the intersection geometry to prevent an unsafe situation is very costly.

The traffic signal controls the movements by considering the user's travel time and safety to increase the efficiency of the intersection. There are some performance measures that we've known as traffic characteristics that help us to measure the level of safety and service at the intersection. Some critical parameters in traffic characteristics fields for measuring the safety and efficiency of intersections are capacity, delay time, queue length, intersection geometry, and environmental emissions.

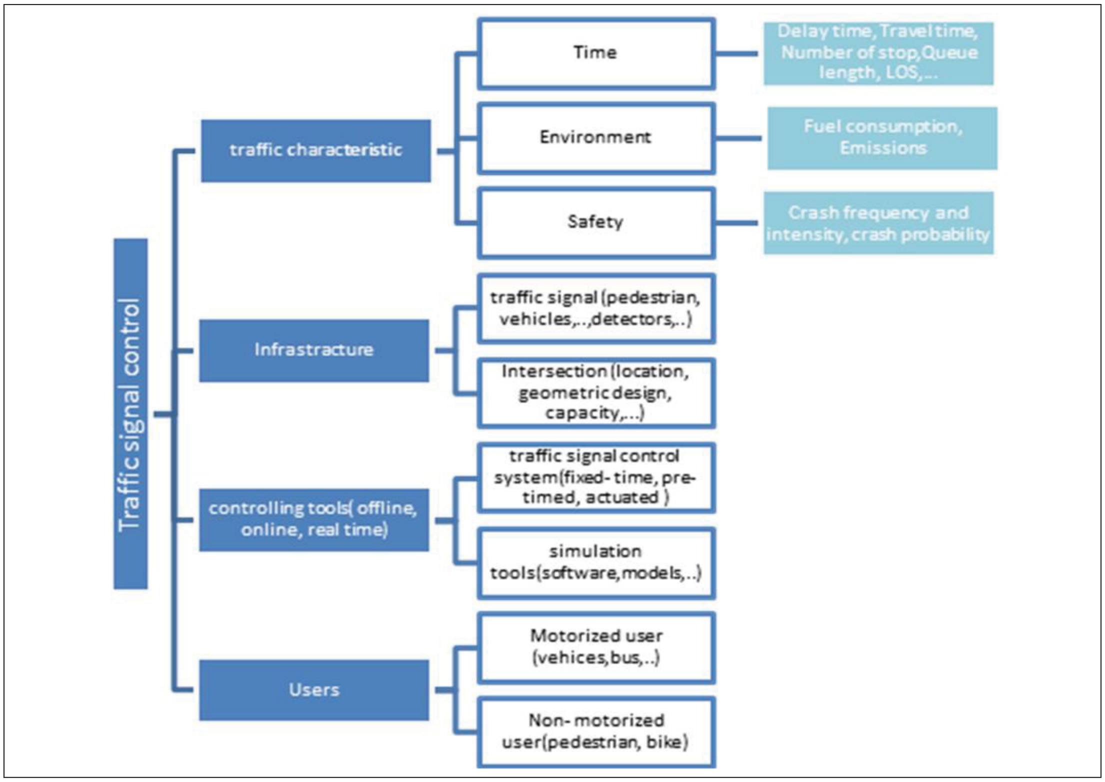

Figure 1.1 Traffic signal control components

Figure 1.1 provides the traffic signal control components that can affect an intersection efficiency. Then, in this section, the current study investigates each component to verify how traffic signal control systems can improve user quality of travel experience.

On the other hand, new technology such as an adaptive traffic control system at the intersection affects vehicular traffic flow and travel time by changing traffic signal cycle length dynamically. However, these systems are mostly not sensitive to non-motorized and motorized users, which influences non-motorized user safety and waiting time at the intersection. This research aims to generalize the traffic signal control method to optimize the multi-objective model for all intersection users.

1.2 Traffic characteristic

The traffic characteristics include any characteristics related to road users and vehicles.

1.2.1 Volume and flow rate

Volume and flow rate are two measures that quantify the number of users passing a point on a lane or roadway or crosswalk during a given time interval. Volume refers to the total number of users that pass over a given point during a given time interval; volumes are typically expressed in terms of annual, daily, hourly, or sub-hourly periods. Flow rate is the equivalent hourly rate at which users pass over a given point during a given time interval of less than 1 h, usually 15 min.

1.2.2 Infrastructure capacity

Infrastructure vehicle capacity is the maximum number of vehicles that can pass specific points during a specific period under prevailing roadway, traffic, and control conditions without considering the influence of downstream traffic during the operation. Infrastructure pedestrians capacity is the maximum number of persons that can pass a given point during a specified period under prevailing conditions.

The capacity is an independent parameter of traffic demand at the intersection. Under real-world traffic conditions, capacity cannot easily be measured for an existing intersection. The capacity of a signalized intersection depends on existing geometric control tools, weather, and other conditions. The capacity directly relates to travel time, queue length, traffic performance, and quality of service at the signalized intersections (Wu & Giuliani, 2016). For example, in the work area, lane closures have a significant effect on the capacity of the road and the mobility of road users. The geometry of the intersection, distance from the intersection, and green-to-cycle length (g/C) ratio are the major factors affecting capacity in a construction zone (Alshababi & Prassas, 2018). Capacity also is related to the saturation flow rate that indicates the number of passenger car units (PCU) for a specific intersection lane group, and queue length. In a situation where the traffic flow is going more than the intersection capacity, we have an over-saturated condition at the intersection.

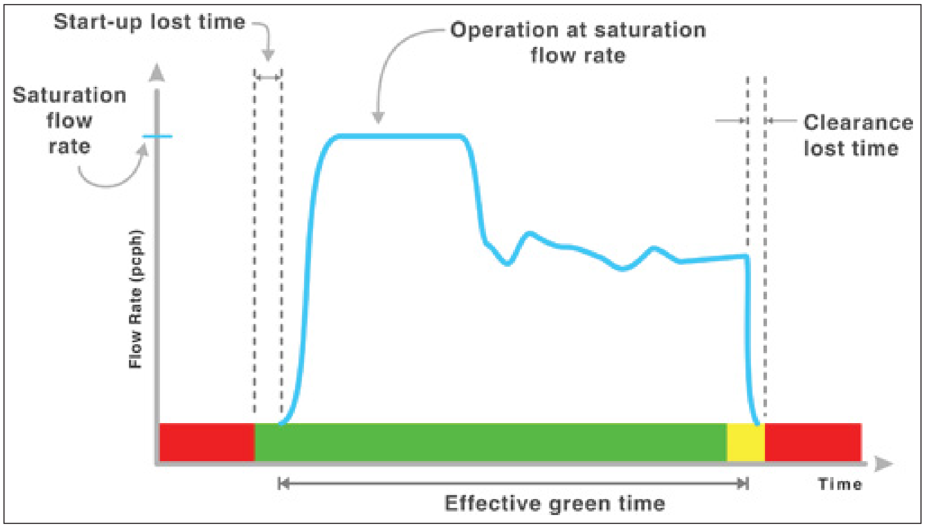

Figure 1.2 Typical flow rates at a signalized movement [1]

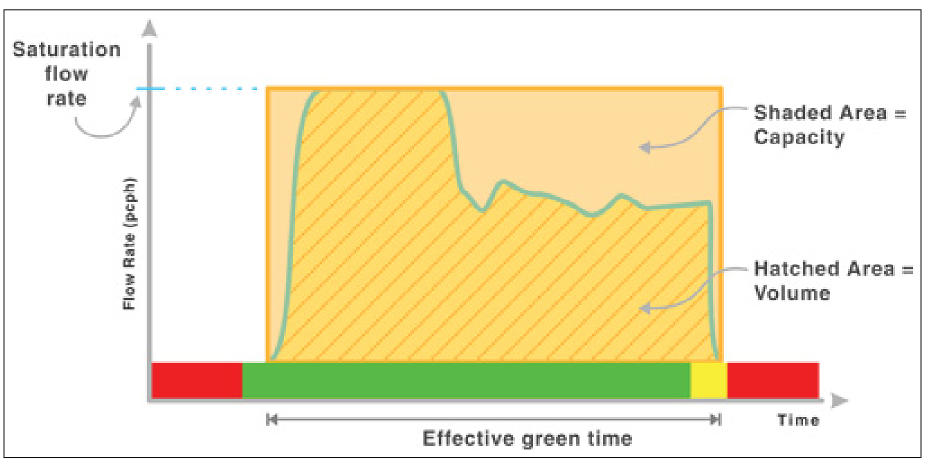

Figure 1.3 Volume and capacity of a signalized movement[2]

Figure 1.2 and 1.3 indicate the relation between the capacity, flow rate (passenger car unit per hour), and traffic signal green time, while the shaded area presents the capacity of the intersection.

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[1] Urbanik *et al.* (2015)

[2] Urbanik *et al.* (2015)

1.2.3 Level of service

The Level of Service (LOS) is a qualitative measure of the traffic signal control system performance based on the delay time of vehicles or pedestrians. It can be characterized for the entire intersection, each intersection approach, and each lane group. Delay alone is used to characterize LOS for the entire intersection or an approach for each group of users. Delay and volume-to-capacity ratio (The volume-to-capacity ratio quantifies the degree to which a phase's capacity is utilized by a lane group) are used to define LOS for a lane group. The literature describes LOS as:

- LOS A: Describe operations with a control delay of 10 s/veh or less and a volume-to-capacity ratio no greater than 1.0. It means most vehicles arrive during the green indication and travel through the intersection without stopping.
- LOS B: Describe operations with control delay between 10 and 20 s/veh and a volume-to-capacity ratio no greater than 1.0 and more vehicles stop than with LOS A.
- LOS C: Describe operations with control delay between 20 and 35 s/veh and a volume-to-capacity ratio no greater than 1.0. One or more queued vehicles are not able to depart as a result of insufficient capacity during the cycle at this level. The number of vehicles stopping is significant, and many vehicles still pass through the intersection without stopping.
- LOS D: Describe operations with control delay between 35 and 55 s/veh and a volume-to-capacity ratio no greater than 1.0. This level is typically assigned when the cycle length is long and many vehicles stop.
- LOS E: Describe operations with control delay between 55 and 80 s/veh and a volume-to-capacity ratio no greater than 1.0. This level is typically assigned when the volume-to-capacity ratio is high, and the cycle length is long.
- LOS F: Describe operations with control delay exceeding 80 s/veh or a volume-to-capacity ratio greater than 1.0. This level is typically assigned when the volume-to-capacity ratio is very high, progression is very poor, and the cycle length is long. Most cycles fail to clear the queue (Transportation Research Board, 2016).

Pedestrian level of service (PLOS) is an important measure of performance in the analysis of existing pedestrian crosswalk conditions. Many researchers have developed PLOS models based on pedestrian delay, turning vehicle effect, and more (Marisamynathan & Vedagiri, 2013).

Level of Service	Flow Rate (pedestrian/minute/meter)	Density (pedestrian per squared meter)
A	≤ 7	≤ 0.08
B	7 - 23	0.08 - 0.27
C	23 - 33	0.27 - 0.45
D	33 - 49	0.45 - 0.69
E	49 - 82	0.69 - 1.66
F	≥ 82	≥ 1.66

Figure 1.4 Pedestrian Level Of Service[3]

Figure 1.4 describes the pedestrian level of service related to the delay and flow rate of the pedestrian while flow rate provides the number of pedestrians per minute that pass a specific length of the crosswalk.

The level of service (LOS) defines the traffic service quality of roads at a given traffic flow rate, but the capacity gives the quantitative measure of traffic in the same area. The capacity is a fixed amount for each intersection, but LOS change is related to traffic conditions such as user volume, intersection geometry, weather conditions, and more. The level of service at the intersection refers to users and can be defined for each user at the intersection. The level of service and the intersection delay are related and regarding the LOS diagram, the increasing delay at the intersection affects the LOS by decreasing the quality of traffic service at the intersection.

[3] Marisamynathan & Vedagiri (2013)

1.2.4 Delay and travel time

Travel time is the time elapsed when a traveler displaces between two places in a network and it depends on user characteristics, traffic regulations, traffic control systems, user interaction, conflict, and environmental conditions.

Delay quantifies the increase in travel time due to traffic control tools. It is also a surrogate measure of driver discomfort and fuel consumption. The delay time is a most specific parameter that can be measured easily at the intersection, and today, the control system uses this item to improve the traffic signal plan. The delay time can be defined for each kind of road and intersection user.

The delay is defined by the difference in travel times through the intersection with and without conflict movement. Vehicle delay has been measured as a total of stopped time delay, approach delay, travel time delay, time-in-queue delay, and control delay. Control delay (the delay because of the traffic control device) is the principal service measure in the HCM for evaluating LOS at signalized and un-signalized intersections.

Control delay includes delay associated with vehicles slowing in advance of an intersection, the time spent stopped on an intersection approach, the time spent as vehicles move up in the queue, and the time needed for vehicles to accelerate to their desired speed.

There are other types of delay such as Geometric delay caused by geometric features causing vehicles to reduce their speed, Incident delay is the additional travel time experienced as a result of an incident, compared with the no-incident condition, Traffic delay is resulting from the interaction of vehicles, causing drivers to reduce their speed. The sum of these delays defines as a total vehicular delay. But, as we mentioned delay can be defined for each user at the intersection. Besides the vehicles, pedestrians are the most important users of the intersection, and pedestrian delay is defined as an additional travel time experienced by pedestrians because of the control device or vehicle interaction. The pedestrian model comprises three parts; the first part is the signal delay, defined as the waiting time of pedestrians stopping at the intersection because of the traffic light. The second part is conflict delay, defined as the additional experienced delay time due to conflicts between pedestrians and turning vehicles. The third part is the detour delay because pedestrians willing to cross the intersection diagonally must perform a detour if the considered signal pattern does not allow diagonal crossing (Transportation Research Board, 2016).

1.2.5 Number of Stops

Traffic control devices separate users on conflicting paths by requiring one user to stop or yield to the other. The stop causes delay and has an associated cost in terms of fuel consumption. For this reason, information about the number of stops is useful in evaluating performance and calculating user costs. The stop rate counts the number of vehicles that stop divided by the total number of vehicles that pass the intersection for the specific time interval. A number of stops is generally expected by motorists arriving at an intersection as a minor movement (e.g., a turning movement, or a through movement on the minor street). However, drivers on major streets expect to arrive at each signal while it is displaying a green interval for the through movement. For this reason, the stop rate is a useful performance measure for evaluating coordinated signal systems (Minnesota Department of Transportation, 2017).

1.2.6 Headway, Spacing, and Gap

Spacing is the physical distance, usually reported in feet or meters, between the front bumper of the leading vehicle and the front bumper of the following vehicle (from the same point on each vehicle). Spacing is the product of speed and headway. Headway is the time between successive vehicles as they pass a point on a lane or roadway, also measured from the same point on each vehicle.

You can measure the headway between two vehicles by starting a chronograph when the front bumper of the first vehicle crosses the selected point and subsequently recording the time that the second vehicle's front bumper crosses over the designated point. Headway is usually reported in units of seconds.

A gap is very similar to headway, except that it is a measure of the time that elapses between the departure of the first vehicle and the arrival of the second at the designated test point. A gap is a measure of the time between the rear bumper of the first vehicle and the front bumper of the second vehicle, whereas headway focuses on front-to-front times. A gap is usually reported in units of seconds (Transportation Research Board, 2016).

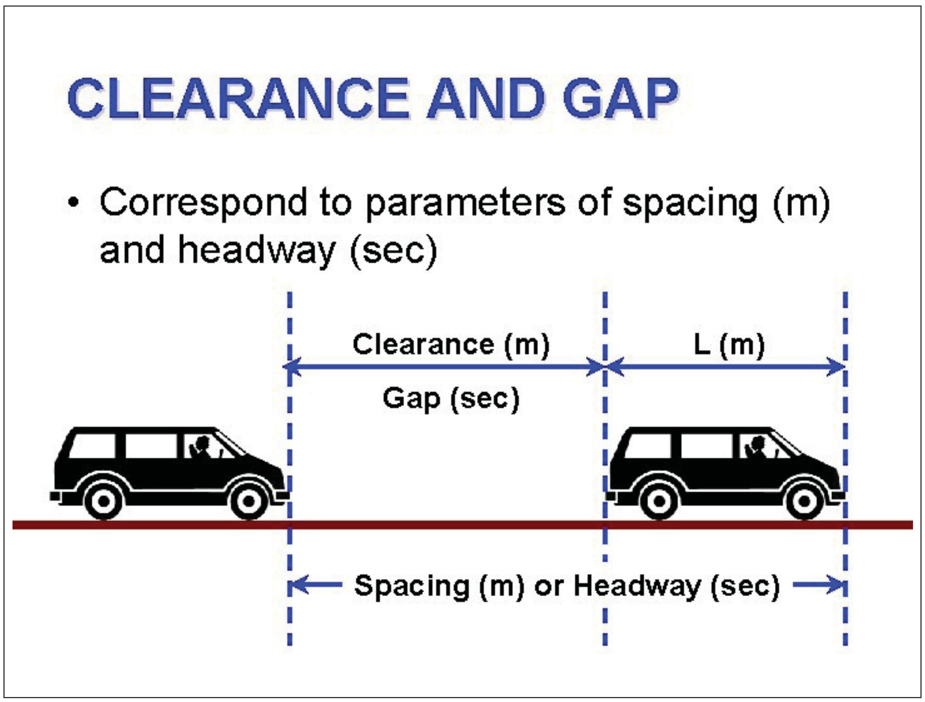

Figure 1.5 Gap, Headway and Spacing[4]

1.2.7 Safety and conflict

Intersection safety is defined as the number of potential vehicle-to-vehicle and vehicle-to-pedestrian conflict situations at the intersection. A conflict is any possible unsafe situation or

[4] Tyne Guevara (2019)

interaction between users' movements at the intersection. A conflict with high severity usually is known as a collision and crash (Brow, 2011).

According to Société de l'assurance automobile du Québec report, in 2015, 55% of accidents causing bodily injury involving at least one pedestrian victim occurred at intersections, where pedestrians and motorists interact most often; and Only 13% of accidents causing bodily injury involving at least one pedestrian victim has occurred between intersections (at more than 100 meters from an intersection) (Société de l'assurance automobile du Québec, 2017).

The traffic signal's main objective is to increase the safety of the intersection; however, some research indicates that a stop sign at an intersection with low traffic flow is more efficient than the traffic signal (Persaud, Hauer, Retting, Vallurupalli & Mucsi, 1997). In the literature, it's been investigated that an up-to-date and well-maintained traffic signal can positively affect intersection safety by reducing conflict at the intersection. Besides the conflict or crush, there is another item that is known as a near-miss accident. We cannot have accurate data from near-miss accidents because they are unplanned incidents that have not resulted in injury, illness, or damage but have the potential to do so. The research mentioned that 70% of pedestrians at intersections or on the roads have experienced near-miss accidents. The situation of the near-miss crash is predictable (Matsui, Takahashi, Imaizumi & Ando, 2011).

The traffic signal could reduce conflict situations and violate behavior that can cause near-miss accidents. The pedestrian and vehicle volume and turning flow at the intersection can predict the probability of a near-miss accident. The following figure shows 20% of the total unsafe act can cause a near-miss accident, while the probability of fatality is $3 * 10^{-6}$ of the total unsafe act.

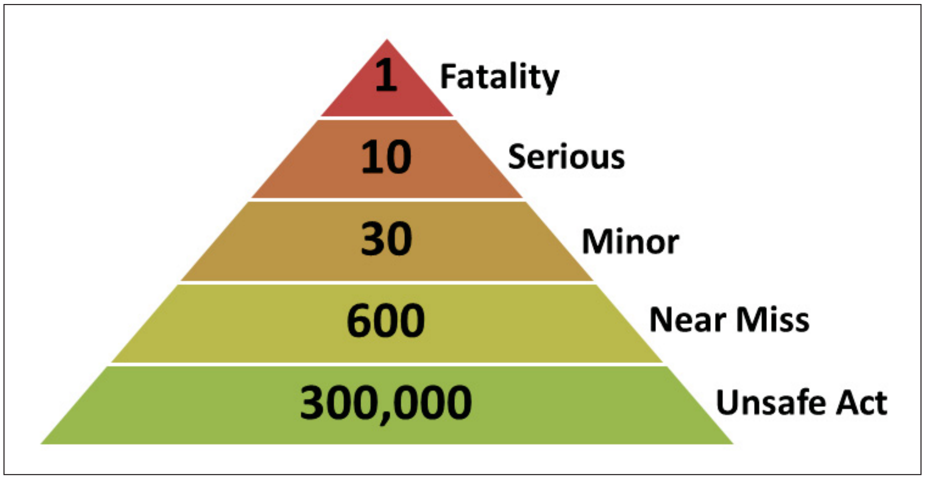

Figure 1.6 Probability of crash frequency, the safety triangle[5]

According to the Florida Department of Transportation (FDOT), a crash analysis reporting system considers the factors influencing crash frequency by modes including macroscopic factors (such as population and economic characteristics, land use characteristics, and travel behaviors), road features, and traffic and individual characteristics (such as gender, age, education, alcohol consumption, and driver or pedestrian behaviors) (Wang, Huang & Zeng, 2017).

Different factors are used to predict or analyze the safety level of intersections based on crash history data, such as:

- The classification of severity: The categorization of road traffic crashes according to the level of injury or damage sustained by the people and vehicles involved,
- The post-encroachment time: The duration from when the encroaching vehicle leaves the conflict point until the vehicle with the right-of-way reaches the same point.,
- The time-to-collision: The amount of time it will take for two objects, such as vehicles, to collide if they continue moving at their current speeds and directions.,
- The average daily traffic: The total traffic volume during a given time period
- Accident modification factor: a factor used to compute the expected number of crashes after implementing a given countermeasure at a specific site,

[5] Matsui *et al.* (2011)

- The time to collision: the time that remains until a collision between two vehicles would have occurred if the collision course and speed difference are maintained,
- The annual average daily traffic: the total vehicle volume for a year divided by 365 days,
- The average hourly conflict,
- The square root of the users' volume at the intersection: A mathematical calculation that involves finding the square root of the total number of vehicles, pedestrians, or other users that pass through a given point within a specified period of time,
- The intersection conflict index: the probability of a collision to occur (Lord, 1996; Torbic *et al.*, 2010; Matsui *et al.*, 2011; Alavi *et al.*, 2013; Abdul Majeed & Ewadh, 2019; Sayed & Zein, 1999).

Most of these factors are more suitable for measuring vehicle–to–vehicle conflict.

Then, to measure the pedestrian-vehicle conflict, some of the literature applied other indices such as:

- Pedestrian level of comfort,
- Pedestrian level of stress,
- Pedestrian intersection index,

All of these measures are related to the pedestrian facility at the intersection, intersection geometry, daily users volume, and the speed of users (Chang & Rodriguez, 2019). These indices have been used to compare the level of pedestrian safety between different intersections while our study intends to investigate the number of conflict situations between pedestrians and vehicles at one specific intersection under different signal patterns.

Zhang & Prevedouros (2003), based on HCM, formulated the potential user conflict (PC) that provides the intersection degree of safety and indicates the frequency of unsafe (conflict) situations. This factor can be applied to pedestrian and vehicle conflicts for an individual intersection according to the traffic flow and signal pattern (Zhang & Prevedouros, 2003).

1.2.8 Emissions and air pollutant

The transportation system has a major part in producing air pollutants, which includes the emissions produced by rail, roads, air, and freight transportation system. In urban areas, traffic management solutions are providing various strategies to reduce the noise and air pollutant emissions caused by traffic signals. One of these ways is coordinated traffic signals that can cause the reduction of noise and air pollutants (De Coensel, Can, Degraeuwe, De Vlieger & Botteldooren, 2012). The emissions produced by vehicles such as SO_X (Sulfur Oxides), NO_X (Nitrogen Oxides), VOCs (Volatile Organic Compounds), CO_2 (Carbon Dioxide), and PM2.5 (fine particulate matter) are major contributors to climate change. In particular, coordinated traffic lights create green waves (when a series of coordinated traffic lights allow continuous traffic flow over several intersections in one main direction) and reduce travel times. Although it is mentioned that an improvement in traffic flow can result in lower vehicle emissions.

Also, sound pressure levels were found to decrease by up to 1 dB(A) near traffic signals but to increase by up to 1.5 dB(A) in between intersections. Moreover, the coordination of traffic signals can increase the total emitted noise by up to 0.6 dB (De Coensel *et al.*, 2012). De Coensel *et al.* (2012) demonstrates that there is not any relationship between the cycle time of traffic signals and emissions, but the green split and traffic flow influence vehicle air pollution at the intersection.

Li & Shimamoto (2011) compares the fixed traffic signal with the traffic signal controlled by the electronic toll system. The results show that the proposed system reduces CO_2 emissions by 26.9% by decreasing the number of stops and waiting times at the toll system. The relation between traffic flow, CO_2 emissions, and average waiting time are shown in figures 1.7 and1.8:

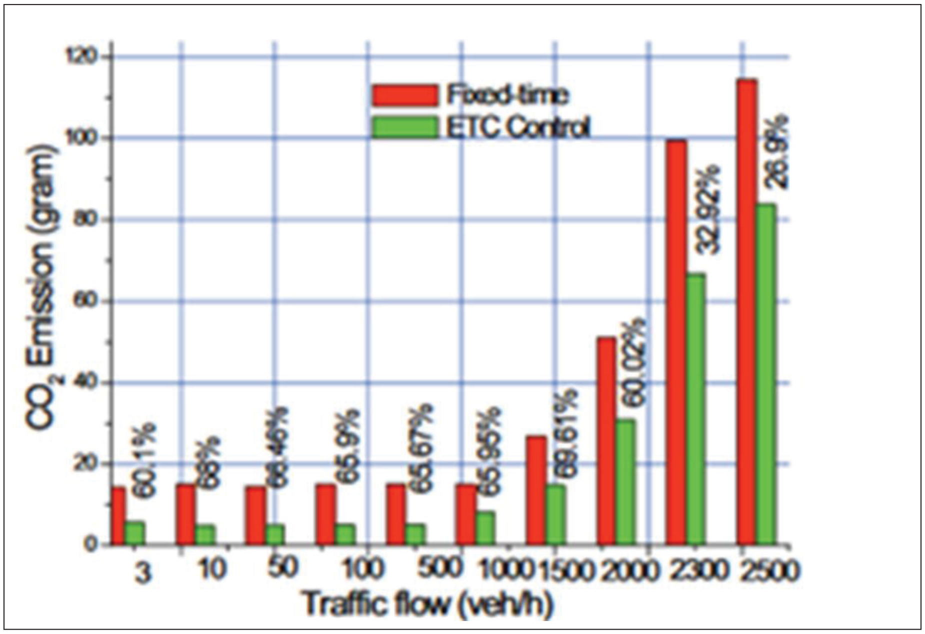

Figure 1.7 CO_2 emissions at the intersection[6]

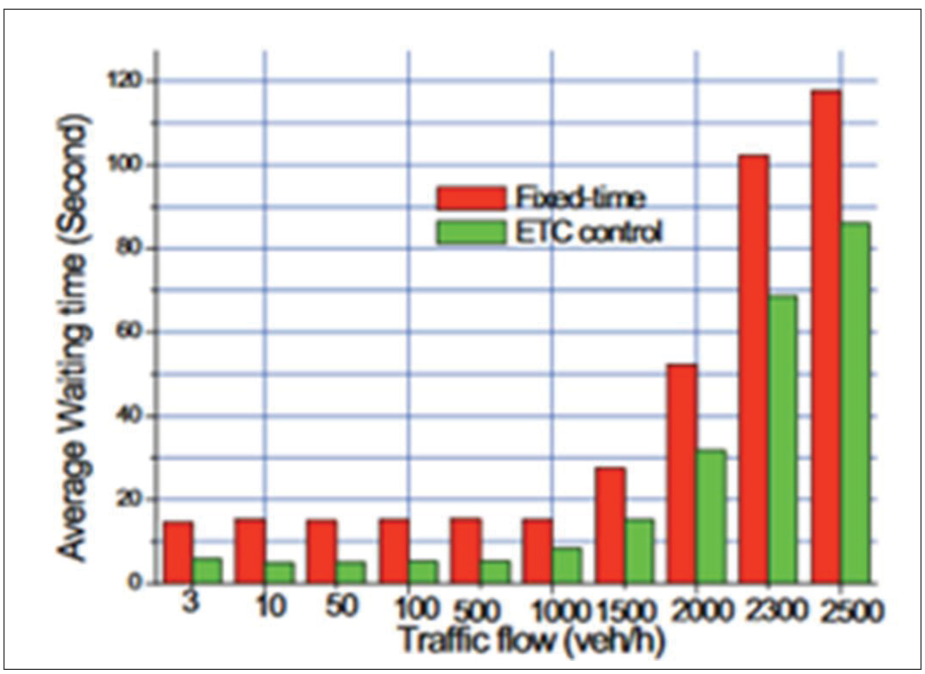

Figure 1.8 Average waiting time at the intersection[7]

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6 Lin, De Schutter, Xi & Hellendoorn (2011)

7 Lin *et al.* (2011)

Figures 1.7 and 1.8 present between 29% to 60% of CO_2 reduction when the traffic signal controls changing caused the reduction in travel time. Then, one of the suitable ways to reduce CO_2 emissions is to reschedule the traffic signal plan. And, optimizing the traffic signal plan affects air pollutant emissions by changing the travel time (Lin *et al.*, 2011).

