Methodology for evaluating the effectiveness of control devices at intersections with a focus on vulnerable road users

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To my mom Rocio and family

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List Of Symbols and Abbreviations

MAS	minor-approach-only
AWS	all-way stop
VRUs	vulnerable road users
SMoS	Surrogate Measure of Safety
RTOR	right-turn-on-red
LOS	Level of Service
PET	post-encroachment time
BC	Base Case
PP	Leading Phase
CP	partially protected
CPT	protected turn phase
CONACyT	National Council of Science and Technology of Mexico
NSERC	Natural Sciences and Engineering Research Council
RRSR	Road Safety Research Network of Quebec
UMSNH	Michoacan University of San Nicolas Hidalgo
MUTCDC	Manual on Uniform Traffic Control Devices for Canada
EU	European Union
CMFs	crash modification factors
SSAM	Surrogate Safety Assessment Model
FHWA	Federal Highway Administration
USA	United States of America
MUTCD	Manual on Uniform Traffic Control Devices
US	United States
AASHTO	American Association of State Highway and Transportation Officials
HSM	Highway Safety Manual
TTC	Time-to-Collision
TAC	Transport Association of Canada
MTQ	Quebec Ministry of Transportation
ETSC	European Transport Safety Council
VPI	vehicle-pedestrian interactions
VCI	vehicle-cyclist interactions
VVI	vehicle-vehicle interactions
CPI	cyclist-pedestrian interactions
CCI	cyclist-cyclist interactions
CVI	cyclist-vehicle interactions
Q05	5th Percentile

Q95	95th Percentile
KS	Kolmogorov–Smirnov test
CP	partially protected
CPT	protected turn phase
IQR	Interquartile Range
AI	Artificial Intelligence
GNSS	Global Navigation Satellite System

Abstract

This research focuses on the safety effectiveness of converting minor-approach-only stop (MAS) intersections into all-way stop (AWS) intersections, as well as the impact of bicycle traffic lights on the safety and behaviours at signalized intersections. A methodology is proposed to examine the effects of stop signs and traffic lights on the different road users, particularly vulnerable road users (VRUs), using Surrogate Measure of Safety (SMoS) indicators.

To conduct the study, a surrogate before-after methodology is developed, and multiple SMoS indicators are derived by analyzing video data collected before-and-after the conversion of MAS to AWS intersections. The video data is gathered from 35 intersections, 109 approaches, and over 71,000 road users. The videos were collected on weekdays between 8:00 am and 6:00 pm during the school year to ensure a representative traffic flow. High-resolution trajectories of road users are extracted from the video data using a commercial software. To investigate the effectiveness of the treatment, a statistical multi-level model was implemented to accommodate for the hierarchical structure (intersection - approach - user) of the data. The Distance-Velocity Framework proposed by (Fu, Miranda-Moreno, and Saunier 2018) is used to assess driver yielding behaviour.

In addition, the impacts of bicycle signals are evaluated using computer microscopic simulations. Four different signal strategies were evaluated on four different intersections designs where right-turn-on-red (RTOR) is prohibited with dedicated bicycle facilities. The Level of Service (LOS) and SMoS indicators are obtained from the simulated microscopic model.

The finding of this dissertation indicates that converting MAS to AWS intersections lead to a significant reduction of vehicle speed and a significant increase of post-encroachment time (PET). Implementing AWS significantly increased the yielding rates from 45.7% to 76.7% and reduced the average speed of motor-vehicles. Regarding cyclists, the study reveals that the presence of a stop sign on the approach does not significantly improves safety based on PET. However, cyclists show a significant reduction in speed when a stop signal is presented. The analysis suggests that cyclists exhibit greater caution when interacting with pedestrians or vehicles compared to other cyclists.

The computer simulation demonstrated that the Leading Phase (PP) in the presence of bicycle

facilities has a similar LOS to the Base Case (BC) in most scenarios. However, the PP can reduce the number of vehicle-cyclist interactions by up to 50% compared to the BC under certain circumstances.

Overall, this dissertation underscores the importance of considering Vulnerable Road Users (VRUs) as individual users and not as part of the motorized user group when designing stop control guidelines. It recommends to federal and state/provincial agencies follow municipal guidelines that recognize this distinction. Future guidelines should not leave VRUs out when evaluating user volumes or behaviours, as demonstrated in the two microscopic analyses presented in this document. VRUs exhibits different responses to control signs, and traffic rules should be developed while considering their characteristics.

Résumé

Cette recherche se concentre sur l'efficacité en termes de sécurité de la conversion des intersections avec panneaux d'arrêt sur les approches secondaires (AAS) en intersections à arrêt dans toutes les directions (ATD), ainsi que sur l'impact des feux de signalisation pour cyclistes sur la sécurité et les comportements aux carrefours à feux. Une méthodologie est proposée pour examiner les effets des panneaux d'arrêt et des feux de signalisation sur les différents usagers de la route, en particulier les usagers vulnérables, à l'aide de méthodes substituts de la sécurité (MSS).

Pour mener à bien cette étude, une méthodologie substitut de sécurité avant-après est développée, et de multiples indicateurs MSS sont dérivés en analysant les données vidéo collectées avant et après la conversion des carrefours AAS en carrefours ATD. Les données vidéo proviennent de 35 intersections, 109 approches et plus de 71 000 usagers de la route. Les vidéos ont été collectées en semaine, entre 8h00 et 18h00, pendant l'année scolaire, afin de garantir un flux de circulation représentatif. Les trajectoires à haute résolution des usagers de la route sont extraites des données vidéo à l'aide d'un logiciel commercial. Pour étudier l'efficacité du traitement, un modèle statistique à plusieurs niveaux a été mis en œuvre pour tenir compte de la structure hiérarchique (intersection - approche - usager) des données. Le cadre distance-vitesse proposé par Fu, Miranda-Moreno et Saunier (2018) est utilisé pour évaluer le comportement des conducteurs qui cèdent le passage.

En outre, les impacts des signaux pour cyclistes sont évalués à l'aide de simulations informatiques microscopiques. Quatre stratégies de plan de feux différentes ont été évaluées sur quatre types d'intersections différentes où le virage à droite sur le feu rouge (VDFR) est interdit avec des aménagements cyclables réservés. Les indicateurs de niveau de service (NS) et de MSS sont obtenus à partir du modèle microscopique simulé.

Les résultats de cette thèse indiquent que la conversion des intersections AAS en intersections ATD conduit à une réduction significative de la vitesse des véhicules et à une augmentation significative du temps post-encastrement (TPE). La mise en œuvre des ATD a augmenté de manière significative les taux de céder le passage de 45,7 % à 76,7 % et a réduit la vitesse moyenne des véhicules à moteur. En ce qui concerne les cyclistes, l'étude révèle que la présence

d'un panneau d'arrêt à l'approche n'améliore pas significativement la sécurité selon le TPE. Cependant, la vitesse des cyclistes est réduite de façon significative lorsqu'un panneau d'arrêt est présent. L'analyse suggère que les cyclistes font preuve d'une plus grande prudence lorsqu'ils interagissent avec des piétons ou des véhicules que les autres cyclistes.

La simulation informatique a démontré qu'une phase avancée (PA) en présence d'aménagements cyclables a un niveau de service similaire au scénario de base (SB) dans la plupart des scénarios. Cependant, la PA peut réduire le nombre d'interactions véhicule-cycliste jusqu'à 50 % par rapport au scénario de base dans certaines circonstances.

Dans l'ensemble, cette thèse souligne l'importance de considérer les usagers vulnérables comme des usagers à part entière, et non comme un groupe d'usagers motorisés, lors de l'élaboration des directives de contrôle de la circulation à l'aide de panneaux d'arrêt. La thèse recommande aux agences fédérales et provinciales de suivre les directives municipales qui reconnaissent cette distinction. Les futures directives ne devraient pas laisser de côté les usagers vulnérables lors de l'évaluation des débits d'usagers ou de leurs comportements, comme le démontrent les deux analyses microscopiques présentées dans ce document. Les usagers vulnérables réagissent différemment aux panneaux de signalisation, et les règles de circulation devraient être élaborées en tenant compte de leurs caractéristiques.

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Contribution Of Authors

I want to declare that I am the first and sole author among the co-authors of the dissertation. My contribution to the articles includes conducting the research studies, collecting, and preparing the data, developing the models, analyzing the data, and writing the manuscripts. The author's supervisors, *Prof. Luis Miranda-Moreno* and *Prof. Nicolas Saunier*, provided guiding research direction, contribution to methodologies, comments, and end editorial revisions throughout the entire process. The additional authors contributed by helping with data analysis guidance and editing the papers.

The below list shows the papers published or submitted to peer-reviewed journals by the dissertation author as part of this Ph.D. dissertation.

Navarro, B*., Miranda-Moreno, L., Saunier, N., Labbe, A., and Fu, T. (2022). Do Stop-Signs Improve the Safety for All Road Users? A before-after Study of Stop-Controlled Intersections Using Video-Based Trajectories and Surrogate Measures of Safety. Accident Analysis and Prevention 167 (February). https://doi.org/10.1016/j.aap.2021.106563.

Navarro, B*., Miranda-Moreno, L., Saunier. (2023). Cyclist Behaviour and Safety Towards Stop Signs. A Study on Stop-Controlled Intersections Using Video Trajectory and Surrogate Measures of Safety. Presented at the 2018 Transportation Research Board 97th annual meeting. No. 18-04807. Under preparation for submission to Accident Analysis and Prevention

Ledezma-Navarro, B*., Stipancic, J., Andreoli, A., Miranda-Moreno, L. (2018). Evaluation of Level of Service and Safety for Vehicles and Cyclists at Signalized Intersections. Presented at the 2018 Transportation Research Board 97th annual meeting. No. 18-04807

Other Contributions

Stipancic, J., St-Aubin, P., **Ledezma-Navarro, B.**, Labbe, A., Saunier, N., Miranda-Moreno, L., "Evaluating Safety-Influencing Factors At Stop-Controlled Intersections Using Automated Video Analysis". Journal of Safety Research 77 (2021) 311–323. https://doi.org/10.1016/j.jsr.2021.03.006

Scholl, L., Elagaty, M., **Ledezma-Navarro, B.**, Zamora, E., & Miranda-Moreno, L. (2019). "A Surrogate Video-Based Safety Methodology for Diagnosis and Evaluation of Low-Cost Pedestrian-Safety Countermeasures: The Case of Cochabamba, Bolivia." Sustainability, 11(17), 4737. https://doi.org/10.3390/su11174737

Fu, T., Beitel, D., **Ledezma-Navarro, B.**, Saunier, N., & Miranda-Moreno, L. (2018). Investigating Cyclist–Pedestrian Interactions at Bus Stops and Non-signalized Intersections Using a Distance–Velocity Model and Speed Measures Derived from Video Data. Presented at the 2018 Transportation Research Board 97th annual meeting. No. 18-05083.

St-Aubin, P., **Ledezma-Navarro, B.**, Labbe, A., Fu, T., Saunier, N., & Miranda-Moreno, L. (2018). Speed at partially and fully stop-controlled intersections. Transp. Presented at the 2018 Transportation Research Board 97th annual meeting. No. 18-05438

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Bocktor, Y., **Ledezma-Navarro, B.**, Miranda-Moreno, (2021). "The Effect of The Geometric Turning Radius on Vehicle Speeds at Urban Non-signalized Intersections as a Safety Indicator". Transportation Research Board 99th. Washington, D.C. No 20-02363

Chapter 1. Introduction

A dissertation introduction is presented in this chapter, which includes the motivation and research context on road users' safety and behaviours at stop-controlled and signalized intersections, with a special focus on cyclists and pedestrians – also referred to as vulnerable road users. Additionally, the objectives, literature review, and the gaps in research on this topic are presented.

1.1. Motivation And Context

Intersections are crucial points in the road network, both and in terms of safety and operations, as they serve as space where all road users interact. As a result, traffic engineers look to implement efficient and safe interventions to accommodate all road users. In North America, there are three levels of intersection control: Level I, which relies on the basic right-hand rule of the road in the absence of traffic control; Level II, involving the installation of stop or yielding signs to prioritize certain movements; and Level III, which involves traffic lights to separate movements crossing the intersection at different times. Stop signs and traffic lights are the most common control measures in urban areas, with Level I more prevalent in rural areas. Each country, and sometimes state/province, has documentation that describes their guidelines for installing control devices. For instance, in Canada, the Manual on Uniform Traffic Control Devices for Canada (MUTCDC) (MUTCDC 2014) outlines the requirements for the installation of control devices at intersections. Similarly, the Quebec Ministry of Transport provide guidelines for the province of Quebec in Tome V, Traffic Control Devices (VolumeV 2016). These guidelines determine the type of stop control device required for an intersection, with a primary focus on vehicular traffic in relation to the vehicular volume, vehicle speed, safety concerns, and visibility.

Over the past decade, active transportation (walking and cycling) has been proved to be one of the sustainable urban mobility solutions. In particular, cycling has been on the rise in North American cities as documented by (Pucher, Buehler, and Seinen 2011; Buehler, Pucher, and Bauman 2020). Zahabi pointed out that cities with an increasing trend in cycling have designed effective interventions to encourage their populations to use this mode of transportation, improving comfort and safety to address this growth (Zahabi et al. 2016). One reason for this growth is that cycling is often a more efficient commuting option in urban areas compared to other transport modes (Faghih-Imani et al. 2017; Ellison and Greaves 2011).

Urban planners, transportation specialists, politicians, and health care professionals view cycling as part of the solution to many societal challenges (Krizec 2007). In addition to the benefits of the individual, there are societal benefits of cycling and walking that have been documented, such as the reduction in emissions and noise pollution, cheaper infrastructure, and public health improvements (Heinen, van Wee, and Maat 2010; Pisoni, Christidis, and Navajas Cawood 2022). Moreover, cyclists generally avoid congestion while benefitting from a healthier and less expensive mode of transportation than utilizing a motorized vehicle (Buehler, Pucher, and Bauman 2020; Mueller et al. 2015). In addition to concerns about public health, physical activity, and livability, the reduction of automobile use and the resulting positive environmental effects, such as the reduction of pollution, consumption of natural resources, and driver stress, are common motivations for cycling and walking initiatives (Barton, Hine, and Pretty 2009; Singleton 2019). Furthermore, during the COVID-19 pandemic, active transportation, in particular cycling, proved to be an efficient way to commute, as evidence showed with the increase in ridership's in some cities, and helped users avoid public transportation, which was perceived to be riskier (Büchel, Marra, and Corman 2022). For example, a study made by Buehler and Putcher showed that there was on average cyclist ridership increase of 8% from a sample of 11 European Union (EU) countries (Buehler and Pucher 2021). The increase in the previous study was mostly observed during the weekend, although in Portugal and France, the increases occurred during the weekdays as well.

Despite the well documented benefits, the development of initiatives for vulnerable road users (VRUs), for this work being pedestrians and cyclists, faces significant barriers, including inadequate road facilities and road safety measures. Specifically, road safety at intersections remains a significant concern for VRUs; for instance, at least half of the vehicle-cyclist collisions occur at intersections (Hunter et al. 1996; Dozza and Werneke 2014) and a similar ratio for vehicle-pedestrian collisions were also observed (Shaaban and Pinter 2022). Moreover, it has been shown that the amount of dangerous interactions and collisions between motor vehicles and cyclists rises with the increase cyclist ridership (Strauss, Miranda-Moreno, and Morency 2013; Stipancic et al. 2020). To better understand the safety effect of pedestrians and cyclists at intersections, several methodologies and indicators have been proposed to identify risk factors and to evaluate countermeasures based on crash data and surrogate measures of safety (SMoS)

(Laureshyn et al. 2016; Arun et al. 2021). To address the safety issues, cities have implemented treatments such as intersection geometric redesign and changes to the types of intersection traffic controls. The changes to the type of intersection control used include the conversion of minor-approach-only stop (MAS) into all-way stop (AWS) controlled intersections, as well as the addition of bicycle traffic lights at signalized intersections. The literature concerning the impact of different types of controls at intersections, such as the reduction of vehicle conflicts and collisions with VRUs, and improvements in the level of service (LOS), is limited. However, some of these control types may negatively impact vehicular traffic by increasing delays for motorized road users (Allen et al. 1998; Montazeri, Errico, and Pellecuer 2022).

Although there have been advancements in the literature, there are still significant gaps in understanding the effect of alternative traffic controls on the safety of VRUs. Specifically, the effectiveness of the conversion of MAS into AWS intersections has been rarely explored through before-after observational studies and SMoS methods. From a behavioural standpoint, what are the potential impacts on VRUs crossing behaviours and vehicle operating speeds? Additionally, what factors need to be considered for the implementation of the control devices (minor-approach-only stops, all-way stops, traffic lights phases)? These unanswered questions highlight the importance of further investigation to gain a comprehensive understanding of the impacts of alternative traffic controls on VRUs safety.

The primary purpose of this research is to develop a methodology for studying the impacts of changes in the traffic controls, such as converting MAS into AWS intersections and installing bicycle signals in traffic lights, on the safety of VRUs and the efficiency of traffic operation. This project aims at filling several literature gaps. Firstly, there are very few studies that investigate VRUs safety and behaviour in stop-controlled intersections using a before-after observational approach. Secondly, large-scale field studies that utilize SMoS to investigate the effects of control devices on both safety and road user behaviours (such as, operating speeds, stopping distance, yielding rates) are rare in the VRUs literature. Thirdly, a methodology is developed to evaluate SMoS while considering different hierarchy levels, including intersection, approach, and individual user. Lastly, the research evaluates the effects of bicycle-friendly traffic signals at intersections where right-turn-on-red (RTOR) is prohibited and dedicated cyclist facilities are present.

Overall, this research aims to contribute to the understanding of how changes in traffic controls impact the safety and behavior of VRUs, filling gaps in the literature related to before-after observational approaches, large-scale field studies with SMoS analysis, hierarchical analysis incorporating different levels, and the evaluation of bicycle-friendly traffic signals in specific intersection scenarios.

1.2. Research Objectives

The research aims to investigate the effect of changes in traffic controls, specifically the conversion of MAS into AWS and the introduction of bicycle signals on traffic lights on road safety and behaviours of various road users, with a particular focus on VRUs. To accomplish this, an observational before-after framework is developed to assess the road safety and behaviours of all modes at non-signalized intersections. Both non-signalized and signalized intersections will be studied in the Montreal context, where RTOR are prohibited. Emphasis will be placed on two types of intersections: AWS and signalized intersections with dedicated VRUs phasing. This multimodal research aims to investigate the interaction of vehicles and VRUs at intersections. A particular focus is placed on cyclists' and their behaviour as a function of the intersection control. To achieve the objectives of this research, a methodology that combines trajectories from video observations and microscopic models is developed. Speed information obtained from the user trajectories was used to evaluate the intersection operations, while SMoS indicators were employed to evaluate the impact of the different types of controls. Two main trajectory datasets were used in this research – video trajectory observations from a before-after study and control sites were used for the stop-controlled evaluations, while microsimulation trajectories were used for the traffic light analysis. A detailed description of the specific objectives follows:

- **To conduct an extensive literature review related to traffic controls at intersections and cyclists.** A detailed revision of local and international standards, as well as some guidelines for traffic control devices are included in this work. In addition, a review was conducted on the different methodologies to evaluate VRUs safety and traffic operations at intersections using microscopic data and SMoS. The existing literature shows an interest in the interactions of pedestrians and vehicles but remains limited with respect to the use of SMoS for cyclists' at intersections.

- **To evaluate safety for all the road users after converting a MAS into an AWS intersection with a before-after approach.** The impact on safety from converting a MAS to an AWS intersection using a before-after observational approach and SMoS, i.e., measures of safety that do not depend on the occurrence of crashes, is investigated. For this purpose, statistical analyses, including a multi-level modelling approach were used to evaluate the impact of introducing stop-sign controls with built environments (i.e., population and land use mix in proximity to the intersection); traffic exposure and intersection geometry. Among the SMoS indicators, this research considered vehicles' and cyclists' speed measures, and post-encroachment time (PET) for vehicle-vehicle, vehicle-pedestrian, and vehicle-cyclist interactions. Furthermore, pedestrian crossing behaviour is used to determine the resulting safety impact of the intersection treatment.

  Despite the popularity of converting MAS to AWS intersections in urban areas, there is little research on the impact of this countermeasure using SMoS on before-after studies, where behavioural measures such as operating speeds and drivers yielding to pedestrians were considered. In addition to the very limited literature on AWS effectiveness and crash modification factors (CMFs) of AWS using crash data, this approach would require long periods of observation (Lovell and Hauer 1986; Deng et al. 2020). The requirement of several years to collect sufficient crash data is a particular problem when studying facilities with low traffic volumes.

- **To propose a methodology to evaluate cyclist behaviour and safety at stop signs.** A multi-level modelling approach is used to evaluate cyclists'' speed and PET for cyclist-pedestrian, cyclist-cyclist, and cyclist-vehicle interactions. The effect of the introduction of stop-signs on the different approaches was studied, controlling for cyclists' characteristics and behaviours (e.g., use of helmet, performing an avoidance maneuver or making a full stop), built environment, approach, and intersection geometry.

  As mentioned, installing stop signs in urban areas is a popular measure. However, there is little research on cyclists' behaviour at non-signalized intersections and the safety impacts of stop signs on bicycle-pedestrian and bicycle-bicycle interactions. Moreover, given the recurrent large number of violations (cyclists not stopping at intersections), the safety of cyclists and pedestrians has raised some concerns. Additionally, the use of proactive video-based automated approaches to investigate the bicyclists' impact on other users' safety at stop-controlled intersections is limited in the literature.

To address this limitation, the cyclists' behaviour, and safety are investigated at non-signalized intersections with stop signs using an observational approach and SMoS.

- **To develop a methodology based on a microscopic simulation to evaluate the traffic operation impacts and safety benefits of the installation of cyclist traffic lights.** A set of microscopic simulation models were built and calibrated with different signal strategies, traffic flow combinations (cyclist & vehicles) and intersection design geometry. Several indicators such as delay, travel time and SMoS were extracted from the obtained trajectories and evaluated for the different scenarios.

1.3. Contributions

The key contributions of the dissertation are summarized as follows:

- This dissertation reviews the existing North American literature concerning the state of the stop control regulations in relation to the consideration of different road users. Researchers and practitioners can use the literature review in this document as a useful reference. Additionally, the identification of the limitation of the guidelines and existing literature related to stop controls and cyclists can motivate future research.
- The safety of the different road users is evaluated after the conversion of MAS to AWS intersections using SMoS indicators. In this thesis, the impact of introducing stop signs was evaluated, controlling for different variables, using a multi-level modelling statistical approach. These results provide insight into the interaction of vehicles towards the different road users (vehicles, cyclists, and pedestrians) on three levels: intersection, approach, and users.
- The behaviour of cyclists toward stop signs and their safety interactions with other road users (pedestrians, cyclists, and vehicles) is explored in this work. SMoS indicators are used to evaluate safety, controlling for different behaviour variables, and user levels. The results from this evaluation provide awareness of the safety risks that cyclists can cause to other road users. A statistical multi-level modelling approach is utilized with

consideration to three levels (intersection, approach, and user) and different geometric and behavioural variables.

- Finally, a methodology to evaluate traffic light leading phases for cyclists is proposed utilizing microsimulations. Alternative phasing strategies at signalized intersections with bicycle facilities are formulated. The road safety and LOS impacts are evaluated using safety indicators and vehicle delays are considered with different user flows and geometric designs.

1.4. Organization of the Dissertation

The thesis is divided into six chapters. Chapter one refers to the introduction. Chapter 2 is a concise literature review. Chapters 3 to 5 refers to submitted or published papers. The document includes one journal-published manuscript (Chapter 3), one in preparation for submission to a peer-reviewed journal (Chapter 4), and a presented paper to a refereed conference (chapter 5). The dissertation ends with chapter 6, the conclusion of the research.

Chapter 3 investigates the safety effectiveness of converting MAS to AWS intersections using an observational before and after approach and SMoS. The safety impacts of AWS conversions were investigated using multiple indicators, including vehicle speed measures, vehicle-pedestrian, vehicle-cyclist, vehicle-vehicle interactions, and yielding rates before and after the treatment implementation. In addition, a multi-level regression approach was adopted to determine the effect of stop signs controlling for built environments, traffic exposure, intersection geometry factors, and site-specific unobserved heterogeneity.

Navarro, B*., Miranda-Moreno, L., Saunier, N., Labbe, A., and Fu, T. (2022). Do Stop-Signs Improve the Safety for All Road Users? A before-after Study of Stop-Controlled Intersections Using Video-Based Trajectories and Surrogate Measures of Safety. Accident Analysis and Prevention 167 (February). https://doi.org/10.1016/j.aap.2021.106563.

Chapter 4 reviews cyclist crossing behaviours at non-signalized intersections with stop signs in two typical settings: intersections with stop signs only in minor approaches and all-way-stop intersections. The effect of stop signs on cyclist behaviour is investigated using multiple indicators: cyclists' speed measures, post-encroachment time (PET) of cyclist-pedestrian, cyclist-

cyclist, cyclist-vehicle interactions, and yielding rates. For this purpose, cyclist behaviours were studied in these different settings using video and trajectory data. Multi-level linear models were used for the speed and conflict analysis, where the two different stop control settings, geometry, and built environment features at the approach and intersection level were evaluated on cyclists.

Navarro, B*., Miranda-Moreno, L., Saunier. (2023). Cyclist Behaviour and Safety Towards Stop Signs. A Study on Stop-Controlled Intersections Using Video Trajectory and Surrogate Measures of Safety. Under preparation to be submitted to Accident Analysis and Prevention

Chapter 5 evaluates the impact of three different bicycle-friendly traffic signal designs compared to a base case at intersections with turn-on-red restrictions and bicycle facilities. These strategies were simulated across four intersection geometry designs and 156 combinations of cyclist and vehicle flows to obtain the LOS and safety provided to crossing cyclists using conflicts measured by PET. Furthermore, vehicle delay was evaluated using VISSIM microsimulation software, while conflicts were measured with trajectory data generated by VISSIM using the Surrogate Safety Assessment Model (SSAM) developed by the Federal Highway Administration (FHWA).

Ledezma-Navarro, B*., Stipancic, J., Andreoli, A., Miranda-Moreno, L. (2018). Evaluation of Level of Service and Safety for Vehicles and Cyclists at Signalized Intersections. The content of Chapter 4 was presented at the 2018 Transportation Research Board annual meeting. No. 18-04807

Chapter 6 summarizes the contributions and key findings in this document, discussion and future research on cyclist behaviour and safety at controlled intersections.

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Chapter 2. Literature Review

2.1. Literature And Research Gap

This section provides a general description of the different methodological approaches used in previous studies on controlled intersections and vehicle-VRUs interactions, as well as the literature gaps.

2.1.1. Literature Summary

2.1.1.1. Warrants

The stop control manuals of the Federal Governments of Canada and the United States of America (USA) are relatively similar, with the main difference being how they consider approaching vehicle speed and volume. Additionally, the American manuals integrate bicyclist volumes as one of the possible requirements in the minor approach. In Canada, most provinces and territories use the Manual on Uniform Traffic Control Devices for Canada (MUTCDC) as their reference, while others use the MUTCDC as a baseline but have fewer requirements. For instance, the manuals from the provinces of Ontario and Quebec are similar regarding volumes, crash rates, etc. Although most of Quebec and Ontario's requirements are related to the Canadian manuals, the main difference with the federal document is that the two provincial manuals add a specified distance to another control device (stop sign or traffic light) as a requirement.

With regard to the inclusion of VRUs in the manuals, pedestrians were first included in the 1948 version of the Manual on Uniform Traffic Control Devices (MUTCD), with the introduction of the 4-ways stop signs, and it was not until the release of the Millennium version that they were also considered on the MAS intersection. In terms of cyclists, their incorporation in the sections of stop signs and traffic lights at intersections is only a recent topic in some countries/legislations. For the United States (US) manual, cyclists were not recognized as a unique road user until the MUTCD millennium edition. One difference between the Canadian and USA manuals, is that in the US manuals, cyclist are integrated as one of the requirements for the minor approach as separate users, while in the Canadian version cyclists are considered as a vehicle. Furthermore, in both manuals, cyclists need to behave and follow the rules of the vehicles. However, North America is not the only region that subjects cyclists to the same road rules as motorized vehicles; many European countries apply the same criteria (Kircher et al. 2018).

Traffic signal phasing and design is another way to improve safety, LOS, and reduce traffic stress. Unfortunately, guidance for implementing these traffic light phases is limited and their effect on VRUs has been infrequently studied (Curtis 2015). The American Association of State Highway and Transportation Officials (AASHTO) developed a series of equations using the crossing distance to estimate minimum green time and clearance intervals, with a focus of balancing cyclist safety with vehicle delay. Rubins and Handy found that cyclist speeds used in the AASHTO equation exceed typically observed cyclists' speeds, resulting in inadequate minimum green times (Rubins and Handy 2005). Korve and Niemeier analyzed the costs and benefits of integrating bicycle traffic light phases at large urban intersections, finding that the construction costs and increases in vehicle delay exceed estimated savings due to crash reduction (Korve and Niemeier 2002).

