An evaluation of the operations and safety issues at reserved lane facilities using microscopic video data and alternative methods

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April 2014

A thesis submitted to McGill University is partial fulfillment of the requirements of the degree of Master of Engineering

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Abstract

This research investigates the operating performance and safety issues of reserved lanes in Quebec, Canada using microscopic data and different methods. Reserved lanes have been around for a few decades in North America, however their effectiveness and safety along congested facilities remains contested. This thesis proposes original methods for collecting microscopic data, analysing and evaluating the performance and safety of reserved lane highway and arterial facilities. The microscopic data (vehicle level data) is collected using video cameras and obtained with an open-source feature-based tracking software. As a first objective, this research work evaluates the accuracy of the automatically calculated speed data by comparing them to manually collected speeds from different camera orientations and concludes that the mean errors are comparable to the current collection technologies. The second part of the research applies the tracked vehicle data from an exclusive bus lane to a microsimulation scenario and calibrates the speeds along the corridor to estimate its effects on the overall performance and emissions. The third section analyses the performance and safety along highway and arterial facilities. The highway segment was evaluated before and after the implementation of an HOV lane by investigating the differences in volumes, speeds and travel times. The arterial segment with a reserved bus lane was evaluated based on lane change violation rates and surrogate safety indicators calculated using trajectory-based tools. Countermeasures for both facilities are discussed based on the results extracted using the alternative data collection process. Overall, the research highlights the video-based application's ability to generate microscopic traffic data and presents new methods that can be implemented along facilities to monitor, build microscopic models and evaluate reserved lanes based on different driver behavior indicators.

Résumé

Cette recherche examine les performances et la sécurité des voies réservées au Québec à partir de données microscopiques en utilisant des nouvelles méthodes. La construction de voies réservées a débuté pendant les années 1970 en Amérique du Nord, mais leur efficacité ainsi que leur sécurité au long des routes congestionnées reste contesté. Cette thèse propose des méthodes originales de collecte de données microscopiques, d'analyse et d'évaluation de la performance et la sécurité des voies réservées sur les autoroutes et les artères. Les données microscopiques (au niveau du véhicule) sont collectées avec l'aide de caméras vidéo et traitées avec un logiciel de suivi basé sur les caractéristiques des véhicules open-source. Dans un premier objectif, ce travail de recherche évalue l'exactitude des données de vitesse calculées automatiquement en les comparant aux vitesses recueillies manuellement de différentes orientations de la caméra et conclu que les erreurs moyennes sont comparable aux technologies de captage utilisé couramment. La deuxième partie de la recherche applique les données des véhicules voyageant sur une route avec une voie réservée d'autobus dans une microsimulation et étalonne les vitesses au long du corridor pour estimer ses effets sur la performance globale ainsi que les émissions. La troisième section analyse la performance et la sécurité des voies réservées le long des autoroutes et artères. Le segment de l'autoroute a été évalué avant et après la mise en œuvre d'une voie réservée en étudiant les différences de volumes, les vitesses et les temps de déplacement. Le segment artériel avec une voie réservée aux autobus a été évalué en fonction des taux d'abus pour les changements de voies et d'indicateurs de sécurité de substitution calculés en utilisant de outils d'analyse basés sur les trajectoires des véhicules. Les contremesures pour les deux installations sont discutées sur la base des résultats extraits en utilisant le nouveau processus de collecte et analyse de données. Dans l'ensemble, la recherche met en évidence la capacité de l'application de vidéo à produire des données de trafic microscopiques et présente des nouvelles méthodes qui peuvent être mise en œuvre le long des voies réservées, construire des modèles microscopiques et évaluer des voies réservées sur la base de différent indicateurs de comportement du conducteur.

Acknowledgments

The author would like to acknowledge the help provided by Dr. Miranda-Moreno and Dr. Alecsandru throughout the research process. Additionally, Dr. Saunier from Ecole Polytechnique de Montréal assisted in the development of the software used throughout the thesis. Paul St-Aubin, a doctoral candidate at Ecole Polytechnique, contributed through the development of the pvaTools software. The author would also like to acknowledge Joshua Stipancic, Shaun Burns, Hamed Shahrokhi, Raphael Lamotte and Huizhu Tao for their help in data collection and processing. This study has been conducted with support through the *Ministère des Transports du Québec* (MTQ) contract number R706.1.

Preface and Contribution of Authors

Luis Miranda-Moreno, Ciprian Alecsandru and Nicolas Saunier were secondary authors for a published conference paper at the 2013 CSCE Annual Conference in Montreal, based on the third chapter of the thesis titled: "*Microsimulation calibration using automated video-based motor vehicle and bus trajectories.*" Their primary contributions included the paper objectives and revisions of the manuscript. Joshua Stipancic is secondary author on a paper accepted for the 2014 TAC Annual Conference in Montreal, based on the second chapter of the thesis titled: "*Performance Evaluation and Error Segregation of Video-Collected Traffic Data.*" His primary contribution to the paper was the literature review and data processing.