1.2.9 Intersection infrastructure

Transport infrastructure is the precise framework that supports the transport system, and generally, the government is responsible for the construction, development, control, and maintenance of them, such as traffic signals at intersections, the data collection systems, and the geometry of intersections. Several features affect the performance of the intersection:

- Location: One of the primary factors that affect signal timing is the environment. Urban environments are characterized by lower speeds and higher degrees of congestion and a higher number of pedestrians, cyclists, and transit. Rural environments are at higher speeds but with fewer pedestrians, cyclists, and transit vehicles.
- Transport network characteristic: The form of intersection, the distance between intersections, and the characteristic of the arterial streets between intersections that can affect the performance of the intersection.
- Intersection geometry: The skew of the intersection affects the length of the crosswalk and pedestrian clearance time. The geometry of an intersection determines its ability to efficiently and safely serve user demand (Minnesota Department of Transportation, 2017). Intersection geometry is generally presented in a diagrammatic form that includes all of the relevant information such as approach grades, exclusive left- or right-turn lanes, the number and width of lanes, and parking conditions (Transportation Research Board, 2016).
- User characteristic: The variety of the users, the demand of users, and users' behavior are the most important characteristic of the user.
- Controlling tools: The intersection can control by signal control such as traffic signals, or they are not signalized such as roundabout and stop sign control system.

We discussed in this section the traffic characteristic parameters that are significant elements in planning and controlling the traffic signal. To increase the efficiency of traffic signals most traffic agencies try to optimize the delay, safety, travel time, and emissions; however, all these parameters are related, and changing one item can affect the others. Then, it's necessary to define the main objective of each traffic signal and provide the best performance measure related to that objective. For example, if the traffic signal targets to minimize the crash and increase safety at the intersection, it is necessary to give the priority to safety measures even if it's increasing the delay at the intersection. Then, it's important to know the traffic signal controlling and planning component to verify the role of each component in optimizing the traffic signals.

1.3 Traffic signal

The capacity of an urban street is related to the traffic signal and the geometric characteristics of the street. The geometric part of the intersections is a fixed element, While other parameters may vary over time.

The traffic signal controllers lead to prioritize traffic movements, coordinate the neighboring controllers, and at the same time avoid conflicting movements that cause the stop-and-go command at the intersection (Mirheli, Hajibabai & Hajbabaie, 2018).

The traffic signal provides at least one of these purposes:

- Arrange the movement of users.
- Improve the efficiency of the intersection by increasing the volume of vehicles that passed the intersection.
- Decrease the frequency and intensity of the crash.
- Provide accessibility for pedestrian and non-vehicle users (Minnesota Department of Transportation, 2017).

Generally, we can initiate the traffic signals for each intersection user, such as vehicles, pedestrians, bikes, and public transportation signals. Moreover, they have different operation and control commands, like fixed time, pre-timed, actuated, isolated, and coordinated.

- Fixed time signal allocates fixed cycle length and green split to the traffic light for the whole day.
- Pre-timed control is appropriate for any intersection with constant traffic volume and traffic pattern. Pre-timed control consists of a series of intervals that are fixed in duration. Collectively, the preset green, yellow, and red intervals result in a deterministic sequence and fixed cycle length for the intersection. For example, we can have different fixed cycles for each day of the week or period of the day.
- Semi-actuated traffic signal control uses detectors on minor movement at the intersection. Semi-actuated control uses detection only for minor movements at an intersection. The phases associated with the major road-through movements are operated as "non-actuated."
- Fully actuated control uses detection for all traffic movement. This controller is situated at an isolated intersection where the traffic volume and pattern are inconstant during the day. This method has some advantages; for example, real-time data allocating the effective cycle time reduces delay. Despite the pre-timed signal, the actuated signal cycle length varies during the day. In contrast to pre-timed control, actuated control consists of intervals that are called and extended in response to vehicle detectors. Detection is used to provide information about traffic demand to the controller. The duration of each phase is determined by detector input and corresponding controller parameters (Urbanik *et al.*, 2015). Calling and extension are two commonly used procedures in actuated control. When a vehicle is stopped in a detection zone of the intersection, then the calling of signal phase occurs. When detectors confirm that traffic is still present on the movement controlled by the phase, then the extension of the green indicator occurs (Yang, Wood & Wang, 2021).
- Coordinated signal coordinates the phases between close-by intersections and provides a continuous vehicular green interval in one direction and reduces the number of stops, delays, and travel time.

1.3.1 Traffic signal users

Generally, we have different traffic signals depending on intersection users: vehicle, pedestrian, bike, and public transportation signals. Each intersection with a traffic signal is planned to control vehicular movements and reduce the interaction between vehicles while optimizing travel time. In some situations with high traffic demands of pedestrians, bicycles, and public transportation, traffic agencies control intersection movements with a different traffic signal for each group of movements. Then, the traffic signals control the interactions between intersection users, and they are defined and planned for each user, such as vehicle traffic signals, pedestrian traffic signals, and more.

1.3.2 Traffic signal characteristics

The traffic signal has three significant parts: cycle (the time allowed for all approaches), split (the percentage of the cycle time allocated to each phase), and offsets (the start of a stage at one intersection relative to the start of a stage at another intersection). For planning each traffic signal, it is necessary to identify the traffic parameters at the intersection, such as flow rate, gap time, capacity, and more. Cycle length and phase pattern represent essential elements in traffic signal investigation. The traffic signal control system, pre-timed, or activated, adapts to the traffic flow's actual situation. The traffic signal cycle length is the most critical part of the traffic signal control system. Optimizing cycle length can cause a reduction in intersection delay (Li *et al.*, 2017; Yu, Ma, Han & Yang, 2017; Li & Sun, 2019a). However, the signal pattern is another parameter that affects intersection delay (Wong & Heydecker, 2011; Ma *et al.*, 2015).

1.3.2.1 Signal cycle

Cycle length is the time a traffic signal requires to complete the sequence of signal phases. Phase pattern is the set of user movements allowed at each phase of the signal cycle. A large part of the literature focuses on multi-objective optimization methods of cycle length to reduce the travel time, number of stops, and intersection queue length for intersection users (mostly vehicles). Mostly, the literature worked on the algorithm to optimize the cycle length of traffic signals based on the performance measure such as the delay, traffic capacity, travel time, system throughput, vehicle-to-vehicle conflict, and emissions of the vehicle (Stevanovic *et al.*, 2015; Jia *et al.*, 2019; Builenko *et al.*, 2018; Chen *et al.*, 2019; Li *et al.*, 2017; Li & Sun, 2019b).

Each traffic signal cycle has a sequence of splits. A split determines how much time each movement gets in a cycle. The split includes the green time and the clearance interval, or the time to clear the intersection, which includes the yellow and red lights.

To plan a traffic signal, traffic guidelines define some parameters such as:

- The effective green time: It is the time during which a given traffic movement or set of movements may proceed at the intersection.
- The minimum green time: It represents the least amount of time that a driver needs to react to the start of the green interval and pass the intersection. A minimum green that is too long may result in wasted time at the intersection, and one that is too short may violate driver expectations or (in some cases) pedestrian safety. The amount for the minimum green can be between 2 to 15 seconds depending on the type of street (Minnesota Department of Transportation, 2017).
- The maximum green parameter represents the maximum amount of time that a green signal indication can be displayed in the presence of conflicting demands. Maximum green is used to limit the delay to any other movement at the intersection and to keep the cycle length to a maximum amount. Maximum green time can be between 15 to 70 seconds regarding the type of road.
- Yellow interval: The yellow change interval is intended to alert a driver to the impending presentation of a red indication. The duration of the yellow change interval is typically based on driver perception-reaction time, plus the distance needed to safely stop or to travel safely through the intersection. The yellow duration should be sufficiently long to allow drivers the time needed to clear the intersection if they determine that it is not possible to safely stop. It ranges from 3 to 6 s, with longer values in this range used with phases serving high-speed movements.

- The red clearance interval: It can be used to allow a brief time to elapse after the yellow indication, during which the signal heads associated with the ending phase and all conflicting phases display a red indication. If used, the red clearance interval is typically 1 or 2 s (Transportation Research Board, 2016; Minnesota Department of Transportation, 2017).

On the other hand, the pedestrian phase consists of three intervals:

- walk: The walk interval should provide pedestrians with time to perceive the WALK indication and depart the curb before the pedestrian clearance interval begins. Some controllers have a mechanism to specify that the walk interval begins before, or even after, the onset of the green interval. The minimum walk duration should be at least 7 seconds.
- pedestrian clearance or flashing don't walk (FDW): The pedestrian clearance interval follows the walk interval. During the clearance interval, pedestrians should either complete their crossing if already in the intersection; or refrain from entering the intersection until the next pedestrian walk interval. Depending on crosswalk length and pedestrian speed, it can be from 10 to 30 seconds (Minnesota Department of Transportation, 2017).
- solid don't walk: Pedestrians are not allowed to cross the intersection.

Crosswalks assist pedestrians in crossing the street and affect pedestrian mobility and the safety performance of signalized intersections. Crosswalk characteristics such as the position and width of the crosswalk describe the vehicle stop line position. Also, their position influences cycle length and delay time at the intersection. The HCM mentioned that the pedestrian crossing time depends on average walking speed (4.0 ft. /s) and crosswalk length (Li *et al.*, 2010).

The pedestrian has the right of way over all vehicles while they are at the curb of the intersection or in a crosswalk. The three basic types of crosswalks are defined:

- Crosswalks controlled by "walk" and "do not walk" electronic signs;
- Crosswalks controlled by other traffic signals (such as traffic lights or stop signs) or police officers;
- Crosswalks recognize by devices or (vertical or/and horizontal) signs on the road.

Nowadays, the fundamental strategy based on the transportation system leads to increased walking and cycling and focuses on balancing all users' facilities at the intersections. A signalized intersection considers the green phase, the clearance phase, and the red phase. Pedestrians can walk during the green phase, stop during the red phase, and not walk in the crosswalk during the clearance phase. Traditional pedestrian control strategies, such as a leading pedestrian interval (LPI) and exclusive pedestrian phase (EPP), lead to improved safety rather than efficiency.

1.3.2.2 Signal patterns

The signal timing has centralized on vehicle improvement by minimizing vehicular delay and stops, or both, and this system causes the delay, unsafe feeling, and anxiety for pedestrians and another mode (Sobie *et al.*, 2016). Regarding the literature, most traffic signal optimization models optimize the cycle length, offset, or split of a traffic signal. Other parameters significantly affect the quality of the travel experience at the intersection. The most effective one is traffic signal patterns, which are usually chosen by experts. We are interested in comparing the behavior of different signal patterns. Generally, a signal pattern dictates the possible user movements that are allowed to be performed during the green interval of a phase (i.e., consisting of a set of green, red, and clearance intervals assigned to specified traffic movement(s) during each cycle) (Urbanik *et al.*, 2015). The signal phase is either actuated or non-actuated and it may be coordinated with neighboring signals on the same route, or they may function in an isolated mode without influence from other signals (Transportation Research Board, 2016).

Signal phasing can provide for protected, permitted, or not opposed turning movements. A permitted turning movement made a permit for a movement while there is a conflict with pedestrian or bicycle flow or opposing vehicle flow; such as a left-turn movement permitted with the opposing through movement or a right-turn movement permitted with pedestrian crossings in a conflicting crosswalk. Protected turns are those made without these conflicts, and they need the exclusive phase for the movements with the conflicts. For example, a right-turn phase in which conflicting pedestrian movements are prohibited. Either permitted or protected turning phases depend on the turning and through volume and intersection geometry may be more efficient in a given situation. Then regarding the permitted, protected, or free phase, in a typical four-leg (two-phase) intersection, we have four possible signal pattern types:

- Free pattern: there are no movement restrictions applied to any phases during the green interval.
- Exclusive pattern: the green interval is partitioned into mutually exclusive (groups of) movements.
- Leading pattern: a group of movements is permitted for the complete green interval duration, while a second restricted group of movements is only permitted after a specific time interval.
- Lagging pattern: this pattern is similar to the leading ones, but the restricted movement group is only allowed before a specific time interval.

Those patterns can be applied to each user category's movements, but current research focuses on pedestrian signal patterns. The most common signal patterns that address the pedestrian interval are EPP (exclusive pedestrian phase), LPI (leading/lagging pedestrian interval), LTI (leading/lagging through interval), and TWC (two-way crossing) (Urbanik *et al.*, 2015; Furth & Saeidi Razavi, 2019). These patterns affect pedestrian safety and delay time at the intersection. Recently, TWC (two-way crossing) has appeared on most traffic signals, and it provides pedestrians with the possibility of crossing the street on the green interval of parallel vehicular movement. The TWC (two-way crosswalk) is the regular signal pattern that prioritizes vehicles at the intersection, and pedestrians use the green time for parallel vehicular movement. Pedestrian flow rates and pedestrian-vehicle conflict at the intersection do not affect this pattern.

The EPP (exclusive pedestrian phase) protects and excludes the pedestrian phase from all vehicular movements, and it is usually used at downtown intersections with a high probability of conflict between pedestrians and vehicles at the intersection. This method reduces conflict and safety issues but depends on pedestrian flow rate and turning vehicle flow rate, increasing the total intersection delay. Some research mentioned, increasing the delay time at an intersection can cause incompliant behavior of pedestrians and reduce the safety at the intersection. The LPI (leading/lagging pedestrian interval) leads or lags the green pedestrian interval and, at the same time, vehicles are not permitted to cross. Similarly, LTI (leading through interval) leads or lags the pedestrian interval; however, only vehicular turning movements are prohibited on a pedestrian green interval of this pattern. Therefore, LTI is commonly preferred to LPI since LPI affects all vehicular movements (Furth & Saeidi Razavi, 2019). Furthermore, LTI is implemented in most of Montreal's intersections (the effectiveness of this system has not been investigated in Montreal yet). The LTI gives priority to pedestrians crossing the street before the vehicles start to turn. In this situation, the turning lane and through lane must be separated on each intersection approach. Otherwise, the vehicle delay increases at the intersection. This method minimizes the conflict between pedestrians and vehicles without having an impact on significant vehicular movement.

For these reasons, the present study focuses on the LTI, TWC, and EPP patterns, and it will not further consider the LPI. These methods are adequate for the specific situation at a specific intersection. The leading, lagging, or separating interval improves the quality of the travel experience at the intersection. This improvement does not happen for the complete daytime and the efficiency of these patterns regarding the performance indicators depends on some traffic characteristics of the intersection, such as user volume, turning flow rate, user behaviors, and more. In this situation, maybe changing the signal pattern can improve the total delay time at the intersection.

1.3.3 Traffic signal control systems

Section 1.3.2.1 identified the traffic signal control as a fixed, pre-timed, and actuated system. Recently, traffic agencies aim to improve the traffic signal control system by using intelligent transportation systems (ITS) which enhance the safety and efficiency of vehicles and roadway systems. ITS includes any technology that allows drivers and traffic control system operators to gather and use real-time information to improve vehicle navigation, roadway system control, or both. Technology has recommended the ITS (intelligent transportation system) tools that link today's technology and infrastructure, vehicles, and users to improve underdeveloped urban, transport, and region efficiency and effectiveness in the last two decades. It affects the economy and the environment. This system is expected to improve traffic flow, public transport service, accessibility, safety, cost of freight transport, knowledge of travelers from a peripheral condition, travel data collection, and reduced environmental impact, noise, and emissions. For signal operation control, the ITS can improve the allocation of green time and increase the capacity of the intersection (Transportation Research Board, 2016).

In the concept of intelligent transportation systems, the adaptive traffic control system (ATCS) is defined as controlling traffic signals based on demand prediction to improve vehicular throughput or reduce vehicular delay. It is a concept where vehicles in a network are detected, at upstream or (and) downstream points, and an algorithm to be used to predict when and where traffic will be changed by optimization of signal timing that adjusts the three fundamental parameters: cycle length, phase split, and offset. They are three components of the system that causes the variety of ATCS:

- Searching through as many possible alternatives as quickly as possible.
- Evaluating each alternative with defined parameters.
- Improvement at an individual intersection with consideration of system-wide performance (Urbanik *et al.*, 2015).

There are different companies that provide adaptive traffic control system software, such as :

- Sydney coordinated adaptive traffic system (SCATS) uses a library of fixed-time plans, which have been developed to work in specific scenarios. It operates at the upper level that considers the offset plan selected, and the lower level involves optimizing split and cycle times. SCATS operates in real-time, and the intersection plan is adjusted based on the critical intersection in each region. SCATS can specify a priority for buses and trams at high, medium, and low levels. SCATS uses stop line detection; then there is not any prediction of the queue length.
- Urban traffic optimization by integrating automation, UTOPIA is a hierarchically decentralized traffic signal control strategy. The reference plan and historical signal timing minimize the total vehicle stop or delay time. It aims to optimize the local signal plan for a 120-second time horizon (repeated every three seconds) and a network plan for building dynamic signal coordination with neighboring intersections. UTOPIA works on three hierarchical levels: 1-local level uses the characteristic traffic parameters (saturation flows, delay) for microscopic

modeling at an intersection. 2- Area level uses historical data to monitor the specific network in a mesoscopic model. 3- The town supervisor level leads to a macroscopic model to collect the information from different sources in a city, then integrate and manage these data.

- Traffic network study tool (TRANSYT) calculates the timings offline, using historical, measured traffic data to propose the optimum plans for the specific time of day, any day of the week for isolated junctions but can be used to coordinate junctions. The traffic model and the signal optimizer are two essential elements of TRANSYT. Due to traffic behaviors, the system predicts the performance index (PI) for a specific time plan and flow rate. Then, the system measures the total delay and the number of vehicles stopping at an intersection. The signal timings continue on the model until the optimum PI is achieved.
- SCOOT is a dynamic urban traffic control system, which uses real-time traffic data to determine an optimum signal plan at an intersection. SCOOT uses inductive loop detectors at the upstream end of links to monitor traffic flow and measure demand in real-time. SCOOT optimizes the split, cycle, and offset times. SCOOT requires every second of information to keep its plan updated; SCOOT has flexibility in the system to consider values and set parameters for different regions at different times, such as providing strategies to protect only one area from bus priority measures.
- Real-time hierarchical optimized distributed and effective system (RHODES) is similar to UTOPIA and has a three-tiered hierarchy level: 1- the highest level considers the traffic demand and network geometry to determine the level of traffic in the network. 2- Predicted platoon arrival patterns to determine signal timing. 3- Model the individual movement at an intersection. RHODES processes in two parts: "estimation and prediction" to collect the upstream data and "the decision system" to optimize the given objective (delay time, queue length) by selecting the split and cycle times.
- The method for optimizing traffic signals in online controlled networks (MOTION) has two levels: MOTION Central and MOTION Local. The system provides (1) data acquisition; (2) a dynamic traffic model; (3) optimizing control variables (cycle time and split time at the intersection and offset time in the network), (4) decision (comparison between new and old

signal plan and improve the new green time, but if the improvement is not significant, the signal doesn't change) (Hamilton, Waterson, Cherrett, Robinson & Snell, 2013).

Adaptive control systems aim to adjust the signal timing plan by using different strategies. The literature used the terminology of "generations" introduced in the Urban Traffic Control System (UTCS) project of the 1970s by introducing adaptive traffic control systems in three generations:

- First generation: traffic-responsive control system that measures traffic volumes and detector occupancy rates at different locations across the system, and selects a pattern based on the information.
- second generation: By using measurements of traffic flow fluctuation, detector occupancy, and other make adjustments to a traffic signal (cycle, offset, and splits).
- Third generation: the real-time traffic information uses to determine the start and end time of greens for phases. Usually, a real-time control system tries to optimize an objective function such as delay by changing the green time of a traffic signal. Real-time control is generally considered the most advanced method of control (Yang *et al.*, 2021).

The adaptive traffic control systems receive the real-time traffic data, and the data is sent to a computer by the controller, and the computer changes the signal timing second by second. The detectors sense each vehicle in this system and send the data to a local or central controller directly. And according to the time of horizon related to ATCS, the pedestrian flow rate, and priority at the intersection, the pedestrian data can be converted periodically or offline to the control system (Mirchandani & Head, 2001).

1.4 Performances indicators

In the literature several indicators are developed to assess the performances of traffic signals, such as the delay time (Jia *et al.*, 2019; Li & Sun, 2019a), the traffic capacity (Jia *et al.*, 2019), the system throughput (Jia *et al.*, 2019; Li & Sun, 2019a), the intersection safety (Stevanovic *et al.*, 2015; Builenko *et al.*, 2018), the GHG emission count (Stevanovic *et al.*, 2015), the queue length (Chen *et al.*, 2019), the travel time (Chen *et al.*, 2019; Li *et al.*, 2017) and others. However, all these indicators are driven by two fundamental measures: the delay time (i.e., the additional travel time experienced by users) and the intersection safety (i.e., any conflict situations or possible interactions between vehicle and vehicle or pedestrian movements at the intersection). Therefore, our literature review focuses on these measures. We also review a third performance indicator called the delay and safety index that provides the level of service of users at a signalized intersection by combining both pedestrian and vehicle delay and safety (represented by the number of users with potential conflicts). The three performance indicators considered in this study are delay time, safety, and delay and safety index. They are presented in Sections 1.4.1, 1.4.2 and 1.4.3, respectively.

1.4.1 Delay time

The delay time at the intersection is the additional travel time experienced by users. In other words, any interaction between users, any command to control the movements of users, and any cause of users' deceleration are known as delay time (Transportation Research Board, 2016). Since the delay is related to users' experience, the delay can be categorized as vehicular delay, pedestrian delay, and other user delays. Generally, intersection delay is estimated as an average pedestrian and vehicular delay. The literature mainly focuses on vehicular delay, but some studies also consider a pedestrian delay.

Delay can be estimated by different models. As reported by Tom V. Mathew (2014), there are four primary methods to estimate delay time: Akcelik (Li, Rouphail & Akcelik, 1994), HCM (Transportation Research Board, 2016), Webster (Wagner, Gartner, Lu, Oertel & Washington, 2014), and HSL (Roshandeh, Li, Zhang, Levinson & Lu, 2016; Tom V. Mathew, 2014).

Among the models mentioned above, the HCM is reputed to be more accurate even in situations with under or over-saturated intersections (Hadiuzzaman, Rahman, Hasan & Karim, 2014). As we mentioned, one part of an intersection delay is a vehicular delay. HCM defines delay control as a vehicle delay related to the control device. Equation (1.1) describes the vehicle delay model of HCM:

$$d^{veh} = d^U + d^I + d^Q, (s/veh) \tag{1.1}$$

where d^U defines the uniform delay based on the assumption of uniform arrivals and stable flow of vehicles; d^I defines the incremental delay due to the effect of random, cycle-by-cycle fluctuations in demand that occasionally exceed capacity and are issued by a sustained over-saturation during the analysis period; and d^Q defines the initial queue delay as a result of unmet demand in the previous period. HCM refers to the saturation flow rate to compute d^{veh} for different signal patterns, and it can be calculated for each approach, lane, and movement group of the intersection (Transportation Research Board, 2016). The delay time is a most specific parameter that can be measured easily at the intersection, and today the control system used this item to improve the traffic signal plan. The delay time can be defined for each kind of road and intersection user.

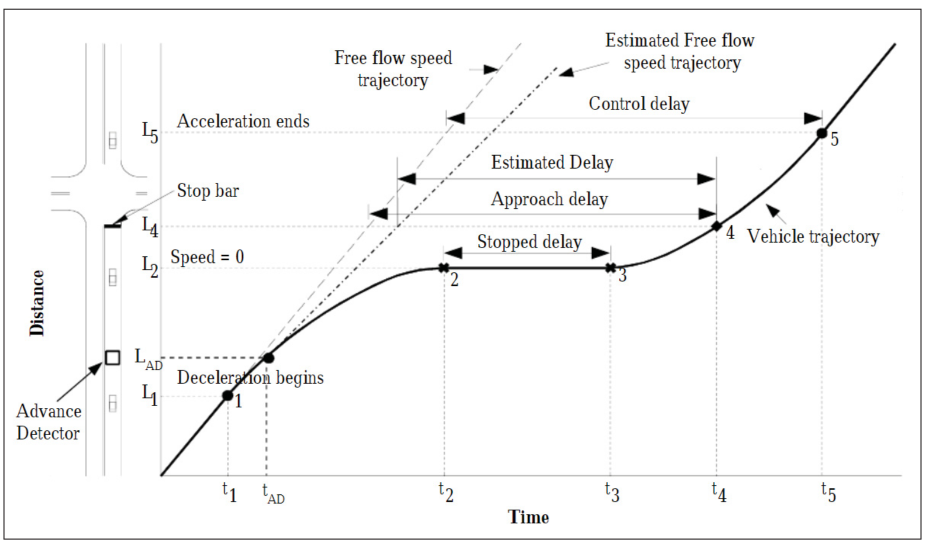

Figure 1.9 Illustration of vehicle delay measures[8]

According to figure1.9, the delay has been measured as a total of stopped time, approach, travel, delay, and-in-queue, and control delay.

- The stopped-time delay refers to when a vehicle stops in the queue while waiting to pass through the intersection.

[8] Siddiqui (2015)

- Approach delay includes stopped-time delay and the time lost for deceleration to stop and re-acceleration to the desired speed.
- Travel time delay is the difference between the expected travel time through the intersection and the actual time taken.
- The time-in-queue delay is the total time from a vehicle joining an intersection queue until crossing the intersection.
- The delay related to a control device is a Control delay, such as a delay at a traffic signal or a STOP sign. It is considering the time-in-queue delay and the approach delay.