2.1.1.2. Safety Studies On Stop Controlled Intersections

According to the Highway Safety Manual (HSM), AWS intersections are recommended as being safer than MAS or no-stop control intersections for crash reduction. Supporting this recommendation, a study by Elvik et al. showed that stop sign installations reduced the crash rate at four-way intersections (Elvik et al. 2009). Similarly, installing stop signs on MAS intersections resulted in an overall significant reduction in conflict frequency by 51% in British Columbia (El-Basyouny and Sayed 2010). Studies have also demonstrated that AWS intersections were adequate to reduce the number of crashes, but only at low-speed rural intersections (Stokes 2004). Moreover, there is conflicting research showing that AWS intersections are not safer than MAS or uncontrolled intersections. Polus found that introducing a stop sign at an uncontrolled intersection increased the average number of crashes from 0.64 to 1.96 for 28 intersections over three years (Polus 1985), suggesting that increasing the level of control at non-signalized intersections does not necessarily result in an overall safety improvement. It should be noted that this study (Polus 1985) did not evaluate the severity of the crashes. Most of these past studies are based on crash data and lack information for a before-after the installation of the stop signs.

Some groups in the society perceive that cyclists do not obey road rules (Shaw et al. 2015), with a focus on failing to stop at stop signs as a problem (Larsen et al. 2011). However, not all road users fall into the same interpretation for disobeying road rules. For example, for some people, drivers going over the speed limit or pedestrians jaywalking are not considered like a violation

(Piatkowski, Marshall, and Johnson 2017). Despite the “bad impression” that cyclists generate while not respecting the stop signs, there is no conclusive evidence that this generates more collisions at the intersection as cyclists treat them as yield signs (Larsen et al. 2011). In general, cyclists are perceived as a “users that break the rules of law” that do not stop at stop signs or ride on the sidewalk. Thus, researchers have investigated to try to find a possible explanation to the cyclist behaviour and their lack of rule following. An online survey of citizens of 73 countries made in 2015 (with a big response rate from the USA, Europe, Australia, and Canada) showed that 71% of the cyclists disregard the traffic rules for safety reasons. Even though most of the respondents to the survey break the law, most do it in situations where there is little risk to harm themselves or the other users of the road (Marshall, Piatkowski, and Johnson 2017). Another reason for cyclists to not stop at the stop sign is the energy-saving and comfort due to the additional effort required to recover their previous speed (Fajans and Curry 2001; Piatkowski, Marshall, and Johnson 2017; Stromberg 2014). Unlike drivers who simply have to shift their foot from the braking to the gas pedal, cyclists require additional physical effort to recover their previous speed at stop signs (Fajans and Curry 2001). An AWS intersections study in Kensington, California, found that almost 90% of cyclists slowed somewhat or came to a full stop at MAS intersections, compared to 33 % of the cyclists at AWS (Ayres et al. 2015). Furthermore, a cyclist wearing a helmet has been linked to good behaviour, such as making a full stop at stop signs (Johnson et al. 2011; Vanparijs et al. 2015). Farris found that cyclists wearing a helmet are 2.6 more likely to make a full stop and 7.1 more likely to use hand signals (Farris et al. 1997). In some cases, an “awkward dance” has been reported between cyclists and drivers at AWS, where the driver is yielding to the cyclist when the preference is for the driver “urging the cyclist to go”, leading to bigger delays on both users (Stromberg 2014).

2.1.1.3. Safety Analysis Methods for Intersections

There are different methods and techniques to analyze safety: using crash counts, deceleration values, SMoS, etc. Unfortunately, for crash counts, not all of them are reported, as was found in a survey made by Robartes, where only 12% of the crashes were documented. Among the underreported crashes involving a cyclist with a vehicle, cyclists had a minor injury in 66% and a severe injury in 19% of crashes (Robartes and Donna Chen 2018). Computer vision techniques have allowed the development of practical tools for safety analysis due to their capacity to extract user trajectories and classify them from videos (Saunier, Sayed, and Ismail 2010). The microscopic trajectory data from the videos is then used to identify patterns in traffic events (Saunier, Mourji, and Agard 2011). SMoS rely on indicators to measure safety at the site level, based on user or interaction-level safety indicators like Time-to-Collision.

Existing indicators can be classified into four groups (Saunier and Laureshyn 2021):

- Time-to-Collision (TTC) is defined as the time remaining until a collision of two road users occurs, assuming they continue travelling as initially planned.
- Post-Encroachment-Time (PET) is defined for users with observed crossing trajectories as the duration between the instant the first road user leaves the crossing zone and the moment the second road user reaches the crossing zone.
- Deceleration is the most commonly observed or necessary evasive action taken by a vehicle to avoid a crash (Laureshyn et al. 2016); and
- Other indicators such as:
    - Conflict Severity, which is combination of an indicator DeltaV (change in velocity forces), time to accident, and assumed maximum average deceleration (Johnsson, Laureshyn, and De Ceunynck 2018);
    - Yielding behaviour, which can be measured in different ways, such as was recently introduced by (Fu, Miranda-Moreno, and Saunier 2018), considering the reaction and braking time of approaching drivers interacting with pedestrians.

2.1.1.4. Alternative Traffic Lights Focused On Cyclist Safety

One of the best methods for optimizing and analyzing traffic signal operations is through simulation (Sadoun 2008). At signalized intersections, traffic simulation has demonstrated promising results to be used for predicting conflicts (Shahdah, Saccomanno, and Persaud 2015; Taha Saleem et al. 2014) and has the potential to predict traffic conflicts between cyclists and turning vehicles (AlRajie and Ismail 2016). In Copenhagen, microsimulations proved to be consistent with numeric methods for estimating the impact of left-turning vehicles on cyclist delay and total capacity (X. Chen and Shao 2014). Using vehicle trajectories simulated in VISSIM, traffic safety can be evaluated with SSAM (Zhou et al. 2017; F. Huang et al. 2013), which provides significant correlated results with filed crash data, but more validation is necessary to reach definitive conclusions (Gettman et al. 2008). Using simulation software, Stanek and Alexander evaluated several methods for reducing the number of conflicts between cyclists and right-turning vehicles, finding that the implementation of a leading green phase for cyclists decreases vehicle-bicycle conflicts (Stanek and Alexander 2016). In addition, using VISSIM as a microsimulation tool to evaluate three different signal-timing strategies, Kading found that leading bicycle phases significantly impacted intersection performance (Kading 2016). Even though traffic simulations and simulated conflict analysis have shown good results, the number of traffic conflicts obtained from traffic simulation and SSAM may not represent the actual number because unexpected driving maneuvers or driver errors are not represented in VISSIM and most of the microscopic traffic simulators (F. Huang et al. 2013).

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Chapter 3. Do stop-signs improve the safety for all road users? A before-after study of stop-controlled intersections using video-based trajectories and surrogate measures of safety.

Do Stop-Signs Improve the Safety for All Road Users? A Before-After Study of Stop-Controlled Intersections Using Video-based Trajectories and Surrogate Measures of Safety

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3.1. Abstract

Converting minor-approach-only stop (MAS) intersections to all-way-stop (AWS) intersections is a prevailing safety countermeasure in North American urban areas. Although the general population positively perceives the installation of stop-signs in residential areas, little research has investigated the impact of AWS on road safety and road user behaviour. This paper investigated the safety effectiveness of converting MAS to AWS intersections using an observational before and after approach and surrogate measures of safety. More specifically, the safety impacts of AWS conversion were investigated using multiple indicators, including vehicle speed measures, vehicle-pedestrian, vehicle-cyclist, vehicles-vehicle interactions as well as yielding rates before and after the treatment implementation. A multi-level regression approach was adopted to determine the effect of stop signs controlling for built environments, traffic exposure, and intersection geometry factors as well as site-specific unobserved heterogeneity.

A unique sample of 31 intersections were used in this before-after study. From this sample, video data were collected before and after implementing AWS. In total, 245 hours of video were automatically processed and corrected using a specialized computer vision software. More than 68,000 (37,668 before and 31,305 after AWS treatment) road user trajectories were obtained from 104 approaches. The results show that the conversion of MAS to AWS intersections significantly decreased vehicle speed and increased post-encroachment time. This work also shows that implementing AWS significantly increased the yielding rates from 45.7% to 76.7% in MAS conditions and reduced the average speed of motor-vehicles. Using multi-level regression model, it is estimated that when the intersection was converted from MAS to AWS, the minimum speed in the major approaches was reduced by 60.0%.

3.2. Introduction

Stop signs and traffic lights are the most common traffic control devices at intersections in urban areas in North America. Federal, state, and provincial governments have documentation describing their warrants for the installation of control devices. In Canada and Quebec, the Manual on Uniform Traffic Control Devices for Canada (MUTCDC) (MUTCDC 2014) and the Tome V, Traffic Control Devices (Quebec 2020), respectively maintained by the Transport

Association of Canada (TAC), and Quebec Ministry of Transportation (MTQ), provide the warrants for installing control devices. Warrants justify the type of stop control device recommended for an intersection, mainly considering motorized vehicular traffic according to a) vehicle volumes, b) vehicle speed, c) average delay for the minor road, d) safety concerns and e) visibility.

In principle, the conversion of a minor-approach-only stop (MAS) intersection into an all-way-stop (AWS) intersection is justified by traffic operation and road safety criteria. In general, warrants justify the installation of AWS signs when traffic, geometry, and/or road safety issues are identified, and specific basic conditions are met. More specifically, AWS is justified when: a) safety is a concern (crashes have been observed), b) vehicular traffic is high and balanced between the approaches c) there are high delays on the minor approach or d) there are visibility (sight distance) problems.

Despite this body of knowledge, some significant controversies in North American cities and limitations in the current literature can be highlighted regarding AWS intersections:

- The justification and use of stop signs have been debated in the literature. This controversy is related to the use of stop signs as a traffic calming measure to reduce vehicular speeds and traffic volumes going through residential areas. Although the general population positively perceives the installation of stop signs in residential areas (Cottrell 1997), stop signs are strictly a traffic control (and not a traffic calming) according to manuals and guidelines (AASHTO 2010; MUTCDC 2014; Montreal 2015; MTO 2000).
- Despite the popularity of converting MAS to AWS intersections in urban areas, there is little research on the impact of this countermeasure using surrogate road safety on before-after studies, where behavioral measures such as operating speeds, and driver yielding to pedestrians are considered.
- Some safety studies have reported crash modification factors (CMFs) for converting MAS to AWS intersections, including the *Highway Safety Manual* (HSM) from the American Association of State Highway and Transportation Officials (AASHTO) (AASHTO 2010) – where CMFs are multiplicative factors that help determine the proportion of crashes that would be expected after transforming MAS to AWS intersections. In addition to the very limited literature on the AWS effectiveness and CMFs of AWS using crash data, this

approach would require long periods of observations (Lovell and Hauer 1986; Deng et al. 2020) This is a particular issue studying facilities with low traffic volumes, taking several years to collect sufficient crash data.

- Finally, existing studies have focused on pedestrian safety (Tageldin, Zaki, and Sayed 2017; Nambisan et al. 2009; Cafiso, Di Graziano, and Pappalardo 2013; Sacchi, Sayed, and Deleur 2013; Ni et al. 2016), with very few looking at cyclist safety (Bassil, K., Rilkoff, H., Belmont, M., Banaszewska, A., Campbell, M., Stover, A., Ansara, D., Drew, K., Mee, C., Biscope, S. and Macfarlane 2015; Tuckel, Milczarski, and Maisel 2014; Beitel et al. 2018) using multiple surrogate safety indicators.

To address the aforementioned research gaps, this paper investigated the impact on safety from converting MAS to AWS intersections using a before-after observational approach and surrogate measures of safety (SMoS), i.e. measures of safety that do not depend on the occurrence of crashes. For this purpose, statistical analyses including a multi-level modelling approach were used to evaluate the impact of introducing stop-signs controlling for built environment, traffic exposure, and intersection geometry. Among the SMoS, this research considered: vehicle and cyclist speed measures, post-encroachment time (PET) for vehicle-vehicle, vehicle-pedestrian and vehicle-cyclist interactions, and pedestrian crossing behaviours. The outcomes of this research are expected to provide novel insights that could be considered for existing warrants.

3.3. Background

A revision of the current warrants in North America for converting a MAS intersection into an AWS intersection is presented in this background section along with a summary of the safety studies on stop-controlled intersections and the alternative approaches that could be used for investigating the effectiveness of such a treatment.

3.3.1. Warrants

The Federal Governments of Canada and the USA have relatively similar stop sign guidelines, where the main difference is how the approaching speed is taken into consideration (see Table 3.1). Also, the American guidelines integrate bicyclist volumes as one of the possible requirements in the minor approach. In Canada, most of the provinces and territories use the

Table 3.1, Canada and USA summary warrants for the AWS installation requirements

Country	Volume Criteria	Crash Rate	Speed Limits	Other comments (e.g., number of lanes, geometry, etc.)
Canada	V_1/V_2* » 1 AND On the minor highway, 200 entering vehicles and pedestrians (combined) per hour over an 8 h period for an average day OR Average delay to the minor road of 30 s during peak hour.	3 or more reported collisions, susceptible to correction by AWS, per year	Safe vehicle speed on approach < 15 km/h	AWS can be installed as an interim to the installation of traffic signals; or As a transition phase to switch the stop control from a one road to an intersecting road
USA	V_1/V_2* » 1 AND On the major road, at least 300 entering vehicles per hour over an 8 h period for an average day; On the minor highway, at least 200 entering vehicles and pedestrians and cyclists (combined) per hour over the same 8hr period per day; Average delay to the minor road of 30 s during peak hour.	5 or more reported collisions, susceptible to correction by AWS, per year	On the major road, if 85th percentile approach speed > 40 mph (» 65 km/h) If the speed limit is met, 70% of the minimum volumes listed under "Volume Criteria" should be taken	AWS can be installed as an interim to the installation of traffic signals; At locations with high pedestrian volumes Sight distance: road user cannot see intersecting street or negotiate intersection unless the conflicting highway is also required to stop

* The ratio of the traffic volume entering from the major highway to that of the minor highway

MUTCDC as their reference, while others use the MUTCDC as a baseline but have fewer requirements. For instance, the AWS installation in the province of Alberta does not have a crash rate criterion. In the province of British Columbia, only traffic volume and crash rates are considered for implementing AWS. Guidelines from the provinces of Ontario and Quebec are similar regarding volumes, crash rates, etc. Whereas most of the Quebec and Ontario requirements are related to the Canadian guidelines, the main difference is that the Federal guidelines do not require another control device within a specified distance. As an example, Ontario requires avoiding traffic lights or stop signs within 250 m in any direction from the intersection to signalize, while for Quebec, the requirement is to avoid traffic lights on any major street within 250 m or stop signs within 150 m.

3.3.2. Safety Studies on Stop Controlled Intersections

According to the HSM, AWS intersections are recommended as being safer than MAS or no-stop control for crash reduction at intersections. Supporting this recommendation, a study by Elvik et al. showed that stop sign installation reduced the crash rate on four-way intersections (Elvik et al. 2009). However, Elvik et al. suggested that this treatment is most suitable for secondary roads outside urban areas (Elvik et al. 2009). Similarly, the installation of stop signs on MAS intersections resulted in an overall significant reduction in conflict frequency of 51% in British Columbia (El-Basyouny and Sayed 2010). Studies have also demonstrated that AWS intersections were adequate to reduce the number of crashes, but only at low-speed rural intersections (Stokes 2004). Recommendations are to implement a series of treatments at the crossing area such as stop signs, pavement markings, geometry improvements, traffic control, etc., to improve the safety and comfort of pedestrians (Fitzpatrick, Turner, and Brewer 2007). In line with this, a literature review recommended changing more than the geometry design at intersections to significantly affect crash rates, as shown in different T-intersection studies (Arndt and Troutbeck 2001). Most of these past studies are based on crash data with a lack of studies using a before-after approach and surrogate safety methods.

Moreover, there is conflicting research showing that AWS intersections are not safer than MAS or uncontrolled intersections. Polus found that introducing a stop sign at an uncontrolled intersection increased the average number of crashes from 0.64 to 1.96 for 28 intersections over 3 years (Polus 1985), suggesting that increasing the level of control at non-signalized intersections does not necessarily result in an overall safety improvement. It should be noted that this study (Polus 1985) did not evaluate the severity of the crashes. A study from Quebec in 1987 observed deterioration in the stopping compliance in eight towns which was not explained by a change in the traffic flow (Kelvie 1987). In New York City, a study found that over 17 years, motorists tended to ignore traffic controls in residential neighbourhoods (Trinkaus 1997). It was also found that regular commuting drivers in low traffic residential areas drive slower at the intersections treated with a stop sign than casual drivers (Smith and Lovegrove 1983).

3.3.3. Safety Analysis Methods for Intersections

Due to the lack of crash data, and other shortcomings of historical crash records, there has been an effort to find other methods that do not require collisions to occur, such as SMoS measures. Computer vision techniques have allowed the development of practical tools for safety analysis due to their capacity to extract user trajectories and classify them from videos (Saunier, Sayed, and Ismail 2010). The microscopic trajectory data from the videos is then used to identify patterns in traffic events (Saunier, Mourji, and Agard 2011). For example, video analysis has been used to compare cyclist safety under different intersection layouts with traffic lights (Madsen and Lahrmann 2017) and develop conflict-based safety performance functions for signalized intersections (Essa and Sayed 2018). SMoS rely on indicators to measure the event proximity to a crash and/or the severity of the potential crash. Existing indicators can be classified into four groups (Laureshyn et al. 2016; Gettman and Head 2003):

- Time-to-Collision (TTC), defined as the time remaining until a collision of two road users occurs, assuming they continue travelling as initially planned.
- Post-Encroachment-Time (PET), defined for users with observed crossing trajectories as the duration between the instant the first road user leaves the crossing zone and the moment the second road user reaches the crossing zone.
- Deceleration, which is the most common evasive action taken by a vehicle to avoid a collision (Laureshyn et al. 2016); and
- Other indicators such as:
  - Speed, which is used as a predictor of collision occurrence and severity (Fu, Miranda-Moreno, and Saunier 2018; Johnsson, Laureshyn, and De Ceunynck 2018);
  - Yielding behaviour, which can be measured in different ways such as the one recently introduced by (Fu, Miranda-Moreno, and Saunier 2018) considering the reaction and braking time of approaching drivers interacting with pedestrians.

3.4. Methodology

The proposed methodology to evaluate the effectiveness of transforming MAS into AWS intersections consisted of four main steps: a) selection of sites from an inventory of intersections; b) data collection and automatic video processing using computer vision tools; c) definition and calculation of surrogate and behavioural measures using speeds, yielding, and conflict measures; d) evaluating the treatment effects using random-effect regression models and complementary statistical analyses. In the following subsections, additional details are provided for each step.

3.4.1. Site Selection

An inventory of the intersections in Montréal was created for this research from the available geospatial data, the Montréal Road network from the city, and borough boundaries. The intersection points were defined based on intersecting polygon lines, then filtered automatically and reviewed manually yielding approximately 13,000 non-signalized intersections.

As a second step, a preliminary sample of 1,000 intersections was randomly selected from the total population of approximately 13,000 intersections. Based on a set of criteria, a sub-sample of more than 100 MAS intersections were chosen as potential candidates for treatment from the initial sample of 1,000 locations. The sub-sample was defined based on:

- Stop-sign-controlled intersections in local-local and local-collector streets. Intersections on arterial roads were excluded.
- Intersections with one or more approaches without stop signs (MAS intersection).
- Intersections where the cameras could be installed on existing infrastructure such as light posts.
- The selected intersections were in boroughs that agreed to participate in the study. Most of these boroughs had previous requests to install stop signs, facilitating the implementation of the AWS intersections.
- Finally, a sample of 31 sites from the 100 sub-samples was chosen for the before-after study after applying the different filters. This sample was selected in coordination with the different participating boroughs.

3.4.2. Traffic Video Data Collection and Processing

For video data collection, video cameras were temporally installed in proximity to the intersection, typically on a nearby lamp post that was no more than 15m (away from the intersection. The video recording took place during weekdays to capture user behaviours on typical working days during peak and non-peak hours. Hence, the videos were collected on each selected site for one day before and one day after MAS treatment implementation, between 8 am and 6 pm. Additionally, to capture user behaviour that could be meaningful in other locations (weather-related), the video data were collected in September and October, when Montreal's temperature ranges between 25º and 15º C and the school period is ongoing. Furthermore, there was 1-year difference between the before and after data collection to ensure the users had at least 6 months to adapt to the AWS implementation and video collection. The video cameras captured the movement of all road users within the zone of interest. Data were then processed to extract high-resolution road user trajectories at each site with the help of TrafxSAFE, a commercial software tool (Transoft Solutions 2022). This software automatically identified, classified, and tracked each road user, then labelled them as pedestrian, cyclist, motor-vehicle (car, motorcycle, truck and bus) and unknown. Before the data processing, a calibration process was implemented so that road user trajectories in the plane of the camera (image space) could be projected in real-world coordinates on the ground level (world space). As part of the quality control, once trajectory data were automatically generated, a manual review was carried out to correct vulnerable road user (VRUs – pedestrians and cyclists) trajectories and to annotate user behaviour employed in this research; this process was accomplished using tvaLib (St-Aubin et al. 2018; St-Aubin 2019), an open-source tool as part of the quality control. Figure 3.1 shows an example of a processed site where the trajectories can be seen in different colours according to the road user type.

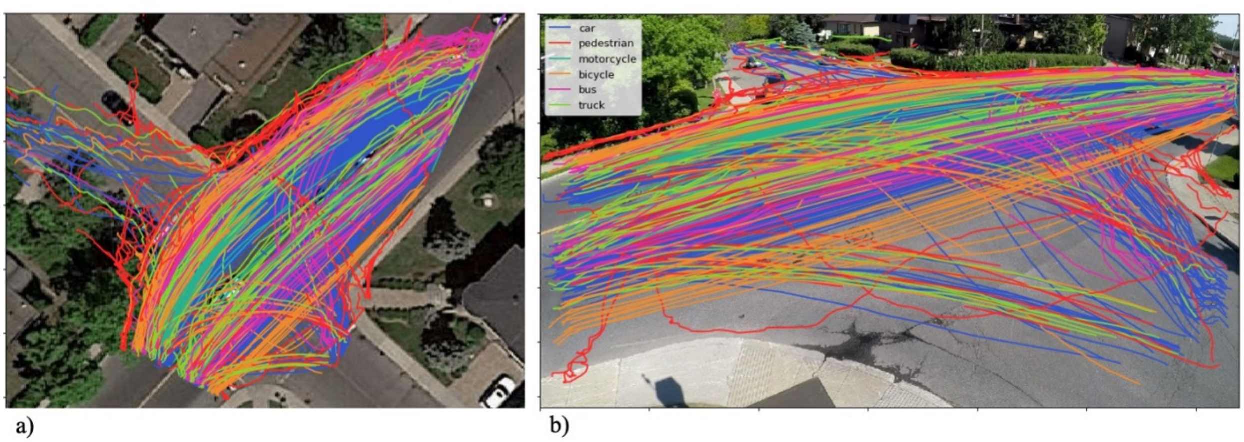

Figure 3.1, Example of processed video trajectories. a) represents the trajectories on an aerial image (world space), while b) represents the trajectories in the image space

3.4.3. Intersection Geometry and Stop Control Scenarios

An inventory of intersection geometry was generated for the study. This inventory included: 1) intersection-level information, such as the intersection layout (number of approaches and branches) and built environment variables; 2) approach-level information, such as the number of lanes per approach and the presence of a crosswalk; and 3) user attributes, such as speed values, vehicle movement and the approach stop-control characteristics. A statistical summary of the collected variables for this study is presented in Table 3.2, with an in-depth explanation of each below:

3.4.3.1. Intersection-level characteristics

- ***Distance to the previous intersection****:* This is the distance to the upstream adjacent intersection, and it was measured from centre to centre of the intersections.
- ***Previous intersection type:*** This variable refers to the kind of stop control at the upstream approach. In another words, it is the previous intersection that the evaluated user went through before getting into to the approach of analysis. i.e. a user that is being evaluated on the northbound approach, the previous intersection type, is the intersection to the south of the northbound approach. The stop-controls considered for this variable are MAS, AWS and traffic lights, which are described as follows:
    - ***MAS upstream intersection***. At this type of intersection, a user can come from a non-controlled or a controlled approach. A user coming through enters from a non-controlled approach, while a turning user enters from a stop-controlled approach.
    - ***AWS upstream intersection.*** Users are entering from a stop-sign controlled approach at the upstream intersection.
    - ***Traffic light upstream intersection***. Users are entering from a controlled intersection by traffic lights.
- ***Number of branches***: Intersection design varies greatly depending on the number of connecting streets, or branches (legs), which is typically three or four. A branch can be a unidirectional street serving as an approach or as an exit to the intersection. It can also be a bidirectional street serving as an approach and exit to that intersection.

- ***Number of approaches****:* This constitutes the portion of a branch dedicated to road users (motorized vehicles and VRUs) entering or leaving an intersection. There may be as many approaches as branches, but not more, and as few as two.
- ***Non-motorized facilities***: This includes the presence and the type of a cyclist facility at the intersection.
- ***Built environment variables:*** These variables include population and employment density, land use mix, and transit accessibility surrounding the studied intersection. A grid-based approach was defined for characterizing the land use around the intersection. The neighbourhood typologies used for the intersections was a collection of data from Statistics Canada, then a grid with 500-m long cells covering the entire island of Montreal was used (Zahabi et al. 2012).

3.4.3.2. *Approach level characteristics*

- **Number of lanes:** This represents the number of lanes in the approach of the incoming direction to the intersection. This variable was captured as 1) one lane, or 2) two or more lanes.
- **Presence of a crosswalk:** This variable indicates where there is a crosswalk of any type marked in the approach or the inexistence of one.
- **Crosswalk marking:** This variable represents the type of crosswalk that is at the approach, if any. It was classified as no crosswalk, striped, or as two-parallel lines.
- **Presence of a vehicles stop line:** this represents the horizontal approach marking on the pavement at the stop sign location, indicating to the drivers where they should stop.
- **Width at the crosswalk level and 10 m upstream:** These are two different variables that describe a similar measure. They indicate the width of the street at the crosswalk level and 10 m upstream of the approach. It can be defined as the distance where the pedestrian is exposed to the vehicular traffic at each location.
- **Bicycle facility (bike-path) presence:** This variable indicates where there is any cyclist infrastructure in the evaluated approach or a lack of cyclist infrastructure.

3.4.3.3. *User attributes*

- **Vehicle movement:** This variable indicates the user movement, which can be through, left turn or right turn movements.
- **Exposure:** This variable measures the number of VRUs presence within a range of 5 seconds before and 5 seconds after the analyzed vehicle reaches the midpoint of its trajectory. This variable was computed to evaluate the effect of VRUs on driver behaviour while navigating the intersection. Simultaneously, the 5 second threshold was considered a limit where other road users could influence a driver.
- ***Stop-control scenarios:*** A set of four different approach conditions or scenarios were defined to evaluate the impact of the traffic control Figure 3.2 on the speed and SMoS of the users. In the scenario description, the major approach had the main effect of the AWS treatment due to the stop sign installation. The minor approach was also evaluated during the before and after condition due to the potential effect of implementing the stop sign in the major approach. A detailed description is as follows:
  - ***Scenario A****:* A major approach, with no stop sign before the conversion of a MAS intersection into an AWS intersection.

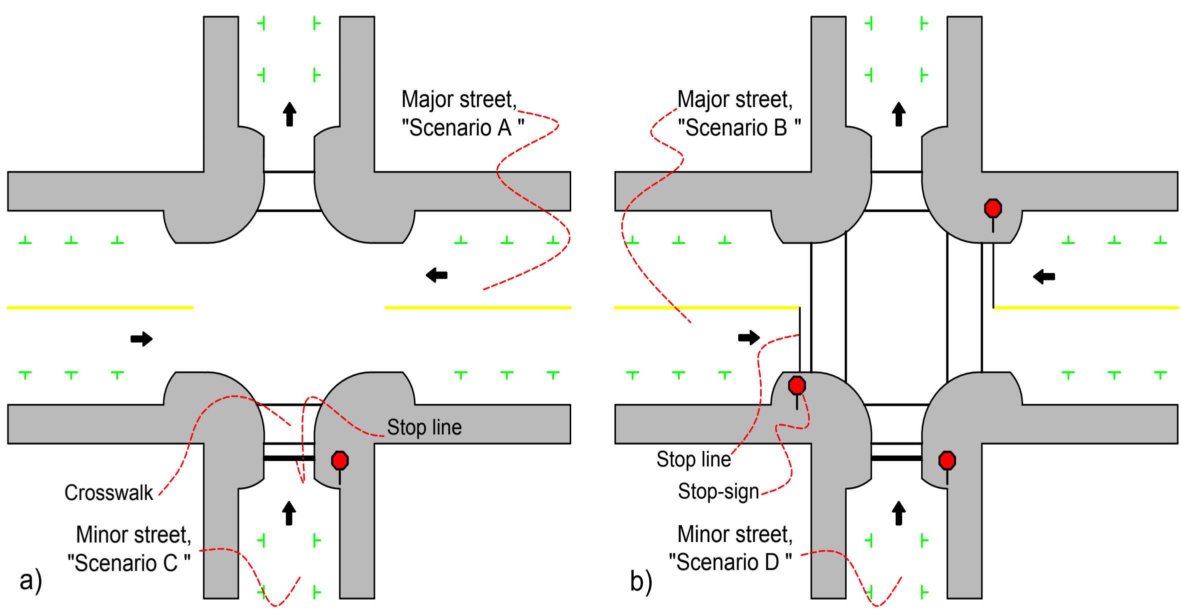

Figure 3.2, Example of an intersection with four branches and three approaches (a) before and (b) after the conversion of an AWS intersection.