Chapter 1:

Introduction

1.1 STUDY OVERVIEW

The goal of this thesis is to propose alternative methods to evaluate the safety and effectiveness of reserved lane facilities. This project focuses on High-Occupancy Vehicle (HOV) lanes along arterials and highways in the province of Quebec, Canada. A review of the application of these facilities across different North American jurisdictions shows that there exist a variety of roadway types that are designed to accommodate HOV lanes. These lanes may differ due to their geometry, positioning with respect to the direction of traffic, types of authorized users, type of physical separation and their type of access. Due to this variety, transportation agencies are sometimes confronted with the situation where HOV lane standards and diagnostic tools are insufficiently specified. This situation can lead to difficult and/or improper decisions in the planning, installation and operating process of HOV facilities. This thesis focuses on how to measure the performance and safety of HOV lanes currently in operation.

1.2 LITERATURE AND ISSUES

In most urban areas an increase in travel demand has occurred over the past few decades resulting in congestion issues. Limited financial capital, corridor space and heightened environmental concerns have made it difficult to address this issue by building more facilities. Additionally, it has been shown that enlarging capacity to deal with congestion usually leads to an augmentation in travel demand, creating a circular problem (Taylor, 2002).

The main objective for HOV lanes is to increase the number of people traveling along a facility by providing travel time reductions, reliability and encouraging modal shifts from single-occupancy vehicles to multi-occupancy vehicles. The proposed benefits related to the facilities are reductions in emissions related to congestion and the number of vehicles, the enhancement of travel speeds along all lane types and the expansion of sustainable transportation options.(Stockton, Daniels, Skowronek, & Fenno, 1999) Thus, a primary goal for the installation of HOV lanes is to increase capacity of overcrowded roads using low cost methods. Many of these lanes are added on to existing facilities by restriping the roadways or by adding a lane on the shoulder. In other instances, HOV lanes are built as permanent improvements by constructing separate rights of way for specific vehicle classes. In North America, the first HOV facilities date back to the late 60's and early 70's and were primarily exclusive bus lanes in the states of New Jersey and California. (Katherine F Turnbull, Henk, & Christiansen, 1991) In Canada, the first HOV facilities were implemented in the cities of Vancouver and Toronto in the early 1990's after numerous studies and policy reports were initiated based on the American precedents. Facilities in Montreal, Gatineau, Calgary and Ottawa soon followed. There are approximately 4,000 kilometres of HOV lanes in over 30 North American cities, and an estimated 300 kilometres at 35 sites across Canada. It should be noted that additional highway and arterial facilities are being planned throughout Canada, with significant proposals in the larger urban centres. (Canada, 2010)

Empirical studies have been undertaken in order to try and understand the effects of the lanes as well as potential issues and countermeasures related to their implementation. These studies have been published in research reports, journal articles and official guidelines. (Henry & Center, 1989; Operations, 2003; transports; K.F. Turnbull et al., 1998; Katherine F Turnbull et al., 1991)

Despite the important body of literature and studies, there are some gaps regarding data collection, monitoring and analytic processes for HOV facilities. The most common data collection methods for HOV facilities are as follows. First, traffic sensors are used to measure speed, travel time, occupancy, volume and vehicle classification. These sensors include microwave, sonic and infrared detectors, inductive loops, cell phone probes and licence plate-matching tools. Second, incident reports that are collected by emergency agencies along facilities are used to analyse the safety and performance of segments. Third, operators use snapshots of the traffic environment taken on premise to estimate performance along HOV facilities and the General Purpose (GP) lanes. Additionally, floating car studies are used for travel time estimates, user surveys are conduct to evaluate public perception and usage trends and finally simulation models are applied to understand the effects of potential countermeasure implemented along the facilities. (Shaw, 2003)

While these studies constitute an important body of literature for HOV facilities, there exists two main gaps in the current data collection and monitoring processes: the absence of microscopic data collection techniques to obtain vehicle level information such as trajectories, speeds, gap time and counts per lane and the lack of automation and continuity when monitoring HOV facilities. Most traffic sensors aggregate the collected data over set periods of time, generally between 5 seconds and 5 minutes. Even technologies with very fine resolutions do not simultaneously collect trajectories, speed and volume data throughout a corridor. Furthermore, the current data collection methods only allow for certain monitoring events to occur quarterly or even yearly within a facility that has limited usefulness. (Carson, 2005) Therefore, the implementation of a flexible, automated and microscopic data collection method would be extremely useful in terms of HOV facility evaluation and monitoring. Additionally, the collection of microscopic behaviour will allow for the calibration of microsimulation scenarios used to evaluate potential countermeasures that may be applied to current and/or prospective HOV facilities. The applicability of microscopic methods to analyze driver behavior and safety in HOV lanes is limited. This research also proposes an alternative method to build and calibrate microsimulation models based on microscopic video-data.