The other part of the intersection delay in our study is a pedestrian delay. Different studies modify the HCM model to include the pedestrian flow rate, pedestrian violation behavior, and traffic signal pattern (Ma *et al.*, 2015; Ma, Liu & Head, 2014; Yang, 2010). The model proposed by Ma *et al.* (2014) and Ma *et al.* (2015) modifies the HCM to account for the pedestrian delay in TWC and EPP. This model comprises three parts. The first part is the signal delay (d^{sig}), defined as the waiting time of pedestrians stopping at the intersection because of the traffic lights. The second part is the conflict delay (d^{con}), defined as the additional experienced delay time due to conflicts between pedestrians and turning vehicles. The third part is the detour delay (d^{det}) due to the fact that pedestrians willing to cross the intersection diagonally must perform a detour if the considered signal pattern does not allow diagonal crossing. As a consequence, Ma *et al.* (2015) determine the average pedestrian delay time as:

$$d^{ped} = d^{sig} + d^{con} + d^{det}.(s/ped) \tag{1.2}$$

While d^{ped} and d^{veh} are the average per-user delay of pedestrians and vehicles, respectively, Ma *et al.* (2014) recommend adapting the weighted delay as the intersection delay (s/user):

$$D = \frac{d^{veh}V^{veh} + d^{ped}V^{ped}}{V^{veh} + V^{ped}}, (s/user) \tag{1.3}$$

where V^{veh} and V^{ped} refer to the vehicle volume and pedestrian volume of the intersection, respectively.

We observe that expressions of both the vehicle delay in the HCM model and the pedestrian delay proposed in Ma *et al.* (2014) depends on the specific pattern to which the measure is applied. For this reason, in the rest of the research, we add a superscript p with $p \in \{TWC, LTI, EPP\}$ to underline such a dependence when needed. For example, we use D^p to denote the weighted intersection delay time for pattern p; similarly, we use d^{veh-p} and d^{ped-p}, for the vehicle delay and pedestrian delay for pattern p.

The HCM model of the vehicle delay is based on the saturation flow rate of each movement group. Therefore, Equation (1.1) will be applied for computing d^{veh-p} for $p \in \{TWC, LTI, EPP\}$ in our study. However, d^{ped-p} has not been fully investigated in the literature. We will address this gap in Section 3.4 of this study.

1.4.2 Safety

Intersection safety is defined as the number of potential vehicle-to-vehicle and vehicle-to-pedestrian conflict situations at the intersection while conflict is a result of an interaction between users' movements at the intersection. A conflict with high severity usually is known as a collision and crash (Brow, 2011).

Different factors are used to predict or analyze the safety level of intersections based on crash history data, such as the classification of severity, the post-encroachment time, the time-to-collision (Lord, 1996), the average daily traffic and accident modification factor (Torbic *et al.*, 2010), the time to collision (Matsui *et al.*, 2011)), the annual average daily traffic (Alavi *et al.*, 2013), the average hourly conflict, the square root of users volume at the intersection, and the intersection conflict index (Abdul Majeed & Ewadh, 2019; Sayed & Zein, 1999). Most of these factors are more suitable for measuring vehicle–to–vehicle conflict. Then, to measure the pedestrian-vehicle conflict, some of the literature applied other indices such as pedestrian level of comfort, pedestrian level of stress, and pedestrian intersection index, which are related to the pedestrian facility at the intersection, intersection geometry, daily users volume, and the speed of users (Chang & Rodriguez, 2019). These indices have been used to compare the level of pedestrian safety between different intersections. However, this study intends to investigate the number of conflict situations for pedestrians and vehicles at one specific intersection under different signal patterns.

Zhang & Prevedouros (2003), based on HCM, formulated the potential user conflict (PC) that provides the intersection degree of safety and indicates the frequency of unsafe (conflict) situations. This factor can be applied to pedestrian and vehicle conflicts for an individual intersection according to the traffic flow and signal pattern (Zhang & Prevedouros, 2003). They studied the intersection with shared, permitted, and protected left-turn movement scenarios based on HCM. Equation (1.4) defines the potential conflict (number of users in conflict/interval) as provided by Zhang & Prevedouros (2003):

$$PC = pc^{v2v} + pc^{v2p}, (user\ with\ conflict\ /time\ interval) \tag{1.4}$$

where pc^{v2v} represents the total number of vehicles with the potential conflict (v2v) for each time interval; and pc^{v2p} is the total number of pedestrians with the potential conflict with a vehicle (v2p) for each time interval. The PC model of Zhang & Prevedouros (2003) computes the number of conflicts for each group of movements based on their interaction with another group of movements for a specific period. Therefore, the PC model can be defined for each pattern of study. In the rest of the research, we use the sum of the number of vehicles with the potential conflict of vehicle-to-vehicle pc^{v2v-p}, and the number of pedestrians with the potential conflict with the vehicle. pc^{v2p-p} for each pattern $p \in \{TWC, LTI, EPP\}$ with PC^p to denote the total number of users with potential conflicts for each time interval.

1.4.3 Delay and safety index

Zhang & Prevedouros (2003) introduced an indicator to compare different patterns called delay and safety index (DS). The DS (s) indicator reflects the combined effects of delay and potential conflict situations for pedestrians and vehicles. Equations (1.5) and (1.6) define the vehicle delay and safety index (DS^{veh}) and the pedestrian delay and safety index (DS^{ped}), respectively.

$$DS^{veh} = d^{veh} \ (1 + pc^{v2v}/V^{veh} \ ), (s) \tag{1.5}$$

$$DS^{ped} = d^{ped} \ (1 + pc^{v2p}/V^{ped} \ ), (s) \tag{1.6}$$

where d^{veh} and d^{ped} refer to an average vehicle and pedestrian delay, respectively, and V^{veh} and V^{ped} refer to the vehicle volume and pedestrian volume of the intersection for each time interval, respectively.

The DS index follows the current HCM level of service (LOS) indicator for signalized intersections. It considers the combination of delay and safety to get a comprehensive measure of LOS (Zhang & Prevedouros, 2003). Their research has used the pedestrian and vehicle volumes to estimate the delay and safety index as a weighted sum of potential conflicts, and delays (Transportation Research Board, 2016). DS has referred to HCM and considered the delay as an inconvenient perception and conflict as a risk. Then, they define the DS as the weighted average of DS^{veh} and DS^{ped} for each period of the study. Equation (1.7) provides the intersection DS as:

$$DS = \frac{DS^{ped} \ V^{ped} \ + DS^{veh} \ V^{veh}}{V^{ped} + V^{veh}} (s) \tag{1.7}$$

Their model is based on the number of users with the potential conflict and average user delay and is compatible with each signal pattern. Therefore, we can modify the DS model for pattern $p \in \{TWC, LTI, EPP\}$ and we define DS^{p}, DS^{veh-p} and DS^{ped-p} as delay and safety index, vehicle delay and safety index, and pedestrian delay and safety index for pattern $p \in \{TWC, LTI, EPP\}$, respectively.

The traffic signal is mostly investigated towards improving the relevant factors, such as traffic capacity, delay time, system throughput, safety, emissions, queue length, and other related factors (Stevanovic *et al.*, 2015; Jia *et al.*, 2019; Builenko *et al.*, 2018; Li & Sun, 2019a; Chen *et al.*, 2019; Li *et al.*, 2017). However, most of these criteria are driven by two fundamental measures:

the delay time (i.e., an additional travel time experienced by users) and safety (i.e., any conflict situations or possible interactions between vehicle and vehicle or pedestrian movements at the intersection). Therefore, our literature review focuses on these measures. We observe that these two measures are not entirely independent as a lower level of safety corresponds to a higher level of potential conflict, and this can, in turn, impact delay time. For this reason, we also review a third performance measure called the delay and safety index which provides the level of service of users at a signalized intersection by combining the pedestrians' and vehicles' delay and safety (represented by the number of potential conflicts). The delay time, safety, and delay and safety index, as performance measures of our study, are treated in Sections 3.2.2.1, 3.2.2.2, and 3.2.2.3, respectively.

1.4.4 Comparison of signal patterns based on the performances indicators

We defined in Section 1.3.2.2 the signal pattern as a set of movements that users are allowed to perform during the green interval of a phase in each cycle. Literature has reported that the signal pattern with leading, lagging, or separating intervals can improve travel experience quality at the intersection by influencing both delay and safety (Furth & Saeidi Razavi, 2019; Li & Sun, 2019c; Wong & Heydecker, 2011; Lam, Poon & Mung, 1997). Some studies have compared these patterns in terms of their cycle length, delay time, and safety (Zhang & Su, 2018; Li & Sun, 2019a). As mentioned in Section 3.2.2, we consider the delay, PC, and DS as reliable and measurable performances that can be used to compare each signal pattern level of service for the specific intersection.

Section 3.2.1 considers the most common signal patterns that account for both vehicles and pedestrians as EPP (exclusive pedestrian phase), TWC (two-way crossing), and LTI (leading through interval). The literature compared these patterns by analyzing how they affect delay time and safety under various user volumes. For example, the comparison between EPP and TWC using different traffic data shows that EPP in the intersection with a low volume of pedestrian increases the delay at the intersection and causes violation behavior of pedestrians, which consequently leads to reduced intersection safety (Ishaque & Noland, 2007; Ma *et al.*, 2015;

Zhang & Su, 2018). TWC with a high volume of pedestrians and the (right or left) turning vehicles can increase the conflict situations (Zhang & Su, 2018).

LTI minimizes the conflict between pedestrians and vehicles without impacting significant vehicular movement. However, separating the turning lane and through lanes on each approach is necessary; otherwise, the vehicle delay increases at the intersection (Saneinejad & Lo, 2015). Also, patterns with exclusive intervals (LTI and EPP) at the intersection with low pedestrian volume can increase the delay. However, it is expected the EPP with more increase the delay since it stops vehicular movements and forces pedestrian movement for the exclusive interval, and it will increase cycle length to reduce the capacity ratio of the intersection.(Furth & Saeidi Razavi, 2019).

1.5 Simulation methods

Traffic simulation is a widely used method applied in the research on traffic modeling, planning, and development of traffic networks and systems to estimate the current state of the traffic. The major types of traffic models are macroscopic, mesoscopic, and microscopic. Macroscopic models consider the aggregate behavior of traffic flow, while microscopic models consider the interaction of individual vehicles. These models include parameters such as driver behavior, vehicle locations, distance headway, time headway, and the velocity and acceleration of individual vehicles. Mesoscopic models share the properties of macroscopic and microscopic traffic models (Imran, Khan, Aaron Gulliver, Khattak & Nasir, 2020). Therefore, macroscopic and mesoscopic models are most suitable for modeling large networks, while microscopic models are usually applied to smaller areas. The microscopic model generally is useful to adjust signal timing (Stevanovic *et al.*, 2015).

A mixed-flow simulation model is expected to address the real-time demands of pedestrians and vehicles; consider any possible movements and potential conflicts of pedestrians and vehicles, and make a dynamic response to users' behaviors. The primary traffic simulation softwares are PARAMICS, RANSIMS, CORSIM, VISSIM, Synchro, and TRANSMODELER, but the available simulation software for this project are Synchro, HCS, and SIDRA. The Highway Capacity Software (HCS) is a user-friendly procedure to estimate intersection capacity and level of service (LOS) based on Transportation Research Board (2016) and includes operational, design, and planning analyses. The software analysis determines and maintains the level of service based on speed, existing traffic volumes, and roadway geometry. The software uses intersection configuration data and traffic flows, signal phasing, and timing as input and gives the stopped delay, V/C ratio, and LOS for output. The HCS application work with up to four legs of the intersection. Signalized and Un-signalized Intersection Design, and Research Aid (SIDRA) is an intersection-based program that analyzes the capacity, timing, and performance of isolated intersections. Signalized intersections, roundabouts, and yield two-way stops or all-way stop-controlled intersections with up to eight approaches can be planned with SIDRA. The software should optimize phase sequences, splits, and cycle lengths by considering intersection geometry, including the number of lanes, movements, and turning lanes. Compared with HCS, SIDRA can perform the best cycle length, and phase sequence includes minimizing the number of stops and delay time, queue length, vehicle emissions, and fuel consumption. SIDRA offers MOEs (measures of effectiveness) parameters such as total and average delay, v/c ratios, queue length, number of stops, speed, fuel consumption, and emissions. It is the only program that calculates capacity-based MOEs parameters per lane for all approaches. SIDRA is designed for fixed-time, pre-timed, and actuated signals.

SYNCHRO is a macroscopic traffic signal timing tool that can be used to optimize signal timing parameters for isolated and coordinated intersections. It can analyze multi-legged signalized intersections with up to six approaches per intersection. SYNCHRO is designed to optimize cycle lengths, splits, offsets, and phase sequences. SYNCHRO calculates intersection and approach delays based on the HCM for calculating delays and LOS. SYNCHRO requires traffic flow and geometric data. The program can evaluate existing traffic signal timing or optimize the settings for individual intersections, arteries, or a network. SYNCHRO has user-specified reports, including capacity analysis, LOS, delay, stops, fuel consumption, blocking analysis, and signal timing settings. SYNCHRO has unique visual displays, including an interactive platoon dispersion diagram (Sabra, Wallace & Lin, 2000).

1.6 Data collection

Data collection is a costly and time-intensive part of signal timing. The traffic data might be related to the traffic control devices, traffic characteristics, intersection geometry, and crash history (Urbanik *et al.*, 2015). Generally, we have three types of data collected: hourly, daily, and yearly. The data is preferably collected during the time with a minimum effect of climatic conditions and for which the data is measurable. Traffic Data can be collected both (1) manually and (2) automatically. There is a different kind of automatic data collection procedures such as Manual/Video which is performed by a person or video imaging located in a special position to count the requested data; Pneumatic tubes detect wheeled vehicles that pass over rubber tubes; Microwave uses radio waves to detect bicycles and pedestrians; Inductive loop sense metal objects that pass over the in-ground loop; Infrared use invisible radiant energy to detect bicycles and pedestrians; and Inductive loop paired with Infrared is a dual technology approach that a short duration or permanent loop is paired with infrared technology to detect both bicycles and pedestrians. These systems detect and collect pedestrian and bike data and are comparable in cost, accuracy, technical requirement, function (cover only pedestrian data or cover the bike, pedestrian, and vehicles at the same time), and the possibility of permanent use (it is not possible to use the manual data collection system permanently). Regarding this comparison, the video imaging automatic system, pressure sensor, and inductive loops are recommended for collecting multi-functional data over a long to permanent period.(Erik Minge, Courtney Falero, Greg Lindsey, Michael Petesch & Tohr Vorvick, 2017) The main techniques for pedestrian data collection are similar to vehicle data collection and may be categorized in:

- Manual field observation (expensive, error-prone, time-consuming)
- Manual observation of a video (error-prone, time-consuming)
- Semi-automated video analysis (the analytic data are limited in comparison to an automated method)

- Automated video analysis (accurate data, cover a variety of data, easy to use)

The video processing is easy to install, provides more information, and has a reasonable price (Ismail, Sayed, Saunier & Lim, 2009). The video imaging system is currently used to collect vehicle data. Due to the accessibility to the system and the saving time and cost with this system, the semi-automated and automated video imaging system is recommended to collect pedestrian data. The video imaging system is a significant method to achieve real-time data from pedestrians and vehicles.

CHAPTER 2

METHODOLOGY

This research investigates whether continuously changing the pattern configuration throughout the day to adapt to real-time traffic flow fluctuations improves the level of service at an intersection. It hypothesizes that considering both the delay time and the number of conflict situations in the design of such patterns will decrease travel time and increase safety. This research is articulated around the following three objectives:

- To specify the methods for measuring real-time delay and the number of conflict situations for the relevant signal patterns (TWC, EPP, and LTI).
- To develop a case study to assess the impact of the different traffic signal patterns on delay time and safety using real-time traffic data.
- To investigate the effectiveness of dynamically changing signal patterns in improving traffic signal performance (i.e., decreased travel time and increased safety) while identifying the best-performing pattern for each individual period of the case study.

Unlike what has been done in a large part of the literature to measure traffic signal performances based on exclusive vehicle-related indicators, the current study includes pedestrian-related performance indicators. Also, we take into account major performance indicators such as delay time, potential conflicts, and their combination to investigate our study regarding both time and safety-related measures. Traffic signals investigation can involve components related to traffic characteristics of roads, infrastructure, controlling tools, and users. Figure Intro.1 is designed based on these traffic signal components to categorize what has been neglected by the literature related to traffic signal optimization. In our research, we focus on the one with the green borders, the remaining parts are not accessible or applicable in our study since we don’t have access to the ITS system to manage the adaptive traffic control system.

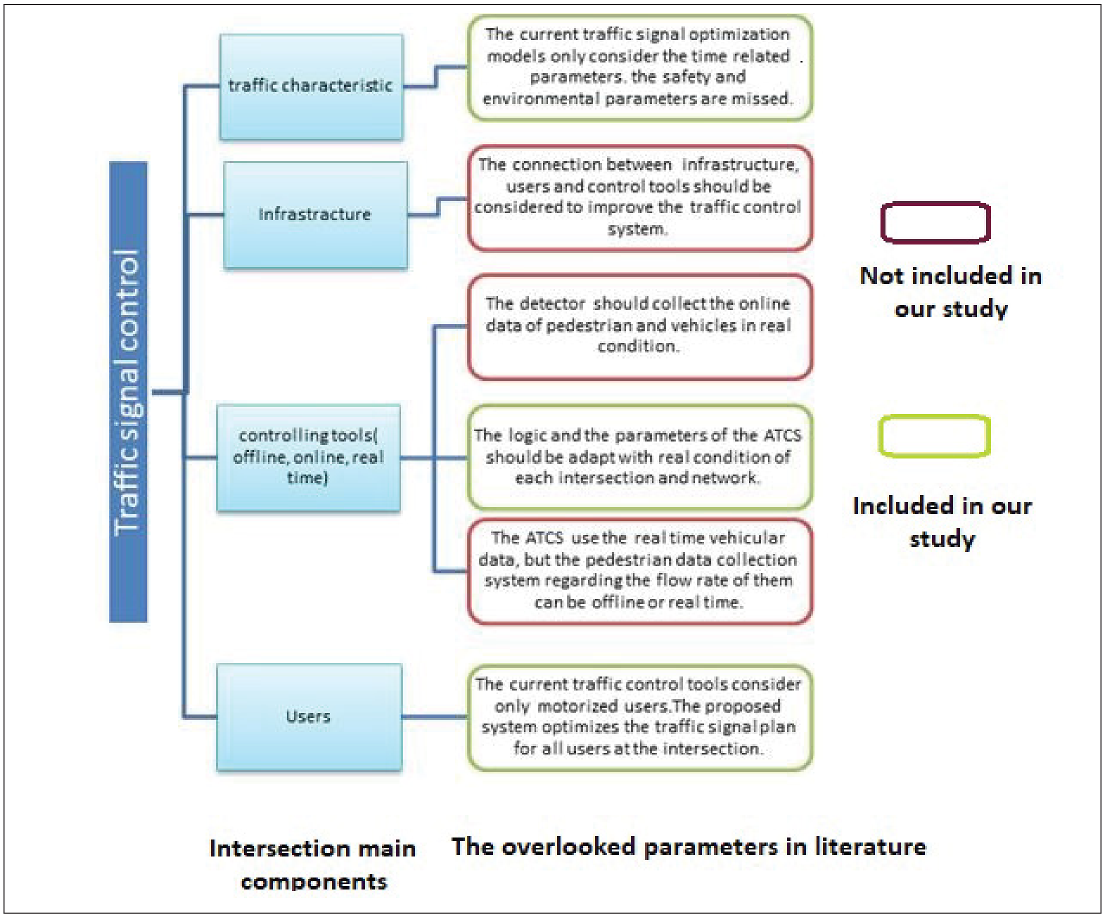

Figure Intro.1 Problem description

The methodological approach for this study differs from existing methods in several ways since, in this research, we discuss considering the time and safety-related performances indicator, using real-time traffic data, and taking into account both pedestrians and vehicles while we investigate the traffic signal pattern for an individual intersection. Figure Intro.2 shows the methodology steps and their relations with the objectives of our study.

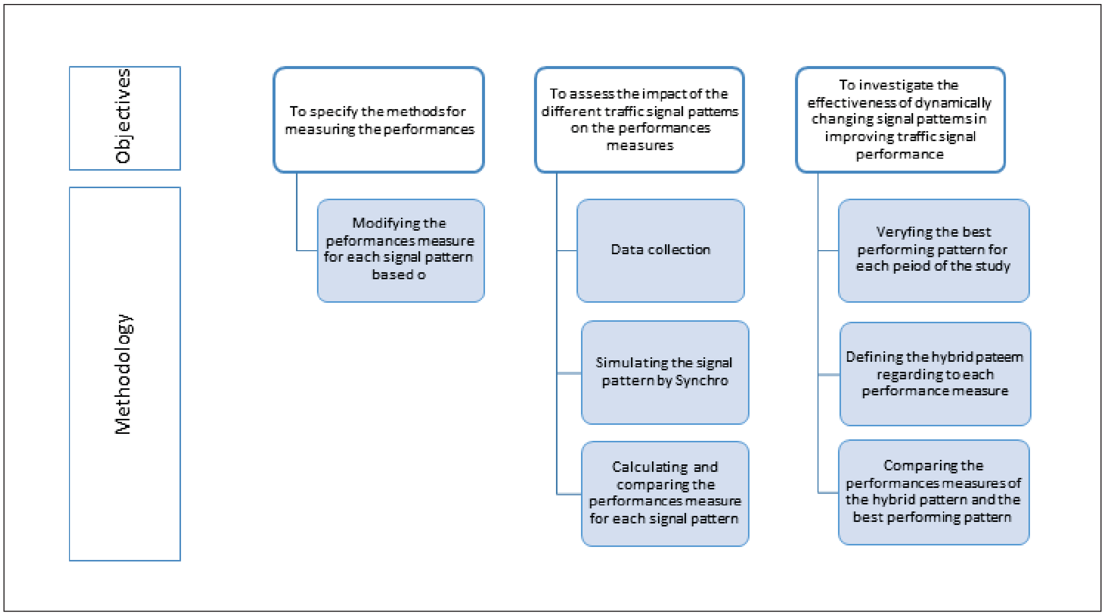

Figure Intro.2 Methodological approach

The equations used in this study were developed based on the HCM. The first stage of our methodology consists in modifying those equations for each studied signal pattern and making sure the performance indicator is pedestrian-sensitive by using the HCM approach. The second stage of the methodological approach is to investigate a case study. This study focuses on an isolated intersection with an average volume of 3660 users per hour for the day of the study.

The case study is selected by choosing a signalized intersection with 1) characteristics of a single and isolated intersection; 2) demand volume varying throughout the typical working day, and 3) for which real-time traffic data can be extracted. Following the HCM approach, the demand data are obtained at regular intervals (15 minutes) for all users.

Then, Synchro version 10 is selected to simulate the traffic data because 1) it allows calculations based on the 6th edition of HCM; 2) it is flexible enough to simulate the signal patterns investigated in this study, and 3) it is available to the authors. Synchro simulates each study period based on the real-time data of the case-study intersection to provide the optimum cycle length, green time, and vehicle delay for each pattern. Then, pedestrian delay and conflict situations are calculated for each studied pattern. Two fixed cycle lengths are tested.

We also investigated the optimum cycle length for each signal pattern. However, the optimum cycle length of Synchro seeks to minimize the delay time and does not consider safety in the objective function. Thus, we only investigated the hybrid pattern optimum cycle related to delay time, and the results are reported in Appendix A.

In the next step, the three studied patterns are compared based on their performance measures and the best-performing pattern is verified for each period of the study. Based on the best-performing pattern, the hybrid pattern is defined for the day of the study as the integration of the best-performing pattern for each period of the study. A final step in the methodology approach, the performance measures of the hybrid patterns are compared with the best-performing pattern performance measure to verify the research hypothesis, which indicates the effect of the hybrid pattern on delay time and safety of the intersection.

The following chapter aims to articulate a detailed and comprehensive account of the methodology employed in this study. As a published article, this chapter explicates the process and outcomes of the research, contributing to the advancement of knowledge in this domain.

CHAPTER 3

COMPARISON OF THE PERFORMANCE OF HYBRID TRAFFIC SIGNAL PATTERNS AND CONVENTIONAL ALTERNATIVES WHEN ACCOUNTING FOR BOTH PEDESTRIANS AND VEHICLES

F. Montazeri[1] , F. Errico[2] , L. Pellecuer,[3]

[1,2] Département de génie de la construction, École de technologie supérieure, 1100, rue Notre-Dame Ouest, Montréal (Québec) H3C 1K3;
[3] School of Engineering, Faculty of Environment and Technology. The University of the West of England (UWE Bristol), Frenchay Campus, Coldharbour Lane. Bristol, BS161QY. United Kingdom;

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3.1 Introduction

With the increasing use of vehicles globally, transportation management and control systems have been developed to facilitate access by motorized users to roads and infrastructures and consequently increase the quality of the travel experience. The urban transportation system includes three general components: the infrastructure (roads, intersections, and bridges), users (vehicles, pedestrians, bicycles, and drivers), and operation tools (signs, traffic signals, and management and control systems). As a tool for traffic management in urban areas, traffic signals feature different control approaches in terms of methods, technologies (hardware and software), and objectives. The common objectives of the traffic signal are to maximize vehicle throughput and intersection safety while minimizing travel time.

This paper focuses on how traffic signal control techniques may be adapted to consider pedestrian-related performance indicators to improve safety and travel time for an intersection. The control of traffic signals is a complex process since it involves many interrelated elements, such as safety, capacity, delay time, queue length, intersection geometries, heterogeneous users, and environmental conditions. All these elements affect the cycle length (the time a traffic signal requires to complete the sequence of signal phases) and signal pattern (the set of user movements

[1] Montazeri, Errico & Pellecuer (2022)

allowed at each phase of the signal cycle). The cycle length and the signal pattern represent essential elements in traffic signal investigation. Most traffic agencies nowadays are interested in the concept of an adaptive control system that applies real-time traffic data to change the cycle length and the pattern of a traffic signal dynamically (Transportation Research Board, 2016).

In the literature, traffic signal control optimization is mainly geared towards minimizing the cycle length and improving measures that are directly or indirectly influenced by the cycle length. These measures include traffic capacity, travel time, system throughput, vehicle-to-vehicle conflict, and vehicle emissions (Stevanovic *et al.*, 2015; Jia *et al.*, 2019; Builenko *et al.*, 2018; Chen *et al.*, 2019; Li *et al.*, 2017; Li & Sun, 2019a). All these measures mainly quantify vehicle-related performance. Pedestrian-related performance indicators have also been studied in the literature (Wong & Wong, 2003; Ishaque & Noland, 2007; Builenko *et al.*, 2018), but in most related works, interactions between pedestrians and vehicles were not explicitly considered.

In real-world intersections, traffic signal control may feature rather complex configurations of signal patterns. The literature, however, mostly focuses only on simple forms of traffic signal phase sequences and patterns (such as a two-phase traffic signal). Even works that focus on optimal cycle length models applied to different signal patterns (Ishaque & Noland, 2007; Li & Sun, 2019a; Zhang & Su, 2018), assume simplified intersection conditions with fixed traffic flow or one-way streets (Ma *et al.*, 2015; Zhang & Su, 2018). Similarly, one specific signal pattern is typically applied for the whole day whereas traffic flows largely change during the day, with a potential increase of delay time and travel time at the intersection (Zhang & Su, 2018). Furthermore, since collecting pedestrian data has traditionally been costly and time-consuming, even advanced traffic control systems capable of dynamically adapting the cycle length to real-time data have not considered pedestrian users (Transportation Research Board, 2016). However, recent development in information technology allows more easily collection and process real-time traffic data, thus enabling more complex signal control policies to see (Feng, Duives, Daamen & Hoogendoorn, 2021), for example.