- ***Scenario B**:* A major approach, with a stop sign after the conversion of a MAS intersection into an AWS intersection.
- ***Scenario C**:* A minor approach, with a stop sign before the conversion of a MAS intersection into an AWS intersection.
- ***Scenario D**:* A minor approach, with a stop sign after the conversion of a MAS intersection into an AWS intersection.

3.4.4. Traffic Safety Indicators

The safety analysis performed in this research made use of the following safety indicators that are part of the SMoS approach:

- ***Road user speed*:** There are strong correlations between speed, crash likelihood, and severity, as shown in several studies (Peden et al. 2004; Kloeden et al. 1997; Gårder 2004; Nemeth et al. 2014). An automated method is used to generate different speed statistics for each road user trajectory. For each user trajectory that crossed an intersection, different speed measures were obtained: minimum speed defined as the 15th percentile ($v_{15^{th}}$), median speed (v_{med}), and maximum speed defined as the 85th percentile ($v_{85^{th}}$). These different percentiles were computed based on the vector of speeds for each individual trajectory while navigating the intersection and not from a specific location (e.g. at the stop sign). A global speed summary of the obtained trajectories in the 31 intersections is presented in Table 3.2.
- ***Post-encroachment time (PET)***: The PET is the time difference between the instant the first road-user (user "a") leaves the crossing zone and the instant the second road-user reaches the mentioned zone (user "b"), as represented in Figure 3.3. In other words, the PET indicates the time which the two users missed each other (Laureshyn et al. 2016). Table 3.2 shows the

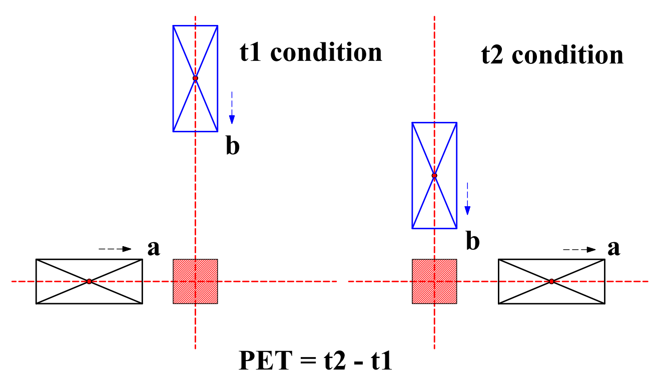

Figure 3.3, Post-Encroachment Time (PET) description

PET statistics values for all 31 intersections. For this work, the PET between vehicles – VRUs that are considered, are the ones where the VRUs arrived first to the crossing zone. This interaction was reviewed due to is the one where the vehicle has a clear view of the pedestrian or cyclist during the interaction.

Table 3.2, Variable Summary Statistics for mixed linear regressions

	Variable	Min	Mean	Max	S.D.	
User attributes	Stop-control scenarios	Explained in description				Factor
	Vehicle movement (through, left or right)	0	0.4	2	0.7	Factor
	Exposure	0	0.47	15	0.83	Integer
	Minimum road users speed (km/h)	0	11.67	48.82	10.52	Numerical
	Mean road users speed (km/h)	0.11	20.26	63.7	12.74	Numerical
	Maximum road users speed (km/h)	0	29.1	80.3	15.59	Numerical
	Post-encroachment time (PET) (seconds)	0	4.48	9.99	1.94	Numerical
Approach-level	Number of lanes	0	0.81	1	0.39	Binary
	Presence of crosswalk	0	0.33	1	0.47	Binary
	Crosswalk marking*	1	1.35	3	0.53	Factor
	Presence of vehicle stop line	0	0.48	1	0.5	Binary
	Approach width at the crosswalk level (meters)	8.1	12.5	24	6.36	Numerical
	Approach width 10 m upstream (meters)	7.5	11	16.2	1.77	Numerical
	Bike-path at the approach	0	0.26	1	0.44	Binary
Intersection-level	Distance to previous intersection (meters)	60	138	690	130.2	Integer
	Previous intersection type**	0	1.07	2	0.61	Factor
	Number of branches (four branches)	0	0.65	1	0.48	Binary
	Number of approaches	2	3.12	4	0.41	Factor
	Non-motorized facilities, bike-path presence***	0	0.85	3	1.22	Factor
	Built environment variables					
	Population density (people/km^2)	16	75.6	135.9	33.84	Numerical
	Employment density (people/km^2)	0.35	59.5	140.0	15.26	Numerical
	Land use mix	0.22	0.5	0.65	0.13	Numerical
	Transit accessibility	61.6	227.5	383.2	110.5	Numerical

* No crosswalk, striped, two-lines and unique

** MAS, AWS or traffic light controlled

*** Shared road, painted bike-path, divided bike-path or no bike-path

- ***Interaction Severity:*** In addition to the PET and speed measures, a classification of the potential severity of an interaction between a vehicle and a pedestrian was estimated to better reflect potential injuries. A similar rating has been previously used (Scholl et al. 2019), where the PET was combined with the $v_{85^{th}}$. This classification was inspired by the report made by the European Transport Safety Council (ETSC), which stated that a pedestrian that is struck by a vehicle travelling at 32 km/h has a 5% probability of dying. If the pedestrian is hit at 48 km/h, the probability of dying increases to 45% and then to 85.0% of the person is hit at 64 km/h. Moreover, one of the study objectives was to evaluate the safety effect of AWS on crossing VRUs and vehicles. Consequently, the side-crash was used to evaluate vehicle crash severity, leaving rear-end crashes for future work. Additionally, PET values were characterized in terms of severity according to their values, with the thresholds used by (Zangenehpour et al. 2016):
  - Very dangerous, PET ≤ 1.5 s
  - Dangerous, 1.5 s < PET ≤ 3.0 s
  - Mild interaction, 3.0 s < PET ≤ 5.0 s
  - Safe interaction, PET > 5.0 s

- Considering this information, a severity classification of an interaction between a vehicle and a pedestrian was proposed similar to the one found in (Scholl et al. 2019). The interactions were divided into four categories: safe interaction, low, moderate, and high risk. A diagram of the four categories is shown in Figure 3.4. As an example, the

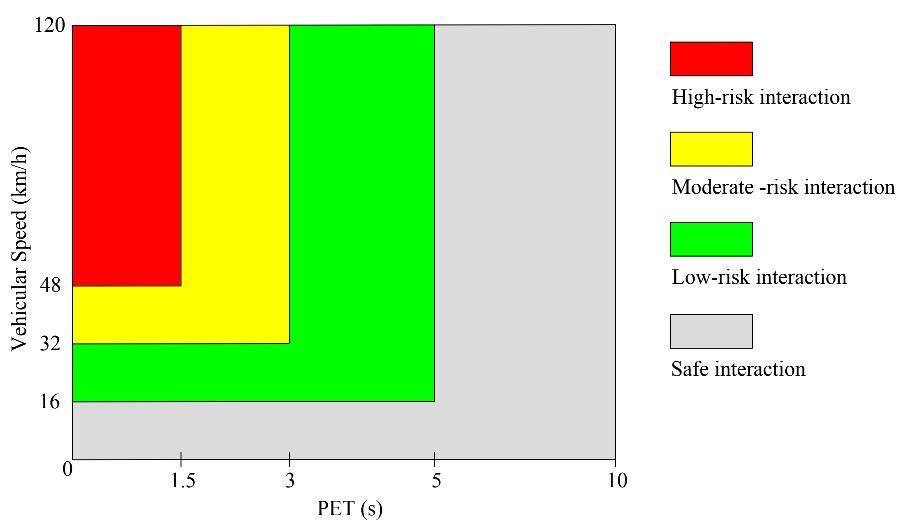

Figure 3.4, VRUs interaction severity

moderate risk interactions (yellow colour) were the ones with a PET lower than 3.0 s and a speed between 32 km/h and 48 km/h, or with a speed higher than 32 km/h and PET values between 3.0 s and 1.5 s. The PET frequency is defined as the ratio of the number of interactions in each of the categories mentioned above throughout the observation period. For example, if scenario A has ten high-risk interactions for 100 h, then the PET frequency for this scenario is 0.1 high-risk interactions per hour.

- ***Distance-Velocity (DV) Framework and Yielding Rates***

  In this work we integrated the driver yielding framework introduced recently by Fu et al. (Fu, Miranda-Moreno, and Saunier 2018), where the DV framework is based on the distance and speed of vehicles approaching a pedestrian crossing. The DV diagram (see Figure 3.5) classifies the vehicle (driver yielding to the pedestrian) during a vehicle-pedestrian interaction into three phases: Phase I) where the driver cannot make a full stop, Phase II) where the ability to yield depends on the driver reaction time and Phase III) where the driver can stop to yield. This classification is derived based on the trajectory data of each vehicle-pedestrian interaction (Fu, Miranda-Moreno, and Saunier 2018). More specifically, the critical elements of this framework are described as follows:

  - **Initial interaction situation**. Each pedestrian crossing is classified into three phases (I, II, III), as shown in the DV diagram presented in Figure 3.5.
  - **Vehicle yielding behavior,** as illustrated in Figure 3.5, the vehicle yielding behaviour is classified at the time when the pedestrian shows the intention to cross

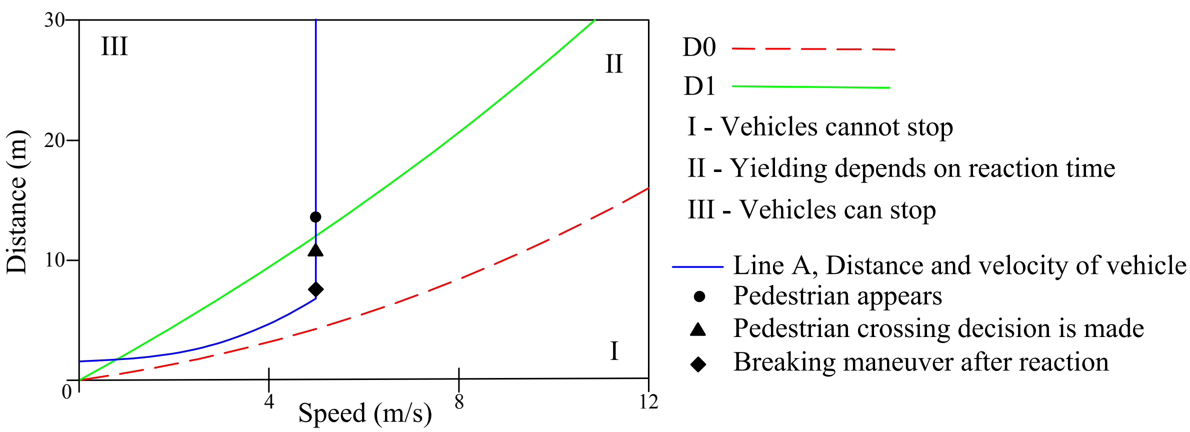

Figure 3.5, DV diagram for vehicle-pedestrian interactions *(30)*

depending on the instant of the yielding maneuver, or the lack thereof, as a) non-infraction, non-yielding maneuvers (Phase I); b) uncertain non-yielding maneuvers (Phase II); and c) non-yielding violations (Phase III). The yielding rate is the proportion of vehicles that yield to pedestrians over the total number of vehicles. The yielding compliance is the proportion of vehicles yielding the right-of-way out of the vehicles that are physically able to yield (interactions in Phase II and Phase III).

- **Pedestrian crossing decisions.** Classified at the time when the pedestrian shows the intention to cross as: a) dangerous crossings (Phase I); b) uncertain risky crossings (Phase II); and c) safe crossings (Phase III). Whether the pedestrian crossed before or after the vehicle was also recorded. The proportions of the type of crossing decisions among the total number of observed interactions was determined.
- **Evasions and retreats**. The most dangerous situations occur when crossing attempts are made and drivers do not yield the right-of-way. In this situation, pedestrians retreat, undertake evasive maneuvers or, in worst cases, crashes occur. Interactions ending with pedestrian retreats, evasive maneuvers, and even crashes were also recorded.

3.4.5. Regression Modeling Approach

To analyze the speed and PET datasets we considered the hierarchical structure of the data and controlled for different observed factors. Therefore, a regression analysis that considered the data hierarchy was necessary with observations nested at the approach and intersection level. Accordingly, a random effect regression model (mixed-effect model) implemented in the R language was used and fitted to the data to address the observed and unobserved variations at the approach and site (intersection) level. The proposed random-effects model takes the following form:

$$y_{ijk} = \beta_0 + \sum_{l} \beta_l X_{ijkl} + u_j + \varepsilon_{ijk} \qquad \text{Equation 1}$$

Where:

- $i = 1,\ldots,m$ for the intersection or site
- $j = 1,\ldots, n$, for the approach of intersection site *i*
- $k = 1,\ldots, o$, for the approaching road user at the approach *j* of the site *i*
- y_{ijk} = dependent variable (e.g., speed measures such as $v_{15^{th}}$, v_{med}, $v_{85^{th}}$) for a site i, approach *j* and user *k*.
- X_{ijkl} is the value of the *l*th covariate of the model for site *i*, approach *j* and user *k*
- β_0, is the model intercept
- β_l, is the slope coefficient for covariate X_l
- u_j = approach specific random error for approach *j* (assumed to follow a normal distribution with mean 0 and constant variance σ_u)
- ε_{ijk} = ordinary regression error (assumed to follow a normal distribution with mean 0 and constant variance σ_ε)

For each type of outcome ($v_{15^{th}}$, v_{med}, $v_{85^{th}}$ and *PET*), the model above was fitted to the data, including the following covariates:

- **As user attributes:** Vehicle movement type and exposure. For the PET evaluation the v_{med} was also included.
- **At the approach level:** Scenario, crosswalk marking, vehicles stop line, number of lanes, presence of a bike path, street width at the crosswalk and 10 m before it, the distance to the previous intersection, and the control type of the upstream approach.
- **At the intersection level:** The built environment (land use mix, transit accessibility, population and employment density), number of branches, number of approaches, number of stop signs and the presence of non-motorized facilities.

The PET model is different from the models where the outcome characterizes a given road user (speed statistics) and was adapted as follows:

- For the PET evaluation, *k* refers to a user pair. A user pair is a fundamental condition for any interaction between two road users with a simultaneous presence in time and space. Hence, every classified road user was paired with every other user of the intersection that existed in a predefined area of interest where the interactions took place. For this study, the area of interest was defined by a zone that included all the possible conflicting areas of the road users with all the other user pairs of the intersection (pedestrian, cyclist and vehicles). This zone included all the in and out approaches (roughly within 15 m of each branch), crosswalks, bike paths and sidewalks.

- The PET approach-level attributes were for the user arriving second to the area of interaction (user b, Figure 3.3), i.e. the user that will hit the other user. Thus, the attributes of the first arriving user were not considered for this research, and all the considered users arriving second to the area of interaction were motorized vehicles.

The scenario is the primary variable to evaluate for this research. This variable is categorical, coded as a factor. i.e. using three binary indicators, with scenario A as a reference. The previous implies that the intercept will represent the estimated mean speed value (or PET) for scenario A when all the other variables are set to 0.

3.5.Results

This section first provides first a data summary, followed by vehicle speed and conflict analyses using several statistical techniques. The results of the yielding to pedestrian behaviour using the D-V approach are also discussed in this section.

3.5.1. Data Summary

After the videos were processed, trajectories were manually validated and corrected for a period of 4 hours for one day before, and 4 hours for one day after the treatment implementation. The video sample was reduced from the initial 8:00 am – 6:00 pm to 8:00 am – 12:00 pm mainly due to limited human resources. This resulted in a cleaned validated video sample during peak and off-peak hours for each day. Incomplete or portioned trajectories were completed or merged as part of the trajectory cleaning process. In the case of motor vehicles, the computer-vision algorithms mostly identified them correctly and the corrections were performed primarily for VRUs. A summary of the data inventory for the before and after period is presented in Table 3.3 as well as general information such as the number and type of intersection, approaches (stop-controlled or not), hours of analyzed video and traffic data in terms of the number of road users crossing the intersection and their types.

Table 3.3, Intersection data inventory for one day before and one day after the AWS treatment from 8 am to 12 pm

Description		Counts			Percent (%)		
		Before	**After**	**Total**	**Before**	**After**	**Total**
Traffic Data	Major approach	**25,854**	**22,453**	**48,307**	**53.5**	**46.5**	**77.9**
	Pedestrians	3,117	3,039	6,156	12.1	13.5	12.7
	Cyclists	1,125	1,028	2,153	4.4	4.6	4.5
	Motorized users	21,612	18,386	39,998	83.5	81.9	82.8
	Minor approach	**7,014**	**6,720**	**13,734**	**51.1**	**48.9**	**22.1**
	Pedestrians	1,084	1,227	2,311	15.5	18.3	16.8
	Cyclists	408	374	782	5.8	5.6	5.7
	Motorized users	5,522	5,119	10,641	78.7	76.1	77.5
	Total number of users	**32,868**	**29,173**	**62,041**	**-**	**-**	**100**
General Information (number of)	Distinct intersections		31		-		
	Three branches		10		-		
	Four branches		21		-		
	Evaluated video data (h)	121	124	245	49	51	
	Total approaches	104	104	208	50	50	100
	Stop-controlled approaches	60	104	160	73.3	-	73.2
	Uncontrolled approaches	44	0	44	26.6	-	26.8

Table 3.4 includes a statistical summary of the motorized users (vehicles), where the 5th percentile (Q05), mean, median, 95th percentile (Q95) and standard deviation (S.D.) of the speeds (see section 3.4.4 for reference) were obtained for each of the speed measures as well as the PET obtained from the video trajectories for each scenario.

Moreover, as a complement to the other indicators (speed and PET), the DV framework resulting between vehicle and pedestrian interactions are presented in section 4.4. The indicators derived from the DV framework were analyzed with a semi-automated approach, yielding the initial interaction situations, vehicle yielding behaviour, pedestrian crossing decisions, and evasions and retreats. A total of 440 and 429 vehicle- pedestrian interactions before and after were observed respectively.

3.5.2. Vehicle Speed Analysis

From the information presented in Table 3.4 and Figure 3.6, one can appreciate that vehicle speeds at the major approach were reduced considerably after installing stop signs. The average

Table 3.4, Motorized vehicle summary statistics

Scenario	Variable	Min (Q05)	Mean	Median	Max (Q95)	S.D.	# Obs.
A[1]	Minimum Speed	0.85	20.46	19.52	40.34	11.43	21,612
	Median Speed	5.64	31.62	31.65	54.55	14.42	
	Maximum Speed	17.09	42.04	42.89	65.29	15.24	
	PET	1.60	4.40	4.24	7.89	1.99	2,233
B[2]	Minimum Speed	1.18	6.98	6.01	15.93	4.62	18,386
	Median Speed	5.54	15.38	14.55	27.64	6.98	
	Maximum Speed	15.41	27.09	26.80	40.44	7.49	
	PET	2.00	4.53	4.14	8.17	1.93	2739
C[3]	Minimum Speed	0.00	7.60	5.22	28.86	8.55	
	Median Speed	2.23	13.85	10.91	41.64	11.19	5,522
	Maximum Speed	11.20	23.44	20.64	49.61	11.38	
	PET	1.34	4.33	4.23	7.66	1.95	2,026
D[4]	Minimum Speed	0.41	6.42	5.74	14.62	4.38	5,119
	Median Speed	4.65	13.17	12.30	25.02	6.08	
	Maximum Speed	12.71	22.17	21.72	33.75	6.60	
	PET	2.00	4.55	4.14	8.16	1.92	2,645

[1] A major approach with no stop sign before the conversion of MAS to AWS
[2] A major approach with stop sign after the conversion of MAS to AWS
[3] A minor approach with stop sign before the conversion of MAS to AWS
[4] A minor approach with stop sign after the conversion of MAS to AWS

vehicle minimum speed ($v_{15^{th}}$) decreased from 20.46 km/h to 6.98 km/h (Figure 3.6a); this speed reduction can be interpreted as a rolling stop for most vehicles instead of a full stop after the AWS treatment. For the average median speed, there was a speed reduction of 17.10 km/h (Figure 3.6b). The average Q95 of the maximum speed ($v_{85^{th}}$), after the stop sign installation, decreased from 65.29 to 40.44 km/h (Figure 3.6c). These results were obtained from 21,612 observations for the before and 18,386 for the after period. All speed comparisons were significant and performed with the Kolmogorov-Smirnov (K.S.) test. Additionally, there was less speed variability from the different motorized vehicles after the installation of stop signs (Figure 3.6 and Table 3.4), where the S.D. reduced by 51.6 % for the median speed, dropping from 14.42 km/h to 6.98 km/h. Similar results for the speed S.D. for the major approach were observed for the other speed indicators: $v_{15^{th}}$ (59.6 %), and $v_{85^{th}}$ (50.9 %).

Contrary to the major approach, the different indicators for the minor approach did not show the same speed reduction, but there were some visible and significant changes (Figure 3.7). The

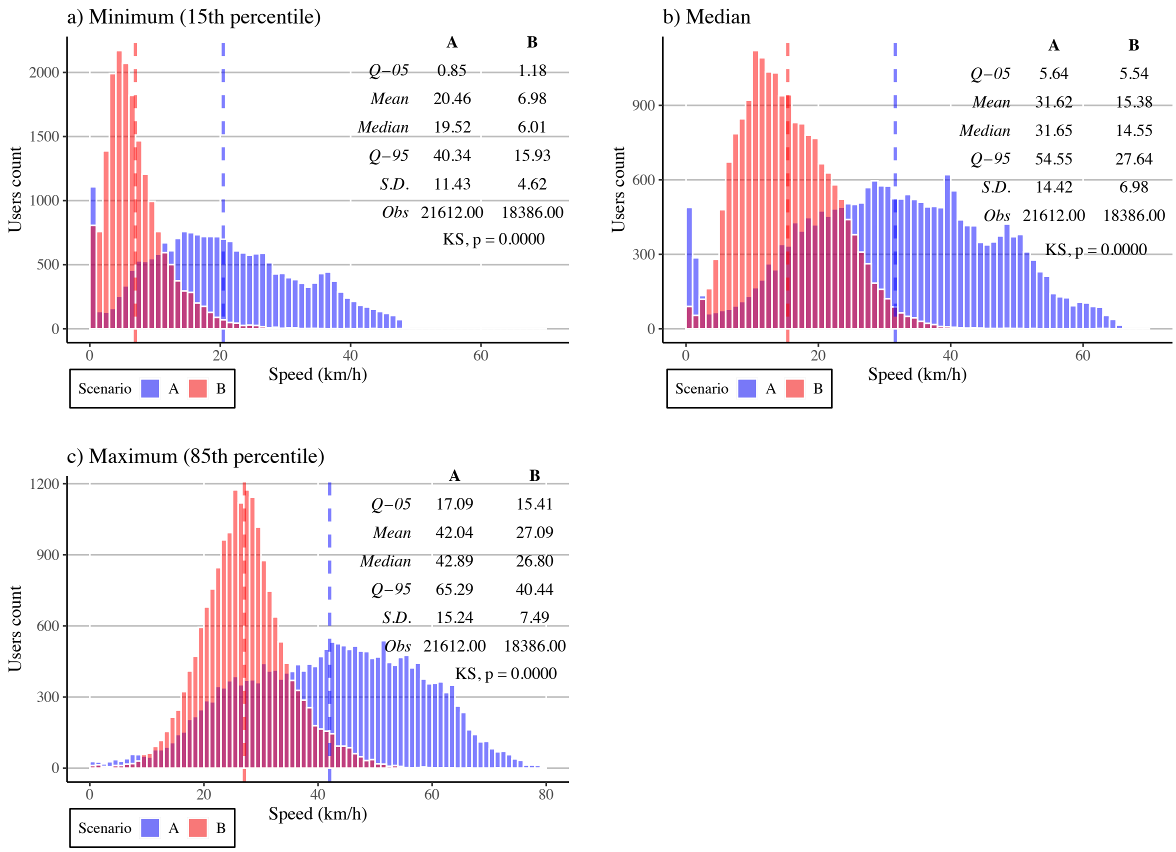

Figure 3.6, Vehicles speed histogram distribution for the major approaches using 15th percentile, median and 85th percentile for scenarios A and B

minor approach speed profiles with the AWS treatment remained similar to when the intersections were MAS. These results were expected for these approaches since a stop sign was already present before converting to AWS. By conducting an observation analysis of the speed profiles from all the sites, we found that the mean speed values for the different indicators decreased slightly. The Q05 showed a small increase in the three speed variables, while the Q-95 exhibited a more marked reduction. This Q95 speed reduction was also reflected in the S.D. decrease, being 42.0% lower for the $v_{85^{th}}$ (Figure 3.7c) and 48.8% lower for the $v_{15^{th}}$ speed (Figure 3.7a). The increase in the Q05 speed may be explained by the confidence that the drivers on the minor approach had towards the drivers in the major approach, trusting that those drivers will stop. These results were obtained from a sample of 5,522 observations from the MAS period and 5,119 observations for the AWS period. The total number of drivers in the minor approach was equivalent to slightly more than 25.0% of the major approach sample. Moreover, the difference in speed distributions between the before and after period was significant for all speeds using the K.S. test.

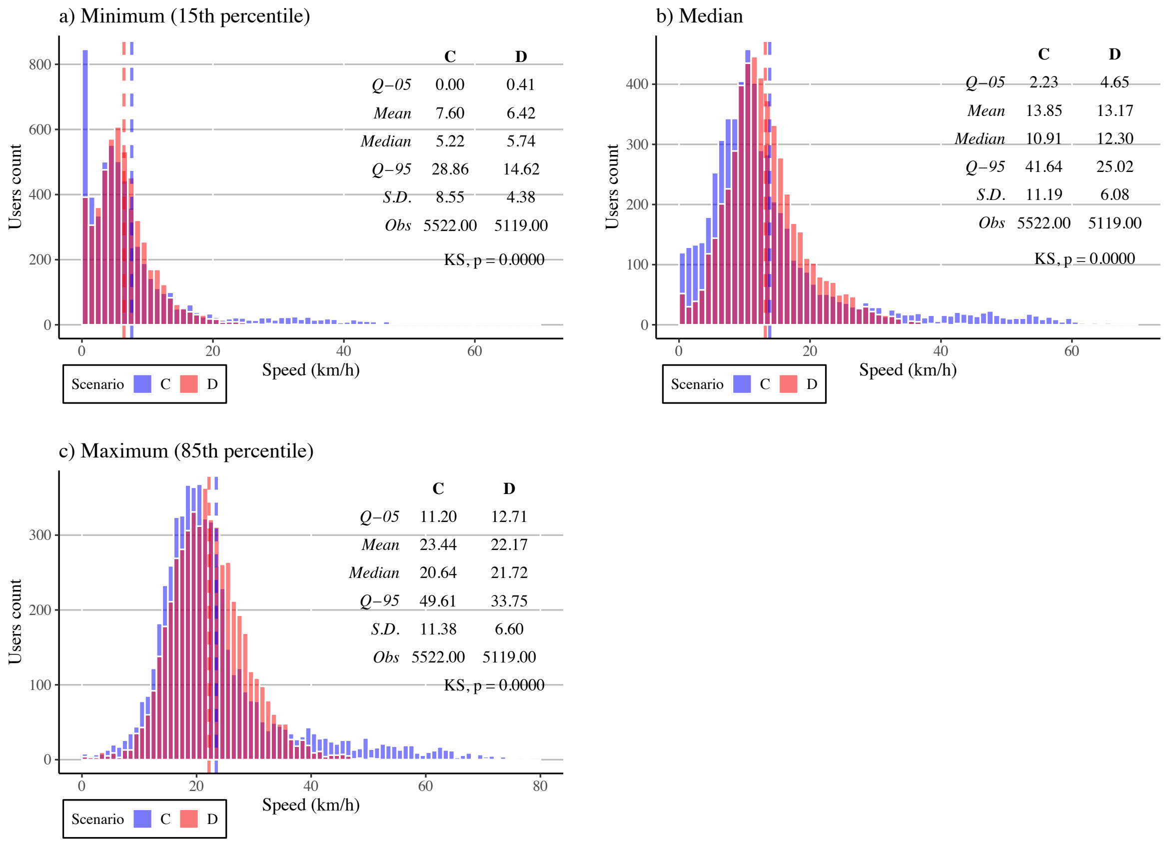

Figure 3.7, Vehicle speed histogram distribution for the minor approaches using 15th percentile, median and 85th percentile for scenarios C and D

A complementary regression analysis is offered here to provide additional evidence on the effects of the treatment on speed indicators after controlling for geometric and traffic variables (Equation 1). In general, variables were carefully selected, while some were removed from the model due to their high correlation. e.g., the number of lanes was highly correlated with the crosswalk width. Other variables, like the employment density, land use mix and public transit accessibility, were removed after an initial evaluation due to their non-significant effect in the model. Also, the random effect corresponding to the intersection I.D. was removed from the speed analysis due to their virtually null effect in the different models. In contrast, the random effect of the different approaches was kept.

For the regression analysis, the entire sample of more than 50,000 vehicle observations was used with 104 approaches (from 31 intersections). To evaluate the effects of AWS treatment on vehicles, the three speed measures ($v_{15^{th}}$, v_{med}, and $v_{85^{th}}$) were used. A summary of the main speed regression models is provided in Table 3.5 – see columns 3 to 5. The effects of treatment were aligned with those presented in the previous section and are as follows:

- **Scenario A**: This is the base or before-treatment scenario in the major approach without stop signs.
- **Scenario B**: This represents the after-treatment scenario. Based on its regression coefficient, the speed reduction is 12.49 and 14.12 km/h for the $v_{15^{th}}$ and v_{med} measures respectively after controlling for other variables. This represents a speed reduction of nearly 60 % with respect to the base scenario.