1.3 STUDY OBJECTIVES

The specific thesis objectives are: (a) to propose and evaluate methods to collect microscopic data and calibrate microscopic models, and (b) propose methods to evaluate the safety and effectiveness of HOV facilities using speed measures and surrogate indicators

The particular objectives of this study are:

1. To conduct a literature review pertaining to the collection of vehicle data along HOV lane facilities and the safety and performance of HOV facilities.
2. To evaluate the performance of microscopic video data using an inventory of HOV facilities in the province of Quebec.
3. To show the advantages of using microscopic video data in the microscopic model calibration.
4. Evaluate the condition of the facilities with a focus on safety and traffic performance indicators using video and conflict based analysis methods.

Additionally, the study incorporates a new video analysis tool called Traffic Intelligence, developed by researchers at Ecole Polytechnique de Montréal, as the primary evaluation method for the HOV facilities. Since the tool has only recently been developed, another objective for this document has been the implementation of a verification study in order to validate the analysis tool’s accuracy and its applicability to this type of research.

The study is divided into the following chapters in order to address the objectives:

1. Chapter 1 presents the objectives of the thesis and information on HOV facilities
2. Chapter 2 investigates the accuracy of the video analysis tool by verifying vehicle speeds and volumes across a number of facilities and camera orientations.
3. Chapter 3 focuses on the application of the video analysis tool in the calibration of HOV facility microsimulation scenarios.
4. Chapter 4 presents performance and safety indicators applicable to HOV facilities and provides results regarding two distinct HOV facilities in Quebec.

1.4 BACKGROUND

The following sections will present some background information regarding HOV facilities as well as a literature review regarding data collection methods, microsimulation calibrations as well as the performance and safety indicators related to HOV facilities.

HOV facility definition and classification

Any vehicle carrying two or more persons at the same time can be classified as a High Occupancy Vehicle (HOV). Examples of HOVs are vehicles used for carpooling and other purposes, buses and taxis. If select lanes along a roadway are specifically designated for the exclusive use of one or more HOV vehicle types, they are referred to as HOV lanes. Consequently, the other lanes along a roadway are referred to as General Purpose (GP) lanes.

HOV lanes can be classified based on five parameters: authorized types of users, type of access/egress, operational treatment, type of separation, and functional classification based on the road type.

The first parameter differentiates the lanes that are reserved for transit vehicles, taxis and/or private vehicles with a minimum number of occupants. While buses are generally allowed on most HOV facilities, some reserved lanes are restricted to buses. These facilities have to be considered separately as they are only used by professional drivers and for very specific usages, depending on pre-defined bus routes.

The second parameter that applies to HOV facilities is the presence of continuous or limited access lanes. The HOV facilities with continuous access allow eligible vehicles to enter and exit at any location along the facility. Consequently, due to control and safety reasons many HOV facilities are designed to provide limited access of vehicles at specific locations for ingress and egress. (Jang, Chung, Ragland, & Chan, 2009) In order to properly implement the limited access facilities, the HOV lane must be adequately separated from the GP lanes. Figure 1 displays examples of these separation types.