The most common signal patterns that explicitly consider interactions between motorized and non-motorized users are: Two-Way Crossing (TWC), Exclusive Pedestrian Phase (EPP), Leading Pedestrian Interval (LPI), and Leading Through Interval (LTI). In the literature, a trade-off between safety and delay time has been considered to measure the efficiency of each signal pattern (Ma *et al.*, 2015). Generally, to investigate the safety of intersections, the literature considers the number of accidents or predicted crash data (Alavi *et al.*, 2013; Torbic *et al.*, 2010; Sayed & Zein, 1999; Li *et al.*, 2012; Frankish *et al.*, 2001). Moreover, to estimate the intersection delay, several researchers have used the HCM delay model. However, their delay and safety models have usually failed to consider the effect of signal patterns or pedestrian data.

This paper aims to investigate whether continuously changing the pattern configuration throughout the day to adapt to real-time traffic flow fluctuations could improve the level of service at an intersection. This paper hypothesizes that considering both the delay time and the number of conflict situations in the design of such a hybrid pattern will decrease travel time and increase safety. This research is articulated around the following three objectives:

- To specify the methods for measuring real-time delay and a number of conflict situations for relevant signal patterns (TWC, EPP, and LTI).
- To develop a case study to assess the impact of the different traffic signal patterns on delay time and safety using real-time traffic data.
- To investigate the effectiveness of dynamically changing signal patterns in improving traffic signal performance (i.e., decreased travel time and increased safety) while identifying the best-performing pattern for each individual period of the case study.

The rest of the paper is organized as follows. Section 3.2 reviews the literature to identify the relevant signal patterns and performance indicator models. Section 3.3 details the methodological approach used in this study. Section 3.4 develops pedestrian-sensitive performance indicators and generates the delay time and potential conflict models for each signal pattern of the study. In Section 3.5, the results and limitations are discussed as the experimental setting is applied to a case study for a specific intersection in Montreal, using real-time traffic data and Synchro software in the simulation phase to verify the impact of the hybrid signal pattern on the level of service at the intersection. In section 3.6, the results and limitations of the study are presented and discussed. Finally, Section 3.7 draws conclusions based on the case study.

3.2 Literature Review

This section identifies the critical parameters related to this paper and discusses how these parameters are dealt with in the literature. A variety of signal patterns and their performance are also described. Furthermore, this section reviews how the performances of signal patterns are compared in the literature. In particular, Section 3.2.1 reviews the literature related to signal patterns while Section 3.2.2 reviews performance indicators such as Delay time, Potential Conflict, and Delay and Safety index. Finally, Section 3.2.3 focuses on the literature comparing signal pattern performance.

3.2.1 Signal Patterns

As previously mentioned, our aim in this paper is to perform comparisons of several signal patterns. Formally, a signal pattern dictates the possible user movements that are permitted during the green interval of a phase (a phase consists of a set of green, red, and clearance intervals assigned to specified traffic movement (s) during each cycle) (Urbanik *et al.*, 2015). In a typical four-leg (two-phase) intersection, we have four possible signal pattern types:

- Free pattern: no movement restrictions are applied to any phases during the green interval.
- Exclusive pattern: the green interval is partitioned into mutually exclusive (groups of) movements.
- Leading pattern: a group of movements is permitted for the complete green interval duration, while a second restricted group of movements is only permitted after a specific time interval.
- Lagging pattern: this pattern is similar to the leading ones, but the restricted movement group is only allowed before a specific time interval.

These patterns can be applied to the movements of each user category, but this study focuses on signal patterns that also explicitly account for pedestrian movements. The most common signal patterns that address the pedestrian interval are (Urbanik *et al.*, 2015; Furth & Saeidi Razavi, 2019):

- TWC (Two-Way Crossing): allows pedestrians to cross the intersection during the full duration of the green interval of the adjacent vehicular movement;
- EPP (Exclusive Pedestrian Phase): protects and excludes the pedestrian phase from all vehicular movements;
- LPI (Leading/Lagging Pedestrian Interval): leads or lags the green pedestrian interval, during which vehicles are not permitted to cross;
- LTI (Leading/Lagging Through Interval): Similar to LPI, it leads or lags the pedestrian interval; however, only vehicular turning movements are prohibited on a pedestrian green interval.

Given that LTI allows vehicles to cross the intersection during the green pedestrian interval, it is commonly preferred to LPI. For this reason, the present study focuses on the LTI, TWC, and EPP patterns, and it will not investigate the LPI pattern in depth.

3.2.2 Performance Indicators

In the literature, several indicators are developed to assess the performance of traffic signals; these indicators include the delay time (Jia *et al.*, 2019; Li & Sun, 2019a), the traffic capacity (Jia *et al.*, 2019), the system throughput (Jia *et al.*, 2019; Li & Sun, 2019a), the intersection safety (Stevanovic *et al.*, 2015; Builenko *et al.*, 2018), the GHG emission count (Stevanovic *et al.*, 2015), the queue length (Chen *et al.*, 2019), the travel time (Chen *et al.*, 2019; Li *et al.*, 2017), etc. However, all these indicators are driven by two fundamental measures: the delay time (i.e., the additional travel time experienced by users compared to free movement through the intersection) and intersection safety (i.e., events to do with any conflict situations or possible interactions between vehicle and vehicle or pedestrian movements at the intersection). Therefore, our literature review focuses on these measures. We observe that these two measures are not entirely independent since a lower level of safety corresponds to a higher level of potential conflict, and this can in turn impact the delay time. For this reason, we also review a third performance indicator called the Delay and Safety index, which provides the level of service of users at a signalized intersection by combining both pedestrian and vehicle delay and safety (represented by the number of users with potential conflicts). These three performance indicators are presented in Sections 3.2.2.1, 3.2.2.2 and 3.2.2.3, respectively.

3.2.2.1 Delay Time

As previously mentioned, the delay time at the intersection represents additional travel time experienced by users because of the traffic control system, changes in speed due to geometric conditions, incidents, and interactions with other road users versus free movement through the intersection (Transportation Research Board, 2016). While the delay time can generally account for several types of users, such as private vehicles, pedestrians, bikes, and transits, we focus here on two aggregate user types: vehicles (including private and transit vehicles and bikes) and pedestrians.

Delay can be estimated using different models. As reported by Tom V. Mathew (2014), there are four primary methods for estimating the delay time: Akcelik (Li *et al.*, 1994), HCM (Transportation Research Board, 2016), Webster (Wagner *et al.*, 2014), and HSL (Roshandeh *et al.*, 2016; Tom V. Mathew, 2014). Among these models, the HCM is reputed to be more accurate even in situations with under or over-saturated intersections (Hadiuzzaman *et al.*, 2014). As mentioned earlier, one component of intersection delay is a vehicular delay. Equation (1.1) describes the vehicle delay model of HCM:

$$d^{veh} = d^U + d^I + d^Q \ (s/veh) \tag{3.1}$$

where d^U defines the uniform delay based on the assumption of uniform arrivals and stable flow of vehicles; d^I defines the incremental delay due to the effect of random, cycle-by-cycle fluctuations in demand, which occasionally exceed capacity and are caused by a sustained oversaturation during the analysis period; and d^Q defines the initial queue delay resulting from unmet demand in the previous period. HCM refers to the saturation flow rate used to compute

d^{veh} for different signal patterns and can be calculated for each approach, lane, and movement group of the intersection (Transportation Research Board, 2016).

The other component of the intersection delay is the pedestrian delay. Different studies modify the HCM model to include the pedestrian flow rate, pedestrian violation behavior, and traffic signal pattern (Ma *et al.*, 2015, 2014; Yang, 2010). The model proposed by Ma *et al.* (2014, 2015) modifies the HCM to account for the pedestrian delay in TWC and EPP. This model comprises three parts. The first part is the signal delay (d^{sig}), defined as the waiting time of pedestrians stopping at the intersection because of the traffic light. The second part is the conflict delay (d^{con}), defined as the additional experienced delay time due to conflicts between pedestrians and turning vehicles. The third part is the detour delay (d^{det}) due to the fact that pedestrians willing to cross the intersection diagonally must perform a detour if the considered signal pattern does not allow diagonal crossing. As a consequence, Ma *et al.* (2015) determine the average pedestrian delay time as:

$$d^{ped} = d^{sig} + d^{con} + d^{det} \ (s/ped) \tag{3.2}$$

where d^{ped} and d^{veh} are the average per-user delay of pedestrians and vehicles, respectively. Ma *et al.* (2014) recommend adapting the weighted delay as the intersection delay (s/user):

$$D = \frac{d^{veh}V^{veh} + d^{ped}V^{ped}}{V^{veh} + V^{ped}} \ (s/user) \tag{3.3}$$

where V^{veh} and V^{ped} refer to the vehicle volume and pedestrian volume of the intersection, respectively.

We observe that expressions of both the vehicle delay in the HCM model and the pedestrian delay proposed in Ma *et al.* (2014) depends on the specific pattern to which the measure is applied. For this reason, in the rest of the paper, we add a superscript p with $p \in \{TWC, LTI, EPP\}$ to underline such a dependence when needed. For example, we use D^p to denote the weighted intersection delay time for pattern p; similarly, we use d^{veh-p} and d^{ped-p}, for the vehicle delay and pedestrian delay for pattern p.

The vehicle delay HCM model is based on the saturation flow rate of each movement group. Therefore, Equation (1.1) will be applied for computing d^{veh-p} for $p \in \{TWC, LTI, EPP\}$ in our study. However, d^{ped-p} has not been fully investigated in the literature. We will address this gap in Section 3.4 of this study.

3.2.2.2 Potential Conflict

Intersection safety is defined as the number of potential vehicle-to-vehicle and vehicle-to-pedestrian conflict situations at the intersection. A conflict is any possible unsafe situation or interaction between user movements at the intersection. A conflict with high severity is usually known as a collision and crash (Brow, 2011).

Different elements are used to predict or analyze the safety level of intersections based on crash history data. These factors include the severity classification, the post-encroachment time, the time-to-collision (Lord, 1996), the average daily traffic and accident modification factor (Torbic *et al.*, 2010), the time to collision (Matsui *et al.*, 2011)), the annual average daily traffic (Alavi *et al.*, 2013), the average hourly conflict, the square root of users volume at the intersection, and the intersection conflict index (Abdul Majeed & Ewadh, 2019; Sayed & Zein, 1999). Most of these factors are suitable for measuring vehicle-to-vehicle conflict. To quantify pedestrian-to-vehicle conflict risk, some authors applied indices such as pedestrian level of comfort, pedestrian level of stress, and pedestrian intersection index, which are related to the pedestrian comfort at the intersection, intersection geometry, daily user volume, and the user speed (Chang & Rodriguez, 2019). These indices are useful for comparing the level of pedestrian safety at different intersections. However, the value of these indices would not change with the signal pattern of the intersection. Therefore, to grasp the influence of the traffic signal pattern on pedestrian safety, another index needs to be developed.

Zhang & Prevedouros (2003), based on HCM, proposed the Potential user Conflict (PC) metric, which is intended to provide a measure of the degree of safety at the intersection and indicates the frequency of unsafe (conflict) situations. This measure can be applied to pedestrian and vehicle conflicts for an individual intersection based on the traffic flow and signal pattern (Zhang & Prevedouros, 2003). They focused on an intersection with shared, permitted, and protected left-turn movement scenarios. Equation (1.4) defines the potential conflict (number of users in conflict/interval) as provided by Zhang & Prevedouros (2003):

$$PC = pc^{v2v} + pc^{v2p} \ (user\ with\ conflict\ /time\ interval) \tag{3.4}$$

where pc^{v2v} represents the total number of vehicles with a potential conflict (v2v) for each time interval and pc^{v2p} is the total number of pedestrians with a potential conflict with a vehicle (v2p) for each time interval. PC model of Zhang & Prevedouros (2003) computes the number of conflicts for each group of movements based on their interaction with another group of movements for the specific period. Therefore, the model can be defined for each pattern studied. In the rest of the paper, we use the sum of the number of vehicles with a potential vehicle-to-vehicle conflict pc^{v2v-p}, and the number of pedestrians with a potential conflict with vehicle pc^{v2p-p} for each pattern $p \in \{TWC, LTI, EPP\}$ with PC^p to denote the total number of users with potential conflicts for each time interval.

3.2.2.3 Delay and Safety Index

Zhang & Prevedouros (2003) introduced an indicator called the Delay and Safety index (DS) for use in comparing different patterns. DS (s/user) indicator reflects the combined effects of delay and potential conflict situations for pedestrians and vehicles. Equations (1.5) and (1.6) define the vehicle Delay and Safety index (DS^{veh}) and the pedestrian Delay and Safety index (DS^{ped}), respectively.

$$DS^{veh} = d^{veh} \left(1 + pc^{v2v}/V^{veh}\right) (s/veh) \tag{3.5}$$

$$DS^{ped} = d^{ped} \left(1 + pc^{v2p}/V^{ped}\right) (s/ped) \tag{3.6}$$

where d^{veh} and d^{ped} denote the average vehicle and pedestrian delay, respectively, and V^{veh} and V^{ped} denote the vehicle and pedestrian volumes of the intersection for a given reference time interval, respectively. We observe that the DS index is a measure of the level of service at the intersection that accounts for both delay time and potential conflicts. Zhang & Prevedouros (2003) proposed to integrate Equations (1.5) and (1.6) into a single weighted expression as:

$$DS = \frac{DS^{veh}\, V^{veh} + DS^{ped}\, V^{ped}}{V^{veh} + V^{ped}}\ (s/user). \tag{3.7}$$

This model is based on the number of users with potential conflicts and the average user delay and can be specified for each signal pattern. Therefore, we can modify the DS model for pattern $p \in \{TWC, LTI, EPP\}$ and we define DS^p, DS^{veh-p} and DS^{ped-p} as the Delay and Safety index, the vehicle Delay and Safety index, and the pedestrian Delay and Safety index for patterns $p \in \{TWC, LTI, EPP\}$, respectively.

3.2.3 Comparison of Signal Patterns

In Section 3.2.1, we defined the signal pattern as a set of movements that users are allowed to perform during the green interval of a phase in each cycle. The literature reports that the signal pattern with leading, lagging, or separating intervals can improve the travel experience quality at the intersection by influencing both the delay and safety (Furth & Saeidi Razavi, 2019; Li & Sun, 2019c; Wong & Heydecker, 2011; Lam *et al.*, 1997). Some studies have compared these patterns in terms of their cycle length, delay time, and safety (Zhang & Su, 2018; Li & Sun, 2019a). As mentioned in Section 3.2.2, we consider D, PC, and DS as reliable and measurable performance indicators that can be used to compare the level of service of each signal pattern for a specific intersection.

Section 3.2.1 considers that the most common signal patterns accounting for both vehicles and pedestrians are EPP (Exclusive Pedestrian Phase), TWC (Two-Way Crossing), and LTI (Leading Through Interval). The literature compares these patterns by analyzing how they affect delay time and safety under various user volumes. For example, a comparison between EPP and TWC using different traffic data shows that EPP in an intersection with a low pedestrian volume increases the delay at the intersection and causes violation behavior among pedestrians, which consequently leads to reduced intersection safety (Ishaque & Noland, 2007; Ma *et al.*, 2015;

Zhang & Su, 2018). TWC with a high volume of pedestrians and (right or left) turning vehicles can increase the number of conflict situations (Zhang & Su, 2018).

LTI minimizes conflicts between pedestrians and vehicles without significantly impacting vehicular movement. However, separating the turning and through lanes at each approach is necessary; otherwise, vehicle delay increases at the intersection (Saneinejad & Lo, 2015). Furthermore, patterns with exclusive intervals (LTI and EPP) at an intersection with low pedestrian volumes can increase delays. However, it is expected that EPP will increase the delay significantly since it stops vehicular movements and forces pedestrian movements for exclusive intervals, and will increase the cycle length to reduce the capacity ratio of the intersection (Furth & Saeidi Razavi, 2019).

Besides looking at the literature that compares the results of different patterns while the traffic signal performs the fixed pattern for the entire period covered by the study, we aim to study how allowing the signal pattern to change dynamically during operations according to observed traffic demand can potentially impact the traffic signal performance. Unlike what is largely observed in the literature, with traffic signal performance based exclusively on vehicle-related measures, this study aims to include pedestrian-related parameters. Delay time, potential conflicts, and their combination are among the most widely adapted performance indicators in the literature. Section 3.3 provides the methodology of our study which investigates how traffic signal efficiency is affected by dynamically changing signal patterns.

3.3 Materials and Methods

The methodological approach adopted for the present study differs from existing methods in several ways. First, the study focuses on adapting a performance indicator model to suit different pedestrian-related signal patterns. Second, it simulates real-time data of pedestrians and vehicles throughout the day. Thirdly, it compares different signal patterns based on performance indicators to provide the best-performing pattern for each study period. Moreover, it investigates how dynamic signal patterns (hybrid patterns) can improve service levels.

To address the three research objectives identified in Section 3.1, we proceed in three stages:

- First, delay and potential conflict parameters of each studied pattern are modified in Section 3.4 (see Table 3.3).
- Then, the studied patterns are investigated through a case study. They are simulated based on observed demand, and D, PC, and DS are computed for each pattern in Section 3.5.
- Finally, the performance of each pattern in the case study is compared for every time step. Following this comparison, a hybrid pattern maximizing the service level over the entire study period is developed and its performance is compared to that of other patterns in Section 3.5.

As discussed in Section 3.2, the equations used in this study are developed based on the HCM. The first stage of our methodology consists in modifying the equations for each studied signal pattern and using the HCM approach to ensure that the performance indicator is pedestrian-sensitive. Therefore, D, PC, and DS equations developed in Sections 3.4.1, 3.4.2 and 3.4.3, respectively, comply with the HCM 6th edition.

In the second stage of the approach, a case study is developed and focuses on an isolated intersection with an average volume of 3660 users per hour for the day of study. The case study is selected by choosing a signalized intersection: (1) having the characteristics of a single and isolated intersection, (2) with a demand volume varying throughout a typical working day, and (3) for which real-time traffic data can be extracted. Following the HCM approach, demand data are obtained at regular intervals (15 min) for all users.

In this second stage, Synchro version 10 is selected to simulate the traffic data because: (1) it allows calculations based on the 6th edition of HCM, (2) it is flexible enough to simulate the signal patterns investigated in this study, and (3) it is freely available to the authors. According to Cubic (2019), “Synchro Software and its suite of associated applications is a traffic signal timing software that assists engineers and transportation planners design, model, optimize, simulate and animate signalized and unsignalized intersections” (Cubic Corporation, 2019). Synchro simulates each study period based on the real-time data of the case study intersection to provide the optimum cycle length, green time, and vehicle delay for each pattern. Synchro's ring-barrier option enables the user to define the traffic pattern to be simulated, while Synchro optimizes the length of each phase. Moreover, the performance, in terms of factors such as vehicle delay, traffic signal cycle length, and green time, is extracted directly from simulation results. The HCM and Synchro consider the saturation flow rate of the movement group in computing the vehicular delay for each signal pattern. Therefore, we use Synchro's estimation of vehicular delay in our study. Following HCM 6th edition, and to ensure results accuracy, Synchro simulates the traffic signal for each 15-min interval.

To assess the impact of the cycle length on the performance of each signal pattern, two sets of simulations are run. First, the green phase and vehicular delay are extracted from Synchro for different fixed cycle length values, and second, the cycle length, green time of each phase, and vehicular delay are optimized by Synchro, from which they are then extracted. For each studied pattern, the pedestrian delay and conflict situations are then calculated based on the equations in Section 3.4.

The next methodological stage consists of a comparison of the performance indicator values obtained from the signal patterns according to the equations in Section 3.4 to identify the best-performing pattern (the pattern that most improve the level of service) for every 15 min. We investigate and simulate three patterns (LTI, TWC, EPP) and build a hybrid pattern, consisting of a pooling of the best-performing pattern for each interval. Finally, for each performance indicator, we compare the performance of the hybrid pattern to that of the three regular patterns (LTI, TWC, EPP) to verify whether the hybrid pattern improves the performance indicators.

3.4 Development of Pedestrian-Sensitive Performance Indicators

The performance indicators mentioned in Section 3.2 are not available for all patterns and do not generally consider signal patterns with both pedestrian- and vehicle-sensitive indicators. The performance indicators used in this paper adapt the state-of-the-art indicators to all signal patterns considered (i.e., TWC, EPP, LTI) and generalize the indicators to account for pedestrians and vehicles.

This paper proposes a new delay measure by building on the model of Ma *et al.* (2015), introduced in Section 3.2.2.1, which suitably accounts for pedestrians. It also modifies the potential conflict and delay and safety models proposed by Zhang & Prevedouros (2003) to cover all signal patterns of our study. These models are introduced in Sections 3.2.2.2 and 3.2.2.3, respectively.

The resulting pedestrian models, namely, the conflict model and the delay and safety model, are presented in Sections 3.4.1, 3.4.2, and 3.4.3, respectively.

3.4.1 Computation of the Delay Time for Each Signal Pattern

In this study, the intersection delay is considered as a weighted average of pedestrian and vehicle delays. Since the pedestrian delay of Ma *et al.* (2015) only considered TWC and EPP, we further develop their delay model to also consider the LTI pattern by modifying the delay time model described by Equation (1.2) for the regular four-arm intersection. Figure 3.1 illustrates the four-arm intersection layout as a reference intersection model for this study. The set, parameters, and variables used to compute the pedestrian delay are described in Table 3.1.

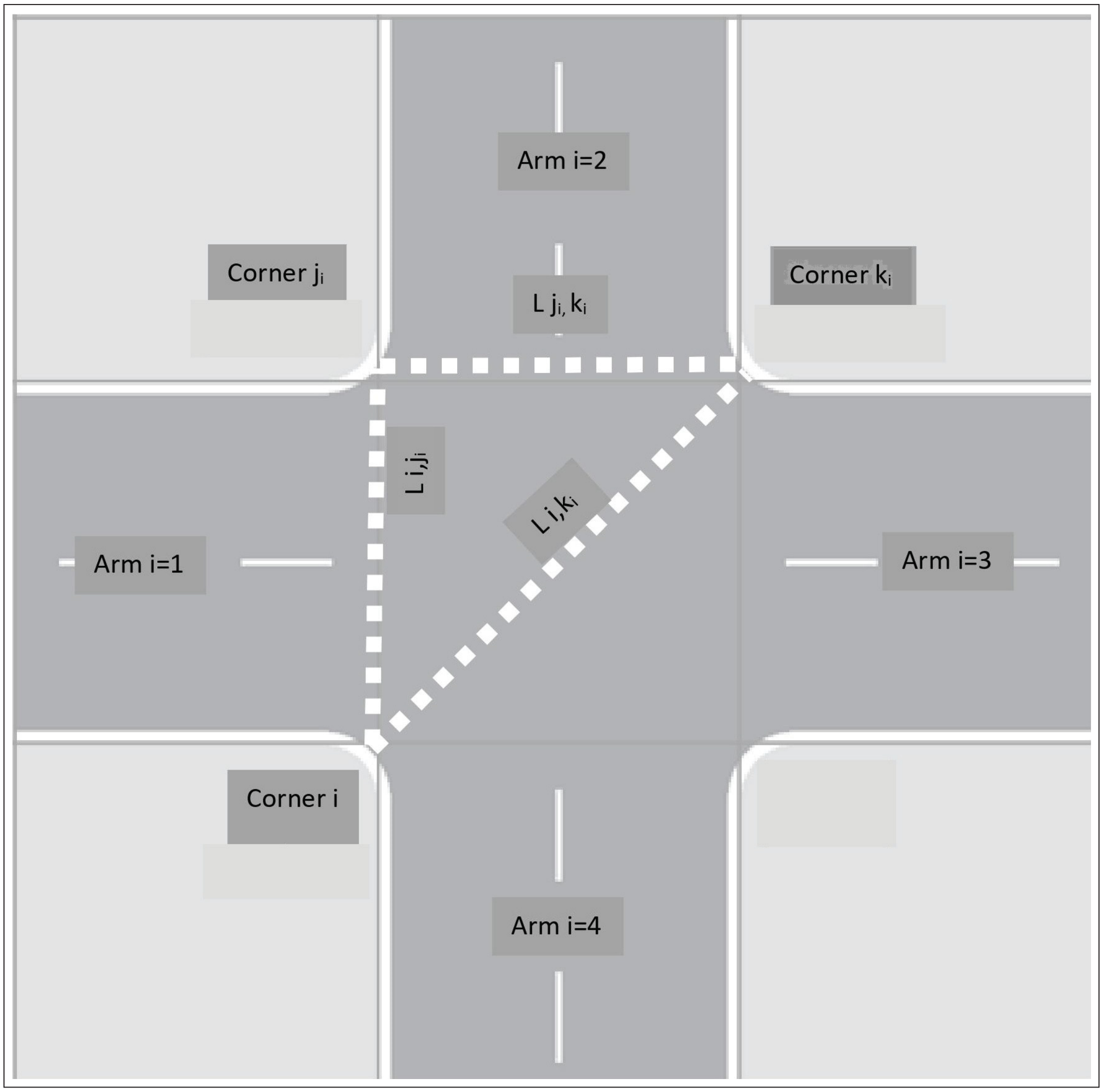

Figure 3.1 Reference intersection layout with key parameters used in the simulation

Table 3.1 Sets, parameters and descriptions

Sets, parameters, variables	**Description**	**Value obtained from**
$i \in I = \{1, 2, 3, 4\}$	Set of arms and corresponding corners at an intersection	–
$j_i \in I$	Arm and corner following $i \in I$ $j_i = \begin{cases} i+1 & i \leq 3 \\ 1 & otherwise \end{cases}, \forall i \in I$	–
$k_i \in I$	Diagonal corner from corner $i \in I$, $k_i = \begin{cases} i+2 & i+2 \leq 4 \\ (i+2)-4 & otherwise \end{cases}, \forall i \in I$	–
g_i^{veh}	Duration of green for vehicles from arm $i \in I$, (s)	Simulation (Synchro)
g_i^{ped}	Duration of green for pedestrian crossing arm $i \in I$, (s)	Simulation (Synchro)
l_{ij_i}	Length of crosswalk from corner i to corner j_i, (m)	Observation
s^{ped}	Average walking speed of pedestrians, (m/s)	Observation
α_{ik_i}	Portion of pedestrian volume from corner i to corner k_i in total pedestrian demand of corner $i \in I$	Observation
t	Acceptable gap: time between vehicles when the vehicle confidently does (a) lane change(s)	Computation
μ_i	Flow rate of vehicles turning on corner $i \in I$ (veh/h)	Observation
C	Cycle length,(s)	Simulation (Synchro)
d^{ped}	Pedestrian delay at intersection(s)	Computation
d^{sig}	Pedestrian delay due to traffic signal at crosswalk(s)	Computation
d^{con}	Pedestrian delay due to conflicts with turning vehicles(s)	Computation
v_i^{lt}	Number of left turning vehicles on approach $i \in I$ during green interval of g_q	Observation
v_i^{ot}	Number of vehicles moving in the opposite direction on approach i during a green interval of g_u	Observation
d^{det}	Pedestrian delay due to detour distance(s)	Computation

As mentioned in Section 3.2.2.1, the three parts constituting the pedestrian delay in Equation (1.2) are calculated by Equations (3.8) to (3.10) (Ma *et al.*, 2015):

$$d^{ped} = d^{sig} + d^{con} + d^{det} \ (s/ped) \quad (1.2)$$

where d^{ped} is the average pedestrian delay at the intersection; d^{sig} is the pedestrian delay due to the traffic signal at the crosswalk; d^{con} is the pedestrian delay due to conflicts with turning vehicles; and d^{det} is the pedestrian delay due to detour distance, which is defined as the difference between the time needed by pedestrians to cross diagonally to corner k_i and the time to cross conventionally from corner i to j_i and then from j_i to k_i.