Table 3.5, Coefficients Summary of Mixed-Effect Regression Models

	Variable	Speed models			PET models		
		Min	Median	Max	VPI	VCI	VVI
Treatment	Scenario A (Intercept)	**22.44**	**33.42**	**44.71**	**6.055**	**3.796**	**4.738**
	Scenario B	**-12.49**	**-14.12**	**-12.31**	**0.359**	0.220	**0.162**
	Scenario C	**-8.15**	**-10.86**	**-10.91**	0.041	0.221	-0.13
	Scenario D	**-10.81**	**-12.59**	**-12.63**	0.496	0.744	0.043
User attributes	Right movement	**-2.75**	**-6.17**	**5.75**	-0.204	-0.104	**-0.202**
	Left movement	**-2.86**	**-5.21**	**-5.12**	-0.089	0.206	0.044
	Exposure	**-0.27**	**-0.36**	**-0.31**	-	-	-
	Presence of crosswalk	**8.36**	**8.34**	**5.75**	0.914	1.35	-0.353
	Presence of vehicle stop line	**-5.18**	**-6.03**	**-5.12**	-	-	-
	Approach width at the crosswalk level	0.01	-0.04	-0.03	-0.007	0.001	0.013
	Bike-path at the approach	-0.22	0.11	**-2.87**	**0.278**	-0.246	-0.042
Intersection-level	Distance to previous intersection	**-0.01**	**-0.01**	**-0.01**	-0.002	-0.003	0.0002
	Previous no stop-control	**8.74**	**12.42**	**10.51**	-	-	-
	Previous stop-sign	**9.52**	**13.23**	**11.14**	-	-	-
	Previous traffic light	**10.24**	**13.8**	**9.91**	-	-	-
	Four branches	**-4.69**	**-5.93**	**-5.3**	**-0.861**	-0.357	0.229
	Built environment variables						
	Population density	**-0.11**	**-0.14**	**-0.12**	**-0.008**	-0.002	-0.005
Model	Random Effect						
	Site	-	-	-	0.28	0.303	0.314
	Approach	4.192	5.152	4.951	0.001	0.522	0.189
	Residual	6.17	7.745	8.479	2.142	1.897	1.777

* Significant variables are indicated in bold values with a 95% confidence interval
- , indicates a dropped variable
n.a., are variables that were not evaluated as independent variables in the model

- **Scenario C:** This represents the before-treatment condition in the minor approach with stop signs. In this case, a speed difference of 8.15 km/h from the base (A) scenario is observed (about 40.0 % lower speed) for the estimated mean $v_{15^{th}}$. As suspected, vehicle speeds in the minor approaches are lower than in the non-treated major approaches.
- **Scenario D**: This represents the after-treatment condition in the minor approach. A speed difference of 10.81 km/h is observed for the mean $v_{15^{th}}$ with respect to scenario A. This result represents an additional 10.0% speed reduction compared to the base scenario or nearly 20.0% lower speed than Scenario C. This then represents a small additional speed reduction in the minor approaches after stop signs are implemented in the major approaches.

From the geometric variables at the approach-level, having a stop-line marking at the approach reduced the minimum speed ($v_{15^{th}}$) by 5.18 km/h compared to those without it. Unexpectedly, the presence of a crosswalk increased the speed of the vehicles which is counterintuitive and can be related to the correlation with other factors. Additionally, the presence of a bike path decreased the minimum speed ($v_{15^{th}}$) by 0.22 km/h, but this reduction was non-significant (except for the $v_{85^{th}}$), as the approach width.

The right and left-turning movement of vehicles for the user variables had a significantly lower speed (with $v_{15^{th}}$ equal to 2.75 km/h and 2.86 km/hr respectively). As expected, vehicles exposure to VRUs and vehicles) at local intersections was associated with lower speed values.

For the site-level variables, the type of control of the previous intersection, the number of branches and population density significantly affect the speed values. For instance, having a traffic light in the previous approach will increase the vehicle's mean $v_{15^{th}}$ compared to having a stop sign. Also, a higher population density surrounding the intersections implies lower speeds. Although the distance to the previous approach is significant, the mean $v_{15^{th}}$ effect is extremely small and can be omitted as a causal variable.

In addition to the analysis of the variables, the standard deviation for the approach I.D. for the mean v_{med} was 5.15 km/h, which showed a variability of nearly 30.0% of the median speed for the different approach locations. Finally, the scenario ANOVA test showed a significant difference between the various scenarios (Table 3.6).

Table 3.6, Vehicle speed models and scenario analysis

Coefficients	Minimum	Median	Maximum
Observations	50,253	50,253	50,253
Groups number*	104	104	104
Pseudo-R2 Marginal	0.527	0.539	0.524
Pseudo-R2 Conditional	0.677	0.681	0.645
AIC	326,054	348,885	357,965
ANOVA test (p-value) for vehicle speed analysis, scenario comparison			
Major approach with vs without stop (scenario A vs B)	**<0.001**	**<0.001**	**<0.001**
Minor approach before vs after (scenario C vs D)	**<0.001**	**<0.001**	**<0.001**
Major vs minor approach (before) (scenario (A vs C)	**<0.001**	**<0.001**	**<0.001**
Major vs minor approach (after) (scenario B vs D)	0.096	0.2178	0.7896
Approach without vs with stop (scenario A vs B+C+D)	**<0.001**	**<0.001**	**<0.001**

* Group number, refers to the total number of different approaches (See Table 3.2).

3.5.3. PET Analysis

PET cumulative probability distributions before and after treatment are first presented in Figure 3.8 for the different scenarios. For PET analysis, interactions were divided in vehicle-pedestrian interactions (VPI), vehicle-cyclist interactions (VCI), and vehicle-vehicle interactions (VVI) before and after treatment. As shown in Figure 3.8, when comparing PET distributions before and after, the effect of treatment varied by interaction type and approach. According to the K.S. test, the treatment was not significant for vehicle-pedestrian conflicts in the treated (major) approach. For the minor approach, there was a significant effect of the treatment on vehicles-pedestrians conflicts using the K.S. test: the median PET was reduced from 4.77 to 4.36 seconds. For vehicle-cyclist conflicts, no changes were observed on PET distributions. For vehicle-vehicle interactions, changes in the proximity of the interactions were also very marginal.

Table 3.5 shows the results of the PET regression analysis to evaluate the treatment effect after controlling for other factors. For the vehicle-pedestrian interactions, we found that scenario B

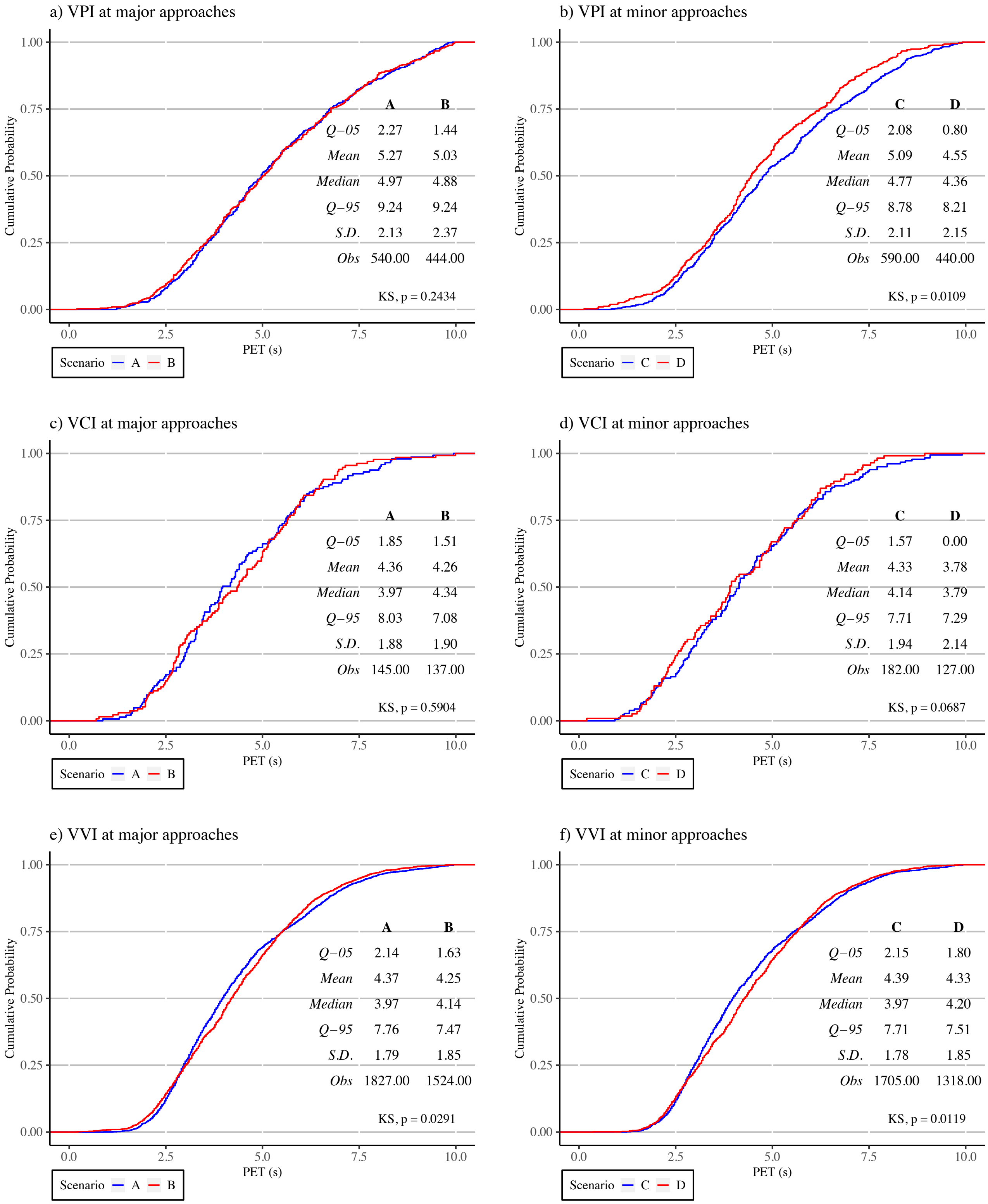

Figure 3.8, PET cumulative distribution functions: a) VPI at major approaches, b) VPI at minor approaches, c) VCI at major approaches, d) VCI at minor approaches, e) VVI at major approaches, f) VVI at minor approaches.

increase in PET. In other words, the VPIs that happened in the major approaches were slightly less severe in the after period (with an increase of 0.5 s after treatment implementation). From scenario D, the effect was also positive but not significant. For VCIs, we found that there was a positive but non-statistically significant impact of the treatment (scenario B). For the other scenarios (C and D), no significant effects were observed. Finally, for VVIs, a pattern similar to the VCI was observed with a small (0.162) but positive significant effect after treatment implementation on the major approach.

For the approach-level variables, having a bike path in the approach was significant and resulted in a small improvement on the PET of the VPIs (0.28s). This result may be explained by the fact that the bike path provided the pedestrians with broader vision when crossing the intersection, which would give the driver a better view of the pedestrians while reducing the size the vehicle lane. As an expected result, the maximum speed $v_{85^{th}}$ was significant and decreased the PET value (-0.02s). The additional approach factors had a negative PET effect but were not significant for pedestrians. For the VVIs approach level factors, the maximum speed $v_{85^{th}}$ and the right turn movement were significant. For the site-level factors, the number of branches and population density had a negative association (-0.86 and -0.01s respectively) on vehicle-pedestrian conflicts. Furthermore, the random effect for the site and approach were minimal in the PET analysis. For the VPIs, the approach did not have an impact on the random effect, while for the VCIs, the random effect of the approaches (0.52s) was larger than the one of the sites (0.30s).

The ANOVA scenario test Table 3.7, indicated that having a stop sign on the approach was significant in most of the scenario comparisons for the different user interactions. In the scenario comparisons, the approaches that did not have a significant effect after the treatment were the major vs minor approach for the VPIs and VVIs. Comparing the VCIs on the minor approach before and after the treatment showed insignificant effect, along with the major vs minor approach after the treatment. The models had a low R^2 and were therefore not suitable for safety predictions. These small PET increases after the conversion to AWS showed some improvements for the different road users at the intersection. For the VVIs and VPIs, the improvement may be explained by the mandatory stop for drivers approaching the intersection. The results of the VCIs indicated the absence of a behavioural shift of incoming drivers on the minor approach towards cyclists on the major approach.

Table 3.7, Model and scenarios analysis for PET between vehicles and other users

Coefficients	**Pedestrian (VPI)**	**Cyclist (VCI)**	**Vehicles (VVI)**
Site groups numbers*	24	20	25
Approaches groups numbers**	77	55	83
Observations	1,968	578	6,243
Pseudo-R2 Marginal	0.0386	0.0308	0.0131
Pseudo-R2 Conditional	0.0548	0.1199	0.0534
AIC	8673	2469	25058
ANOVA test (p-value) for PET scenario evaluation between vehicles and other users			
Major approach with vs without stop (scenario A vs B)	**0.001**	**0.01**	**0.001**
Minor approach before vs after (scenario C vs D)	**0.002**	0.075	**0.021**
Major vs minor approach (before) (scenario (A vs C)	**0.001**	**0.046**	**0.001**
Major vs minor approach (after) (scenario B vs D)	0.588	0.382	0.294
Approach without vs with stop (scenario A vs B+C+D)	**0.001**	**0.035**	**0.001**

* Refers to the number of intersections that presented an interaction between the evaluated users

** Refers to the number of approaches that presented an interaction between the evaluated users

Finally, the PET analysis is complemented by computing the conflict frequency as shown in Table 3.8 for the three conflict types (vehicle-pedestrian, vehicle-cyclist, and vehicle-vehicle conflicts), where the PETs are classified first according to threshold values described in Section 3.4. Following classification, the number or frequency of conflicts was computed and the rates per hour were derived. In addition to the rates, the percentage of conflicts across the four different scenarios (before and after treatment) are presented in the same Table 3.8. Was also observed that there was an absence of high-risk interactions (PET values less than 1.5 seconds are not observed) and a large percentage of conflicts (97.4% of all the events) were in the low and safe categories.

Furthermore, the benefit of the AWS treatment can be observed through the interaction severity comparison. A generalized reduction in the moderate interactions (PET between 1.5 and 3.0 s) that were recorded in the before scenarios ("A" and "C") was observed for all the different users. For example, the moderate VPIs frequency on the minor approach (scenario C) went from 0.14 interactions per hour to 0.02 (Scenario D). A similar trend was observed for the minor approach, which went from one moderate interaction in 7 hours to one every 50 hours. The observed

Table 3.8, PET events frequency

Scenario		Frequency of events			Events per hour		
		Dangerous	Mild	Safe	Dangerous	Mild	Safe
Vehicle - Pedestrian	A	3	48	393	0.02	0.39	3.17
	B	1	60	478	0.01	0.50	3.95
	C	17	124	299	0.14	1.00	2.41
	D	3	89	497	0.02	0.73	4.10
Vehicle - Cyclist	A	0	21	115	0.00	0.17	0.93
	B	0	29	115	0.00	0.24	0.95
	C	18	42	67	0.15	0.34	0.54
	D	1	50	131	0.01	0.41	1.08
Vehicle - Vehicle	A	16	263	1243	0.13	2.12	10.03
	B	9	560	1255	0.07	4.62	10.36
	C	143	480	691	1.15	3.87	5.58
	D	19	546	1134	0.16	4.51	9.36

*Dangerous is for events with 1.5s < PET ≤ 3s, Mild for 3s < PET ≤ 5s and Safe for PET > 5s

increase in the low and safe interactions likely resulted from the right-of-way while crossing that the "conflicting" or "opposite" user experienced after the AWS treatment. However, since the increases are in the low or "safe" PET interaction range, this would also provide the driver with more time to stop or the VRUs with more time to react and avoid the collision.

3.5.4. D-V Framework Analysis

This section outlines the results of the yielding to pedestrian behaviour. The driver and pedestrian crossing decisions for all the different approaches were classified into the three phases according to the methodology presented in section 3.4. Based on the classified events, rates were first computed and then compared between the before and after conditions. The outcomes of this analysis are presented in Table 3.9 and Figure 3.9, where one can see that the percentage of interactions that fall in Phase III (vehicles that are able to stop) increased from 83.4% to 91.1% in the before and after condition respectively. In Phase I, they went from 5.7% to 2.1% in the after period, indicating that the conversion to all-way-stop intersections significantly reduced the number of interactions where drivers had difficulties or could not yield to pedestrians. Table 3.9 also presents the yielding rates before and after treatment which were 45.7% and 76.7%, respectively. Moreover, vehicle compliance increased from 48.4% in the before condition to 78.3% in the after condition (Figure 3.9a and b). These results indicate that the treatment significantly increased (by 31.0%) the vehicle yielding rates. However, 21.7% of drivers still did not yield to pedestrians after the treatment implementation. This analysis showed that 51% of pedestrians crossed after the vehicles passed in the before condition, mainly because they were not given the right-of-way. This situation improved considerably in the after condition, where the percentage of pedestrians crossing after the vehicle was reduced to 22.0%. The decisions of pedestrians to cross the street before the vehicles passed is closely related to their safety as they expose themselves in front of vehicles. Among pedestrians who crossed before the vehicle, most of the crossing decisions (97.0%) were made in a safe situation in the after condition, compared to 90.0% before the treatment. Furthermore, almost all pedestrian crossing decisions fall in Phase II and Phase III in the after (AWS) condition (Figure 3.9d). Finally, Table 3.9 provides the number of evasive maneuvers, which were also reduced from 13 (out of 214 crossing decisions made before the vehicle) in the before condition, to 3 (out of 332) in the after conversion.

Table 3.9, Outcomes of the before-after analysis

Outcome	Before Conversion	After Conversion
Interactions outcomes		
No. of total interactions	440	429
No. of interactions in phase I	25 (5.7 %)	9 (2.1 %)
No. of interactions in phase II	49 (11.1 %)	29 (6.8 %)
No. of interactions in phase III	366 (83.2 %)	391 (91.1 %)
Yielding Behavior Outcomes		
Yielding rate	45.7 %	76.7 %
Yielding compliance	48.4 %	78.3 %
Pedestrian Crossing Decision Outcomes		
No. of decisions to cross after vehicle passage	226 (51%)	97 (22%)
No. of decisions to cross before vehicle passage	214 (49%)	332 (75%)
No. of dangerous crossings	5 (2.3 %)	3 (0.9 %)
No. of risky crossings	16 (7.5 %)	7 (2.1 %)
No. of safe crossings	193 (90.2 %)	322 (97.0 %)
No. of crossings with evasive maneuvers	13	3

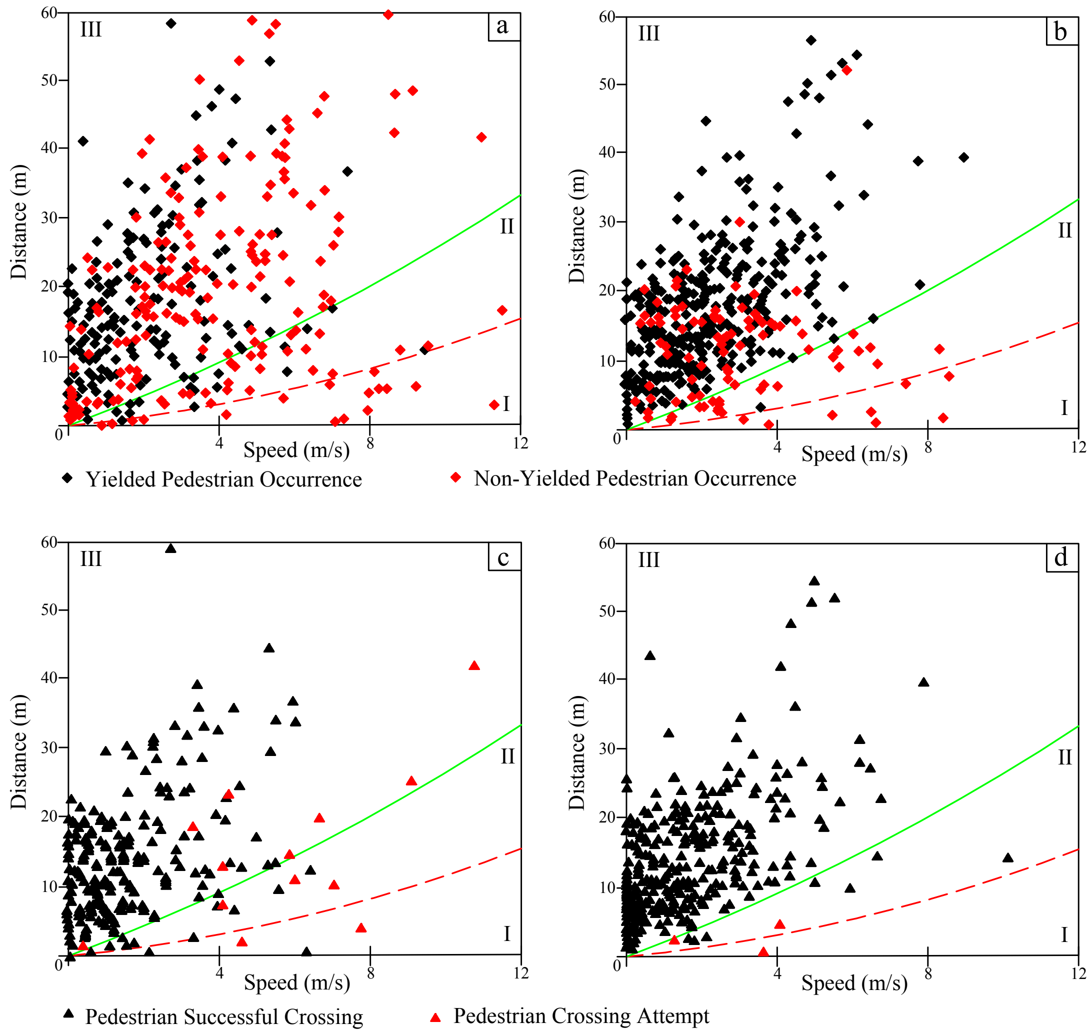

Figure 3.9, DV Pedestrian crossing plot: a) occurrence and yielding before conversion; b) occurrence and yielding after conversion; c) crossing decision before conversion; d) crossing decision after conversion.

3.5.5. Final Discussion of Results

As discussed previously, very few before-after studies exist in the literature on the conversion of MAS to AWS intersections. According to the HSM, the effectiveness of the treatment with respect to all types of injury crashes is 70% (with a CMF of 0.30 and a standard error of 0.06). It is worth mentioning that the effectiveness of the treatment is mainly related to right-angle collisions with a CMF of 0.25. For rear-end crashes, the CMF is 0.82, representing only a modest reduction. In the case of pedestrian injuries, the reported CMF is of 0.57 with the remark in the

HSM that this is less reliable since there is not sufficient evidence. These factors are mainly based on a single before-after study published 35 years ago (Lovell and Hauer 1986). In a more recent study by (Deng et al. 2020) relied on a randomly selected comparison group approach and cross-sectional data. The authors found an overall reduction of 36.0% in all crashes and a 42.0% reduction in injury crashes associated with converting intersections from MAS to AWS.

Even though our results are not directly comparable with this existing literature based on crash data, we are able to provide here a simple comparison. First, our results are in the same directions; that is, for the observed reductions in crashes, a significant reduction is also observed after the treatment implementation according to the SMoS: vehicle speeds, severity, frequency of interactions and yielding rates. Moreover, from the general statistics, we observe a reduction of vehicle speeds close to 40.0% and a reduction of close to 80.0% in the most critical conflicts (with PET < 3.0 s). In the case of yielding rates, the reduction is of approximately 21.0% before and after treatment. The surrogate safety indicators used in this study provide results in the same direction and range, although the link between SMoS and crashes was not determined in this work.

3.6. Conclusions

The conversion of intersections with minor-approach-only stop (MAS) to all-way-stop (AWS) intersections is a popular treatment in North American cities. However, there is little research on the impact of this countermeasure on vehicle speed, conflicts, yielding rates and other road user behaviours. In this research, the impact of converting MAS intersections to AWS intersections was investigated using an automated surrogate video analysis and a before-after approach involving multiple road safety indicators. For this purpose, user trajectories were extracted from a unique large sample of video data collected at 31 intersections before and after the AWS conversion. With automated video processing and computer vision techniques, 245 hours of video were analyzed and validated, resulting in more than 68,000 (37,668 before and 31,305 after treatment implementation) road user trajectories. Based on the trajectory data, speeds, conflicts and yielding rates were computed and analysed using different statistical analyses including a multi-level regression analysis to evaluate the treatment effects after controlling for geometric and traffic condition factors.

Among the main results, there was a significant reduction after the AWS treatment implementation in vehicle operating speeds. Also, there was a clear improvement in yielding rates to pedestrians. Overall vehicle median speeds decreased by 14.12 km/h after stop controls were implemented in the main approaches. In the minor street approaches, the reduction in speed was also significant but smaller. The distance-velocity model outcomes showed that in general, the all-way-stop treatment improved pedestrian yielding rates by 31.0% when comparing the before and after conditions. The AWS treatment also increased the percentage of safer pedestrian crossing decisions and decreased the proportion of pedestrians crossing after the vehicle passed by 29.0%. With the regression analysis, a small reduction in the PET severity was observed after the AWS implementation for vehicle-pedestrian and vehicle-vehicle conflicts. Finally, the frequency of the PET events was evaluated, where the events were divided into four different categories. On the conflict frequency rates, marginal improvements were observed for the moderate category, while no high-risk conflicts were observed.

This work has some limitations that need to be recognised and addressed in future work. First, PET analysis deals mostly with right-angle conflicts. Although right-angle conflicts and crashes (see HSM, 2010) are the main source of dangers in non-signalized intersections, rear-end conflict events could be analysed as part of future work to evaluate the treatment effect on these types of events - this could be done using the TTC, and an additional evaluation to the right-angle conflicts with this indicator. Speed analysis could be further expanded to consider speeds at specific locations or speed profiles as opposed to measures derived from each vehicle trajectory. Approaching vehicle speeds (before stop signs or stop lines) would help determine whether a vehicle stops and if it stops in the appropriate location. Data used in this study consider all vehicle speeds; however, some vehicle/driver behaviours can be influenced by others. Hence, further analysis could separate vehicles approaching in free-flow conditions. As part of the general validation of surrogate measures of safety, the correlation between surrogate measures and observed crashes should also be investigated despite the low frequency of crash events.

Moreover, future work could investigate the long-term impacts of converting MAS to AWS on road user adaptation. Some research has shown that installing stop signs everywhere may decrease driver compliance over time (Trinkaus 1997). Likewise, the upstream effect of the approach should be investigated with network-level user tracking i.e. GPS data. The poor fit of the PET models should be investigated – accordingly, the reported PET models should not be utilized for safety predictions in other sites. Lastly, cyclist behaviour should be investigated in more detail, in particular the interactions between cyclists and pedestrians should be evaluated including cyclist yielding compliances towards pedestrians, and vehicles compliances with cyclists.

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Connection Between Chapter 3 and 4

In Chapter 3, vehicle drivers' behaviours towards stop signs are studied on a Before and After study when the intersections change from MAS to AWS. In Chapter 4, cyclist behaviour towards stop signs is evaluated between approaches that are controlled vs not controlled. The proposed methodology to evaluate vehicle behaviour in Chapter 3, utilizing a random-effect regression model to evaluate empirical trajectories on a hierarchical level is adjusted in Chapter 4 to analyze the cyclist behaviour and safety. Both chapters investigate the safety impact of the cyclist on the other road users utilizing speed values and PET values obtained from microscopic data.

Chapter 4. Cyclist Behaviour and Safety Towards Stop Signs. A Study on Stop-Controlled Intersections Using Video Trajectory and Surrogate Measures of Safety

Cyclist Behaviour and Safety Towards Stop Signs. A Study on Stop-Controlled Intersections Using Video Trajectory and Surrogate Measures of Safety

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4.1. Abstract

The installation of stop signs in non-signalized intersections bring a positive perception to the general population, in particular to drivers and pedestrians. However, little research has looked at cyclist behaviors towards stop signs at intersection approaches and cycling safety impacts. This paper aims at investigating the cyclist crossing behaviours at non-signalized intersections with stop signs in two typical settings: intersections with stop signs only in minor approaches and all-way-stop intersections. For this purpose, cyclist behaviors are studied in these different settings using video data and automated trajectory information. The effect of stop signs on cyclist behavior is investigated using multiple indicators: cyclists' speed measures, post-encroachment time (PET) of cyclist-pedestrian, cyclist-cyclist and cyclist-vehicle interaction. Different statistical analyses are implemented to study the safety of cyclists. Multi-level linear models were used for the speed and conflict analysis, where all models control for cyclist-level characteristics, geometry and built environment features at the approach and intersection level. From the different outcomes analyses, it was found that there is not a significant reduction in the conflict severity based on PET in the approaches with stop signs. However, cyclists will show a significant reduction on speeds when there is a stop sign at the approach. The results show that stops signs do not significantly affect cyclist behaviour, compared to the different reactions they are already having with the different users of the road.