The pedestrian signal delay is defined as a waiting time due to the red interval of a traffic signal, and was introduced by Ma *et al.* (2015) as Equation (3.8):

$$d^{sig} = \sum_{i \in I} \left(\frac{(C - g_i^{ped})^2}{2C} + \alpha_{ik_i} \frac{(g_i^{veh} - \frac{l_i}{s_i^{ped}})(C - g_i^{ped}) + 0.5 g_{j_i}^{ped} \, (g_{j_i}^{veh} - \frac{l_{j_i}}{s_{j_i}^{ped}})}{C} \right) (s/ped) \tag{3.8}$$

The first part of Equation (3.8) calculates the pedestrian signal delay for a pedestrian intending to cross from arm i to arm j_i (conventionally). The second part of Equation (3.8) measures the pedestrian waiting time to cross diagonally from corner i to corner k_i. However, because of traffic light patterns, pedestrians have to cross from corner i to j_i and stop for the pedestrian green interval of arm $i + 1$, and then cross from corner j_i to k_i.

The pedestrian conflict delay was defined in the model of Ma *et al.* (2015) as Equation (3.9):

$$d^{con} = \sum_{i \in I} \left(\frac{e^{\mu_i t} - \mu_i t - 1}{\mu_i} + a_{ik_i} \frac{e^{\mu_{j_i} t} - \mu_{j_i} t - 1}{\mu_{j_i}} \right) \, (s/ped) \tag{3.9}$$

where d^{con} is recalculated as a result of the interaction between pedestrians and vehicles, related to the volume of turning vehicles and gap time between vehicles at arm i. Equation (3.9) is also divided into two parts. The first covers pedestrians crossing from corner i to corner j_i, and the second is related to pedestrians intending to cross from corner i to k_i. The latter may experience interactions with vehicles at corner j_i.

The last part of the pedestrian delay in the model of Ma *et al.* (2015) is the detour delay. This delay is related to the length of the crosswalk and the pedestrian speed. It is the difference between the time required for a pedestrian intending to cross the intersection diagonally to cross the intersection conventionally (i.e., one approach after the other) as compared to diagonally. The detour delay is defined as follows:

$$d^{det} = \sum_{i \in I} \frac{l_{ij_i} + l_{j_i k_i} - l_{ik_i}}{s^{ped}} \quad (s/ped) \tag{3.10}$$

We adapt Equations (3.8)–(3.10) to define the pedestrian delay for TWC, EPP, and LTI. User movements under a typical TWC phase at a four-approach intersection are shown in Figure 3.2. In TWC, pedestrians cannot cross the intersection directly from corner i to corner k_i. First, they have to cross from corner i to j_i, and then from corner j_i to k_i. Therefore, the pedestrian delay for TWC includes a detour delay and both the first and second parts of a signal delay and a conflict delay. The pedestrian delay in TWC is defined as follows:

$$d^{ped-TWC} = d^{sig} + d^{con} + d^{det} \ (s/ped), \tag{3.11}$$

where $d^{ped-TWC}$ is calculated with Equation (1.2).

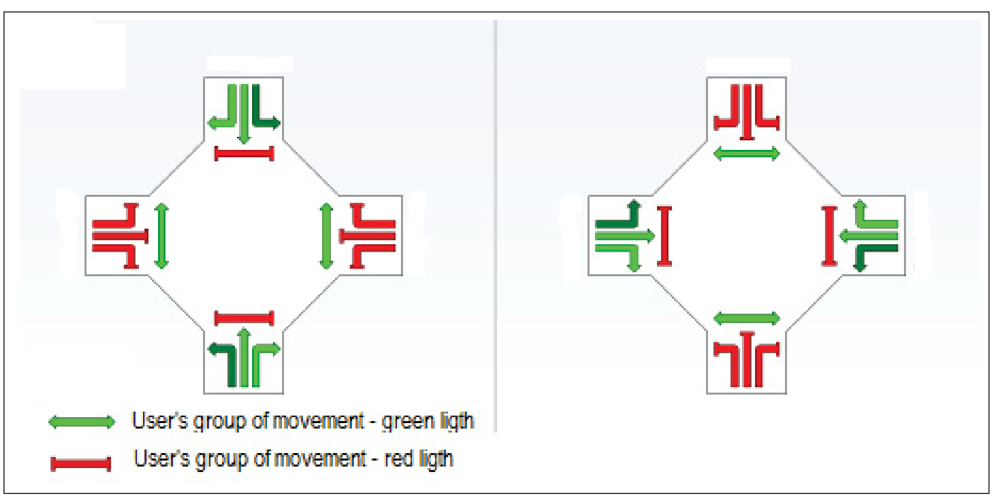

Figure 3.2 Typical TWC phase diagram for a four-arm intersection

The EPP pattern allows pedestrians to cross the intersection conventionally or diagonally without interaction with turning vehicles. Therefore, the study only expects the first part of d^{sig} in Equation (3.8) to be applied for pedestrians coming to the intersection during the "do not walk" or "stop" intervals of the pedestrian light. Figure 3.3 shows that all vehicle movements are stopped at the intersection under the EPP pattern; therefore, the conflict delay and the detour delay are not applied to this pattern. Equation (3.12) defines the EPP pedestrian delay as:

$$d^{ped-EPP} = d^{sig-EPP} \ (s/ped) \tag{3.12}$$

where the pedestrian delay of the exclusive pedestrian pattern ($d^{ped-EPP}$) only includes the signal delay defined as:

$$d^{sig-EPP} = \sum_{i \in I} \frac{(C - g_i^{ped})^2}{2\ C} \qquad (s/ped) \tag{3.13}$$

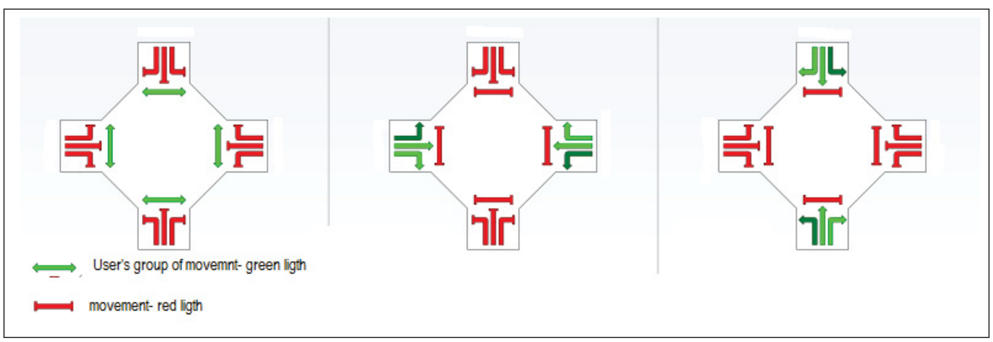

Figure 3.3 Typical EPP phase diagram for a four-arm intersection

Figure 3.4 presents the typical LTI phase diagram at the intersection with four approaches:

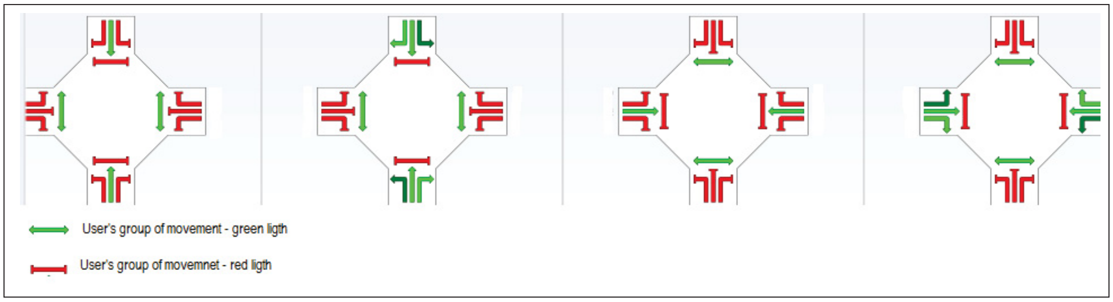

Figure 3.4 Typical LTI phase diagram for a four-arm intersection

LTI assumes that pedestrians cross the street only during the "walk" interval and does not consider any pedestrian violation behavior. In the LTI pattern, the green interval for turning vehicles starts while pedestrians are in the "do not walk" interval. Therefore, the study does not expect any pedestrian conflict delay for this pattern; as well, d^{sig} and d^{det} are calculated with Equations (3.8) and (3.10), respectively. The LTI pedestrian delay is then defined as follows:

$$d^{ped-LTI} = d^{sig} + d^{det} \qquad (s/ped) \tag{3.14}$$

Therefore, we modified d^{ped} according to each signal pattern of the study; in the next section, we modify the conflict-related equations for each signal pattern. As we discussed in Section 3.2.2.1, we respect the HCM vehicular delay model since it reflects each pattern by considering the saturation flow rate of the group of movements for each lane. Then, we compute the intersection delay (D) according to Equation (1.3) for each study pattern.

3.4.2 Computation of the Potential Conflict for Each Signal Pattern

Table 3.2 lists the parameters and variables for the intersection depicted in Figure 3.1 that are needed to compute pc^{v2v} and pc^{v2p}.

The number of potential conflicts between vehicles caused by left-turning vehicles at the intersection is defined as follows (Zhang & Prevedouros, 2003):

$$pc^{v2v} = \sum_{i \in I} (pc_i^{lt} + pc_i^{ot}) \quad (vehicle\ with\ conflict/time\ interval) \tag{3.15}$$

where pc_i^{lt} is equal to pc_i^{ot} if the conditions of Equation (3.16) are valid:

$$pc_i^{lt} = pc_i^{ot} = \begin{cases} v_i^{lt} p_i^{pc} & if\ v_i^{lt} \leq v_i^{ot} \\ v_i^{ot} p_i^{pc} & if\ v_i^{lt} > v_i^{ot} \end{cases} \quad \forall\, i \in \{1, 2, 3, 4\} \tag{3.16}$$

Equation (3.16) considers that $pc_i^{lt} = pc_i^{ot}$ at the specific condition related to v^{ot} and v^{lt} on the green interval of g^u, while g^u is defined as Equation (3.17):

$$g^u = \begin{cases} g - g^o & if\ g^o \geq g^f \\ g - g^f & if\ g^o < g^f \end{cases} \quad \forall\, i \in \{1, 2, 3, 4\} \tag{3.17}$$

where g^f is part of the green time (g) before the first turning vehicle arrives at the intersection and g^o is part of the green time while left-turning vehicles have to stop until opposing through a queue of vehicles is cleared up.

Table 3.2 Sets, parameters, variables and descriptions

Sets, parameters, variables	Description	Value obtained from
$i \in I = \{1, 2, 3, 4\}$	Set of approaches at intersection	–
v_i^{lt}	Number of left-turning vehicles on approach $i \in I$ during the green interval of g_q	Observation
v_i^{ot}	Number of vehicles moving in the opposite direction on approach i during the green interval of g_u	Observation
p_i^{pc}	Probability of potential left turn conflict on approach $i \in I$	Computation
v^{ped}	Pedestrian flow rate in the subject crossing (walking in both directions) (ped/h)	Observation
g^{ped}	Pedestrian service time(s)	Simulation(Synchro)
g^{veh}	Vehicle service time(s)	Simulation(Synchro)
g^q	Amount of permitted green time that is not blocked by (an) opposing lane(s)	Observation
occ^l	Relevant conflict zone occupancy for conflicts between permitted or protected left-turning vehicles and pedestrians	Computation
v^o	Opposing demand flow rate (veh/h)	Observation
g^{pl}	Effective green time for permitted left turn operation(s)	Observation
t^c	Critical gap(s)	Computation
V^{veh}	Total vehicle volume (veh/h)	Observation
V^{ped}	Total pedestrian volume (ped/h)	Observation
pc^{v2v}	Total expected number of vehicles with potential conflicts (veh/interval)	Computation
pc^{v2p}	Total expected number of vehicles with potential conflicts (veh/time interval)	Computation
pc_i^{lt}	Number of left-turning vehicles with potential conflicts on approach $i \in I$	Computation
pc_i^{ot}	Potential conflicts of opposing vehicles resulting from left turn on approach $i \in I$	Computation
occ^{ped-g}	Pedestrian occupancy	Computation
occ^r	Relevant conflict zone occupancy for conflicts between right-turning vehicles and pedestrians	Computation
g^f	Part of green time (g) before the first turning vehicle arrives at the intersection(s)	Observation
g^o	Part of the green time while left-turning vehicles stop to opposing through a queue of vehicles get clear(s)	Observation
g^u	Portion of green time during which there is no potential conflict between left-turning and through the vehicle(s)	Observation
v^{ped-g}	Pedestrian flow rate during pedestrian service time	Computation
occ^{ped-u}	Pedestrian occupancy when the opposing queue is clear	Computation

Zhang & Prevedouros (2003) considered that left-turning vehicles do not get into conflict with vehicles moving through in the following circumstances:

- At the beginning of the green interval, when the turning vehicle has to stop for the through vehicles, and then there is no conflict.
- When the gap between the vehicles in through movement is less than 4 s, the driver cannot make a left turn.
- When the gap between vehicles' through movement is more than 8 s, the driver has enough time to make a left turn, and there is no conflict.

For left turn situations that are not included above, Zhang & Prevedouros (2003) defines the probability of a potential left turn conflict (p^{pc}) on each approach based on the turning time and turning distance for left-turning vehicles when the gap time for through vehicles is between 4 and 8 s. In the case of the LTI pattern, g^f is zero because there is already an accumulation of left-turning vehicles during the late start of the green interval. Then, g^u of LTI is defined as:

$$g^u = g - g^o \quad \forall\, i \in \{1, 2, 3, 4\} \tag{3.18}$$

Regarding Equations (3.15) and (3.17), pc^{v2v} is related to the number of vehicles and the effective green interval for the left-turning vehicles.

Besides Equation (3.15), which computes pc^{v2v} based on the traffic flow rate and to estimate pc^{v2v}, Zhang & Prevedouros (2003) proposed the following model based on the conflict zone occupancy at the intersection for pedestrian and turning vehicles:

$$v^{ped-g} = v^{ped} \left(C/g^{ped} \right) \tag{3.19}$$

where v^{ped-g} is the pedestrian flow rate during the pedestrian service time. The authors used Equation (3.19) to define the pedestrian occupancy at the intersection based on the pedestrian flow rate, as shown in Equations (3.20) and (3.21):

$$occ^{\,ped-g} = v^{\,ped-g}/2000 \qquad If\ v^{\,ped-g} \leq 1000\ (ped/h) \tag{3.20}$$

$$occ^{\,ped-g} = 0.4 + (v^{\,ped-g}/10000\ ) \qquad If\ v^{\,ped-g} > 1000\ (ped/h) \tag{3.21}$$

Depending on the pedestrian flow rate, $occ^{\,ped-g}$ is calculated by Equations (3.20) or (3.21), and then the number of conflict situations between pedestrians and right-turning vehicles at the intersections is introduced in the literature as Equation (3.22):

$$occ^{r} = \frac{g^{ped}}{g^{veh}}\, occ^{\,ped-g}, \tag{3.22}$$

where occ^{r} defines the number of pedestrian conflicts with right-turning vehicles related to pedestrian occupancy and the green interval of the traffic signal.

To compute the number of pedestrian conflicts with left-turning vehicles, the previous literature presented the pedestrian occupancy when the opposing queue is clear:

$$occ^{\,ped-u} = (1 - \frac{0.5\ g^{q}}{g^{ped}})\ occ^{\,ped-g} \tag{3.23}$$

If $g^{q} < g^{ped}$, then Equation (3.23) is applied to calculate $occ^{\,ped-u}$; otherwise, $occ^{\,ped-u} = 0$.

Equations (3.24) or (3.25) define the conflict between pedestrians and left-turning vehicles.

$$occ_{l} = \frac{g^{ped} - g^{q}}{g^{pl} - g^{q}}\ occ^{\,ped-g}\ e^{-t_{c}\ (v^{o}/3600)} \tag{3.24}$$

Then, Zhang & Prevedouros (2003) defined pc^{v2p} as:

$$pc^{v2p} = \sum_{i \in I} (v_{i}^{\,ped}\ occ_{i}^{\,r}\ )\ (pedestrian\ with\ conflict/time\ interval) \tag{3.25}$$

They also considered PC at the intersection as a sum of pc^{v2v} and pc^{v2p} for each period of the study, as presented in Equation (3.26):

$$PC = pc^{v2v} + pc^{v2p} \; (user\ with\ conflict/time\ interval) \tag{3.26}$$

Zhang & Prevedouros (2003) did not provide the PC models for the specific pattern of our study, but only investigated the effect of shared, protected, and the permitted vehicle left turn movements. For the present study, PC models of Zhang & Prevedouros (2003) as presented in Equation (3.15) to Equation (3.26) were modified for each signal pattern, considering the logic of relevant conflict movements. For example, pc^{v2p} is not applied to the EPP pattern since there is no vehicle-pedestrian interaction in this pattern. Therefore, Equations (3.27) and (3.28) describe the potential pedestrian conflict for TWC and LTI patterns based on pedestrian conflict with left- and right-turning vehicles (Equations (3.22) and (3.24)):

$$pc^{v2p-TWC} = \sum_{i \in I} (v_i^{ped}\ occ_i^{r} + v_i^{ped}\ occ_i^{ped-u}) \; (\ pedestrian\ with\ conflict/time\ interval) \tag{3.27}$$

$$pc^{v2p-LTI} = \sum_{i \in I} (v_i^{ped}\ occ_i^{r} + v_i^{ped}\ occ^{l}) \; (pedestrian\ with\ conflict/time\ interval) \tag{3.28}$$

The only difference between these two equations is related to pedestrian interference with left-turning vehicles. Following Equation (1.4), Equations (3.29)–(3.31) define the total expected potential conflicts at the intersection for each pattern as the sum of the total expected number of potential conflicts between vehicles (pc^{v2v}) (Equation (3.15)), and the total expected potential pedestrian conflicts (pc^{v2p-p}) (Equation (3.27) or (3.28)).

$$PC^{TWC} = \; pc^{v2v} + pc^{v2p-TWC} \; (user \; with \; conflict/time \; interval) \qquad (3.29)$$

$$PC^{LTI} = \; pc^{v2v} + pc^{v2p-LTI} \; (user \; with \; conflict/time \; interval) \qquad (3.30)$$

$$PC^{EPP} = \; pc^{v2v} \; (user \; with \; conflict/time \; interval) \qquad (3.31)$$

It should be noted that the value of the potential conflict related to each signal pattern (PC^{p}) depends on pc^{v2p-p} only since pc^{v2v} does not vary with the traffic signal pattern. Zhang & Prevedouros (2003) computed PC as an hourly number of potential conflicts, considering the hourly volume and green interval of the traffic signal. The models used in the present study are based on 15-minute intervals, and therefore, PC refers to the number of potential conflicts for every 15 min herein.

3.4.3 Computation of the Delay and Safety Index for Each Signal Pattern

Delay and safety index (DS) values show the effect of different signal patterns on the level of service. DS, as defined in Equation (1.7), must be adapted for signal pattern $p \in \{TWC, LTI, EPP\}$ by considering pc^{v2v-p}, pc^{v2p-p}, d^{veh-p} and d^{ped-p}. Equation (3.32) describes DS^{p}:

$$DS^{p} = \frac{DS^{veh-p} \; V^{veh} + DS^{ped-p} \; V^{ped}}{V^{veh} + V^{ped}} \; (s/user) \qquad (3.32)$$

where DS^{veh-p} and DS^{ped-p} define DS of the vehicle and DS of pedestrian for pattern $p \in \{TWC, LTI, EPP\}$.

As mentioned in Section 3.4.2, pc^{v2v} is not dependent on the signal pattern, whereas the vehicle delay varies for each signal pattern. Since Zhang & Prevedouros (2003) do not investigated

DS according to the signal pattern, we modify Equations (1.5) and (1.6) to take into account DS^{veh-p} and DS^{ped-p} in Equations (3.33) and (3.34):

$$DS^{veh-p} = d^{veh-p}\ (1 + \frac{pc^{v2v}}{V^{veh}}\ )\ \ (s/veh) \tag{3.33}$$

$$DS^{ped-p} = d^{ped-p}\ (1 + \frac{pc^{v2p-p}}{V^{ped}}\ )\ (s/ped) \tag{3.34}$$

where DS^{veh-p} and DS^{ped-p} respectively describe the level of service and safety for vehicles and pedestrians for each period of the study under each signal pattern $p \in \{TWC, LTI, EPP\}$. d^{veh-p} is extracted from Synchro based on Equation (1.7). d^{ped-p} are computed based on Equations (3.11), (3.12) and (3.14). pc^{v2v} is computed based on Equation (3.15) and pc^{v2p-p} is computing based on Equations (3.27) and (3.28). One of the goals of the present study is to identify the pattern with the minimum DS value that represents the best service and safety level for an intersection. Table 3.3 summarizes the equations related to the methods used to measure the delay and conflict developed in this section.

Table 3.3 Equations related to each pattern

Pattern	D **(s/user)**	PC **(user with conflict/interval)**	DS **(s/user)**
TWC	$\frac{d^{veh}V^{veh}+(d^{sig}+d^{con}+d^{det})V^{ped}}{V^{veh}+V^{ped}}$	$pc^{v2v} + pc^{v2p-TWC}$	
EPP	$\frac{d^{veh}V^{veh}+(d^{sig-EPP})V^{ped}}{V^{veh}+V^{ped}}$	pc^{v2v}	$\frac{DS^{veh-p}\ V^{veh}+DS^{ped-p}\ V^{ped}}{V^{veh}+V^{ped}}$
LTI	$\frac{d^{veh}V^{veh}+(d^{sig}+d^{det})V^{ped}}{V^{veh}+V^{ped}}$	$pc^{v2v} + pc^{v2p-LTI}$	

In the following section, we investigate our performance for each pattern and look into whether it can be affected by dynamically changing the pattern during the course of the day.

3.5 Case Study

This section describes the experimental campaign developed to dynamically assess the potential impact of allowing traffic system controls to change the pattern according to real-time traffic conditions. The experiment consists mainly of a computational case study where an existing traffic signal is selected and its performance is simulated under real-life traffic conditions. First, three patterns, namely, TWC, EPP, and LTI are simulated. Then, a hypothetical hybrid pattern is created by choosing, for each time interval, the best-performing pattern associated with each performance indicator. For those simulations, two pre-defined cycle lengths are tested. We also investigate the optimum cycle length for each signal pattern. However, the optimum cycle length in Synchro seeks to minimize the delay time and does not consider safety in its objective function. Thus, we exclude the investigation of the signal patterns with the optimum cycle length from our study.

Section 3.5.1 describes the case study and the demand collection mechanism. Section 3.6 presents the computational results for the fixed cycle length experiments. Finally, Section 3.6.5 provides an in-depth discussion to validate the proposed model.

3.5.1 Description of the Case Study

The considered intersection is close to downtown Montreal (Notre-Dame and Peel Streets), with École de Technologie supérieure (ÉTS) situated on both sides of its southern arm, and with one full day of data being available. In the present study, the intersection is considered isolated (not coordinated with other intersections), and therefore, the target traffic signal runs in an uncoordinated semi-actuated mode. It is assumed that vehicles cannot turn right on red traffic signals, based on Montreal traffic rules.

Real traffic data are collected from the ÉTS security camera system on a regular day (Wednesday, 8 October 2018, from 8 a.m. to 8 p.m.). A video camera is installed on top of the ÉTS building to capture a full view of the intersection. A manual video imaging process is applied to manage the data collected from Notre-Dame and Peel (Figure 3.5). Detailed data on pedestrian and vehicle volumes and the traffic signal configuration associated with the intersection are also collected. The average pedestrian/vehicle flow rate at this intersection is approximately 900 users /15 min. The pattern currently applied to this intersection is the LTI.

Figure 3.5   Aerial view of the case study site–Notre-Dame and Peel intersection

Figure 3.6 demonstrates the pedestrian and vehicle flow during the day. It shows that pedestrian traffic at the intersection experiences is at a peak at 8:45 a.m. (748 pedestrians/ 15 min), while for vehicles, it is at 5:30 p.m. (633 vehicles/15 min). Furthermore, pedestrians outnumber vehicles on three occasions during the day (8:30 a.m., 1:00 p.m., and 5:30 p.m.).

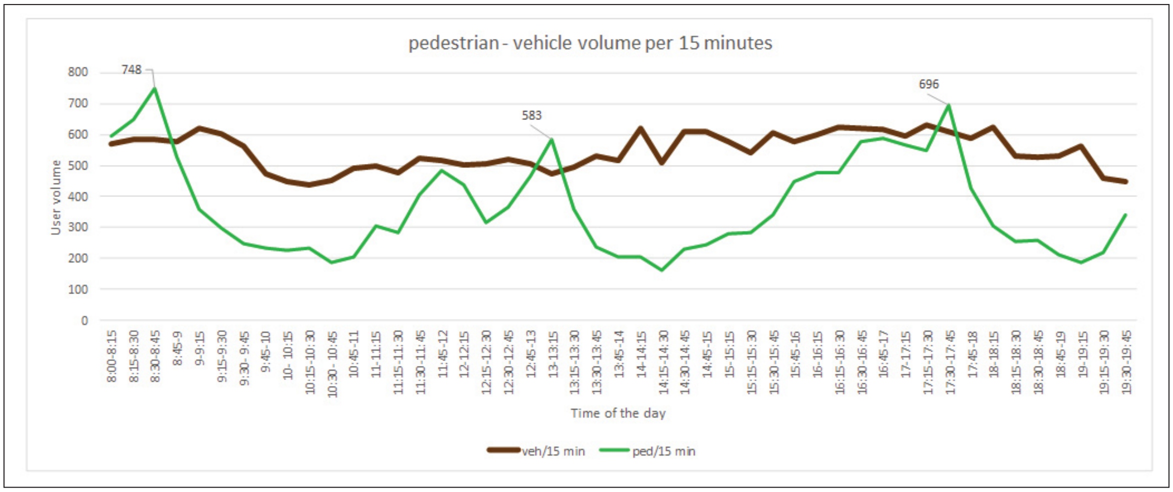

Figure 3.6 Pedestrian and vehicle volumes during the course of the day for every 15 min

The following section investigates the results for performance indicators when two fixed cycle lengths are applied to the case study data.

3.6 Results

We perform the case study using different fixed cycle lengths and investigate whether performance indicators can be improved by dynamically changing signal patterns. The current operational cycle length at the considered intersection is approximately 80 s. For this reason, we compare the patterns by assigning an 80-s fixed cycle length in the first experiment. Moreover, when the cycle lengths are 45 (minimum acceptable cycle length by Synchro) and 60 s, we simulate the data with Synchro. The case of a 45-s cycle length resulted in an over-saturated intersection and, as a result, we only focus on 60- and 80-s fixed cycle lengths. Synchro's ring-barrier option enables the simulation of different signal patterns, while the lane setting remains the same for all signal patterns. The input data are the pedestrian and vehicle volumes, lane group movements, and possibly turning movements for each intersection approach. All other parameters are set at their Synchro default values. Figure 3.7 shows the Synchro interface while it displays the results for the TWC pattern at 7:45 p.m., including the cycle length, delay, and phase duration.

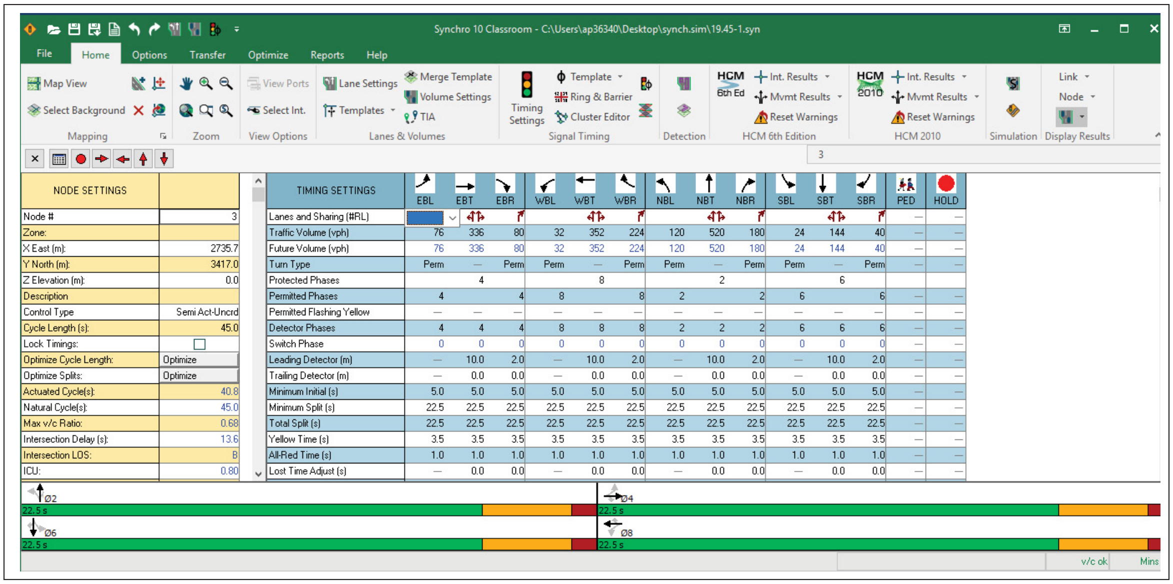

Figure 3.7 Screenshot of the Synchro interface for the TWC pattern

We compare the three patterns for 60- and 80-s cycle lengths according to the performance measures D, PC, and DS in Section 3.6.1, 3.6.2, and 3.6.3, respectively.

3.6.1 Comparison Based on the Delay Time

In this section, we compare the vehicle and pedestrian delays for signal patterns, TWC, LTI, and EPP. We first analyze the 80-s cycle length case. Figures 3.8 and 3.9 present the vehicle and pedestrian delay, respectively.

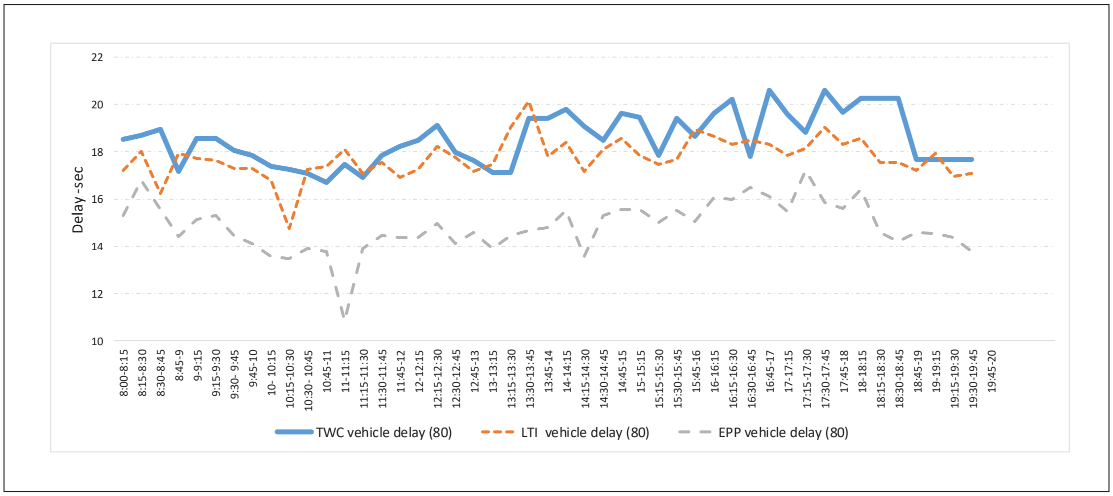

Figure 3.8 d^{veh-p} for 80-s cycle length, with $p \in \{TWC, LTI, EPP\}$

Figure 3.8 presents the average vehicle delay for different signal patterns for each study period, d^{veh-p} for $p \in \{TWC, LTI, EPP\}$, during the day as returned by Synchro. We observe that EPP has the minimum vehicular delay during the day. This is due to the fact that, differently from the other patterns, the EPP vehicle green interval does not overlap with the pedestrian walk interval, while the cycle length is fixed for all patterns.

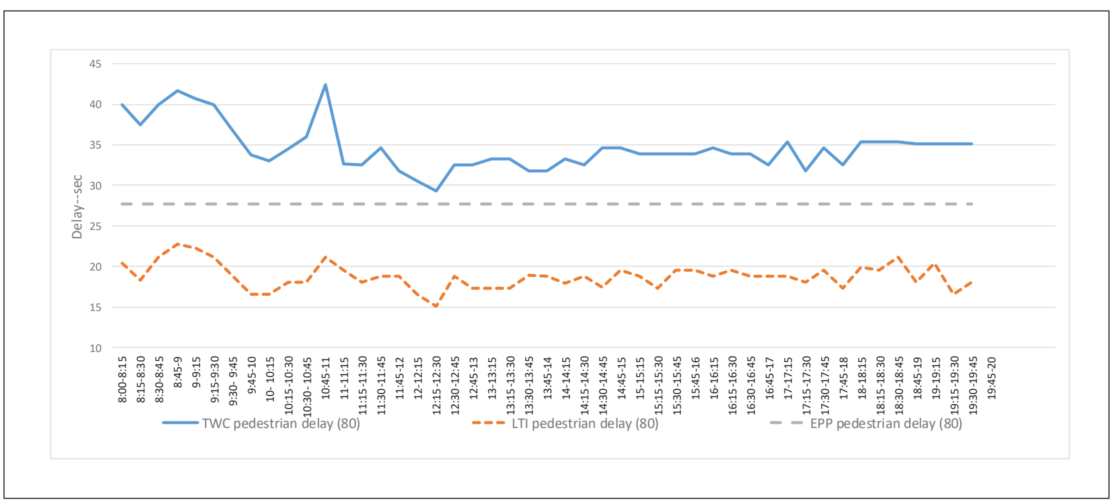

Figure 3.9 d^{ped-p} for 80-s cycle length, with $p \in \{TWC, LTI, EPP\}$

Figure 3.9 depicts the average pedestrian delay of different patterns for each study period, d^{ped-p} for $p \in \{TWC, LTI, EPP\}$, computed according to Equations (3.20)–(3.22) in Section 3.4.1. According to this figure, the LTI pattern presents a minimum average pedestrian delay during the day.

Figure 3.10 shows the values of the weighted intersection delay D^p for $p \in \{TWC, LTI, EPP\}$ during the day as computed by Equation (1.3), and reflects the average waiting time of each user at the intersection. We observe that LTI is the overall best-performing pattern, with an average delay of 18.17 s/user, followed by EPP. TWC is the least-performing pattern in terms of D^p. It is worth noting that this is in contrast with what is reported in Ishaque & Noland (2007) and Zhang & Su (2018), where a greater delay for the EPP in comparison with the TWC is expected when pedestrian demand is low (such as 10:15, 14:15, and 19:00 in our case study). This discordance is due to the fact that this study modifies the pedestrian delay model by taking into account the detour delay and the conflict delay (Section 3.4.1). Figure 3.10 leads us to choose a combination of EPP and LTI as a hybrid pattern with the minimum delay for the day of study.

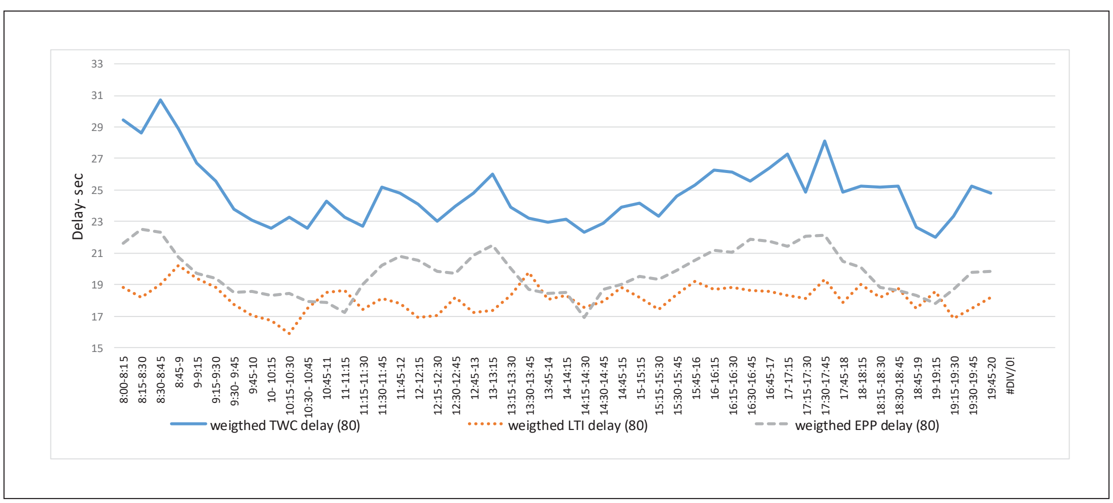

Figure 3.10 D^p for 80-s cycle length, with $p \in \{TWC, LTI, EPP\}$

According to the definition of the hybrid pattern in Section 3.3, this combination of LTI and EPP is called H^D80 (hybrid delay pattern for 80-s cycle length) in our study, and it performs the traffic signal with 87.50% of LTI and 12.50% of EPP for the day of study.

Table 3.4 reports the delay's improvement for the day of study when comparing the hybrid delay with the best-performing single pattern. The table reports the pattern in the first column and the weighted intersection's delay in the second column. We observe a 0.49% improvement for $H^D 80$ as compared to LTI, which is the best-performing pattern.

Table 3.4 Hybrid improvement in comparison with the best performing pattern

Pattern	**D (s/user)**
LTI	18.17
$H^D 80$	18.08
Improvement	0.49%

We repeated all the computations for the scenario with a fixed cycle length of 60 s. Figures 3.11 and 3.12 present the vehicle and pedestrian delays during the day for this scenario.

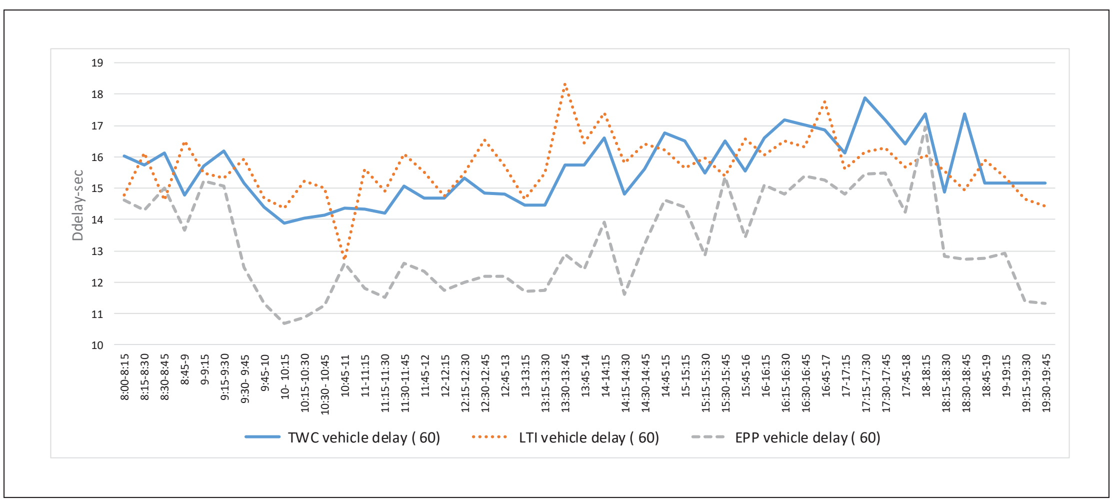

Figure 3.11 d^{veh-p} for 60-s cycle length, with $p \in \{TWC, LTI, EPP\}$

Figure 3.11 reports the comparison of d^{veh-p} for $p \in \{TWC, LTI, EPP\}$. We observe that EPP is the best-performing pattern in terms of vehicle delay time. We also observe that the maximum vehicle delay for EPP is reached at the vehicle peak hour volume.

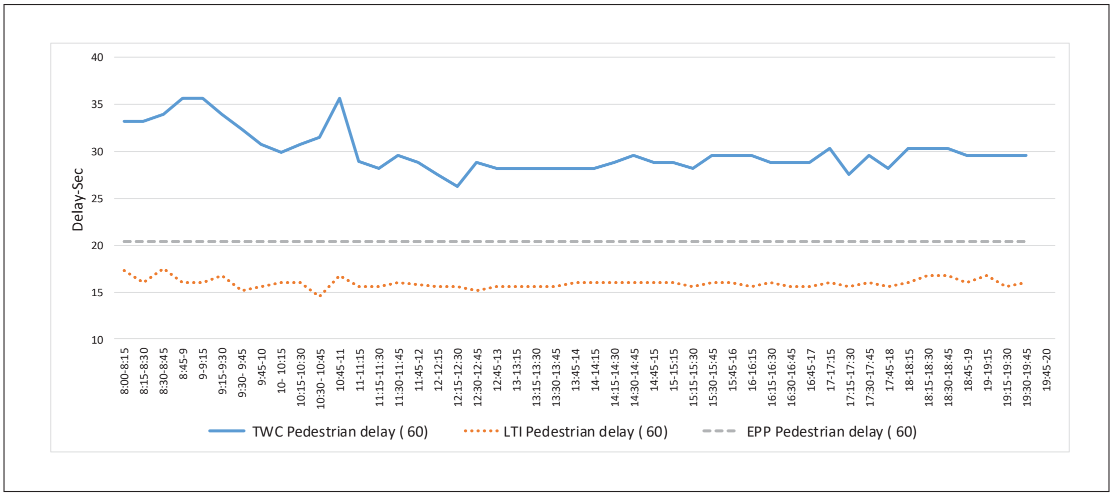

Figure 3.12 d^{ped-p} for 60-s cycle length, with $p \in \{TWC, LTI, EPP\}$

Figure 3.12 reports a comparison of the pedestrian delay times for different patterns and for the 60-s cycle length. It shows that LTI has the smallest pedestrian delay during the day. This is due to the fact that the pedestrian green interval for the LTI is larger than that for the EPP.

Figure 3.13 presents the average weighted delay time during the day for the 60-s cycle length. We see that there is close competition between the EPP and LTI delay charts. This is in contrast with what was reported in Furth & Saeidi Razavi (2019), where LTI was assessed superior to EPP.

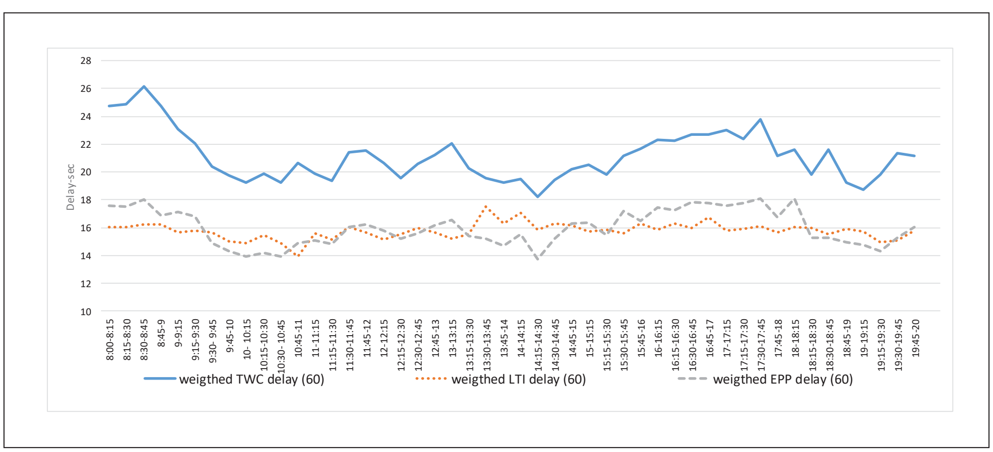

Figure 3.13 D^p with 60-s cycle length, with $p \in \{TWC, LTI, EPP\}$

In the case of the 60-second cycle length, the hybrid delay 60 ($H^D 60$) has a portion consisting of 47.90% of EPP and 52.10% of LTI for the day of study. Table 3.5 compares the $H^D 60$ and the pattern with minimum delay. The first column presents the pattern, and the second one shows the average weighted delay.

Table 3.5 Hybrid improvement in comparison with the best performing pattern

Pattern	***D* (s/user)**
LTI	15.78
H^D 60	15.39
Improvement	2.47%

Table 3.5 reports the exact information of Table 3.4, but for a cycle length of 60 seconds and shows a 2.47% improvement in the intersection's delay when we run the $H^D 60$ as a pattern for the day of study. The $H^D 60$ reduces the delay for each user by 2.47% on our day of study.

To summarize, the results in this section show that the EPP and LTI patterns perform best in terms of vehicle and pedestrian delay, respectively. LTI is the best-performing single pattern according to the weighted delay time. Furthermore, we have seen that the hybrid patterns $H^D(80)$ and $H^D(60)$ can potentially be improved over LTI.

3.6.2 Comparison Based on Potential Conflicts

Section 3.2.2.2 of this study investigates the performance indicators related to intersection safety. Potential user conflict represents a significant measure of unsafe situations for pedestrians and vehicles at the intersection. We compare the PC of patterns with 60- and 80-s cycle lengths. Figures 3.14 and 3.15 present pc^{v2v} and pc^{v2p} when the cycle length is 80 s for the case study intersection.

Figure 3.14 shows pc^{v2v} during the day. According to Equations (3.15)–(3.17), pc^{v2v} is related to the effective turning time. Therefore, it is similar for all three patterns since it is based on vehicle flow for every hour of study, and is not related to the cycle length or signal pattern.

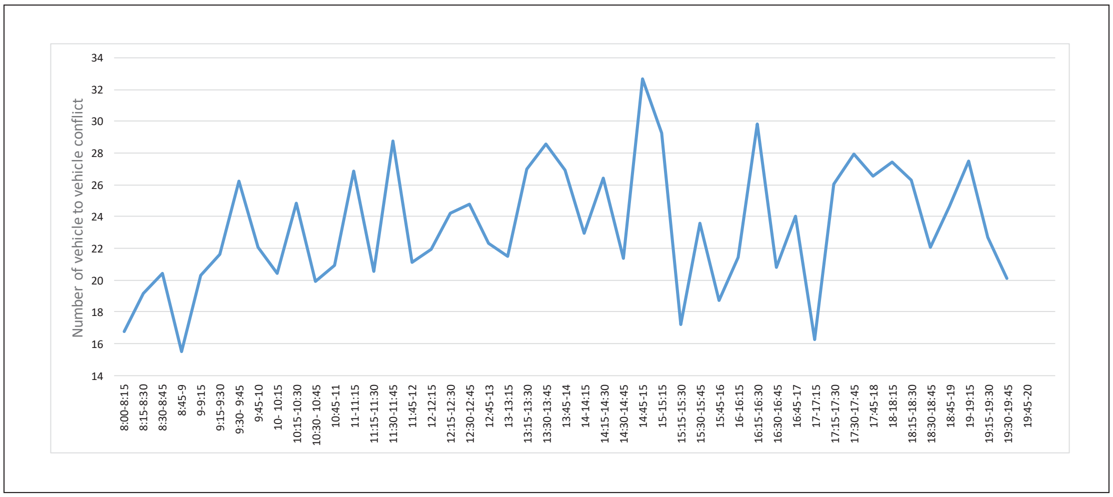

Figure 3.14 pc^{v2v} during the day

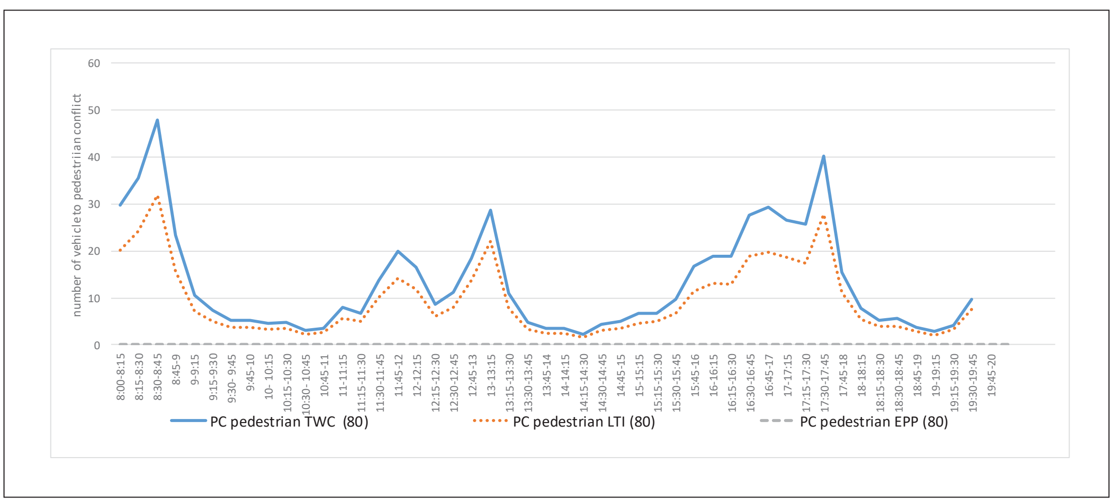

Figure 3.15 pc^{v2p-p} for 80-s cycle length, with $p \in \{TWC, LTI, EPP\}$

Figure 3.15 compares pc^{v2p-p} values during the day for $p \in \{TWC, LTI, EPP\}$ when Equations (3.27) and (3.28) are applied to compute pc^{v2p-p}. Since it is assumed that the pedestrian always respects traffic signal rules, pc^{v2p} for EPP is considered zero. In comparison with TWC, LTI in Figure 3.15 shows fewer pedestrian conflicts, specifically at peak pedestrian periods.

Figure 3.16 compares the total number of potential conflicts at the intersection for $p \in \{TWC, LTI, EPP\}$ based on Equations (3.29)–(3.31), for each study period and shows that EPP has the minimum number of conflicts during the day. The figure shows three periods of the day in which LTI and EPP have the same number of potential conflicts; these pedestrian volume values for these periods are in the order of fewer than 250 pedestrians per 15 min.

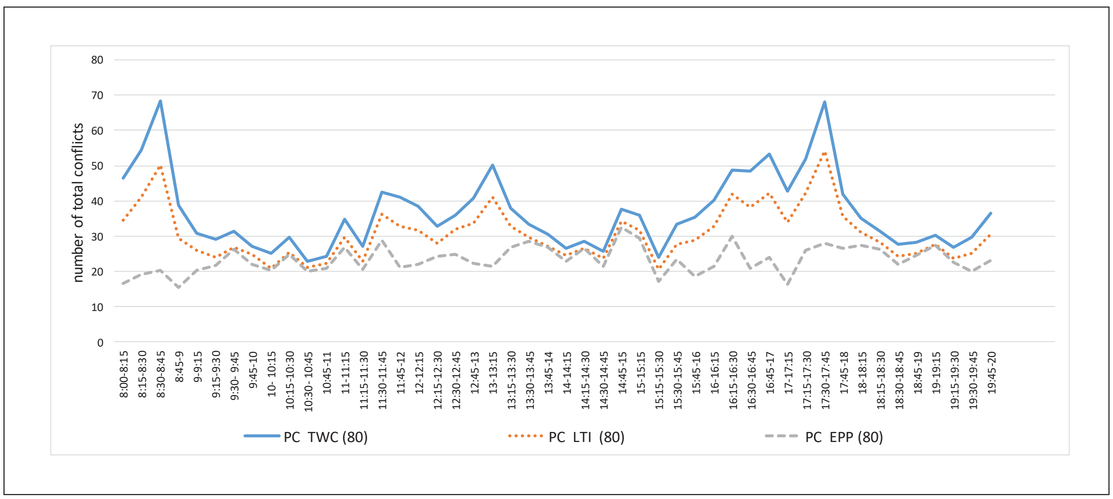

Figure 3.16 PC^p for 80-s cycle length, with $p \in \{TWC, LTI, EPP\}$

Table 3.6 compares the best-performing pattern in terms of the numbers of potential conflicts (PC), with the hybrid pattern $H^{PC}80$. $H^{PC}80$ has no improvement since EPP is the only pattern composing the $H^{PC}80$. We performed the same computational experiment for a 60-s cycle length, and the results are discussed next.

Table 3.6 Hybrid improvement in comparison with the best performing pattern

Pattern	**PC (users with conflict/15 min)**
EPP	23.09
H^{PC} 80	23.09
Improvement	0%

Similar to Figure 3.15, Figure 3.17 compares pc^{v2p} for $p \in \{TWC, LTI, EPP\}$, but with a 60-s cycle length. In both the 60-s cycle length pc^{v2v} and pc^{v2p}, the EPP presents the minimum potential conflict during the day.

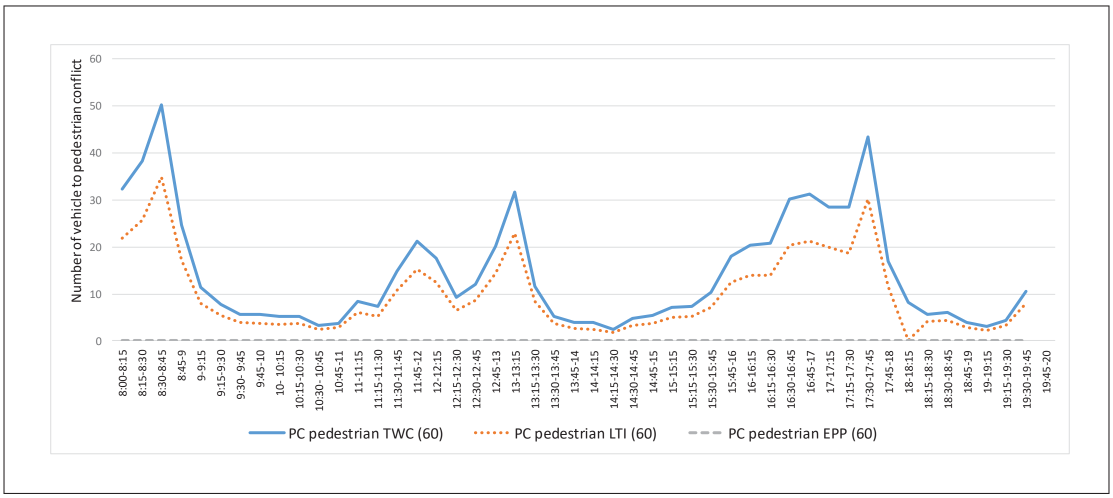

Figure 3.17 pc^{v2p-p} for 60-s cycle length, with $p \in \{TWC, LTI, EPP\}$

Figure 3.18 presents the same information as Figure 3.16, but with a 60-s cycle length, and reports the EPP as the minimum number of potential conflicts for our study period. Table 3.7 presents the same information as Table 3.6, but for a 60-s cycle length setting.