4.2. Introduction

Urban cycling as a transportation mode is rising its popularity globally. With the COVID-19 pandemic its popularity become even more pronounced (Büchel et al., 2022; Buehler & Pucher, 2021; Möllers et al., 2022). The growth of cycling is not an exception in North America, having New York City, Portland, San Francisco, Washington D.C., Montréal, Vancouver, etc., as the main big cities leading this adoption. The previous cities have designed effective interventions to encourage cycling and improve cyclist comfort and safety to address this increase in bicycle demand (Pucher, Buehler, and Seinen 2011; Zahabi et al. 2016). One of the reasons for this growth is that cycling is often a more efficient commuting option in urban areas than other transport modes. Cyclists generally avoid congestion while benefitting from a healthy and inexpensive mode of transportation. In addition to the cyclist, society benefits from cycling by reducing emissions and noise pollution, cheaper infrastructure, and public health improvements (Heinen, van Wee, and Maat 2010). Despite the many benefits of urban cycling, safety is still a very important concern in particular at intersections that play a critical role given that at least half of the collisions between cyclists and drivers occur at this road network location (Hunter et al. 1996; Dozza and Werneke 2014). To improve cycling safety, cities have implemented cyclist-friendly treatments such as the installation of cycling facilities, pavement marking strategies (e.g., bike boxes) and changes in traffic controls. Among the common improvement of the type of intersection traffic control one could mention the conversion of a minor-approach-only stop (MAS) intersection into an all-way-stop (AWS) controlled intersection, and more recently, the addition of bicycle traffic lights at signalized intersections.

The modification of the traffic control in an intersection is in principle justified from the traffic operation and safety of all road users point of view. In general, warrants justify converting of a MAS intersection into an AWS, or from MAS, AWS to traffic light signalized when traffic, geometry, and/or road safety issues are identified, and some basic conditions are met. However, those conditions often do not consider cyclists or consider them as pedestrians or vehicles, which does not reflect how they behave towards the other road users. In the MAS to AWS warrants conversion, cyclists are subjected to the same rules as motorized traffic, where it is also recommended to use the bikeways, if there is any. As cities have realized the importance of cycling as transportation mode, cyclist infrastructure has been installed in more locations. However, this implementation has been retroactively and in some areas of the cities it still inexistent, which has led cyclists and pedestrians to share the same space (Latham and Wood 2015).

Yet, the warrants do not consider that a bicycle uses human power to move, and at a stop sign, a cyclist requires an additional physical effort to recover its previous speed, while drivers only have to shift their foot from the braking to the gas pedal. It has been estimated that a cyclist that rolls through the intersection at a speed of 8 km/h instead of coming to a full stop saves 25% of energy to recover its previous speed (Fajans and Curry 2001). Nevertheless, a cyclist that breaks the law carries a higher level of scorn than the other road users without considering the main reason behind this behaviour. In contrast, drivers and pedestrians break the rules primary to save time, and cyclists have been reporting to do it for “personal safety”, saving energy and saving time as a minor reason (Marshall, Piatkowski, and Johnson 2017). Still, most local warrants consider the cyclist as a vehicle, which in the USA has been classified since 1926 as such and has stayed that way (Tekle 2017). The previous has led to have some discrepancies between the formal codes (warrants) and informal city codes (manuals) that are seeing the importance of classifying the cyclist as another individual (Pelzer 2010).

Canada and the USA have documentation describing their warrants for the installation of traffic control devices, while some states and provinces have adapter their own documents. In Canada and Quebec, the Transport Association of Canada (TAC) and Quebec Ministry of Transportation (MTQ) respectively maintain the Manual on Uniform Traffic Control Devices for Canada (MUTCDC) (MUTCDC 2014) and the Tome V on Traffic Control Devices (Quebec 2020). These manuals contain the warrants for the installation of traffic control devices such as stops. The type of stop control device for an intersection is justified by the warrants, where motorized vehicles are the main considered users. The warrants revolve around: a) vehicle volume, b) vehicle speed, c) average delay for the minor road, d) safety concerns and e) visibility. In the Canadian warrants, cyclists are not considered in the users' criteria, while the USA standards (MUTCD 2012) consider cyclists and pedestrians for the volume criteria.

Despite the emerging literature on bicycle safety in the last years, there are some controversies and limitations in the current literature regarding cycling safety at intersections with stop signs in North American:

- Despite the popularity of installing stop signs in urban areas, there is little research on cyclist behaviour at non-signalized intersections and the safety impacts of stop signs on bicycle-pedestrian and bicycle-bicycle interactions. Given the large amount of violations (cyclists not stopping at intersections), the safety not only of cyclists but also of pedestrians have raised some concerns.
- Existing studies on stop signs have focused on drivers and pedestrians, with very few looking at cyclists. Most of these studies have used crash data and very few have used before-after observational approaches.
- The use of proactive video-based automated approaches to investigate bicycle safety is limited in the literature.

To address the mentioned research gaps, this paper investigates the cyclist behaviour and safety of cyclists at non-signalized intersections with stop signs using an observational approach and surrogate measures of safety (SMoS), i.e. measures of safety that do not depend on the occurrence of crashes. For this purpose, a video dataset of 35 intersections is used, where users' trajectories were extracted using specialized computer vision tools. From the 35 sites, 30 of them were converted from MAS to AWS, where users' information is available for the before and after period. Using the extracted road user trajectories, SMoS are generated for cyclists. This research considers cyclist speed measures and the post-encroachment time (PET) for cyclist-pedestrian, cyclist-cyclist and cyclist-vehicle interactions as SMoS. A multi-level modelling approach is used to evaluate the effect of the introduction of stop-signs on the different approaches controlling for cyclist characteristics and behaviors (e.g., use of helmet, making an avoidance maneuver or making a full stop), built environment (i.e., population and land use mix in the proximity of the intersection), approach and intersection geometry.

4.3. Background

Intersections represent a complex road entity where the users from different traffic streams interact, making it the most critical network location from the safety and operations perspective. At intersections with a high number of users, signalized intersections are used to coordinate traffic movements efficiently and safely. At the other end, at intersections with very low traffic, no signalization is deemed necessary, letting users' follow the right-hand rule for the occasional interaction. In between, stop signs have proliferated and might be the most common traffic control device in urban areas. From the previous, there are some studies focused on pedestrians' or cyclists' waiting time and dangerous crossing, but mainly at signalized intersections (Brosseau et al. 2013). This section provides a short summary of warrants and safety literature at intersections for cyclists.

4.3.1. Control Device Warrants and Cyclist accountability

Cyclists being included in warrants for stop signs and traffic lights at intersections is a recent topic in some warrants. In the MUTCD they were recognized as individual users until the 2,000 version. For stop signs, before the release of the MUTCD Millennium version, pedestrians were distinguished from vehicles only in the four-way stop signs section. In the pedestrians' situation, they were included in the warrants until the 1948 version, with the introduction of the 4-ways stop signs to the standards. For cyclists, the USA warrants recognized as a unique individual in the mentioned MUTCD millennium edition. Before that, cyclists were defined as vehicles in 1926 and removed four years later in 1930. Finally they were brought back as a vehicle in 1975 (Tekle 2017). After being recognized as individuals, cyclists obtained their own infrastructure chapter in the 1979 MUTCD version Part IX and stayed there until the last one published (MUTCD 2012).

Stop sign guidelines between Canada and the USA are relatively similar, where the main difference is how the approaching vehicle’s speed is taken into consideration. In Canada, most of the provinces and territories follow the MUTCDC as their reference. However, some of the Canadian provinces develop their own guidelines, several of them having fewer requirements than the MUTCDC. For instance, the AWS installation in Alberta does not have a vehicular crash rate criterion. In British Columbia, only the vehicular traffic volume and crash rates are considered for implementing AWS. Guidelines from Ontario and Quebec are mostly similar regarding motorized volumes, accident rates, etc. Whereas most of the Quebec and Ontario requirements are based on the Canadian guidelines, the main difference is that the Federal guidelines do not have a requirement about the existence of other control devices within a specified distance. Ontario requires to avoid traffic lights or stop signs within 250 m in any direction, while for Quebec, the requirement is to avoid traffic lights on the major street within 250 m or stop signs within 150 m.

In the cyclists’ context, a difference between the Canadian and USA warrants is the integration of cyclist in the users’ volume as one of the possible requirements for the minor approach, where cyclist need to behave and follow the rules of the vehicles. But North America is not the only region that subjects the cyclist to the same rules of the road as motorized vehicles, many European countries apply the same criteria (Kircher et al. 2018). However, some states or cities want to evaluate cyclists in a different category than vehicles, like the state of Idaho that allows the cyclist to treat the stop sign as a yielding sign and the red on traffic lights as a stop sign (Meggs 2010). Like Idaho, in Delaware, the stop signs have been introduced as yield signs for cyclists, helping to reduce injury crashes with cyclists involved (Delaware 2021). In this context, a study compared bicycle crashes between two similar cities in the USA, Boise (Idaho), where the Idaho Stop rule is applied and Champaign (Illinois), where cyclists need to do a full stop in the stop sign. The final results did not show a safety difference at the intersections with stop signs (Whyte 2013).

4.3.2. Cyclist behaviour and control devices at intersections

There is a perception by some groups in society that cyclists fail to obey road rules (Shaw et al. 2015), where failing to stop at a stop sign is identified as a problem (Larsen et al. 2011) Still, there is another conception for failed road rules as drivers going over the speed limit or pedestrians jaywalking (Piatkowski, Marshall, and Johnson 2017). Piatkowski also found that a person who utilizes a bicycle with a certain frequency tends to be more tolerant to "cyclist violations" in the same way that drivers are more tolerant to speeding behaviours. Also, it was found that society has a different perception of cyclists, where the tight-fitting lycra or the bicycle courier are viewed less favourable on the society than others (Piatkowski, Marshall, and Johnson 2017).

Despite the "bad impression" that cyclists have while not respecting the stop signs, there is no conclusive evidence that this generates more accidents at the intersection since cyclists informally treat them as yield signs (Larsen et al. 2011). For instance, a research made in Melbourne (O'Hern and Oxley 2019) found that less than 4% of the pedestrians admitted to a hospital after being struck by a cyclist or vehicle are from a cyclist-pedestrian collision. The previous result is from a 10-year period, where 273 of the pedestrians admitted to a hospital were struck by a cyclist. In contrast, 6,699 pedestrians were admitted as a result of a collision with a vehicle. From the registered accidents in Melbourne, 45.8 % of them occur at an intersection. Furthermore, wearing a helmet has been linked in a cyclist to make a full stop at stop signs and have a safer behaviour (Johnson et al. 2011; Vanparijs et al. 2015). Farris found that cyclists wearing a helmet are 2.6 more likely to make the full stop and 7.1 more likely to use hand signals (Farris et al. 1997).

Then, why do cyclist break the rules of law at traffic controls like stop signs? A study in Sydney reported that cyclists believe that breaking the rules of traffic would translate into an increase in safety (Shaw et al. 2015). Also, an online survey to citizens of 73 countries made in 2015 (with a big response rate from the USA, Europe, Australia and Canada) shown that 71% of the cyclist disregards the traffic rules for safety reasons. Even most of the respondents to the survey break the law, most of them do it in situations that little harm will be done to themselves or the other users of the road (Marshall, Piatkowski, and Johnson 2017). A study made in Vancouver and Montreal found that from 3,884 pedestrians crossing, only 14.5% had an interaction with a cyclist, and none of them resulted in a major conflict or collision, highlighting the exceptionality of these events (Hosford, Cloutier, and Winters 2020). However, collisions between pedestrians and cyclists are also a problem given the risk of an injury for pedestrians (Cole et al. 2011).

Another reason for cyclists to not stop at the stop sign is the energy-saving and comfort due to the additional effort that the cyclist will need to recover its previous energy (Fajans and Curry 2001; Piatkowski, Marshall, and Johnson 2017; Stromberg 2014). Cycling requires an additional physical effort to recover one’s previous speed at stop signs, while drivers simply have to shift their foot from the braking to the gas pedal (Fajans and Curry 2001). However, if a cyclist fails to come to do a complete stop, they balance slowing down or conduct a precautionary visual search (Ayres et al. 2015). In a four-stop-controlled intersections study in Kensington, California, it was found that almost 90% of cyclists slowed somewhat or came to a full stop at a two-way stop sign intersections, compared to 33 % of the cyclists at AWS (Ayres et al. 2015). In some cases, it has been reported an “awkward dance” between cyclists and drivers at AWS, where the driver is yielding to the cyclist when the preference is for the driver “urging the cyclist to go”, leading to bigger delays on both users (Stromberg 2014). Also, it was found that traffic flow is improved when cyclists do not come to a complete stop at non-signalized intersections since cars do not have to wait for the cyclist to clear the intersection (Fajans and Curry 2001).

Knowing that cyclists do not consider a priority to make a full stop at stop-controlled intersections, there have been some efforts to deal with this behaviour. One of the measures is the use of traffic wardens (Yang et al. 2016); in China, they have been implemented to handle the mixed traffic flow at intersections and make the VRUs follow the rules. While the most common approach is the one used by Australia and many other legislations, where obey the traffic signals and stop signs is universal with no exception for any user. However, when a group of cyclists are making a transit violation, they are hard or too costly to prosecute by the police due to the difficulty of identifying the individual rider (Johnson, Oxley, and Cameron 2009). The Chicago Attorney James Freeman claims that cyclist law enforcement is essential, if the authorities dedicate the resources and take the ordinance seriously (Caldwell and Yanocha 2016). However, as Caldwell indicates, even if the resources are destinated, as in Chicago or New York, law enforcement is not always the solution. In Chicago between 2006 and 2015 there was an average of four tickets per day, while in New York City in 2015 the police issued 47 per day.

Nonetheless, ticketing is not the only solution for traffic behaviour, especially if the goal is to attract cyclists, "bike-friendly" policies should be more widely implemented. One of the options that have been debated is the one know as Idaho Stop, which was implemented as law in 1982 in the State of Idaho, USA, allowing the cyclist to yield instead of coming to a complete stop at stop-controlled intersections, reducing bicyclist injuries (Meggs 2010). While some people argue that allowing cyclists not to make a full stop at the stop signs will bring more accidents, there is no strong evidence for such argument. On the contrary, Idaho has experienced a fatality rate of 1.22 per million inhabitants, and the national USA rate is 2.28. The previous statists suggest that allowing cyclists to treat signal controls differently as vehicles like the Idaho rule is not "inherently unsafe" (Tekle 2017). One of the additional advantages of the adoption of this law is the potential of making cyclists behaviour more predictable for motorists, making roads safer for everyone and improving the intersection flow for all road users (Caldwell and Yanocha 2016)

4.3.3. Safety Analysis Methods at Intersections

There are different methods and techniques to analyze safety conflicts, crash counts and surrogate measures of safety (SMoS). Unfortunately for crash counts, not all of them are reported, as it was found in a survey made by Robartes, where it was found that only 12% of the crashes were reported. Among the underreported crashes involving a cyclist with a vehicle, cyclists had a minor injure in 66 % and a severe injure in 19 % of them (Robartes and Donna Chen 2018). In general, cyclists statists have been obtained by counting accident numbers rather than accident rates (Kobas, G. V 1976). Brüde and Larsson say that besides the average daily number of cyclists and vehicles, it may be hard to define the additional factors that significantly influence the number of crashes (Brüde and Larsson 1993). However, Hunter found that in addition to traffic volumes, the vehicle speed, the bicyclist's age, and the presence of a right turn-lane could lead to a higher number of cyclist-vehicle collisions (Hunter et al. 1996). Carter developed an index to evaluate safety at a macroscopic level for cyclists at intersections as a function of traffic volume, type of signalizations and geometric factors (Carter et al. 2008). Cho confirmed an association between the crash risk and the built environment factors (the neighborhood compactness and land use mix) (Cho, Rodríguez, and Khattak 2009).

As mentioned before, using accident records to study cyclist safety has many downsides, such as under-reporting, a lack of accident data and information about the interaction process (Laureshyn et al. 2017). Due to the lack of crash data, and other shortcomings of historical crash records, there has been an effort to find other methods, relying on surrogate measures of safety (SMoS), measures that do not require collisions to occur. To better understand the events, SMoS are often combined with other variables to provide a better understanding of safety and risk (Ismail, Sayed, and Saunier 2011). With the improvement and easy access to computing power, computer vision techniques are becoming a useful tool for safety analysis due to the capacity to extract users' trajectories and classify them from videos (Saunier, Sayed, and Ismail 2010). The microscopic data extracted from the videos have been used to identify traffic events' patterns (Saunier, Mourji, and Agard 2011). As an example, video analysis has been used to compare cyclist safety with a set of different layouts of intersections with traffic lights (Madsen and Lahrmann 2017) and develop conflict-based safety performance functions for signalized intersections (Essa and Sayed 2018). SMoS rely on severity indicators to measure traffic events' proximity to a crash and/or the severity of the potential crash. Existing indicators can be classified into four leading families (Laureshyn et al. 2016):

- Time-to-Collision (TTC), defined as the time remaining until a collision of two road users assuming they continue travelling as initially planned.
- Post-Encroachment-Time (PET), defined for users with observed crossing trajectories as the duration between the instant the first road user leaves the crossing zone and the moment the second road user reaches the crossing zone.
- Deceleration, which is the most common evasive action taken by a vehicle to avoid a collision (Laureshyn et al. 2016).
    - Other indicators such as speed, which is used as a predictor of collision occurrence and severity (Fu, Miranda-Moreno, and Saunier 2018; Johnsson, Laureshyn, and De Ceunynck 2018).

4.4. Methodology

The followed methodology utilizes the cyclists' speed behaviour and SMoS safety effect to evaluate the effect of the stop signs' presence at the approach. This methodology is based on four main steps: a) sites selection, b) video data collection, c) video data, and SMoS process and d) users' trajectory evaluation. For the site's selection, a sample was carefully chosen from more than 13,000 non-signalized intersections of Montreal. Video data collection followed for the selected intersections in their different stop control state (MAS and AWS). Then, the collected video is processed to obtain users' trajectories with computer vision programs with manual correction for VRUs. The compute of the SMoS was follow after the users' trajectories were corrected. Finally, cyclist's effect of having a stop sign at the approach is evaluated with speed and SMoS values using a random effect regression model to assess the collected data hierarchy (intersection > approach > user).

4.4.1. Site Selection

An inventory of the intersections in Montréal was created for this research from the available geospatial data, the Montréal road network from the city and borough boundaries. The intersection points were defined based on intersecting polygon lines, then filtered automatically and reviewed manually to yield about 13,000 non-signalized intersections.

As a second step, a preliminary sample of 1,000 intersections was randomly selected from the identified intersections in the previous step. A sub-sample of more than 100 MAS intersections was selected as possible candidates to be treated as an AWS from this initial sample. This sub-sample was defined based on:

- Stop-controlled intersections in local-local and local-collector streets.
- Intersections where the cameras could be installed on existing infrastructure such as lamp posts.
- Intersections with one or more approaches without stop signs (MAS intersection).
- The intersections should be located in boroughs that agreed to participate in a before and after MAS to AWS study. Most of these boroughs had a previous request to install stop signs, facilitating the implementation of the AWS intersections.

Finally, a second and final sub-sample of 30 sites was selected for the before-after study, plus five additional intersections with a perceived high cyclists flow after applying the different filters for a total of 35 intersections. This sample was selected in coordination with the different participating boroughs.

4.4.2. Traffic Video Data Collection and Processing

For video data collection, sites were instrumented using regular video action cameras installed in the intersection's proximity, typically on a nearby lamp post. The site's instrumentation took place during weekdays to capture users' behaviour on working days during peak and non-peak hours. For the 30 sites that have a before and after period, there is one year of difference between the data collection sessions to give the local users' a period of adaptation of at least six months after implementing the AWS and the video collection. Also, the video data of the five sites that are not part of the MAS to AWS study were collected with the initial data collection campaign (before period). For all the different sites, the video was collected between 8 am and 12 pm. Furthermore, to capture the users' behaviour that could be meaningful in other locations (weather-related), the video data was collected in September and October, when Montreal's temperature range between 15º and 25º C, and the school period is ongoing.

For the selected sites, the video cameras capture all road users' movements inclusively within the zone of interest. Data were then processed to extract high-resolution road user trajectories at each site with TrafxSAFE help (Transoft Solutions 2022), a commercial software. This software automatically identifies, tracks and classifies each road user into one trajectory and labels them as pedestrians, bicycles, motor-vehicles (car, motorcycle, truck and bus) and unknown. Before the video is processed, a calibration process is implemented where road user trajectories in the camera plane (image space) are projected onto the real world at ground level (world space). Once trajectory data is automatically generated, a manual review is carried out to correct VRUs trajectories and annotate the cyclists' behaviour (use of helmet, avoid interaction, full stop) used in this research. The previous process was accomplished using the tvaLib software (St-Aubin et al. 2018) as part of the quality control. Figure 4.1 shows a sample of processed sites. One site is a four branches intersection with oncoming traffic in all directions (4-ways) where all the trajectories are shown as a heat map (Figure 4.1a and b) A sample of two cyclist trajectories is also shown in Figure 4.1c, it shows a cyclist crossing the vehicle's conflicting area after slowing down to let the vehicle pass (through observational video). Figure 4.1d, presents a cyclist merging the vehicle's lane after the vehicle passed the area of interaction (yellow circle). Users' trajectories can be identified in different colours according to the represented road user.

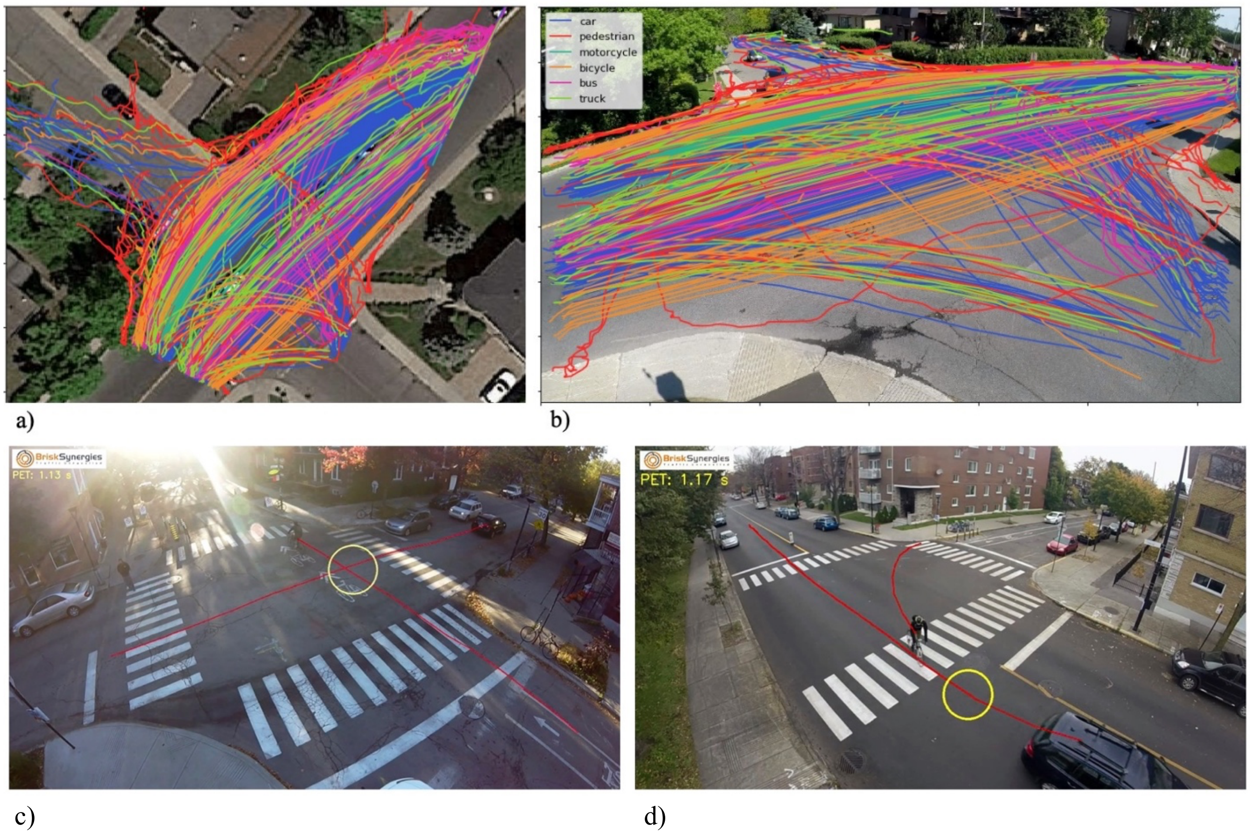

Figure 4.1, Example of processed video trajectories. a) represents the trajectories on a world space picture, b) represents the trajectories on the image space, c) a cyclist crossing a vehicles trajectory on a 4 branches intersection, d) a cyclist joining the trajectory of a vehicle on a T intersection.

4.4.3. Intersection Geometry and User's Attributes

A geometry inventory was generated for the study. This inventory includes intersection-level information as the intersection layout (number of approaches and branches) and built environment variables. Approach-level information, as the number of lanes per approach and the presence of a crosswalk. And user attributes, such as speed values, cyclist movement, and the approach stop-control characteristics. A summary statistic of collected variables for this study is presented in Table 4.1, and the explanation of them is below:

User level characteristics:

- **Cyclist movement:** variable indicating the user's direction when it reaches the approaches, it can be through, left turn or right turn movement.
- **Helmet:** a binary variable indicating if the detected user was wearing a helmet while crossing the evaluated area.
- **Cyclist behaviour:** a factor variable composed of three cyclist reactions while crossing the intersection and there is the presence of another user which might be in the cyclist path. These cyclists' reactions consist of a full stop, avoidance maneuver (swavering) and no visible reaction, which might involve a speed reduction, but it was not captured as a visible behaviour.
- **Exposure:** binary variable indicating the presence of a VRUs within a range of five seconds before and five seconds after the analyzed cyclist trajectory reaches its midpoint. This variable evaluates the effect of VRUs presence on the cyclist's behaviour while navigating the intersection. Simultaneously, the five seconds threshold is considered a limit where the other road users can influence a cyclist.
- **Cyclist Speed, PET and Conflicts pairs:** explained in a safety section below.

Approach level characteristics:

- ***Stop -Control Scenarios:*** A set of three different conditions or scenarios were defined to evaluate the effect on the cyclist of the traffic control devices (Figure 4.2) as follows:
  - ***Scenario A,*** for the users coming from an approach with no stop sign. These approaches are on a MAS intersection, evaluating the cyclists' behaviour when there is no traffic control in their path (major approaches). As these are MAS intersection, the users coming from the adjacent approach (minor approaches) have to do a full stop and find for a gap on their way. This scenario is considered the base case because cyclists do not have any traffic control restrictions.
  - ***Scenario B,*** for the users coming from an approach with a stop sign. These approaches (minor approach) are also part of a MAS intersection, defined to evaluate the cyclists' behaviour when there is a stop sign in their path. In contrast, the users in the adjacent

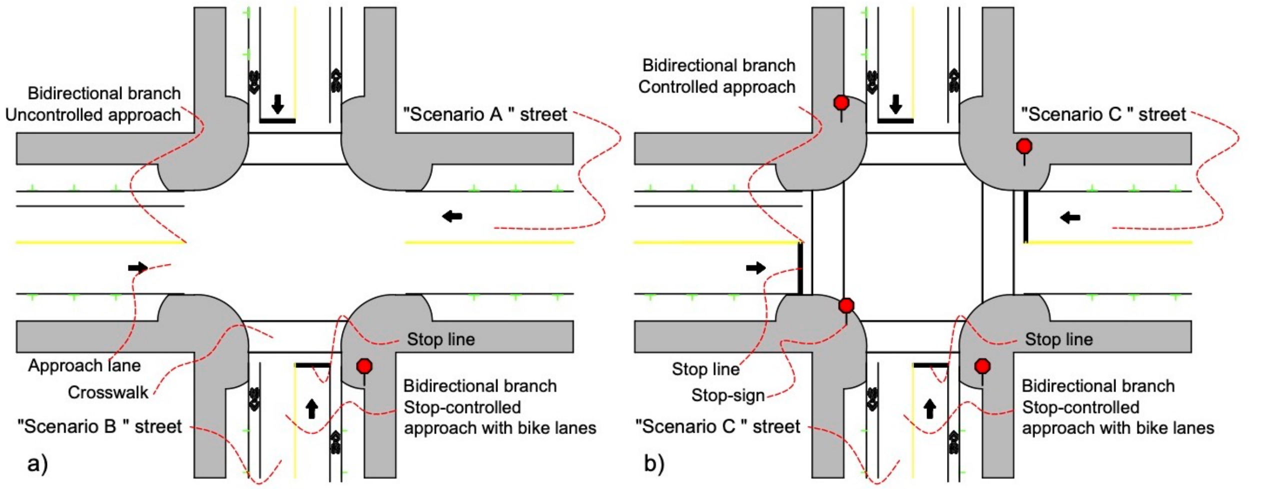

Figure 4.2, Example of the three scenarios on an intersection with four branches and four. a) represents an intersection where one street does not have stop controls (scenario A) and the other street is stop sign controlled (scenario B) and b) it is an all-way stop sign intersections, where all the approaches are stop controlled (scenario C)

approach do not have the make a mandatory stop.

- ***Scenario C,*** defined for the user's coming from any approach with a stop sign belonging to an AWS intersection. This scenario is defined to evaluate the cyclists' behaviour towards the stop sign in an environment where all the approaches have a stop sign.