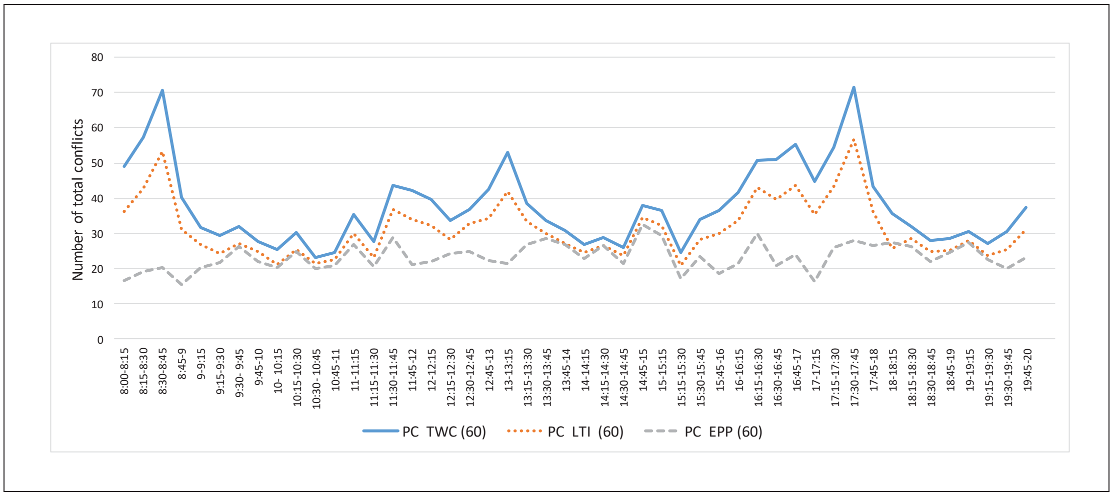

Figure 3.18 PC^p for 60-s cycle length, with $p \in \{TWC, LTI, EPP\}$

Table 3.7 Hybrid improvement in comparison with the best performing pattern

Pattern	PC (users with conflict/15 min)
EPP	23.09
H^{PC} 60	23.09
Improvement	0%

Table 3.7 reports the same information as Table 3.6 when the cycle length is 60 s. As for the previous case, also $H^{PC}60$ does not improve over the best performing EPP pattern. We observe that H^{PC} reports the same amount of conflicts for 60- and 80-s cycle lengths, since for the EPP pattern, $pc^{v2p} = 0$ and PC^{EPP} score the same as pc^{v2v} for both cycle lengths.

3.6.3 Comparison Based on the Delay and Safety Index

Section 3.4.3 of this study investigates DS (Delay and Safety index) as a combination of delays and a potential number of conflicts related to the user volume at the intersection.

In this section, we compare the DS^{veh-p} and DS^{ped-p} computed according to Equations (3.33) and (3.34), respectively. The first experiment compares DS for different patterns with 80-s cycle lengths. Figure 3.19 compares DS^{veh-p} for $p \in \{TWC, LTI, EPP\}$, with an 80-s cycle length. It shows that the EPP pattern provides the most acceptable DS during the day when only vehicles are considered in our study.

Figure 3.20 presents a comparison of DS^{ped-p} for $p \in \{TWC, LTI, EPP\}$ for the day of study. It reports LTI as the best-performing pattern in terms of DS^{ped}.

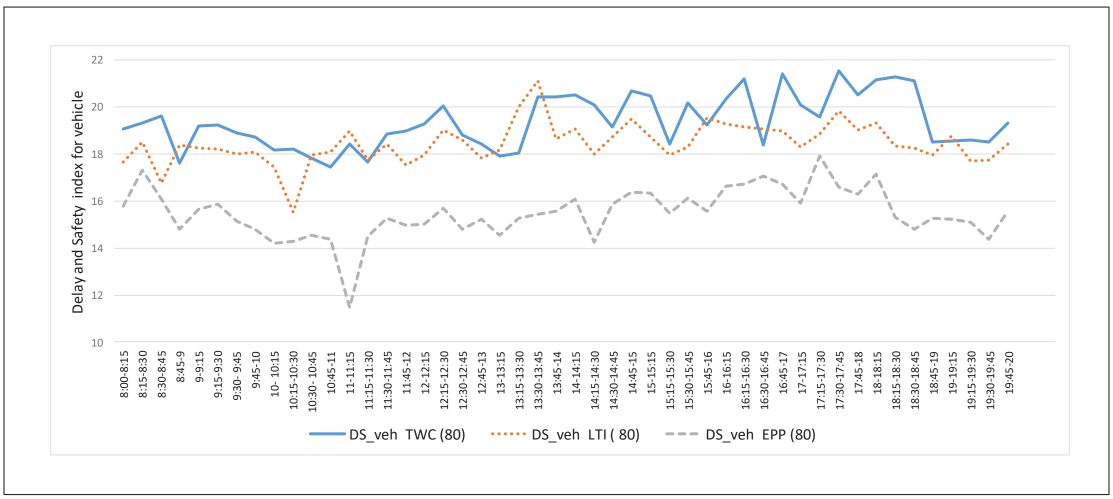

Figure 3.19 DS^{veh-p} for 80-s cycle length, with $p \in \{TWC, LTI, EPP\}$

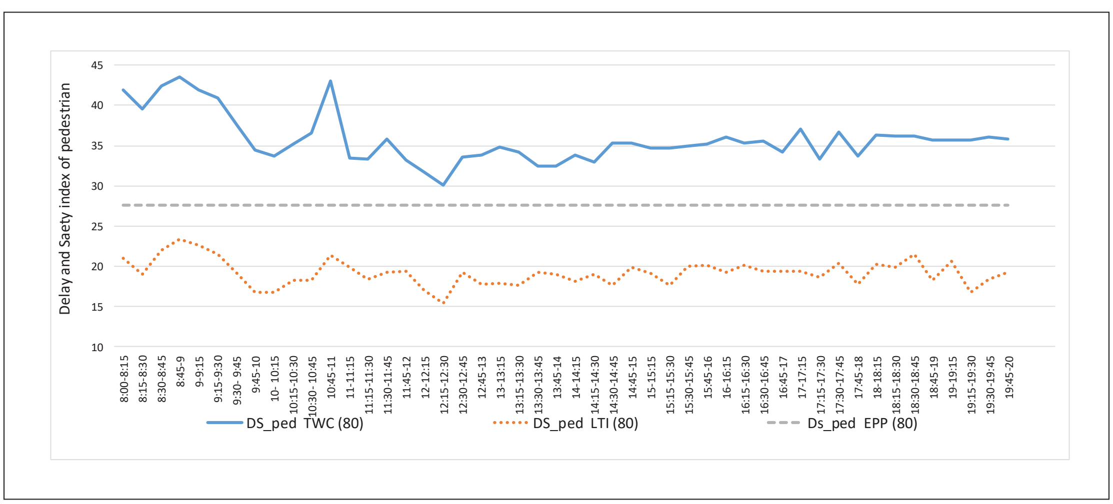

Figure 3.20 DS^{ped-p} for 80-s cycle length, with $p \in \{TWC, LTI, EPP\}$

Figure 3.21 presents a comparison of DS for $p \in \{TWC, LTI, EPP\}$ for the study day when both user delay and conflict are taken into account to calculate DS, according to Equation (3.32). Figure 3.21 proposes the hybrid pattern as a more efficient pattern during the day of study. The hybrid DS (80) ($H^{DS}80$) leads mainly to the LTI pattern (87.50%), and occasionally to EPP (12.50%) during the day.

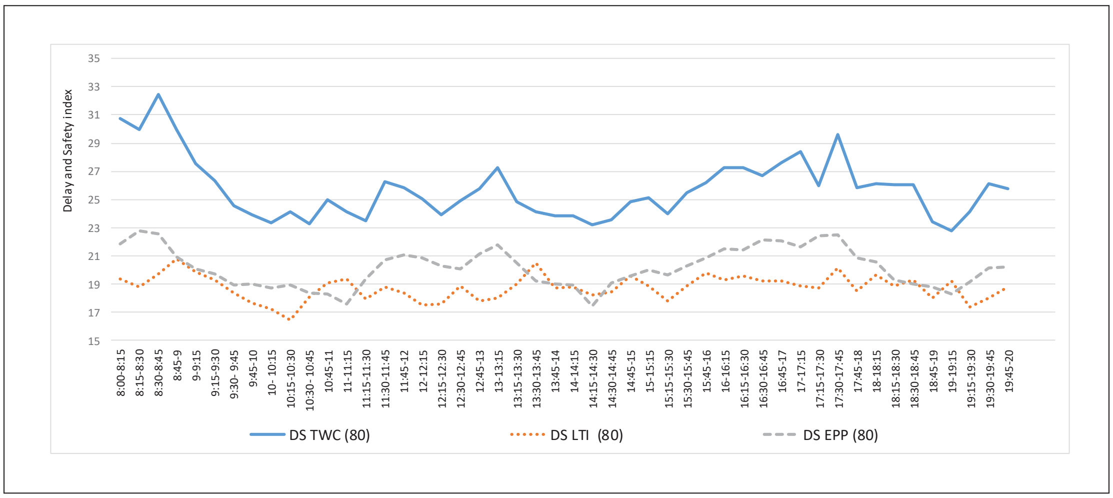

Figure 3.21 DS^p comparison for 80-s cycle length, with $p \in \{TWC, LTI, EPP\}$

Table 3.8 presents a comparison of $H^{DS}80$ with the best performing pattern, where the first column shows the pattern and the second column presents the average DS for that pattern for the study day. The $H^{DS}80$ reduces the average Delay and Safety index of each user for the study day by 0.64%, marking an improvement in the level of service and of safety for each user.

Table 3.8 Hybrid improvement in comparison with the best performing pattern

Pattern	**DS(s/user)**
LTI	18.77
H^{DS} 80	18.65
Improvement	0.64%

In the next section, we repeat the computation of DS^{veh-p} and DS^{ped-p} with a 60-s cycle length. Figure 3.22 compares DS^{veh-p} for different patterns and presents the EPP as the pattern with the minimum DS, but not for all periods of study. In this investigation, the hybrid pattern is presented as a combination of two patterns; however, the figure mainly is mainly comprised of the EPP.

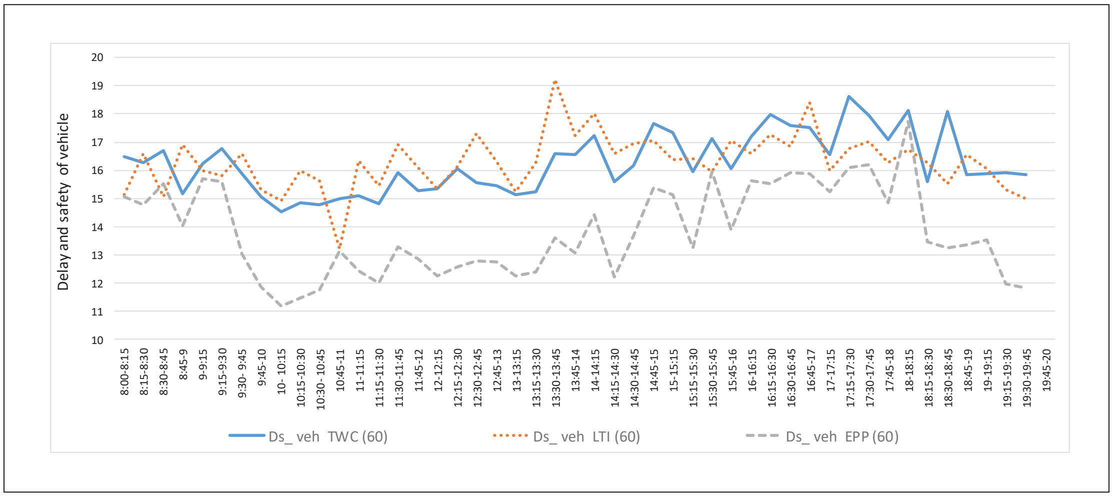

Figure 3.22 DS^{veh-p} for 60-s cycle length, with $p \in \{TWC, LTI, EPP\}$

Figure 3.23 presents a comparison of DS^{ped-p} for $p \in \{TWC, LTI, EPP\}$ during the day of study. Here, LTI is the more efficient pattern since both pedestrian delay and conflict are included in our investigation.

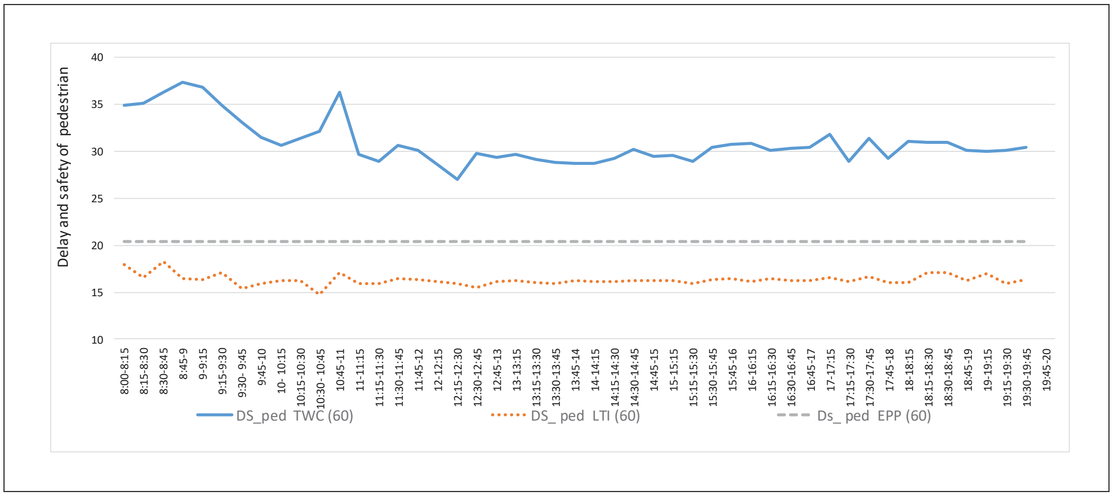

Figure 3.23 DS^{ped-p} for 60-s cycle length, with $p \in \{TWC, LTI, EPP\}$

Figure 3.24 compares the intersection DS for all three study patterns. From this comparison, we get the hybrid DS 60 ($H^{DS}60$), which does not show any dominant pattern, with $H^{DS}60$ constantly fluctuating between LTI and EPP during the day. In fact, on the day of study, the composition of $H^{D}60$ breaks down to 50.00% EPP and 50.00% LTI. Table 3.9 contains the same information as Table 3.7, but with a 60-s cycle length setting.

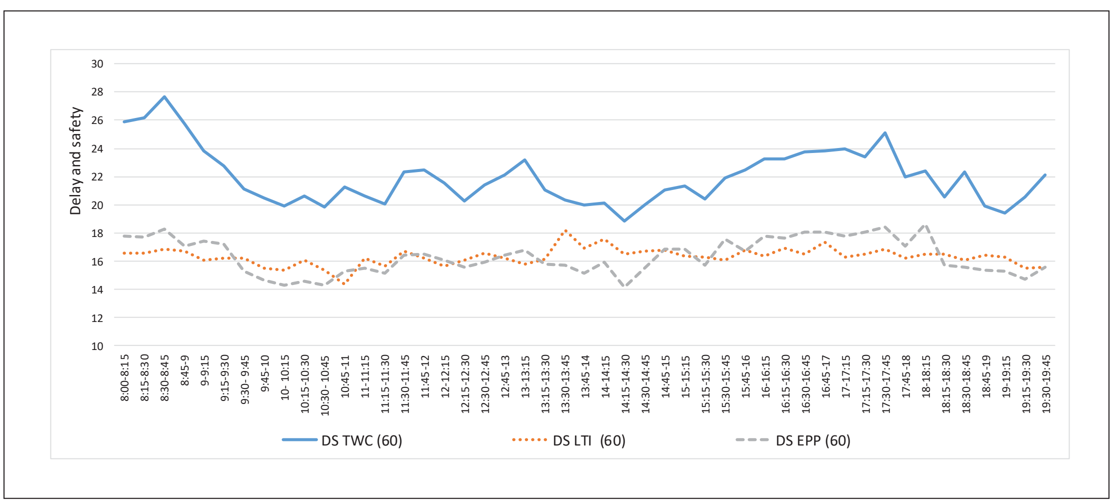

Figure 3.24 DS^{p} for 60-s cycle length, with $p \in \{TWC, LTI, EPP\}$

Table 3.9 Hybrid improvement in comparison with the best performing pattern

Pattern	**DS (s/user)**
LTI	16.42
H^{DS} 60	15.85
Improvement	3.47%

Table 3.9 presents a comparison of $H^{DS}60$ and the best-performing pattern and shows a 3.47% improvement of DS when we choose $H^{DS}60$ over the LTI as the pattern with the minimum DS. It improves the average Delay and Safety index for each user by 3.47%.

The study reports the LTI as the single pattern with the minimum DS for the cycle length of 80 and 60, while the hybrid pattern shows slight improvement over both fixed cycle lengths.

3.6.4 Analysis of Performance Measures Related to Hybrid Patterns

In the last section, we obtained the hybrid pattern for each performance measure (D, PC, and DS). This section compares the performance of hybrid patterns when considering 60 and 80-s cycle lengths. Results are reported in Tables 3.10 and 3.11, which compare the performance of the hybrid patterns. In each case, the first and second columns identify the considered pattern and its unit of measure. The third, fourth, and fifth columns report D, PC, and DS averages over the operating day for each hybrid pattern.

Table 3.10 Comparison of 80-second cycle length hybrid patterns in terms of delay, conflict, and DS

Pattern	**Unit of measure**	H^{D} **80**	H^{PC} **80**	H^{DS} **80**
D	s/user	18.08	19.83	18.08
PC	user with conflict/15 min	28.98	23.09	28.96
DS	s/user	18.90	20.22	18.65

From Table 3.10, we infer that $H^D 80$ is the best-performing pattern in terms of delay time. This result is not surprising considering that the patterns composing $H^D 80$ have been chosen to minimize the delay time. However, we also observe that $H^D 80$ is the worst-performing algorithm in terms of potential conflict. In other terms, patterns minimizing the delay time generally expose users to higher risks of conflict. The situation is inverted for $H^{PC} 80$ as the best-performing pattern in potential conflict but the worst pattern in terms of delay time. Again, potential conflict and delay time are conflicting objectives, and minimizing one results in a deteriorated performance for the other. In this sense, Table 3.10 suggests that $H^{DS} 80$ provides an excellent compromise in terms of delay time and potential conflicts. It scores a delay time of 18.08 s, which is similar to a delay time of $H^D 80$, and the number of potential conflicts of 28.96, against 23.09 of $H^{PC} 80$. In the second case, we compare the performance of each 60-s cycle length hybrid pattern in Table 3.11.

Table 3.11 Comparison of 60-second cycle length hybrid patterns in terms of delay, conflict, and DS

Pattern	**Unit of measure**	H^D **60**	H^{PC} **60**	H^{DS} **60**
D	s/user	15.39	16.07	15.41
PC	user with conflict/15 min	29.91	23.09	29.31
DS	s/user	15.98	16.41	15.85

Similar to the previous case, Table 3.11 shows that the $H^D 60$ pattern with a minimum delay and H^{PC} 60 patterns with a minimum conflict. Table 3.11 also suggests that $H^{DS} 60$ provides an excellent compromise in terms of delay time and potential conflicts. It scores a delay time of 15.41 s, against the 15.39 s of $H^D 60$, and the number of potential conflicts of 29.31 against 23.09 of $H^{PC} 60$.

From Tables 3.10 and 3.11 it can be seen that the 60-s cycle length improves for all three performance indicators versus the 80-s cycle length case, suggesting that the current configuration (80 s) is sub-optimal.

Table 3.12 presents improvements of the hypothetical hybrid pattern obtained by dynamically adapting the signal pattern to real-time data, over the best-performing single pattern measured by the three performance indicators (D, PC, DS). Results show that the hybrid pattern H^D was able to improve the D by 0.49% and 2.47%, for the 60 and 80-s cycle lengths, respectively. Similarly, H^{DS} improved the DS by 0.64% and 3.47%, for the 60 and 80 cycle lengths, respectively. However, H^{PC} did not improve versus the best-performing single pattern. The improvements of H^D and H^{DS} are explained by the fact that both these hybrid patterns are composed of a combination of LTI and EPP. On the contrary, H^{PC} is entirely composed of EPP, and thus there is no advantage in adopting a hybrid pattern. Further analyzing Table 3.12, we also observe that hybrid patterns provide greater improvements for the 60-s cycle length. We argue that this is due to the fact that the best-performing single pattern constitutes a smaller portion of the hybrid patterns for the 60-s cycle length relative to the 80-s case. For example, the best-performing single-pattern makes up 50.00% of the hybrid $H^{DS}60$, whereas, for the hybrid $H^{DS}80$, this portion becomes 87.5%. A more detailed discussion of this can be found in the next section, where we propose several sensitivity analyses.

Table 3.12 Improvement of hybrid patterns in comparison with best-performing patterns

Cycle length	Percentage of improvement		
	H^D	H^{PC}	H^{DS}
80	0.49	0	0.64
60	2.47	0	3.47

3.6.5 Sensitivity Analyses

To enrich our computational study, in this section, we perform several sensitivity analyses on the variation of two important elements: (1) the passenger occupancy rate (the average number of passengers carried by vehicles), and (2) the relative weight of the potential vehicle-to-pedestrian conflict (pc^{v2p}) to the potential vehicle-to-vehicle conflict (pc^{v2v}). Both these analyses require parameterizing some of the equations involved in the performance indicator evaluations, together with performing extensive computational experiments. Given that the previous section showed that the 60-s cycle length case consistently outperformed the 80-s case, we only focus on the 60-s case in this section.

The first analysis focuses on the impact of the passenger occupancy rate (we denote it α) on the performance of the hybrid patterns. Variations of α will require parametrizing the weights in the weighted averages in Equations (1.3) and (3.32). These equations are modified by substituting V^{veh} by αV^{veh} as follows:

$$D^p = \frac{d^{veh-p}\alpha V^{veh} + d^{ped-p}V^{ped}}{\alpha V^{veh} + V^{ped}} \quad \alpha \geq 1 \;\; p \in \{TWC, LTI, EPP\} \; (s/user) \tag{3.35}$$

and

$$DS^p = \frac{DS^{veh-p} \; \alpha V^{veh} + DS^{ped-p} \; V^{ped}}{\alpha V^{veh} + V^{ped}} \; \alpha \geq 1 \;\; p \in \{TWC, LTI, EPP\} \; (s/user) \tag{3.36}$$

Note that α does not affect PC measure, and therefore, PC is not considered in the proposed analysis.

The European Environment Agency and The US Office of Energy Efficiency and Renewable Energy have reported that the average passenger occupancy rate is approximately 1.45 (European Environment Agency, 2010) and 1.59 (Office of Energy Efficiency & Renewable Energy, 2018) per vehicle (including the driver), respectively. Thus, in our study, we let α vary in $\{1, 1.2, 1.4, 1.6, 1.8, 2\}$. For each of these values, we recompute the measures D and DS and determine the best-performing single pattern and the hybrid pattern.

Figure 3.25 shows the composition of the hybrid pattern in terms of proportions of the basic patterns when optimizing the delay time. We observe that TWC is never chosen, and the hybrid pattern is composed of varying portions of LTI and EPP. In particular, the portion of EPP increases from 45.84% for $\alpha = 1.2$ to 68.75% for $\alpha = 2$. This might be due to the fact that EPP generally provides better performance in terms of vehicle delays (see Figure 3.11).

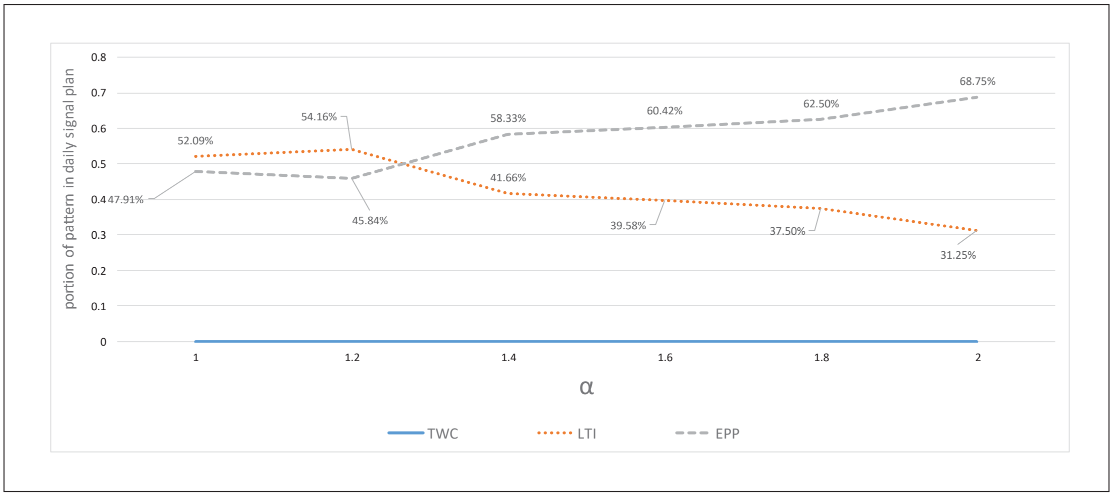

Figure 3.25 Portion of signal pattern in H^D60 by varying values of α

To understand how the improvements of the hybrid pattern change with α, we compared the delay time of H^D60 with the best performing single pattern in Table 3.13, where the first column refers to α and the following columns present D for the H^D60, the best performing pattern for each value of α and the improvement percentage, while we choose H^D60 over the best performing pattern, respectively. We observe that the improvements range from 2.12% to 3.23%. We cannot, however, identify a monotonic relation between improvements and values of α.

Table 3.13 Comparison of D for H^d60 and the best performing pattern

α	**D for H^d60**	**D for the best performing pattern**	**Percentage of improvement**
1	15.39	15.78	2.47
1.2	15.26	15.77	3.23
1.4	15.08	15.55	3.02
1.6	14.95	15.36	2.66
1.8	14.84	15.20	2.36
2	14.74	15.06	2.12

We repeat the methodology of the previous experiment to study the impact of α on DS. Figure 3.26 shows the composition of the hybrid pattern in terms of the proportion of the basic patterns when optimizing DS. Similar to the Delay Time case, we observe that TWC is never chosen in the hybrid pattern. Furthermore, following a similar pattern as in the previous experiment, the portion of EPP in the hybrid pattern increases with α, and in particular, ranges from 50.00% to 77.08%. This tendency might still be due to the fact that EPP performed particularly well in terms of Vehicle Delay Time.