- ***Vehicles stop line*:** a binary variable indicating to the vehicles where they should make the full stop in the approach.
- ***Crosswalk***: presence and type of crosswalk marking. The crosswalk presence variable is defined by a binary variable indicating if there is or not a crosswalk at the approach. The crosswalk marking is a factor variable that indicates crosswalk marking when there is a crosswalk at the approach. It is defined with no crosswalk, stripped, two-lines and unique (i.e., crosswalk with a different pavement texture, crosswalk level raised).
- ***Bike-path presence:*** a binary variable that indicates the presence of any type of cyclist infrastructure treatment.
- ***Approach width:*** a set of two variables with the measure of the approach at the crosswalk level and 10 m upstream of it.
- ***Number of lanes:*** a binary variable that indicates one or more lanes in the approach. i.e.,

an approach with one lane in the direction of the user is label as 0, while an approach with two or more lanes is indicated with 1.

Intersection-level features:

- ***Distance to the Previous Intersection****:* the distance to the upstream adjacent intersection for the studied approach, it was measured from center to center of the intersections.
- ***Previous Intersection Type:*** variable that refers to the kind of stop control of the upstream intersection. The considered stop-controls for this variable are MAS, AWS and traffic lights, which are described as follow:
  - ***MAS upstream intersection***, in this type of intersections, a user can come from a non-controlled or a controlled approach.
  - ***AWS upstream intersection,*** users from this upstream intersection are coming from a stop-sign controlled approach.
  - ***Traffic light upstream intersection***, users are coming from traffic lights a controlled intersection.
- ***Number of Branches***: intersections design varies greatly depending on the number of connecting streets or branches (legs), typically three or four. A branch can be a unidirectional street serving as an approach or as an exit to the intersection. It can also be a bidirectional street serving as an approach and an exit to that intersection.
- ***Number of approaches****:* constitutes the portion of a branch dedicated to road users (motorized vehicles and VRUs) entering an intersection. There may be many approaches as branches, but not more, and as few as two.
- ***Non-Motorized Facilities***: includes the presence and the type of a cyclist facility at the intersection. The defined bicycle facilities are shared road, painted bike-path, divided bike-path or no bike-path.
- ***Built environment variables:*** is represented by the population or employment density, land use mix, and transit accessibility surrounding the studied intersection. A grid-based approach was defined for characterizing the land use around the intersection. The neighbourhood typologies used for the intersections are a collection of data from Statistics Canada, then a grid based on a 500 m covering the entire island of Montreal was used (Zahabi et al. 2012).

4.4.4. Safety Indicators

The safety analysis performed in this study makes use of the following safety indicators that are part of the surrogate safety approach:

- ***Bicycle speed measurements*:** There are strong correlations between speed, crash likelihood, and severity, as shown in several studies (Peden et al. 2004; Kloeden et al. 1997; Gårder 2004; Nemeth et al. 2014). Different speed statistics are generated in an automated way from the different users' trajectories. For each user trajectory that crosses an intersection, different speed measures are obtained: minimum, defined as the 15^{th} percentile ($v_{15^{th}}$), median (v_{med}), and maximum, defined as the 85^{th} percentile ($v_{85^{th}}$) speed. These different users' speed measures are obtained from all the user trajectory points.
- ***Post-Encroachment Time (PET)***: the PET indicates the time in which two users missed each other (Laureshyn et al. 2016), situation defined as a "near misses". The PET is the time difference between the moment the first road-user (user "a") leaves the crossing zone and the moment the second road-user (user "b") reaches the mentioned zone (Laureshyn et al. 2016). Table 4.3 shows the PET statistics for the 35 intersections. PET values are characterized in terms of severity according to their values. A set of three different cyclist thresholds were adapted from the ones used by Zangenehpour et al. (Zangenehpour et al. 2016). The PET interactions are divided into the following categories:
  - Dangerous, PET $\leq$ 1.5 s
  - Mild, 1.5 s < PET $\leq$ 3 s
  - Safe, 3 s < PET $\leq$ 5 s

4.4.5. Speed and PET Regressing Analysis

A regression analysis that considers data hierarchy is needed given that some observed and unobserved variations can exist at the road user, approach and intersection levels. For this, a random effect regression model (Mixed-Effect Model) implemented in the R language was used and fitted to the data to handle the different sites and approaches' variability. The proposed random effect model takes the form of Equation 1:

$$y_{ijk} = \beta_0 + \sum_l \beta_l X_{ijkl} + u_{ijk} + \varepsilon_{ijk} \qquad \text{Equation 1}$$

Where:

- i = 1, …, m for the intersection site
- j = 1,…, n_i for the approach of intersection site i
- k = 1,…, o_{ij} for the approaching road user at the approach j of the site i
- y_{ijk} = dependent variable for each of the different user models (i.e., $v_{15^{th}}$, v_{med}) for a site i, approach j and user k.
- X_{ijkl} is the value of the lth *covariate* of the model for site i, approach j and user k
- β_0, is the model intercept
- β_l, is the slope coefficient for covariate $X_l, l = 1, \ldots 14$
- u_{ijk} = approach specific random error for approach j on intersection i (assumed to follow a normal distribution with mean 0 and constant variance σ_u)
- ε_{ijk} = ordinary regression error (assumed to follow a normal distribution with mean 0 and constant variance σ_ε)

For each type of outcome ($v_{15^{th}}$, v_{med}, $v_{85^{th}}$ and *PET*), the model above was adjusted to the *covariates* described in Table 4.1.

There are some differences between the speed and the PET model. The PET model's outcome is evaluating a user pair, while the speed model outcome is characterized by being a single road user. Hence, the PET model is adapted as follows:

- For the PET evaluation, k refers to a user pair. A user pair is a fundamental condition for any interaction between two road users with a simultaneous presence in time and space. Hence, every classified road user was paired with every other user of the intersection that existed in a predefined area of interest where the interactions took place. For this study, the
- area of interest is defined by a zone that includes all the possible conflicting areas of cyclists with all the other users' pairs of the intersection (pedestrian, cyclist and vehicles). This zone includes all the "in" and "out" approaches (roughly 15 m of each branch), crosswalks, bike paths and sidewalks.
- As mentioned in the previous point, the PET evaluation requires a user pair (two interacting

Table 4.1, Cyclist Summary Statistics of variables for statistical analysis

	Variable	Min	Mean	Max	S.D.	Type
User-level	Cyclist movement (through, left or right)	0.00	0.96	2.00	1.24	Factor
	Helmet	0.00	0.41	1.00	0.49	Binary
	Behaviour (avoid, stop)	0.00	0.03	2.00	0.23	Factor
	Exposure	0.00	2.04	22.00	2.39	Integer
	Minimum Road Users Speed	0.00	10.51	27.06	5.47	Numerical
	Mean Road Users Speed	0.49	15.63	33.52	5.79	Numerical
	Maximum Road Users Speed	0.91	20.32	41.88	6.82	Numerical
	Post-Encroachment Time (PET)	0.00	4.21	9.99	2.09	Numerical
	Conflict (CPI, CCI, CVI)	0.00	2.59	3.00	0.77	Factor
Approach-level	Scenarios	Explained in description				Factor
	Presence of vehicle stop line	0.00	0.28	1.00	0.45	Binary
	Presence of Crosswalk	0.00	0.29	1.00	0.45	Binary
	Type of crosswalk*	0.00	0.32	2.00	0.51	Factor
	Bike-path at the approach	0.00	0.52	1.00	0.50	Binary
	Approach width at the crosswalk level	7.50	11.46	24.00	2.76	Numerical
	Approach width 10 m upstream	7.50	11.05	16.20	2.48	Numerical
	Number of lanes	0.00	0.791	1.00	0.41	Binary
Intersection-level	Distance to previous intersection	60.00	124.90	690.00	84.95	Integer
	Previous intersection type**	1.00	3.34	4.00	0.72	Factor
	Number of branches (Four Branches)	0.00	0.78	1.00	0.41	Binary
	Number of approaches	1.00	2.52	4.00	0.73	Factor
	Non-Motorized facilities, bike-path presence***	0.00	1.29	3.00	1.34	Factor
	Built environment variables					
	Population density	16.00	101.40	135.90	22.39	Numerical
	Employment density	0.35	59.50	140.00	34.41	Numerical
	Land use mix	0.22	0.58	0.65	0.08	Numerical
	Transit accessibility	61.65	303.20	405.9	72.87	Numerical

* No crosswalk, stripped, two-lines and unique
** MAS, AWS or traffic light controlled
*** Shared road, painted bike-path, divided bike-path or no bike-path

users), which will double the covariates for the analysis due to the different approaches they are coming from (two crosswalk marking values, two previous intersection types, etcetera). To simplify the analysis, the PET approach-level attributes used in this paper are the ones from the users arriving second to the area of interaction (user b, Figure 4.3), i.e., the cyclist that might hit the other user.

- For this research, the scenario is the primary variable to evaluate due it is the variable indicating the stop control at the approach. This variable is categorical, coded as a factor using scenario A as a reference as mentioned in section 4.3. The previous implies that the intercept on the regression analysis will represent the evaluated mean speed value (or PET) for scenario A when all the other variables are set to 0. Additionally, to the regression analysis, the different evaluated variables are evaluated with the Kolmogorov-Smirnov test (K.S.) to help determine if the compared datasets differ significantly.

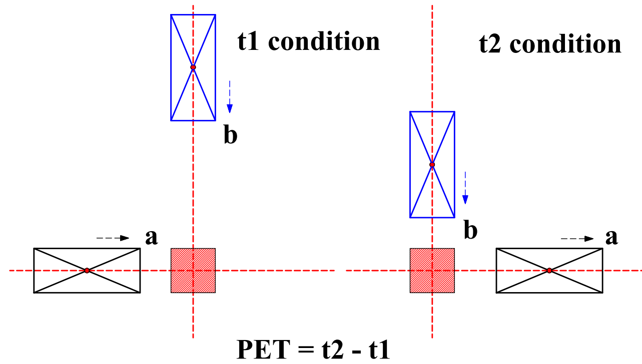

Figure 4.3, Post-Encroachment Time (PET) description

4.5. Results

4.5.1. Data Summary

After the video was processed, the VRUs trajectories were manually verified and corrected to provide ground truth data. An inventory of the processed video data is presented in Table 4.2, with general information such as the number and type of road users crossing the intersection and type, hours of analyzed video, the total number of different intersections analyzed and approaches, etcetera. Following, Table 4.3 includes a statistical summary of cyclist speed and PET interactions, where the 5th centile (Q05), mean, median, 95th centile (Q95) and Standard Deviation (S.D.) are obtained for each of the three obtained speed variables and, PET interactions from the video trajectories for each scenario.

4.5.2. Cyclist Speed Analysis

An initial observational analysis of cyclist speed for the different approaches is performed from Figure 4.4. From this table, few observations could be made:

- It can be remarked that cyclists coming from the minor approach in scenario B will have a lower speed than the ones coming from the major approach.
- The cyclists' speed reductions are 19.7 % for the $v_{15^{th}}$, 25 % for the v_{med} and 24.4 % for the $v_{85^{th}}$ speed on the users coming from the minor approach in scenario B. This is

Table 4.2, Intersection's data inventory collected from 8 am to 12 pm for each intersection

Definition	**Scenarios counts**				**Hourly Ratio**		
	A	**B**	**C**	**Total**	**A**	**B**	**C**
Pedestrians	4,914	1,537	3,692	10,143	35.1	11	30.8
Cyclist	2,636	951	1,336	4,923	18.8	6.8	11.1
Motorized	26,163	6,868	23,358	56,389	186.9	49.1	194.7
Total number of users	**33,713**	**9,356**	**28,386**	**71,455**	240.8	66.8	236.6
Video data (h)	140		120	260	-		
Total approaches	109				-		
Distinct intersections	35				-		
Three branches	12				-		
Four branches	21				-		

Table 4.3, Cyclist speed and PET summary statistics per scenario

Scenario	Variable	Min (Q05)	Mean	Median	Max (Q95)	S.D.	Obs
A	Minimum Speed	1.1	11.05	10.71	21.24	5.96	2,636
	Median Speed	4.23	16.42	16.48	27.74	6.88	
	Maximum Speed	10.13	21.33	20.94	33.32	7.17	
	PET	0.1	2.93	3.04	4.7	1.3	287
B	Minimum Speed	0.87	8.74	8.6	16.84	4.53	951
	Median Speed	4.49	12.59	12.35	21.75	5.07	
	Maximum Speed	9.3	16.57	15.83	26.43	5.47	
	PET	1.2	3.07	3.1	4.71	1.14	167
C	Minimum Speed	3.64	10.69	10.27	19.14	4.76	1,336
	Median Speed	8.06	16.05	15.64	25.59	5.44	
	Maximum Speed	12.29	20.99	20.35	32.15	6	
	PET	0.94	2.96	3.04	4.6	1.16	224

expected since cyclists coming from this approach have to look and wait for a gap on the major approaches that do not have a stop restriction.

- Cyclists crossing all-way-stop intersections have similar speed values to cyclists from coming from an approach without any restriction (major street). The median speed variations between the different variables are not bigger than 1 km/h, as it can be observed in B, D and F. These reductions represent barely 5 % of the speed difference for the v_{med}. The similarity of cyclist speed profile under scenario C to the ones under scenario A can be explained by the "false sense" of confidence that all-way-stop intersections generate on cyclists.

- Overall, cyclists reduce speeds when approaching a non-signalized (without stop) approach. However, cyclist minimum and median speeds stay relatively high showing the “rolling stop” phenomenon. As discussed before, a large proportion of cyclists do not come as a full stop in particular at AWS intersections.

Complementarily, Table 4.4 shows two cyclists' speed reduction thresholds classified by scenarios. These thresholds are 50 % and 80 %, representing the amount of speed that the cyclists reduced their speed with respect to their median speed when crossing the intersection. This general speed reduction has the scenario as the main influencing variable and might be affected by an interacting user. Additionally, the number of cyclists who interacted with the classified road user is presented on each threshold. From this analysis, with 1,216 users with a speed reduction of 50 % or more on scenario A, making this scenario the one with the larger number of cyclists reducing their speed, with 50.7 % of them crossing the intersection from this approach. Of these 1,216 cyclists, 12 were involved in interaction with a pedestrian, 24 with another cyclist and 204 with a vehicle, which might explain the speed reduction of these specific cyclists. For the 80 % threshold, the larger number of cyclists reducing their speed was on scenario B with 9 % of the detected cyclists; where 9 of these cyclists were involved with a pedestrian, 2 with another cyclist and 40 with a vehicle.

Table 4.4, Scenario’s cyclists Speed Reduction

Definition	Scenario A		Scenario B		Scenario C		Total
	Count	%	Count	%	Count	%	
Total users	2,400	100.0	1,074	100.0	1,449	100.0	4,923
50% speed reduction	1,216	50.7	360	33.5	606	41.8	2,182
Interaction with:							
Pedestrian	12	1.0	24	6.7	38	6.3	74
Cyclist	24	2.0	8	2.2	10	1.7	42
Vehicle	204	16.8	96	26.7	103	17.0	403
80% speed reduction	191	8.0	97	9.0	63	4.3	351
Interaction with:							
Pedestrian	2	1.0	9	9.3	5	7.9	16
Cyclist	2	1.0	2	2.1	0	0.0	4
Vehicle	56	29.3	40	41.2	12	19.0	108

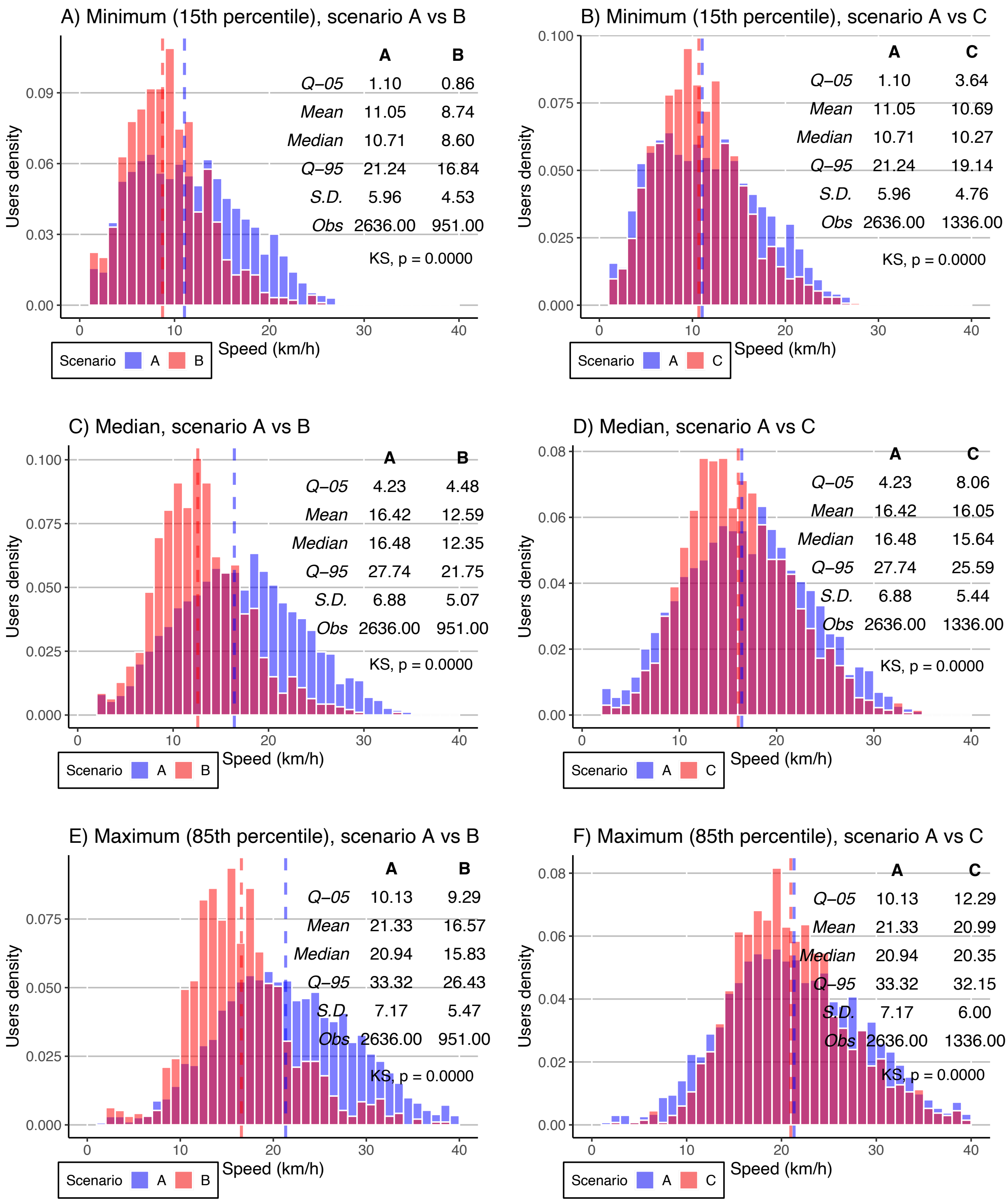

Figure 4.4, Cyclist speed histogram distribution, scenarios comparison: A) Minimum (15th percentile) on scenario A vs B; B) Minimum (15th percentile) on scenario A vs C; C) Median on scenario A vs B; D) Median on scenario A vs C; E) Maximum (85th percentile) on scenario A vs B; F) Maximum (85th percentile) on scenario A vs C.

4.5.3. Cyclist Regression Analysis

The 22 covariates presented in the methodology (Table 4.1) were evaluated using a multi-level regression model (random effect regression model), with a 95 % confidence interval. Thus, the data used for this research has a hierarchical nature (user – approach – intersection), the site and approach I.D. were included as random effects in the Mixed-Effect model. Some variables were removed from the model due to their high correlation. i.e., the number of stop signs and period of analysis were removed due to their correlation with the scenario, and the number of lanes for its correlation with the crosswalk width. Other variables, like the employment density, land use mix and public transit accessibility, were removed after an initial evaluation due to their non-significant effect in the model.

4.5.3.1. Cyclists Speed

The effects of treatment on speed indicators were introduced through the scenarios defined above, and the main results are as follows (see Table 4.5):

- Scenario A is an approach without a stop signs in a MAS intersection. This scenario is used as the base case.
- Scenario B represents the users with a stop sign at the minor approach in the stop-controlled approach in a MAS intersection. There is a lower speed of 4.49 km/h for the estimated mean $v_{15^{th}}$ compared to the base scenario (32 % lower speed) after
  controlling for other factors. As expected, this suggests that the approaching cyclists in this scenario have lower speeds due to the stop sign, making the cyclists wait for a gap in the major (opposite) approach. In this stop control configuration (MAS), the users' in the major approach have the priority to cross the intersection.
- Scenario C represents cyclists on an AWS intersection, where all the approaches have a stop sign. For this scenario, a speed decrease of 1.78 km/h is observed for the mean $v_{15^{th}}$ compared to Scenario A, representing nearly a 13 % reduction of the minimum speed compared to the base scenario. Comparable to scenario B, cyclists on scenario C are presenting a speed increase of 2.71 km/h (29 % major speed).

Table 4.5, Cyclist Summary Statistics of variables for statistical analysis

	Variable	Min	Mean	Max	PET
User attributes	(Intercept)	13.890***	17.730***	21.970***	2.727***
	Movement B	-0.424*	-1.089***	-1.538***	0.088
	Movement C	-0.403	-1.365***	-1.693***	0.031
	Helmet	0.479***	0.747***	0.968***	-0.101
	Avoid	-2.156**	-2.948***	-2.518**	-0.928*
	Stop	-6.690***	-7.590***	-5.245***	0.771
	Exposure	-0.147***	-0.153***	-0.199***	-
	Cyclist - Cyclist	-	-	-	-0.393*
	Cyclist - Vehicle	-	-	-	0.633***
Approach-level	Scenario B	-4.490***	-3.867***	-2.341***	0.186
	Scenario C	-1.782***	-1.072**	-0.622	0.244*
	Presence of Crosswalk	0.203	0.151	-0.548	-0.635*
	Bike-path at the approach	-1.009*	-0.336	0.168	+
	Number of lanes	1.236*	2.236**	2.102*	0.312*
Intersection-level	Distance to previous intersection	0.001	0.001	-0.004	0.001
	Previous intersection stops	-0.908	-0.202	0.639	0.264
	Previous intersection traffic	-0.445	0.738	1.460	0.216
	Number of branches (four branches)	0.202	0.524	1.219	-0.036
	Bike-path (shared road)	-	-	-	-0.541**
	Painted bike lane	-	-	-	-0.221
	Separated Bike path	-	-	-	-0.437
	Built environment variables				
	Population density	-0.027	-0.034*	-0.03	-0.004
	Employment density	0.032*	0.027	0.004	0.008*
Model	Random Effect				
	Site	1.96	2.13	2.12	0.01
	Approach	1.8	2.12	2.3	0.17
	Residual	4.36	5.06	5.43	1.16

Note: *p<0.1; **p<0.01; ***p<0.001
- Variable not evaluated in the model

For the user attributes variables, cyclists wearing a helmet have higher speed values in all the different speed analyses. Conversely, when cyclists are exposed to another user in the intersection, they have a lower speed. However, when cyclists realize a maneuver to avoid another user, the speed values are between 2.15 and 2.95 km/h lower. The cyclists that make a full stop present the lower speed values from the analysis (5.25 to 7.59 km/h). Finally, with expected results, the cyclists that are turning left or right have lower speed values, between 0.40 km/h for the left mean $v_{15^{th}}$ and 1.69 km/h for the mean $v_{85^{th}}$. All the previous results are significant values in the regression analysis.

The approach-level factors have mixed significant results according to the speed variable that is evaluated. Furthermore, to the scenario comparison, a bike path in the approach reflects a significantly lower mean $v_{15^{th}}$ of 1 km/h, while the number of lanes in the approach reflects a significant$v_{15^{th}}$ increase of 1.24 km/h. Contrary to an expected general speed increase on an approach with bike-paths, the cyclists seem to be more cautious or show more compliance when travelling on designated infrastructure (there is a minor speed increase for the $v_{85^{th}}$indicator, but this result is not significant in the regression analysis). Also, the extra room in the approach that has more lanes provides the cyclists with a wider viewing angle when approaching the intersection, allowing the cyclist to keep their speed momentum. Finally, the $v_{15^{th}}$ is the indicator with the most significant variables, and the $v_{85^{th}}$ has the smallest number of significant variables (4 of 5 and 2 of 5 evaluated variables).

For the intersection-level variables, the conditions of the previous intersection (distance and control type) and the number of branches in the analyzed intersection do not significantly affect the cyclists' speed behaviour. However, increasing the employment density will have low estimated mean speeds, and the population density has an opposite effect on cyclists' speed, being the $v_{15^{th}}$the only significant indicator for employment density and v_{med} the significant indicator for the population density.

Additionally to the variable analysis, S.D. for the site and approach I.D. have variability between 1.80 and 2.30 km/h for the different estimated speeds indicators. With the S.D. range of random effect, the speeds variability for the site and approach vary between 9.6 % for the $v_{85^{th}}$ and 14.1 % for the $v_{15^{th}}$. The ANOVA tests (Table 4.6) show a significant difference for the comparison between the different behavioural variables. It can be observed that a stop sign is significant for any of the different indicators. Also, it is observed that converting intersections from MAS to AWS has a significant effect on the cyclist speed behaviour, as is appreciated in the ANOVA evaluation. Furthermore, the observed speed behaviour differences for a cyclist wearing a helmet is significant on the different indicators. Finally, the behaviour comparison between cyclists avoiding a conflict or making a full stop is also significant.

Table 4.6, Cyclist speed, PET model and ANOVA analysis

Coefficients	Minimum	Median	Maximum	PET
Observations		4,923		678
Site Number		35		25
Groups number *		121		58
Pseudo-R2 Marginal	0.167	0.175	0.143	0.108
Pseudo-R2 Conditional	0.394	0.390	0.360	0.127
AIC	28,737	30,213	30,889	2,226
ANOVA test (p-value)				
Helmet	**0.001**	**0.001**	**0.001**	**0.001**
Wavering vs Full stop	**0.001**	**0.001**	**0.015**	**0.009**
Period	**0.001**	**0.001**	**0.001**	**0.001**
Stop Sign	**0.001**	**0.001**	**0.001**	**0.001**

* Group number, refers to the total number of different approaches (See Table 4.2).

4.5.3.2. Cyclists PET Analysis

As a first step, the PET cumulative distributions are analyzed to compare between scenarios A vs B and A vs C (Figure 4.5). Interactions are divided into three categories: cyclist-pedestrian interactions (CPI), cyclist-cyclist interactions (CCI) and cyclist-vehicle interactions (CVI). In this analysis, the PET is not controlled for additional factors but the stop sign and its effect on the cyclist interaction with the different road users. With this simple analysis, it can be observed a different pattern for the CPIs' scenario comparison. In scenario B, the presence of a stop sign makes the PET values shift the proportion of PETs' with 3 seconds and lowers to a safer range (higher PET vales), while the 3 and 5 seconds range remain similar (Figure 4.5A). Contrary to the previous comparison, scenario A vs C has a similar CPIs' pattern on the far lower end PETs' values (< 1 second). In contrast, the shift of scenario C's mid-values is towards smaller PET's values (Figure 4.5B). There is a similar pattern in the two evaluations for the CCI's comparison, having lower PET's values on scenarios B and C than A (Figure 4.5C and D). The CVI's comparison shows similar PET's values for the different scenarios (Figure 4.5E and F). However, all the different Kolmogorov–Smirnov (KS) test cumulative comparisons are not significant.

To complement the analysis and identify the conflict-related factors, the results for the multi-linear model of the PET values are presented in Table 4.7. The avoidance maneuver is a significant factor in the cyclist attributes, decreasing the PET value in almost one second.