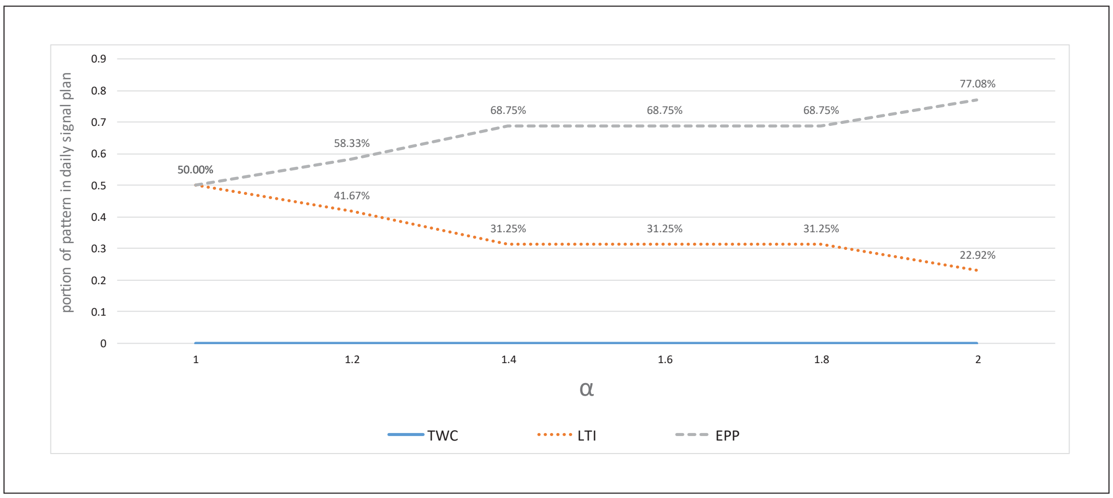

Figure 3.26 Portion of signal pattern in $H^{DS}60$ by varying values of α

Table 3.14 shows improvements of the hybrid pattern $H^{DS}60$ relative to the best-performing single pattern. The meaning of each column is similar to what is provided in Table 3.13, but in Table 3.14, instead of D, DS is investigated. We observe that the improvements of $H^{DS}60$ range from 1.07% to 3.47%. Differently from the previous case, here, we identify a monotonous relation between the improvements and α. In particular, we observe that by increasing the value of α, the efficiency of the hybrid pattern over the best-performing pattern decreases. This is due to the fact that when α increases, the performance of the EPP pattern in terms of DS also increases, and consequently, the portion of EPP composing the hybrid $H^{DS}60$ also increases by up to 77.08%. We also observe that LTI still outperforms EPP for time periods with high pedestrian volumes.

Table 3.14 Comparison of DS for $H^{DS}60$ and the best performing pattern

α	**DS of $H^{DS}60$**	**DS of the best performing pattern**	**Percentage of improvement**
1	15.85	16.42	3.47
1.2	17.53	17.96	2.39
1.4	19.42	19.75	1.67
1.6	21.41	21.72	1.42
1.8	23.55	23.81	1.09
2	25.73	26.01	1.07

The second sensitivity analysis focuses on the impact of changing the relative weight of pc^{v2p} to pc^{v2v}. This mostly requires parametrizing Equation (3.26) by substituting pc^{v2p-p} with σpc^{v2p-p}, where σ is a suitable weighting factor:

$$PC^{p} = pc^{v2v} + \sigma pc^{v2p-p} \qquad sigma \geq 1\ (user\ with\ conflict\ /time\ interval) \tag{3.37}$$

We observe that changes in σ do not have any impact on the Delay Time, which is consequently excluded from further analysis. Concerning the Delay and Safety index, we need to modify Equation (3.34) as follows:

$$DS^{ped-p} = d^{ped-p}\ (1 + \frac{\sigma pc^{v2p-p}}{V^{ped}}\ ) \quad sigma \geq 1\ (s/user) \tag{3.38}$$

To the best of our knowledge, the literature does not provide a methodology to assign suitable values to σ or to estimate the impacts of a given value in terms of fatalities, injuries, etc. (Roshandeh, Levinson, Li, Patel & Zhou, 2014). However, when comparing the fatality, major injury, and minor injury counts due to a given value of pc^{v2v}, Zhang & Prevedouros (2003) estimates that the corresponding count for the same value of pc^{v2p-p} is about 12, 6 and 1.7

times higher, respectively. In practice, traffic agencies set the value of σ for pc^{v2p-p} by rules of thumb (Roshandeh *et al.*, 2014). In this study, we let σ vary in $\{1, 2, 3, 4, 5, 6\}$.

As shown in Figure 3.17, EPP scores a value of $pc^{v2p} = 0$. Furthermore, $H^{PC}60$ is completely composed of EPP, and therefore, the PC will not change, even by varying σ; as well, EPP will remain the best-performing pattern in terms of PC. Therefore, we will now concentrate on studying the performance of $H^{DS}60$.

Figure 3.27 presents the composition of the hybrid pattern in terms of the proportion of basic patterns when optimizing the DS. We observe that, as in all previous experiments, TWC is never chosen as part of the hybrid pattern. This pattern is only composed of LTI and EPP, with EPP increasing from 50.00% to 66.66%. This increase is due to the fact that $pc^{v2p} = 0$ for EPP, and thus, increasing σ has no impact on EPP, while it deteriorates the performance of the other patterns.

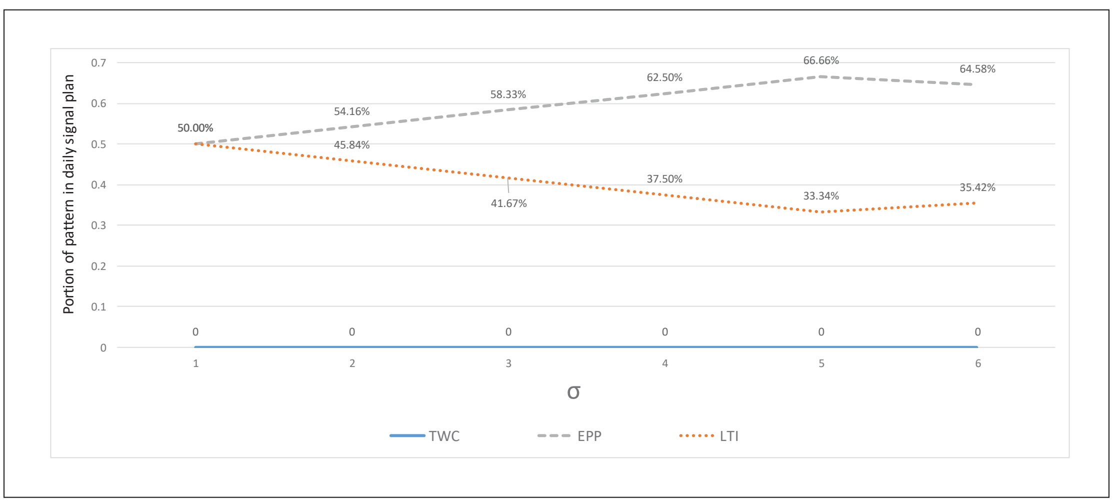

Figure 3.27   Portion of the signal pattern in $H^{DS}60$ by varying values of σ

Table 3.15 presents the improvements seen in the hybrid patterns $H^{DS}60$ relative to the best-performing single pattern when varying σ. The meaning of each column is similar to what is provided in Table 3.14, but, instead of α, we now vary the parameter σ in the first column. We observe that improvements range from 0.73% to 3.41%. We also observe the existence of a monotonic relation between σ and the improvements. Specifically, the improvements decrease as σ increases. This is probably due to the fact that EPP constitutes a larger portion of the hybrid $H^{DS}60$ when σ increases. In fact, larger values of σ imply a larger penalization of pedestrian-to-vehicle conflicts, and EPP performs particularly well in terms of this performance measure. We note that LTI is still competitive in time periods with low pedestrian volumes.

Table 3.15 Comparison of DS for $H^{DS}60$ and the best performing pattern

σ	**DS of $H^{DS}60$**	**DS of the best performing pattern**	**Percentage of improvement**
1	15.85	16.41	3.41
2	15.95	16.41	2.80
3	16.05	16.41	2.19
4	16.15	16.41	1.58
5	16.22	16.41	1.15
6	16.29	16.41	0.73

3.6.6 Limitations and Recommendations

This research is naturally subject to limitations that need to be investigated. Below are recommendations for future research paths. The result of our study only applies to one specific intersection on one specific day. This study should be performed on other intersections and for different time periods to account for a variety of user flow rates as this should provide reliable results regarding how traffic signal performance indicators are impacted by dynamically changing signal patterns.

In this study, because of the limitations of the software used, the effects of signal patterns on the intersection's performance indicators were investigated using only a fixed cycle length. Therefore, it is recommended to investigate the effect of changing or optimizing both the cycle length and the signal pattern on the performance indicators.

In our study, we made the hypothesis that the Peel-Notre-Dame intersection is isolated. In reality, some interaction with close-by intersections may exist. It is then recommended to investigate the coordination between intersections.

According to general observations, 20.00% of pedestrians cross the intersection during the flashing or red intervals. However, in this study, we considered that all pedestrians were crossing during the green interval. Therefore, further research is needed to assess the impact of pedestrian behavior on the performance of traffic signal patterns.

Finally, it is recommended that future studies investigate how users deal with the signal pattern changing dynamically as this may affect users' behavior and, in turn, the effectiveness of dynamically changing the signal patterns.

3.7 Conclusions

This study investigates how dynamically changing the traffic signal pattern configuration allows to better accommodate traffic flow variation throughout the day. More specifically, this research aims to determine whether an optimized hybrid pattern can decrease travel time and increase safety at the intersection for both vehicles and pedestrians.

To investigate the impact of a hybrid pattern on traffic flow and safety performance, methods used to measure the delay (D), conflict situations (PC), and Delay and Safety index (DS) were adapted to include both vehicles and pedestrians for different signal patterns (TWC, EPP, and LTI). The methods were applied to the Notre-Dame and Peel intersection in Montreal. The traffic data of the intersection was collected and simulated. Video data were collected on Wednesday, 8 October 2018, from 8 a.m. to 8 p.m. Then, traffic data was simulated on Synchro. Finally, performance indicators (D, PC, DS) were computed based on the real-time traffic data and Synchro outputs.

The case study results show the effect of each signal pattern considered by the study on the performance indicators. EPP is shown to be the best-performing pattern, for a fixed cycle length of 80 and 60 s, regarding PC, while LTI is shown to be the best-performing single pattern regarding D and DS. A dynamic hybrid pattern is developed by combining LTI and EPP when considering DS or D as performance indicators. However, for PC, the dynamic hybrid pattern consists of EPP only as it is the best-performing pattern.

Among the three hybrid patterns formulated in the study, H^{DS} was the best-performing one, improving the average intersection DS. A comparison of the $H^{DS}80$ and $H^{DS}60$ with the best performing non-hybrid pattern shows a 0.64% and 3.47% improvement in DS, respectively. Therefore, the hybrid pattern has a favorable but limited impact on the quality of travel at the intersection for the one day of data used in this study. However, further research based on additional observations made on different days is needed to verify whether the hybrid pattern significantly improves the quality of travel.

CONCLUSION AND RECOMMENDATIONS

As we discussed in 3.1, traffic signals are the main part of the traffic control system that directly affects the delay time and safety, which are the two main objectives of the transportation system. Traffic signal optimization appeared in most of the studies related to urban areas. A traffic signal plan is made based on cycle length and phase sequences. Mostly, the literature focused on how optimizing the traffic signal cycle length can affect the quality of travel experience by considering various objectives (delay time, safety, emissions, queue length, etc) and users (vehicles. pedestrians, bicycles, transit, etc). However, phase sequences of the traffic signal or a signal pattern can be optimized to identify the best sequences of users' movements for each cycle length. This study investigates how dynamically changing the traffic signal pattern configuration allows to better accommodate traffic flow variation throughout the day. Specifically, this research aims to determine whether an optimized hybrid pattern can reduce travel time and increase safety at the intersection for both vehicles and pedestrians while maintaining a fixed cycle length.

To compute delay and safety for each signal pattern, this research focused on the performance measures defined based on the group of user movements. We adapted each performance measure for each user by considering the signal pattern as a sequence of a phase related to a group of users' movements.

To investigate the impact of a signal pattern on traffic flow and safety performance, we measure Delay (D), Potential Conflict situations (PC), and Delay and Safety index (DS) of different signal patterns (TWC, EPP, and LTI) for both vehicles and pedestrians.

The methods were applied to the Notre-Dame and Peel intersection in Montreal. The traffic data of the intersection was collected and simulated. Video data were collected on Wednesday, October 8, 2018, from 8 a.m. to 8 p.m. Then, traffic data was simulated on Synchro. Finally, performance indicators (D, PC, DS) were computed based on real-time traffic data and Synchro outputs.

The case study results show the effect of each signal pattern considered by the study on performance indicators. EPP is shown to be the best-performing pattern regarding PC, for a fixed cycle length of 80 and 60 seconds while LTI mostly is shown to be the best-performing pattern regarding D and DS. A dynamic hybrid pattern is developed by combining LTI and EPP when considering DS or D as performance indicators. However, for PC, the dynamic hybrid pattern consists of EPP only as it is the best-performing pattern. The EPP signal pattern is mostly used for intersections with high pedestrian demand to increase the quality of travel by pedestrians. However, as shown in the results, this signal pattern is not the best option for the whole day when we consider a pedestrian delay. It may cause an unacceptable amount of delay for the pedestrians, and as a result, it increases the violating behavior of pedestrians to cross the street at the red pedestrian light and it can increase the potential of conflict between pedestrians and vehicles at the intersection. However, choosing the EPP for the period of the day when the intersection has a significant amount of left or right-turn vehicles and high pedestrian demand can reduce the potential conflicts and delay for both pedestrians and vehicles.

Based on the users' flow rate at the studied intersection, LTI(80) is resulting as the best performing for 87.50% of the day, while LTI(60) has a portion of 52.10% of the day as the best performing pattern. However, the best-performing pattern related to a number of conflicts is always EPP. Then, as we defined DS as a combination of Delay and Safety, LTI(80) performs 87.50% of the day as the best-performing pattern while LTI(60) performs 50% of the day. This suggests that using a fixed signal pattern for the whole day could affect the performance measures of the study. Therefore, it is recommended to modify both the signal pattern and cycle length based on the traffic data throughout the day to optimize the traffic signal plan and increase its efficiency.

Among the three hybrid patterns formulated in the study for fixed cycle length, H^{DS} was the best performing one, improving the average intersection DS. A comparison of the H^{DS} 80 and H^{DS} 60 with the best-performing non-hybrid pattern shows a 0.64% and 3.47% improvement in

DS, respectively. Therefore, the hybrid pattern has a favorable but limited impact on the quality of travel experienced by users at the intersection.

The H^d60 shows a 2.47% delay improvement compared with LTI(60) while we had approximately 43926 users (vehicles and pedestrians) that passed the intersection on the day of the study. The improvement in user delay with a hybrid signal pattern is expected to save at least 4.75 hours of travel time at the intersection on the day of our study which increases the quality of travel and improves the level of service for both pedestrians and vehicles.

Due to the high cost and time required for data collection, we only studied the hybrid pattern for one day. However, we recommend utilizing advanced traffic data collection systems to incorporate both pedestrian and vehicle data to optimize the traffic control system's performance for both user groups. Additionally, further research can investigate the use of qualitative pedestrian data for traffic signal optimization in place of quantitative pedestrian data.

Naturally, this research has limitations that require further investigation. As such, we suggest the following areas of focus for future research. It should be noted that the findings of this study pertain only to a single intersection on a particular day. To account for varying user flow rates and obtain reliable results regarding the impact of dynamically changing signal patterns on traffic signal performance indicators, it is recommended to conduct similar studies on multiple intersections and for different time periods.

As a result of limitations in the software employed, this study solely examined the impact of signal patterns on intersection performance indicators using a fixed cycle length. Consequently, we recommend exploring the effects of varying or optimizing both the cycle length and signal pattern on performance indicators.

We posited in our study that the Peel-Notre-Dame intersection operates independently. Nevertheless, it is possible that there is some interaction with an adjacent intersection. Hence, it is advisable to explore the coordination between intersections.

Based on general observations, 20.00% of pedestrians cross the intersection while the traffic signal is flashing or red. However, in this study, we assumed that all pedestrians cross during the green signal interval. Therefore, further research is needed to examine the impact of pedestrian behavior on traffic signal pattern performance.

Finally, future investigations should explore how users respond to dynamically changing signal patterns, as this could affect user behavior and consequently, the efficacy of dynamically changing signal patterns.

APPENDIX I

OPTIMUM CYCLE LENGTH

This section compares the effect of fixed cycle length and optimum cycle length on the hybrid pattern; we redo all the experiments of Section 3.6 to compare the patterns with the optimum cycle length. To optimize the cycle length, we use Synchro 10 to simulate our data for each period, and we relax the fixed cycle length assumption by optimizing it for any 15 minutes for each pattern.

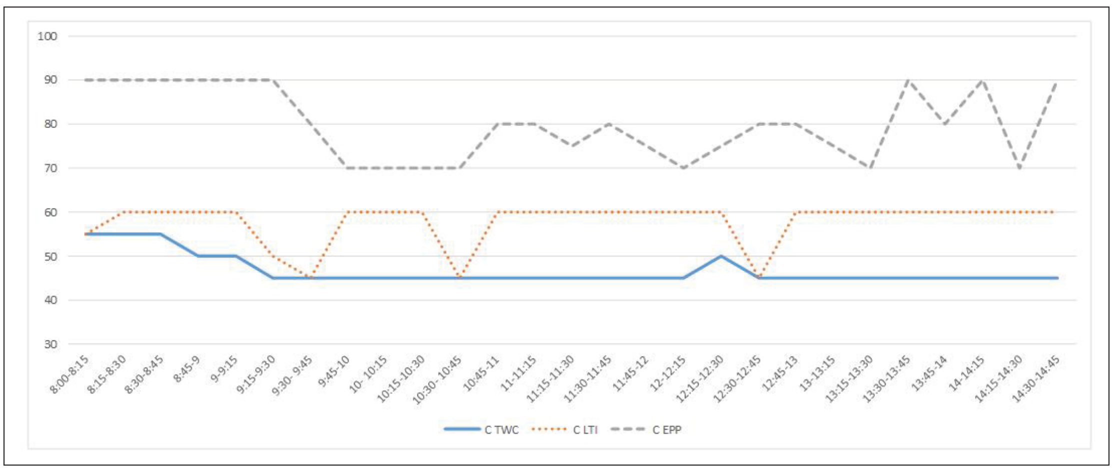

Figure-A I-1 Optimum cycle for each pattern during the day

Figure I-1 presents the optimum cycle length during the day for each pattern when Synchro simulates the same users' data for each period. According to the optimum cycle length on each time interval, we have to compute the performance measures for our patterns. Synchro's objective function is based on delay or/ and the number of stops at an intersection, and it is not specified how Synchro considers the number of conflicts in its optimization of cycle length. Therefore, we decide to investigate the optimum cycle length scenario regarding only the delay criteria.

1. Comparison of delay time for optimum cycle length

In this section, the intersection delay time is compared for various signal patterns with the optimum cycle length. The following figures show the pedestrian and vehicle delay for three signal patterns (TWC, EPP, LTI) during the day. As we discussed in Sections 3.2.2.1 and 3.3, the vehicle delay has been computed by Synchro, when the pedestrian delay has been estimated according to the method introduced in Section 3.4.1.

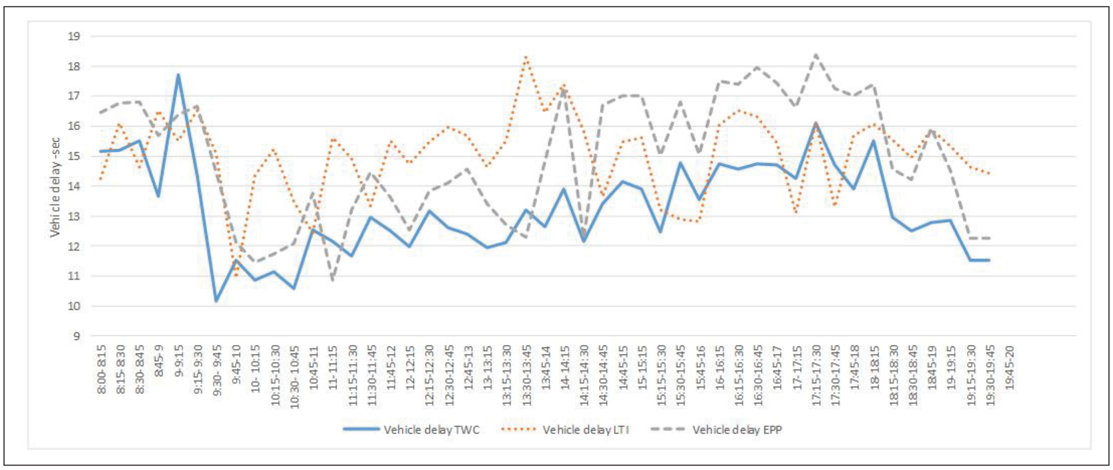

Figure-A I-2 d^{veh-p} for optimum cycle length with $p \in \{TWC, LTI, EPP\}$

Figure I-2 presents the comparison of d^{veh-p} for $p \in \{TWC, LTI, EPP\}$ during the day of study. In this case, TWC provides the minimum vehicle delay (13.28 veh/sec), which is different from the fixed cycle length that provides the EPP with minimum vehicle delay during the day. Also, the H_o^{d-ped} (hybrid pedestrian delay with optimum cycle length) provides a combination of 91.66% of the LTI, 6.25% of the TWC, and 2.09% of the EPP as a pattern for the day of the study.

Figure I-3 presents the comparison of d^{ped-p} for each signal pattern. Like the pedestrian delay of fixed cycle length, the pedestrian delay of optimum cycle length has also resulted in the LTI pattern as minimum pedestrian delay (an average of 15.86 sec/ped).

Figure I-4 shows the comparison of D for each pattern with the optimum cycle length. Comparing average delays over the day leads us to LTI with the minimum delay (15.45 sec/per). However,

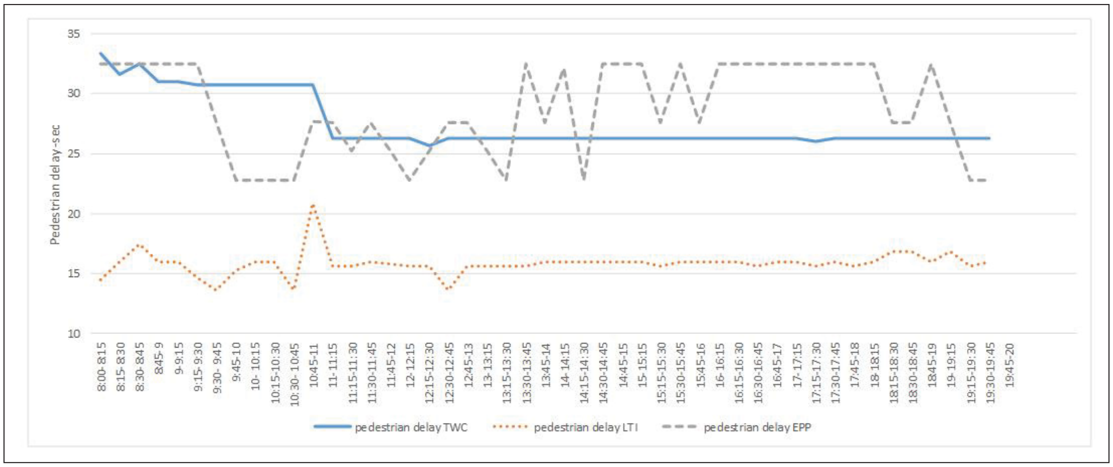

Figure-A I-3 d^{ped-p} for the optimum cycle length with $p \in \{TWC, LTI, EPP\}$

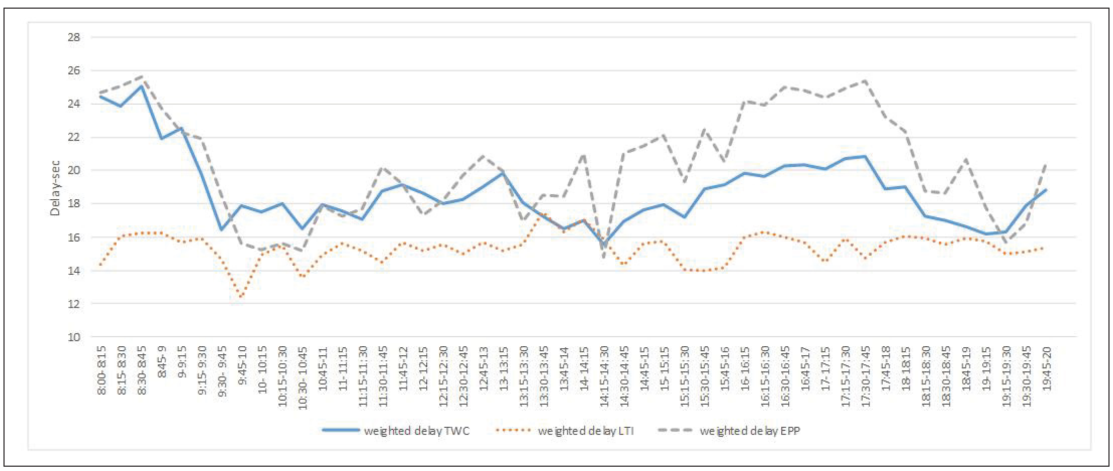

Figure-A I-4 D^p for optimum cycle length with $p \in \{TWC, LTI, EPP\}$

partially during the day, EPP shows the minimum total delay. Also, it demonstrates EPP pattern cannot improve the intersection delay or even pedestrian delay, but LTI has decreased the pedestrian delay and improved the intersection efficiency. It indicates the LTI and EPP as a hybrid delay of the optimum cycle (H_o^d).

Table I-1 compares H_o^d with the best performing pattern (LTI), and it presents a 0.26% improvement of the hybrid pattern in comparison with LTI when LTI has the lowest intersection delay among the other patterns. To specify the effect of hybrid pattern on a performance measure, Table-A I-1 Hybrid improvement in comparison with the best performing pattern

pattern	D(s)
LTI	15.37
H_o^d	15.33
Improvement	0.26%

we compare the delay (since PC is not applicable for optimum pattern) related hybrid patterns of our study in Table I-2 that the first row indicates the patterns and the second row presents the D :

Table-A I-2 Delay per user for the day of the study

pattern	(H_o^d)	H^d60	H^d80	Existing pattern (LTI 80)	H^{DS}80	H^{DS}60
D (s)	15.33	15.38	18.06	18.16	20.76	16.08

Table I-2 reports the comparison of delay-related hybrid patterns of our study with LTI as a current pattern of the intersection, and it shows H_o^d as a pattern with minimum user delay during the day. As we expect, it clarifies that optimizing the cycle length can reduce the average delay of users and increases traffic signal efficiency. Also, the idea of a hybrid pattern shows the improvement of performance measures in our study. The result indicates that the optimization of the cycle length or signal pattern alone cannot lead to an intersection signal plan with maximum efficiency, just as the delay alone cannot evaluate the effectiveness of an intersection signal plan. Then, it is recommended to optimize both cycle length and signal pattern according to the real-time traffic data to improve the quality of the travel experience for the user at the intersection. The next part investigates how changing the weight of performance measures can affect the hybrid pattern.

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