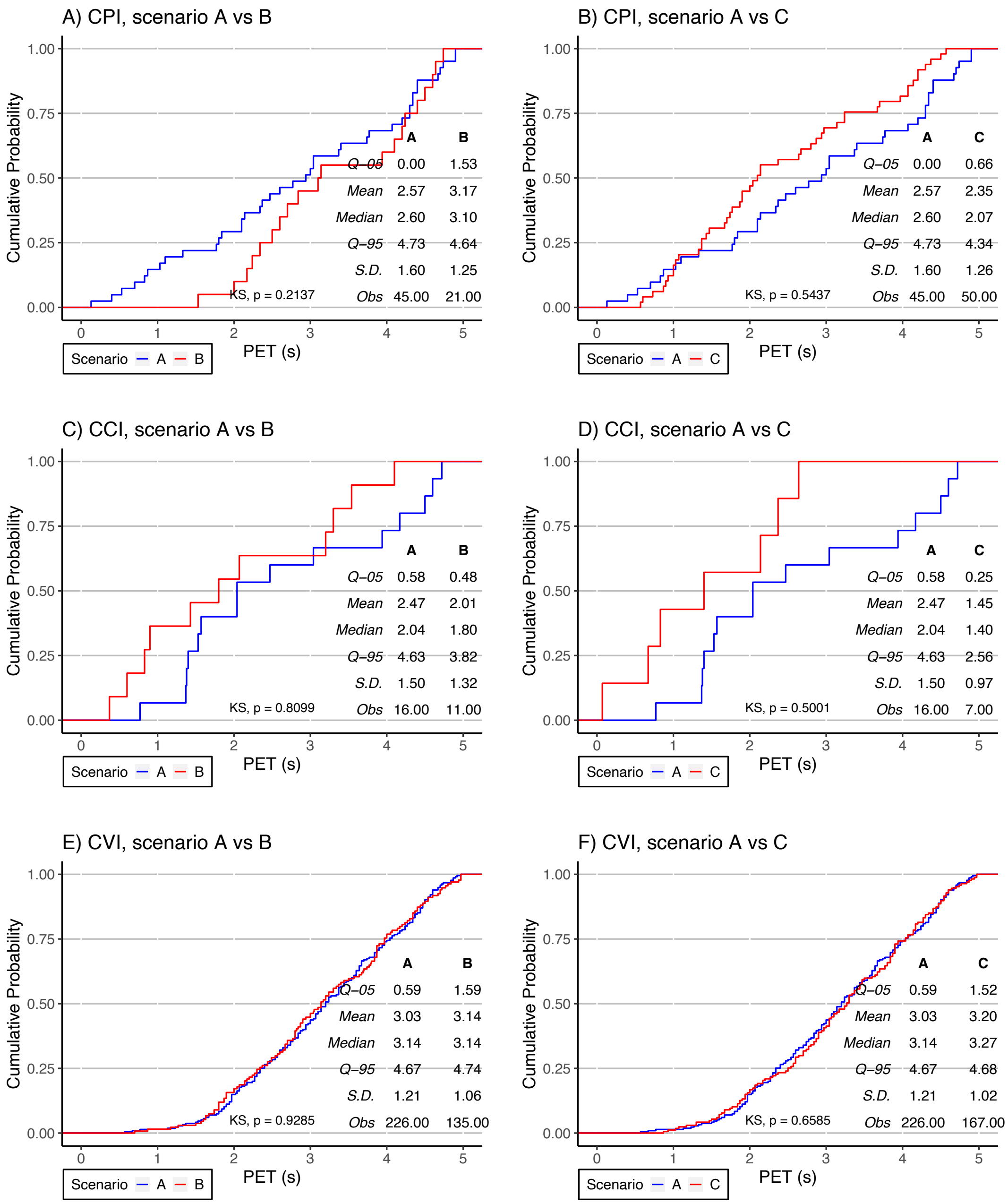

Figure 4.5, PET cumulative distribution, scenarios comparison: A) CPI on scenario A vs B; B) CPI on scenario A vs C; C) CCI on scenario A vs B; D) CCI on scenario A vs C; E) CVI on scenario A vs B; F) CVI on scenario A vs C.

Table 4.7, Cyclists PET Interactions range

Scenario	PET Range (%)				Rate per 1,000 cyclists		
	0 - 1.5 (Dangerous)	1.5 - 3.0 (Mild)	3.0 - 5.0 (Safe)	Total	0 - 1.5 (Dangerous)	1.5 - 3.0 (Mild)	3.0 - 5.0 (Safe)
Pedestrians							
A	13 (28.9)	13 (28.9)	19 (42.2)	45	49.3	49.3	72.1
B	1 (4.8)	9 (42.9)	11 (52.4)	21	10.5	94.6	115.7
C	16 (32.0)	19 (38.0)	15 (30.0)	50	119.8	142.2	112.3
Cyclists							
A	5 (29.4)	5 (29.4)	7 (41.2)	17	19.0	19.0	26.6
B	5 (45.5)	2 (18.2)	4 (36.4)	11	52.6	21.0	42.1
C	4 (57.1)	3 (42.8)	0 (0.0)	7	29.9	22.5	0.0
Vehicles							
A	20 (8.8)	85 (37.3)	123 (53.9)	228	75.9	322.5	466.6
B	6 (4.32)	57 (41.0)	76 (54.7)	139	63.1	599.4	799.2
C	9 (5.3)	60 (35.5)	100 (59.2)	169	67.4	449.1	748.5

Note: (percentage of the interactions in the scenario)

Additionally, the type of road user involved in the interactions is also significant, with cyclist-cyclist interactions having a negative effect on the PET value, and the cyclist-vehicle interactions presents a positive one, indicating more cautions from cyclists on the presence of motorized vehicles. The use of a helmet, a full stop and the cyclist movement ended having a non-significant impact on PET values. For the approach-level attributes, scenario C has a small positive effect of 0.24 and the number of lanes of 0.31 on the PET values. On the contrary, the presence of a crosswalk has a negative effect on PET of 0.64, which might be explained by the confidence that the pedestrians have when crossing the intersection. Still, more research and a bigger sample are needed to establish a stronger conclusion on this result. On this attribute, scenario B has a non-significant positive result.

Finally, on the intersection level, the only variables with a significant negative relationship with PET are the employment density and the variable for a shared road between cyclists and the vehicles. Contrary to the previous results, a painted bike-lane or separated bike-path are not significant variables in the intersection. Also, the other analyzed variables (population density, previous intersection variables and the number of branches) are not significant.

The ANOVA test shows a significant effect on the period of analysis and the presence of a stop sign on the model evaluation. Furthermore, wearing a helmet and the different avoidance behaviour are significant also for this test.

In Table 4.7, a summary of the cyclists' PET interaction range divided by the cyclists interacting user on the different scenarios is presented. On this classification, scenario C presents the greater number of CPI's; from these 50 interactions, 32 % of them are classified as dangerous (0 – 1.5 sec. range), 38 % as mild and 30 % as safe interactions. For the CCI's, scenario A has the higher number of interactions with 17, where the majority are classified as safe (41.2), and the dangerous and mild interactions have 30 % each of them. Finally, the CVI's have also on scenario A the higher number of interactions, where 9 % are classified as dangerous, and more than 50 % are considered safe interactions.

4.6. Conclusions

This paper investigates the road safety of cyclists in non-signalized intersections using an observational video-based approach and surrogate measures of safety (SMoS). For this purpose, video data was collected from 35 intersections from which 30 of them were treated or transformed from minor-approach-only stop (MAS) to all-way-stop (AWS) intersections. The cyclist behaviour is analyzed in three different scenarios, two of them on the MAS intersections, where the behaviour at an approach without stop control (scenario A) and with a stop sign (scenario B) is evaluated. The third scenario (scenario C) is on AWS intersections, where the behaviour towards the stop signs in an intersection where all the approaches are signalized is evaluated. The cyclist speed behaviour and safety analysis were evaluated with multi-level linear models for site and approach variance, with information from user trajectories extracted from video data. The models were controlled for behaviour variables, built environment features, approach and intersection geometry for 22 variables in 35 intersections with 260 hours of video data, with more than 71,000 users from 109 approaches.

From the regression analysis, it was found that there is not a significant safety improvement (PET) in the approaches with stop signs. However, when cyclists interact with other cyclists, the PET's values are lower (negative effect) than the PET's values of the interaction with pedestrians or vehicles (significant values). Contrary to the PET's, cyclists will show a significant speed reduction when there is a stop sign signal at the approach. It is a major speed reduction when the cyclists come from an approach with a stop sign (MAS intersection, scenario B) of 4.49 km/h, compared to a scenario when all the users have to stop (AWS, scenario C) of 1.78 km/h. However, cyclists coming from an approach that does have a stop sign on a MAS intersection, after the conversion to AWS, it will increase its speed while crossing the intersection, this might be explained by a sense of security that the other user will stop. Also, the estimated mean speed of cyclists using helmets will be significant with lower (negative effect) PET values. Cyclists making an avoidance maneuver will have the lowest PET values, with a speed reduction that might reduce the severity of a conflict if this occurs. As expected, a cyclist making a full stop presents the higher PET values (positive effect) and the lower mean speeds. These results are in concordance with previous research that evaluates the feasibility of allowing cyclists to treat the stop sign as a yielding sign (Delaware 2021; Tekle 2017; Whyte 2013). In addition, despite their popularity, stop signs may play very little role in road users' safety behaviour like cyclists when results are showing a low number of cyclists reducing their speed a reason of the stop sign as it is shown in Table 4.4, where there is a higher speed reduction for the cyclists on the approach without a stop sign, and a low amount of these cyclists' are reducing their speed in reason of the interaction with another user.

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Connection Between Chapter 4 and 5

The previous chapter presents an investigation of the effect of stop signs on cyclist behaviour and the safety impact on other road users with a methodology that utilizes SMoS obtained from microscopic empirical video data. Interesting findings have been obtained from Chapters 2 and 3. Additional to stop signs, traffic lights are an essential part of the traffic control measures used at intersections to regulate traffic, where the effect on vulnerable road users, especially cyclists has been recognized in the literature. Considering the previous, the outcome of implementing different traffic light treatment phases is studied in Chapter 4, where safety indicators obtained from simulated microscopic data are utilized.

Chapter 5. Evaluation of Level of Service and Safety for Vehicles and Cyclists at Signalized Intersections

Evaluation of Level of Service and Safety for Vehicles and Cyclists at Signalized Intersections

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5.1. Abstract

Delay, or level of service (LOS), and road safety are two of the main factors considered when designing traffic control. Urban cycling has been growing in recent years as an efficient, healthy, and inexpensive transportation mode. Cities are seeking strategies to enhance comfort and safety for commuting cyclists, particularly on high-demand urban corridors. The purpose of this study is to evaluate the impact of different bicycle friendly traffic signal designs at intersections with turn-on-red banned with bicycle facilities. Three strategies are evaluated and compared to the base case (BC) scenario: a leading phase (PP) design, a partially protected (CP) design, and a partially protected with protected turn phase (CPT). These strategies were simulated across four intersection designs and 156 combinations of cyclist and vehicle flow to obtain LOS and safety provided to crossing cyclists using conflicts measured by post-encroachment time. Vehicle delay was evaluated using VISSIM microsimulation software, while conflicts were measured using the Surrogate Safety Assessment Model (SSAM) developed by the FHWA. The simulation results showed that the CP phase provides the highest level of safety for all four intersections, though it also yields the worst LOS. Although the PP design was not the superior considering any one metric, it shared approximately the same LOS compared to the BC while reducing the number of crossing conflicts by as much as 50%. Future work will validate the actual performance of several intersections within the city of Montreal with video data to evaluate vehicular delay and PET crossing conflicts.

5.2. Introduction

Urban cycling has been on the rise over the past decades in North American cities like Portland, San Francisco, Washington D.C., and Montréal. To address this increase in bicycle demand, these cities have designed effective interventions to improve cyclist comfort and safety (Pucher, Buehler, and Seinen 2011). In Montréal, Quebec, the utilization of cycling infrastructure has increased significantly over the last 10 years (Zahabi et al. 2016). One reason for this growth is that cycling is often a more efficient commuting option in urban areas compared to other transport modes. Cyclists avoid congestion while benefiting from a healthy and inexpensive mode of transportation. In addition to the cyclist, society benefits from cycling through reduction in emissions and noise pollution, cheaper infrastructure, and public health improvement (Heinen, van Wee, and Maat 2010). Reduction of automobile use and its consequent environmental effects (reduction of pollution, consumption of natural resources, and driver stress) is a frequent motivation for cycling initiatives, in addition to concerns about public health, physical activity, and livability. Urban planners, transportation specialists, politicians, and health activists see no-motorized travel as part of the solution to their concerns (Krizec 2007).

Yet road safety for cyclists at intersections remains a major concern, particularly when the increase in bicycle ridership results in an increase of dangerous interactions and collisions between motor vehicles and no-motorized modes (Strauss, Miranda-Moreno, and Morency 2013; National Post 2015). Considering this, cities have implemented bike-friendly treatments like cycling facilities, bike boxes, and more recently, bike traffic signals, which provide several benefits including the reduction of vehicle-bike conflicts, red violations, and collisions, and improve the level of service (LOS) by reducing bicycle delays. However, bike signals can potentially negatively impact vehicular traffic by increasing delays for motorized road users (Allen et al. 1998). Despite recent developments in the cycling literature, several key questions regarding the installation of bicycle signals must be addressed. First, what criteria should be used to identify the intersections that would benefit from treatment? Second, what are the potential impacts of introducing bike signals and how can the impacts be measured? Third, what are the elements to be considered in their design (phasing strategies, green time, yellow and all-red-time durations)?

To address the questions surrounding the implementation of bicycle signals, the City of Montréal has undertaken an important step in the development of a bicycle traffic signal guide. These guidelines are expected to guide transportation engineers through the justification and design of bicycle signals in the city. Nevertheless, it is highly recommended to validate these guidelines before they are implemented in practice. The city’s main approach is to categorize traffic lights according to the degree of protection provided to the cyclist. The three categories are:

- No protected phase. This is the traditional traffic light treatment where all users move simultaneously in the same phase.
- Leading phase. In this design, cyclists or pedestrians have a leading green while through movements are allowed for vehicles.
- Partially protected phase. This design gives the cyclists a leading green while all vehicle

movement is restricted.

In this context, the goal of this study is to determine the impact of the installation of bicycle friendly traffic signal strategies at intersections where turn-on-red is banned with bicycle facilities, where right-turn-on-red is not permitted. The impact is evaluated for different intersection designs and traffic flow conditions. Indicators such as median vehicle delay, LOS, and conflicts measured with post-encroachment time (PET) are used to evaluate performance using a microsimulation approach. This paper is broken down into several sections, starting with the literature review in Section 2. Section 3 outlines the methodology applied and the definition of the microsimulation modeling parameters and the safety indicator. Section 4 contains the analysis of the models with the accompanying results. Finally, Section 5 presents the conclusions of this study as well as its limitations and future work.

5.3. Literature Review

Physical bicycle infrastructure has been used to improve cyclist experience and has been shown to have positive impacts on safety. A before and after study in New York City indicated that installation of bike lanes increased cycling as much as 51% between 1996 to 2006 (10 years following installation) and 48% from 2006 to 2008. Despite the growth in cycling, conflicts between cyclists and vehicles did not increase. In fact, after the implementation of bike lanes, crash frequency decreased (L. Chen et al. 2012). A study in Montreal by Zangenehpour et al. (Zangenehpour et al. 2016), found that adding cycle tracks on the right side of the street could decrease conflicts by 40% (measured using PET of less than 5 seconds), but recommended intersection treatments to maintain safety levels experienced at mid-block locations.

In addition to physical infrastructure, traffic signal phasing and design has been used to improve safety, LOS, and reduce traffic stress. Unfortunately, guidance for the implementation of these traffic light phases is limited and their effect on motorized and no-motorized users has infrequently been studied (Curtis 2015). AASHTO developed a series of equations using the crossing distance to estimate minimum green time and clearance intervals, with the idea of balancing cyclist safety with vehicle delay. Rubins and Handy found that cyclist speeds used in the AASHTO equation exceed typically observed cyclist speeds, resulting in inadequate minimum green times (Rubins and Handy 2005). Korve and Niemeier analyzed the costs and benefits of the integration of bicycle traffic light phases at large urban intersections, finding that the construction cost and increase of vehicle delay exceed estimated savings due to crash reduction (Korve and Niemeier 2002).

Existing methods for controlling traffic signals include vehicle-actuation or fuzzy logic-based controllers (Shahraki, Shahraki, and Mosavi 2013). There are also more intelligent traffic light controllers, including the Timed Coloured Petri nets system, proposed as a solution for modeling complex urban traffic light systems (Y.-S. Huang and Su 2009). Several technologies are capable of obtaining traffic density information for traffic control. Despite their time in the market, inductive loops remain popular (Bhaskar et al. 2015). Recently, wireless technologies like Wi-Fi and Bluetooth sensors have been used to measure traffic flow and travel times. With information provided by wireless sensors, adaptive traffic controllers with innovative algorithms have been proposed for controlling dynamic traffic light phases (Collotta et al. 2014; Yousef, Al-Karaki, and Shatnawi 2010; Park and Haghani 2014). Moreover, global positioning system (GPS) data has been proposed for the design and implementation of automatic traffic light systems to reduce delays for emergency vehicles (Eltayeb, Almubarak, and Attia 2013).

One of the best methods for optimizing and analyzing traffic light operations is through simulation (Sadoun 2008). At signalized intersections, traffic simulation is a useful tool for predicting conflicts between cyclist and right-turning vehicles. However, Alrajie and Ismail found that the accuracy of conflict detection decreases as volumes of cyclist and right-turn vehicles increase (AlRajie and Ismail 2016). In Copenhagen, microsimulations proved to be consistent with numeric methods for estimating the impact of left turning vehicles on cyclist delay and total capacity (X. Chen and Shao 2014). Using vehicle trajectories simulated in VISSIM, traffic safety can be evaluated with the Surrogate Safety Analysis Model (SSAM), with promising results that demonstrate the feasibility of these tools for conflict analysis (Zhou et al. 2017; F. Huang et al. 2013). Using simulation software, Stanek and Alexander evaluated several methods for reducing conflicts between cyclists and right turning vehicles, finding that the implementation of a leading green phase for cyclists decreases vehicle-bicycle conflicts (Stanek and Alexander 2016). In addition, using VISSIM as a microsimulation tool to evaluate three different signal-timing strategies, Kading found that leading bicycle phases have a significant impact in terms intersection performance (Kading 2016). Though traffic simulations and simulated conflict analysis have shown good results, outstanding constraints should be considered. First, measurement of traffic conflicts in SSAM may be inaccurate because unexpected driving maneuvers or driver errors are not well represented in VISSIM (F. Huang et al. 2013). Further studies are recommended to continue evaluating the effectiveness of SSAM with simulated trajectories.

5.4. Methodology

5.4.1. Model Intersections

This study considered four different intersection designs with cycling infrastructure, shown in Figure 5.1 and described in Table 5.1, selected as some of the most popular intersection designs within the city of Montreal. The four intersection designs are as follows:

a) Intersection 1, a two-way cycle track along one side of four bi-directional traffic lanes, crossing a two-lane one-way street.

b) Intersection 2, a bike lane on both sides of four bi-directional traffic lanes, crossing a four-lane bi-directional street.

c) Intersection 3, a contraflow bike lane on a one-way street, crossing a major bi-directional street with four lanes.

d) Intersection 4, a single bike lane on the right side of a one-way street, crossing a four-lane bi-directional street.

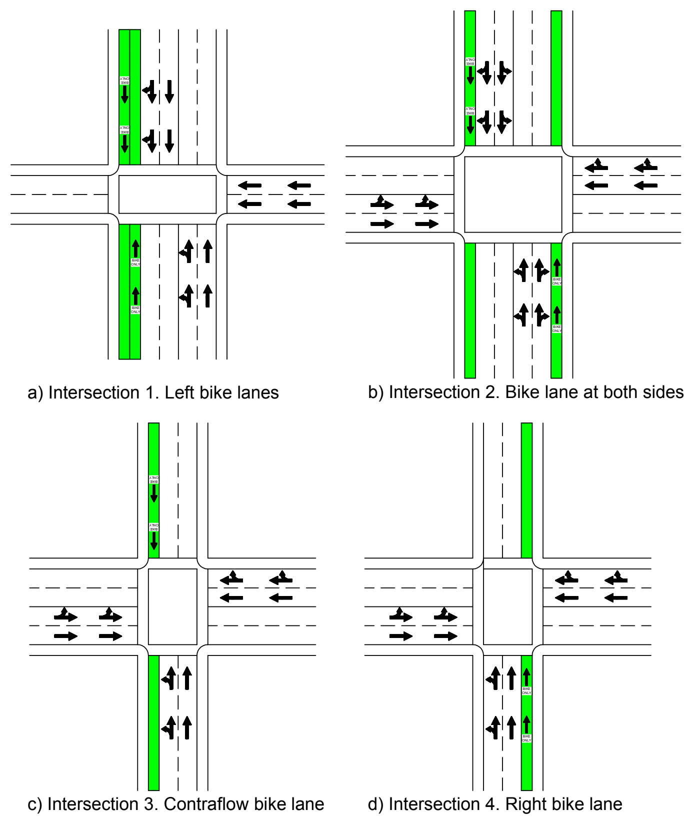

Figure 5.1, Intersections geometry. a) Intersection 1, b) Intersection 2, c) Intersection 3, d) Intersection 4

Table 5.1, Geometric Description of Simulated Intersections

Description	Street with cycling infrastructure			Crossing road		
	Width (m)	Lanes	Circulation flows	Width	Lanes	Circulation flows
Intersection 1. Bi-directional bike lane on one of the sides.						
Street	14	4	2	7	2	1
Cycle track	4	2	2	-	-	-
Cars turning ratio		30%			-	
Intersection 2. Bike lane on the right side of the circulation flow.						
Street	14	4	2	14	4	2
Cycle track	2 X 2	1 X 2	2	-	-	-
Cars turning ratio		30%			-	
Intersection 3. Contraflow cycle track.						
Street	7	2	1	14	4	2
Cycle track	2	1	1	-	-	-
Cars turning ratio		30%			30%	
Intersection 4. Bike lane on right side of the street.						
Street	7	2	1	14	4	2
Cycle track	2	1	1	-	-	-
Cars turning ratio		30%			-	

5.4.2. Description of Traffic Light Phases

This research evaluates the three signal design strategies considered the most popular designs in Montreal. The signal timings used in the simulations were obtained via fieldwork in the city. The duration of the cycle was selected to be 84 seconds, with three seconds of amber and two seconds for all red between phases. Table 5.2 shows a description of the complete timing sets. The different traffic phasing strategies, shown in Figure 5.2, are the following:

- *No protected phase or base case scenario* (BC). This is the traditional traffic light treatment also known as solid green, where all the users move in the same phase. This phase is used as base case scenario to which other treatments are prepared.
- *Leading protected cyclist phase* (PP). In this phase, cyclists have a green phase while vehicles going through are allowed to move. Turning vehicles must wait between 7 and 12 seconds before the through green arrow changes to solid green.
- *Partially protected cyclist phase* (CP). This phase gives cyclists an exclusive green phase while all vehicle movement is restricted. After this exclusive green phase for cyclist, vehicles are allowed to move on the solid green but must still yield to cyclists.

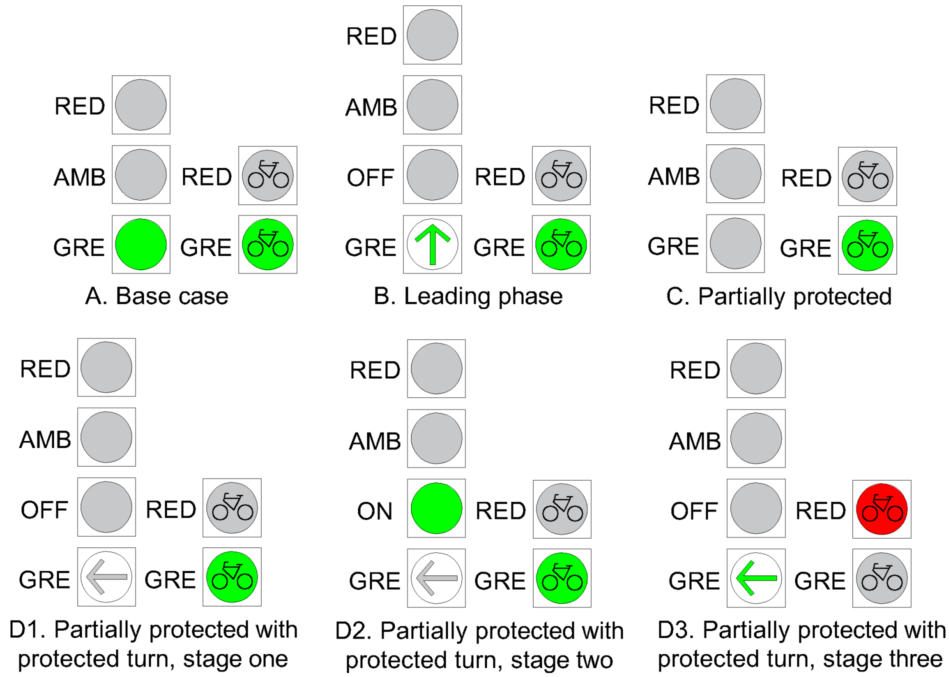

Figure 5.2, Traffic Lights Phases

- *Partially protected cyclist with vehicle turn phase* (CPT). This design is divided into three phases. First, cyclists receive an exclusive green light while vehicles have a red light (Figure 5.2D1). The second correspond to a similar phase as the one on the CP (Figure 5.2D2), which allow vehicles to move, but they have to yield to cyclist. The third phase gives drivers a protected turning phase at the end of the solid green, while cyclists and through vehicles have a red light (Figure 5.2D3).

Table 5.2, Detailed Speed Distribution Inputs

Vehicle Type	Flow	Desired speed (km/h)	Min. speed (km/h)	Max. speed (km/h)
Car	0.980	50	48	58
HGV	0.020	50	48	58
Turning vehicles	1.00	15	12	20
Cyclist (average)	0.800	15	10	20
Cyclist (fast)	0.200	20	20	25

5.4.3. Traffic Inputs and Speed Distribution

The driving vehicles behaviour was modeled using the Wiedemann 1991 model with the default parameters. Cyclist are modeled with a non-lane-based behaviour, where they always choose the lateral position that allows them to move as far as possible with the desired speed. The performance of the various treatments on the different intersection types was analyzed using a combination of different cyclist and vehicle volumes. Cyclist volume was varied between 1 and 600 cyclists per hour, while turning vehicular volumes ranged between 50 to 600 vehicles per hour, both with 50 users per hour flow increments. Each unique cyclist flow rate was paired with every unique turning vehicle flow rate, yielding 156 different traffic flow configurations. Speed distributions were obtained from automated video speed trajectories obtained from a previous conflict study at signalized intersections (Zangenehpour et al. 2016) and for urban speed limits in Montreal. The desired speed for mixed vehicles was 50 km/h and 15 km/h was used for turning vehicles. For cyclists, two speed values were assumed: 80% of average cyclists with a mean speed of 15 km/h, and 20% of them that were considered as fast cyclists with mean speed of 20 km/h. Table 5.2 shows the traffic flow and speed distributions, as desired, minimum, and maximum speeds.

5.4.4. Simulation Settings

The simulation software used for this research is VISSIM Version 5.4. Each of the four intersection designs were evaluated with respect to each of the signal design strategies (BC, PP, CP and P). Each of these signal designs are evaluated under 156 different traffic flow combinations, resulting in 624 simulation sets per intersection (2,496 total). Each simulation set consists of 10 unique simulations, based on different random arrivals determined using a seed number. The simulation task was automated using several python scripts to efficiently run all 24,960 required simulations. The python scripts manipulated several inputs through the COM interface provided internally within VISSIM and the pywin32 library. An additional Python GUI was created to facilitate the process, shown in Figure 5.3 which contains several options to be manipulated by the user, including:

- Number of simulations or the number of times to run the simulations with a different seed number. The seed number allows VISSIM to run with different driver behavior and path each time that this number is changed.
- Periods, which refers to the time length in 'simulation seconds' for each simulation. 900 simulation seconds are added as a warmup period. Each simulation runs at maximum speed (set within the code), where 3,600 simulation seconds requires 5 to 10 real seconds.

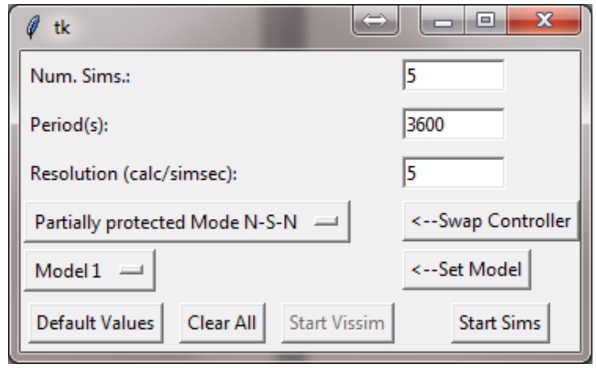

Figure 5.3, Python GUI Window

- Resolution or the number of calculations done by VISSIM for each simulation second. At lower values, the simulation(s) computation time is decreased, as is accuracy, and vice versa. In order to balance accuracy and simulation time, a default value of five was set.

The two last options allow the user to switch between the four signal controllers and to change the intersection model. All desired flows and signal controllers are stored in separate '.csv' files for quick and simple modification between simulations. After completing all simulations, two output files are created, one with all raw data for each turning movement (e.g. north-south) and the different data types (e.g. delay). The second file is an average of all raw data into a single value for each movement and data type.

5.4.5. Calibration And Evaluation

Each of the four intersection designs were evaluated separately. As this study involved a considerable amount of data, each signal design is evaluated on only three criteria: vehicle delay, cyclist delay, and number of conflicts. First, delay data was organized by vehicle and cyclist hourly volumes (for example, 300-150 signifies 300 vehicles and 150 cyclists per hour). Secondly, the median, 25 centiles, 75 centiles and Interquartile Range (IQR) delay for each traffic flow combination was computed from the 10 different simulations for each of the 156 traffic flows. Several contour plots were generated using the median delay to determine LOS for the different signal designs at each intersection for through vehicles, turning vehicles, and through cyclists. Then, box plots were generated with the RAW data to illustrate the general performance of turning vehicles at each intersection. Finally, the possible number of PET crossing interactions with a maximum range of 5 seconds for each traffic light phase were obtained from the SSAM evaluation.

5.5. Results

5.5.1. User Delay

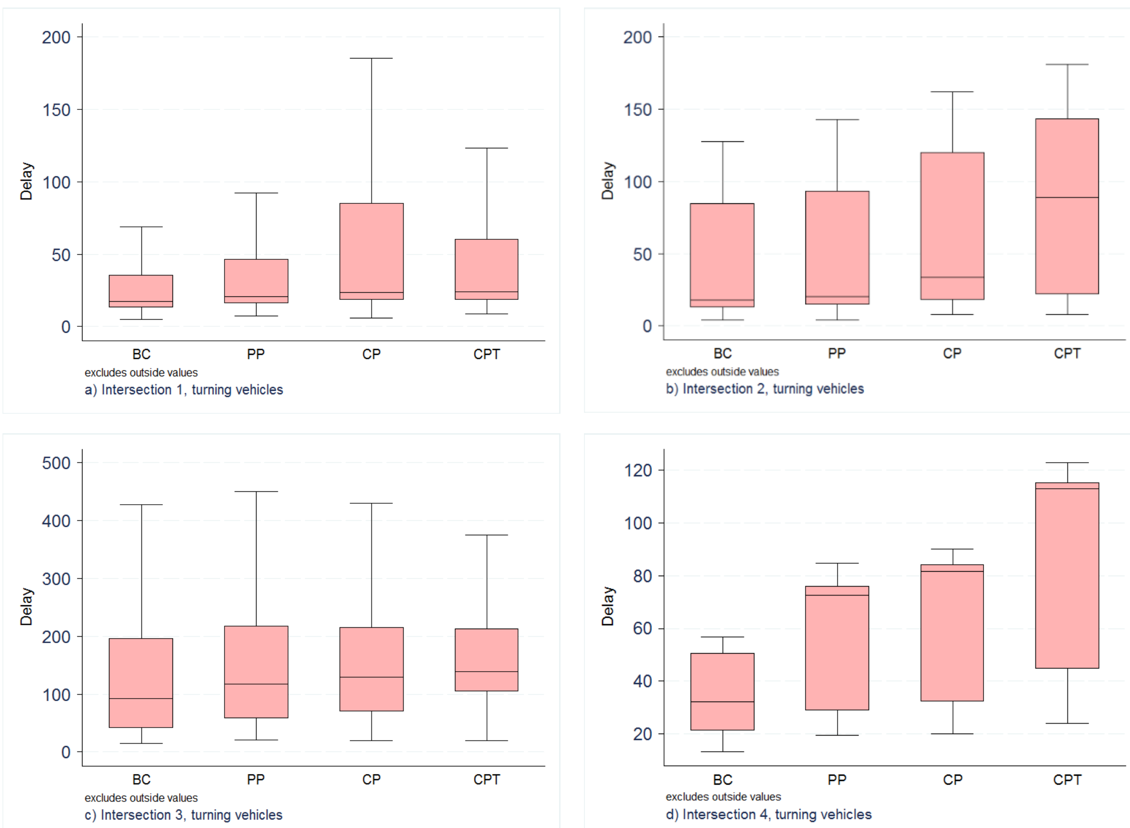

Figure 5.4, (a) Turning vehicle delay for Intersection 1, (b) Intersection 2, (c) Intersection 3, (d) Intersection 4

Comparing delay (seconds) for turning vehicles in Figure 5.4 the BC and PP light phases share approximately equal median and IQR values for Intersections 1 and 2, while for Intersections 3 and 4 there is a slightly larger time difference, as shown in c and 4d. The two completely protected designs share larger delays and IQR than the BC. While for Intersection 1, both CP and CPT are very similar, for the other intersections, the CPT has the largest delay. The CPT has a similar IQR value for Intersections 3 and 4. For turning vehicles, the increase in delay is more pronounced for the completely protected designs compared to the base case. At Intersections 2 and 4, the CPT has a larger delay compared to the other designs, and only for Intersection 1 it does have a smaller IQR than the CP. The PP and BC signal phases also remain most similar for turning vehicles. At Intersections 1 and 2 they share almost the same delay and IQR. Figure 5.5 contains box plots for high and low flow combinations for through and turning vehicles at Intersection 1. It is observed that low traffic flows have a lower IQR (smaller variation in expected delay), while for higher vehicles flows the IQR tends to be greater. Similarly, the median delay for the protected phases is higher in both completely protected designs compared to the PP and BC cases. Cyclist delay is relatively insensitive to intersection type, as simulated vehicles yield consistently to cyclists, this can be observed on Figure 5.6. Cyclist delay only increases in the CPT design, as there is extra time during the protected turning phase during which cyclists must wait.

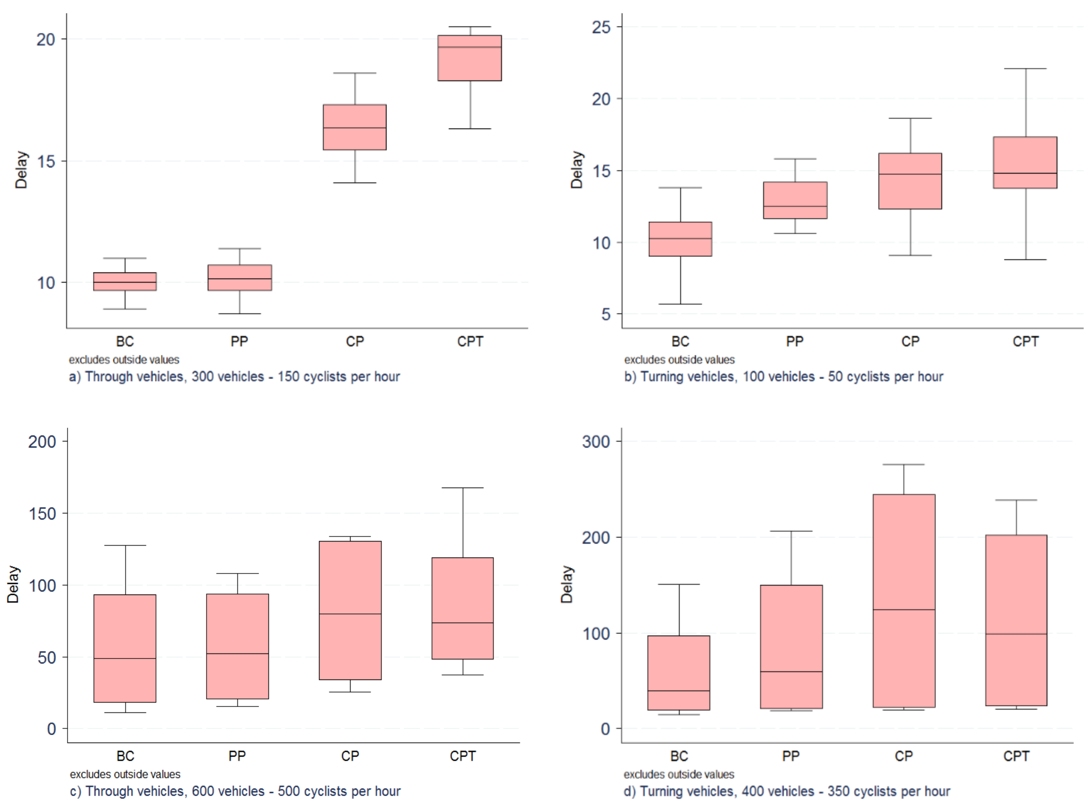

Figure 5.5, Partial users delay at Intersection 1. Through vehicles, 300 vehicles-150 cyclists per hour (a), Turning vehicles, 100 vehicles-50 cyclist per hour (b), Through vehicles, 600 vehicles-500 cyclists per hour (c), Turning vehicles, 400 vehicles-350 cyclists (d)

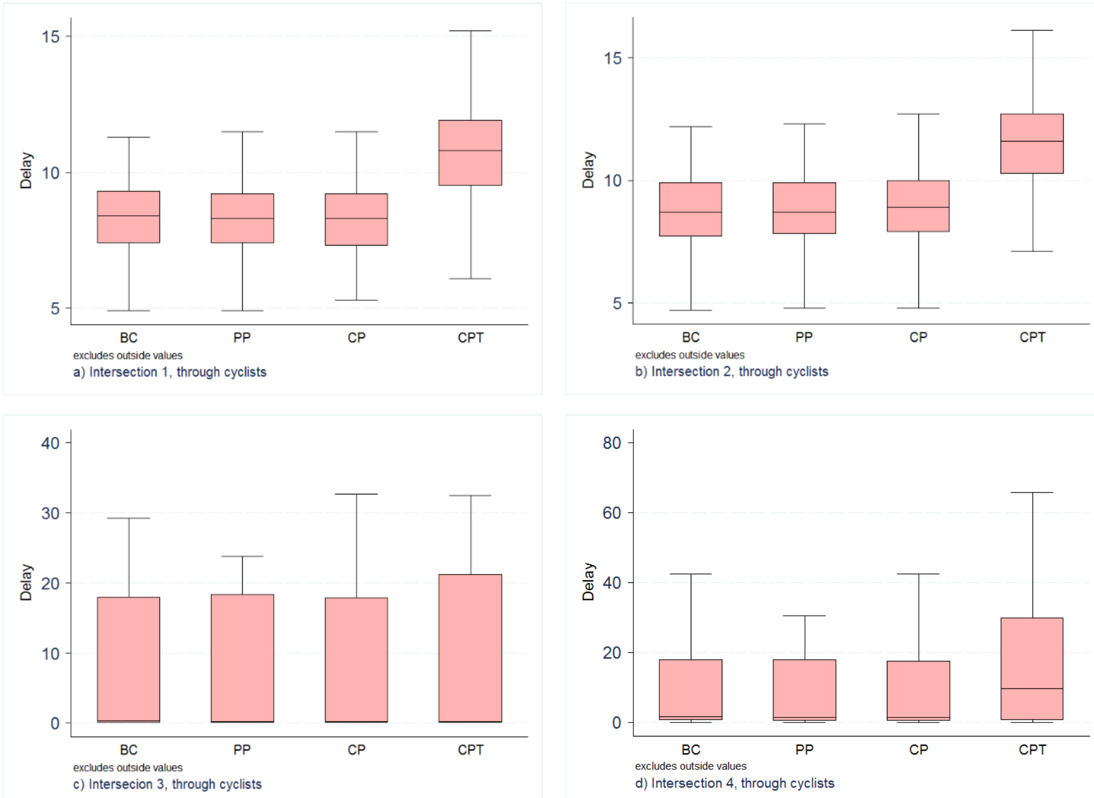

Figure 5.6, Through cyclist delay for Intersection 1 (a), Intersection 2 (b), Intersection 3 (c), Intersection 4 (d)

5.5.2. Conflict Analysis

The expected number of PET crossing conflicts is also compared in Table 5.3. The effectiveness of the CP design is clear, with the lowest number of crossing conflicts between vehicles and cyclists along all intersection types. In general, the second safest scenario is the PP, except for Intersection 2. At Intersection 4, the CP is the design yielding the fewest conflicts, followed by the CPT and PP.

Table 5.3, Median Data Summary for the Four Intersection Types

	Variable (seconds)	Light phase, turning direction			
		BC	PP	CP	CPT
Intersection 1	Through vehicles (IQR)	10.6 (3.6)	10.8 (4.8)	16.7 (8.4)	20.0 (9.7)
	Turning vehicles (IQR)	17.5 (22.3)	20.6 (30.5)	23.6 (66.9)	23.9 (41.9)
	Through cyclists (IQR)	8.4 (1.9)	8.3 (1.8)	8.3 (1.9)	10.8 (2.4)
	PET Crossing conflicts	678	390	293	402
Intersection 2	Through vehicles (IQR)	18.6 (73)	19.9 (80.8)	35.1 (101.2)	90.3 (120.9)
	Turning vehicles (IQR)	18 (71.8)	20.35 (78.5)	33.7 (101.9)	88.95 (121.4)
	Through cyclists (IQR)	8.7 (2.2)	8.7 (2.1)	8.9 (2.1)	11.6 (2.45)
	PET Crossing conflicts	416	330	182	247
Intersection 3	Through vehicles (IQR)	59.6 (58.65)	69.4 (63.8)	89.6 (68.3)	115.75 (60.75)
	Turning vehicles (IQR)	92.55 (155.4)	117.5 (159.65)	129.3 (144.7)	139.25 (108.45)
	Through cyclists (IQR)	0.3 (18)	0.2 (18.4)	0.2 (17.9)	0.25 (21.2)
	PET Crossing conflicts	4,051	2,681	2,642	2,894
Intersection 4	Through vehicles (IQR)	26.85 (25.5)	53.4 (36.3)	69.40 (43.2)	97.9 (61.5)
	Turning vehicles (IQR)	32.1 (29.3)	72.60 (47.2)	81.7 (52)	112.9 (70.35)
	Through cyclists (IQR)	1.65 (17.45)	1.4 (17.6)	1.5 (17.1)	9.65 (29.35)
	PET Crossing conflicts	1,193	1,109	1,038	1,053

Note: IQR or Interquartile range is the difference between the 75th and 25th centiles

5.5.3. Level Of Service

With a protected bi-directional cycle track on one side as in Intersection 1, vehicle delay is heavily influenced by cyclist volumes. At Intersection 1, LOS is similar for the BC and PP designs, while the CP has the poorest LOS. Vehicle delay at intersections with two unidirectional cycle tracks, as for Intersection 2, is influenced mainly by the number of turning vehicles. At Intersection 2, the number of cyclists has a lower impact on vehicle delay in the BC and PP designs than for the completed protected modes, as can be appreciated in Figure 5.7. For Intersection 3, cyclists have a large impact on turning vehicles, as delay increases with both the flow of vehicles and cyclists. For this type of intersection, PP and CP share LOS characteristics, with PP performing slightly better for some flow combinations. CPT continues having the poorest LOS for contraflow cycle tracks as in Intersection 3. Intersection 4 showed a stable behavior for vehicles delay. In this scenario, vehicle delay is hardly affected by the number of cyclists and is instead influenced by traffic light configuration and the number of turning vehicles. None of the traffic light phases demonstrated LOS A, and the BC was the only capable of providing LOS B. For this intersection, PP and CP shared the same upper limit for LOS D.

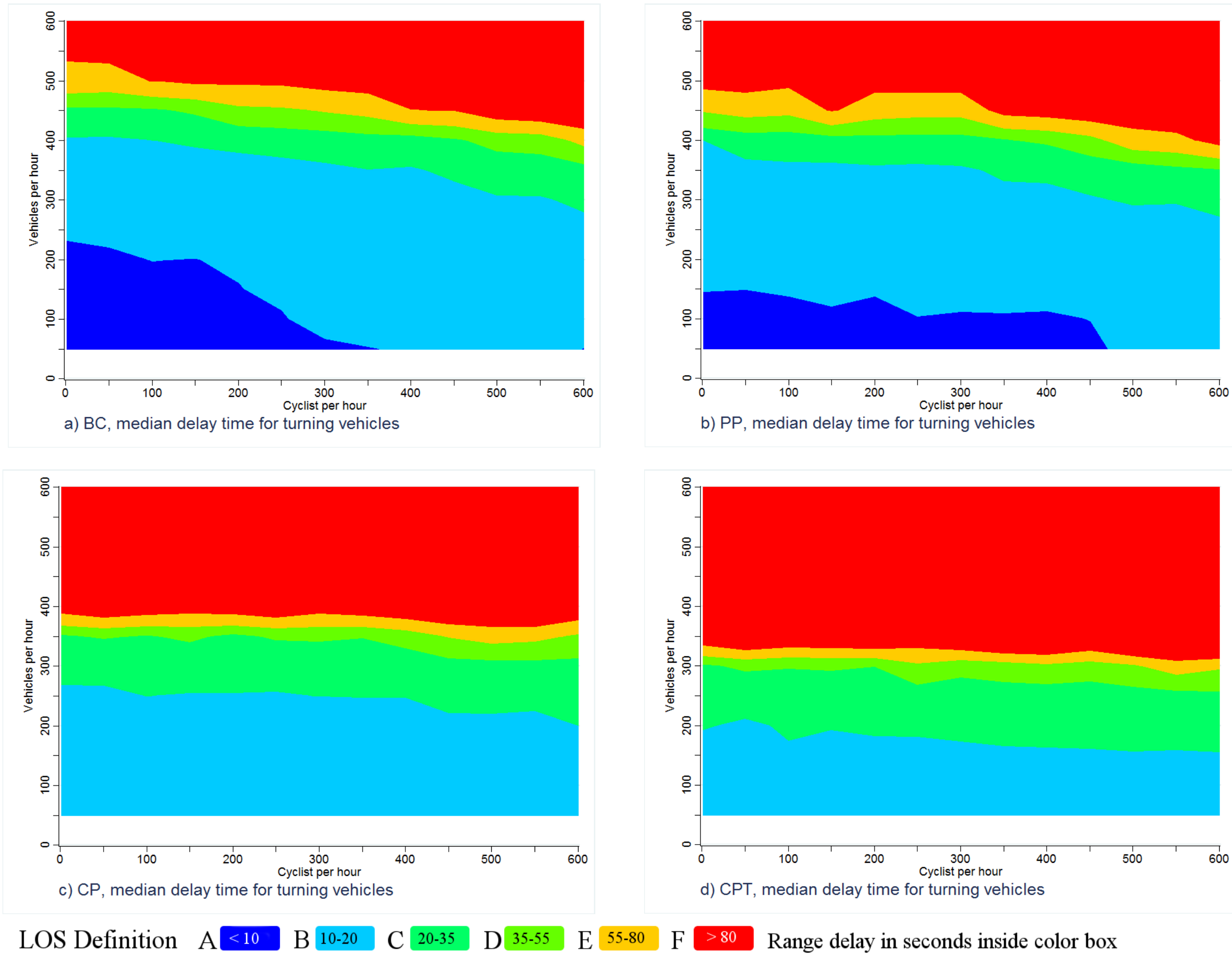

Figure 5.7, Level of Service for turning vehicles at intersection 2. BC median delay (a), PP median delay (b), CP median delay (c), CPT median delay (d)

5.6. Conclusions and Future Works

Several conclusions can be drawn from this microsimulation study of different bicycle phasing signal strategies at various intersections with bicycle facilities. Although the completely protected phase demonstrated the greatest improvement in bicycle safety (with the lowest number of conflicts regardless of intersection design or flow combinations), the CP also produces the longest delays compared to the BC with a larger IQR in most scenarios, which provides a poorer LOS as observed in the contour plots. In some cases, the CP reduces the number of conflicts by as much as 60% compared to the BC, but with a delay increase between 35 and 87 percent.

Although the PP phase design has neither the fewest conflicts nor lowest delay, it is often the design that best balances these goals. The LOS provided by the PP is similar to the BC for most intersections (at Intersection 3, the LOS is more similar to the CP design). In most of the scenarios, the PP can reduce vehicle-cyclist conflicts by nearly 50% compared to the BC. In addition, from the LOS analysis, it is observed that at Intersection 1 and 3, the number of cyclists has a significant impact on user delay that increases as cyclist flow increases, while for Intersection 2 and 4, vehicle delay is heavily influenced by the increase in the number of turning vehicles. In summary, the PP phase strategy could be a low-cost intervention that may help improve cyclist safety with a relatively small penalty for vehicle traffic. This solution could be installed at intersections with turn-on-red banned with bike facilities.

Limitations of this study are related to microsimulation and safety analysis. First, measurement of traffic conflicts in SSAM may be inaccurate because unexpected driving maneuvers or driver errors are not well represented in VISSIM (F. Huang et al. 2013). Second, this study is calibrated using general numbers for the city of Montreal. Third, though this study is focused on general intersections with cyclist facilities, only four types are considered from a range of different geometries. The main goal of this paper is to show the LOS and safety indicators for different traffic flow configurations in a general geometry. In future work, an observational before-after or cross-section study for validation will be performed for some intersections in the city of Montreal, where video data will be recorded to evaluate vehicle delay. The results from the obtained video analysis can be compared to the results of the simulation to demonstrate the accuracy of the delay and LOS indicators proposed.

5.7. Acknowledgments

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Chapter 6. Conclusions

This chapter provides a general overview of the key findings from this dissertation, which are related to current safety issues of VRUs at intersections with stop signs and traffic lights. In addition, the chapter discusses the research limitations, the practical implications that can be drawn from the findings, and directions for future research.

6.1. Findings

This thesis addresses some of the main limitations of the current road safety literature concerning the incorporation of VRUs, in particular cyclists, in the design and guidelines of traffic controls such as stop signs and traffic lights. Intersection safety for pedestrians and cyclists is a critical concern as research indicates that a significant proportion of vehicle-VRUs interaction occur in this part of the road network (Hunter et al. 1996; Dozza and Werneke 2014). However, from the literature review it was identified that the Canadian guidelines needs to consider bicycle traffic in their requirements, neglecting the inclusion of cyclists in the implementation of stop controls. In contrast, in the US and European guidelines, cyclists are expected to adhere to vehicle regulations. European countries also follow that same rule, where cyclists adhere to vehicle guidelines. Furthermore, some research shows that the implementation of AWS provides a reduction in crash rates. Unfortunately, the use of crash data can take many years in before-after studies before conclusions can be reached on the treatment efficiency. Like the AWS, the impact of bicycle signals on cyclist safety and bicycle operations has been rarely studied. Also, there is a lack of guidelines to design bicycle signals at signalized intersections with bicycle facilities.

To evaluate the conversion of a MAS intersection to AWS, a before-after methodology is proposed. This methodology combines an observational approach using surrogate measures of safety and statistical analysis. Data is collected and analyzed from a set of treated intersections before and after treatment implementation in the city of Montreal, comprising more than 68,000 road user trajectories. The analysis reveals a significant speed reduction in vehicle operation after the AWS treatment, particularly on the major approach, with a median speed decrease of 14.12 km/h. Along minor street approaches, speed reduction was also significant but was comparatively smaller. The statistical analysis using a mixed effect model, demonstrated a slight reduction in the PET for vehicle-pedestrian and vehicle-vehicle interactions after the AWS implementation. Furthermore, the frequency of these conflicts, categorized by severity, shows marginal improvements in the moderate severity category, while no high-risk conflicts were observed. Additionally, the distance-velocity framework showed a clear improvement on the vehicles' yielding rate to pedestrians'.

Furthermore, the study also evaluates cyclists' behaviour at stop-controlled approaches using a statistical mixed effect model. The analysis utilized trajectory data from five MAS intersections with heavy cyclist flow (Chapter 4). The findings reveal no significant safety improvement based on PET along the approaches with a stop sign, compared to the ones that did not have a stop sign. However, contrary to the PET results, cyclists will show a significant speed reduction when there is a stop sign on the approach. The analysis of the results indicates that cyclists tend to be more cautious when interacting with pedestrians or vehicles compared to other cyclists. As expected, cyclists making a full stop resulted in a higher PET value (positive effect) and lower mean speeds. On the other hand, cyclists making an avoidance maneuver will have lower PET values, but will experience a speed reduction, reducing the severity of a possible crash. Interestingly, cyclists wearing helmets have a lower PET and a higher speed compared to those without a helmet. The results from the presented analysis show that stop signs do not significantly affect the cyclist behaviour. Additionally, this research aligns with prior research (Larsen et al. 2011) and support the notion that cyclists treat stops signs as yielding signs.

Lastly, the impact of bicycle signals on traffic safety and operations is evaluated using a computer microsimulation approach. Four bicycle signal phasing strategies are compared for various intersections geometries with bicycle facilities. When compared to a Base Case phase (BC), the Leading Phase (PP) shows similar LOS but reduces the number of vehicle-cyclist interactions by up to 50% in some circumstances. The CP demonstrated the most significant improvement in bicycle safety with the lowest number of conflicts, but it also results in the longest vehicle delay compared to the BC. Cyclist delay was relatively insensitive to intersection geometry, as simulated vehicles yield consistently to cyclists. For the CPT, the only change was the increase in cyclist delay, as there is an additional time during the protected turning phase during which cyclists must wait. In summary, the PP phase strategy could be a low-cost intervention that may help improve cyclist safety with a relatively small penalty for vehicle traffic. However, it is important to consider the limitations of computer simulation studies, particularly regarding the yielding and error-free behavior of different road users.

Overall, this dissertation highlights the significance of carefully integrating all road users when formulating traffic control guidelines. It highlights the need to consider VRUs, in particular cyclist, in the design of intersection traffic controls (in particular stop signs), which is currently lacking in several existing guidelines (AASHTO 2010; MUTCDC 2014). Crossing cyclists' behaviours are very different from motorized vehicles, consequently, they need special attention when revising guidelines. This includes the fact that cyclists treat stop signs as yield signs, which is consistent with previous research. This supports ideas such as the IDAHO stop (Delaware 2021; Tekle 2017; Whyte 2013), which permits cyclists to treat stop signs as yielding signs. The methodologies proposed in this thesis combined a set of techniques including automated video analytics combined with manual annotations, surrogate measures of safety and statistical analyses which could be replicated easily in other studies.

6.2. Practical Implications

As demonstrated in this dissertation, trajectory video data and computer micro-simulated data can provide valuable insights into the implications of stop control treatments on VRUs. This was demonstrated through before and after analysis on a short period of time with SMoS, behaviour and user data from obtained trajectories. However, while SMoS can expedite treatment analysis, it should be noted that these approaches require significant resources, both in terms of computing power and human effort, to generate the necessary data. Nevertheless, the ability to collect and analyze large amounts of data develops greatly every year as computer power expands, providing researchers and professionals with more detailed information.

Moreover, as highlighted in the literature review, several guidelines do not consider VRUs completely for the stop control definitions. The methodologies and findings presented in this dissertation help bridge these gaps and offer valuable insights into the implications of stop control treatments.

The results of this dissertation demonstrate that AWS treatments have a greater impact on the speeds of vehicles approaching from the major approach. However, safety benefits were observed across all approaches, with the minor approach showing the most significant improvement for all road users when the evaluated road user was a vehicle. From the perspective of cyclists, precautions were taken even when there was no significant difference in speed between the stop-controlled and non-controlled approaches. Some cyclist measures taken include a) ceasing pedalling, which allows the cyclist to evaluate the intersection, b) swerving to avoid other road users, and c) making a full stop. Additionally, the statistical multi-level modelling approach employed in the analysis proved to be a useful tool for evaluating users' speeds when different locations were being evaluated.

Lastly, this dissertation demonstrates the importance of considering VRUs as individual users and not as part of the motorized users when designing stop control guidelines. Future guidelines should not leave them out when evaluating users' volumes or behaviours, as it has been presented with different microscopic analyses. VRUs react in a different way to control signs, and vehicle rules should not be applied indifferently to them.

6.3. Limitations

Despite our best efforts to provide a complete contribution to this research, there are some limitations that must be acknowledged. The limitations include data collection, processing, analysis, and microsimulation, as discussed below.

6.3.1. Data collection

The data collection was conducted with normal action cameras mounted on a mast. This process results in some limitations to the field of view and length of the obtained trajectories. It also limits the length of the user trajectories for some approaches, where only a couple of meters could be captured. To keep uniformity within the research, the captured area for each approach was kept similar for each intersection, resulting in the loss of some meters of analysis under certain circumstances. It is recommended to use masts with greater heights to extract user trajectories more effectively. Alternatively, installing additional cameras before each approach to capture the users' behaviour on the mid-block before the approach could provide a better understanding. However, this data collection approach could require multiple (4-5) cameras per intersection and would require a procedure that links all the different user trajectories from the different cameras.

6.3.2. Data Processing & Analysis

The data processing for VRUs faces limitations in certain conditions, such as when there are several pedestrians or cyclists in a confined space. This creates a situation of occlusion, causing trajectories to jump between users due to confusion faced by the Artificial Intelligence (AI) algorithm. This issue was corrected manually in this work. To mitigate this effect, it would be beneficial to train specialized AI models for different intersection types. However, as mentioned, the users' specific behaviour still undergoes manual correction and this information would be merged with the one that the AI models provide. This manual process is time-consuming and resource-intensive, limiting the amount of information that can be evaluated. Therefore, only four hours of video data were processed for each intersection instead of the entire day to conserve resources for the entire sample of intersections. Additionally, the mixed-effect model developed on this research showed a low R2, which make it suitable only for the analysis presented on this work.

6.3.3. Microsimulation Study

The SSAM used to measure the traffic conflicts has some limitations, and caution should be exercised when interpreting the results. One limitation is the simplifying assumption of constant speed and direction when computing safety indicators. Additionally, VISSIM does not replicate behavioural errors, which are a significant cause of crashes. Furthermore, this study was calibrated using speed values from previous video analysis research (Zangenehpour et al. 2016), city speed limits for the city of Montreal and expected volumes. Finally, although this study focuses on general intersections with cyclist facilities, only four design types are considered from various geometries.

6.4. Future Work

In future work, it would be valuable to conduct a longitudinal before-after evaluation to study the long-term impacts of converting MAS to AWS on road user adaptation. This study would involve evaluating user behaviour several years after the AWS implementation and compare the SMoS with the traditional method based on historical crash data after a three to five years period. This comparison could contribute the literature by assessing and validating the effectiveness of SMoS in relation to the crash-based methods commonly used in the traditional approach. The correlation of surrogate and crash-based measures is still an active area of research. Additionally, it is important to investigate the potential decrease in driver compliance over time when stop signs are installed everywhere, as previous research has indicated (Trinkaus 1997). Likewise, the upstream effect of the approach should be investigated with network-level user tracking, i.e., Global Navigation Satellite System (GNSS) data. The interactions between pedestrians and e-bicycles (and other micro-vehicles) deserve more attention in the current context of micro-mobility. Very few studies have been reported using observational surrogate methodologies.

Another recommended future work is to conduct an observational before-after study to validate the proposed traffic lights control guidelines by evaluating vehicle delay with trajectory video data. The obtained results can be compared to those obtained from the microsimulation model to validate user delay and proposed LOS. To achieve this, the microsimulation model can be calibrated, extending the corridor beyond the intersection of interest. This approach would enable decision-makers to understand the effects of changes that occur upstream and downstream of the affected area, providing a more comprehensive assessment of the impact of the proposed guidelines.