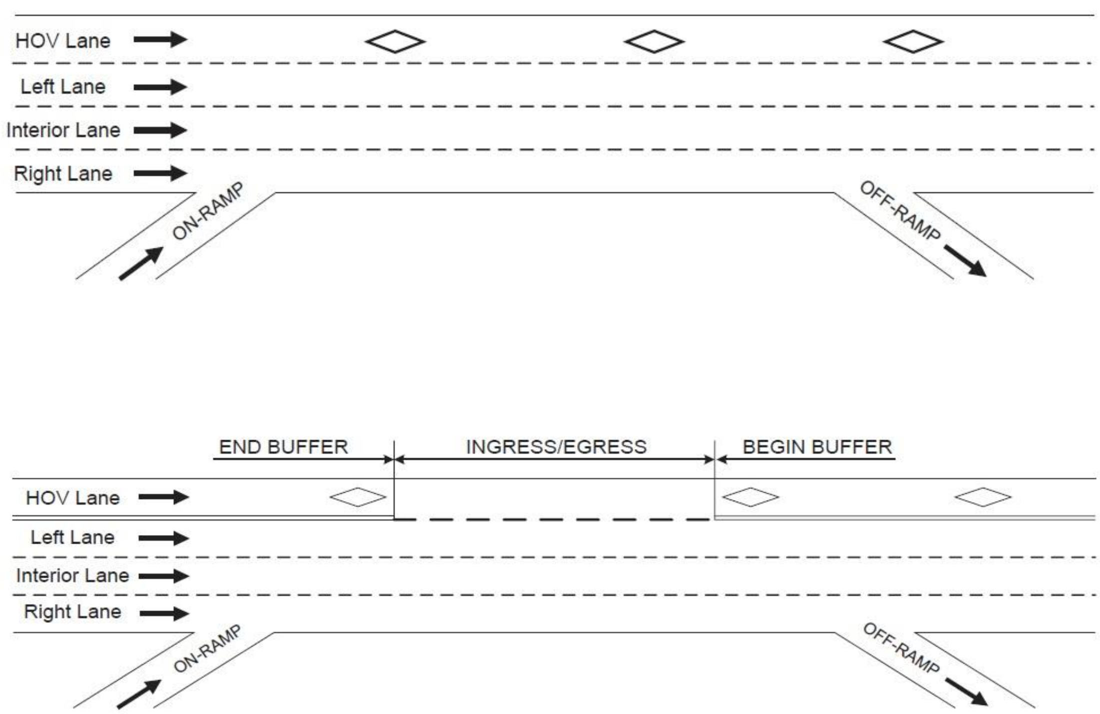


Figure 1: HOV lane with continuous access (a) and limited access (b) (Jang et al., 2009)

The third classification parameter is the type of separation used along HOV facilities: separated by a line (dashed or continuous), by a wide buffer zone or by a physical barrier. Examples of possible designs are shown in Figure 2. The different types of separation have various advantages and drawbacks. For example, pavement-marking separators are not recommended along facilities where large speed differentials between the vehicles on the HOV and the GP lanes are present. Consequently, a physical barrier is more costly and may cause problems for emergency vehicle access along the facility.

The fourth parameter is the operational treatment and divides HOV lanes into the following four groups: concurrent, contraflow, reversible and two-way flow operations. Concurrent HOV facilities allow users to move in the same direction as the traffic flow on the adjacent GP lane. Contraflow HOV facilities allow vehicle movements in the opposite direction of traffic flow and primarily used due to space constraints. The third separation type is the reversible HOV lane that allows for alternating movements based on the peak direction. This application is also warranted when a limited right of way is available. The last type includes the two-way HOV lanes that are typically designed in the middle of the roadway to allow for the movement of HOV vehicles in both directions along adjacent lanes. Figure 2 displays examples of these operational treatments.

a) HOV lane separated by a wide painted area (Planet, 2011)

b) Barrier-separated HOV lane (FHWA, 2003)

c) Contraflow HOV lane (PANYNJ, 2013)

d) Reversible HOV lane (Skyscrapercity, 2008)

Figure 2 Examples of various HOV facilities

The fifth parameter categorizes HOV lanes based on the classification of the roadway. The primary categories are facilities along freeways or urban roadways (mainly arterials). Although more precise classifications are often used by transportation agencies, they were generalized for the purpose of this study for the following reasons. First, these classifications vary depending on the local agency. Second, HOV lanes are usually implemented as a response to congestion and are rarely implemented on local streets. Third, the distinction between freeways and urban roadways results from two different situations observed in HOV facility implementations. Urban HOV lanes are generally installed to promote public transportation and are placed on the right side of the road. Consequently, most freeway HOV facilities are installed on the left side or within the median in order not to impede on the access to and from the freeway.

Literature review

Data collection methods

Vehicle tracking through computer vision techniques provides practitioners with a powerful tool that has seen implementation in several areas of transportation and safety research. Compared to traditional traffic detection devices, vehicle-tracking techniques are able to provide additional information in the form of vehicle trajectories.(Coifman, Beymer, McLauchlan, & Malik, 1998) Trajectories are representations of objects and their characteristics, such as position and velocity, over both time and space. The nature of video detection allows vehicles to be tracked continuously over a road segment rather than being detected at a singular location. In practice, the analysis of vehicle trajectories can be used to automate otherwise resource-intensive studies, including vehicle manoeuvring (Coifman et al., 1998), lane-changing, and queuing patterns. (Cho & Rice, 2006) Combinations of these measures are potentially useful in the field of automated incident detection.(Coifman, 2005) The additional flexibility has made video data a common tool in road traffic studies focused on driver behaviour. (Laureshyn & Ardö, 2006)

One particularly interesting application of video data in transportation safety is in the area of conflict analysis. Due to both statistical and social concern related to traditional safety analysis using crash data, the use of safety surrogates has become increasingly popular. Traffic conflicts are interactions between road users that re sufficiently close to real crashes such that they are physically and predictably related to crash events. Saunier et al. (Saunier & Sayed, 2007) presents one example, in which an additional interpretation module complements the traditional video detection and tracking techniques. Once trajectories are extracted, the interactions between road users can be interpreted as normal operation, conflict, or dangerous conflict. Sayed et al. (Sayed, Ismail, Zaki, & Autey, 2012) implemented a similar system and were able to demonstrate a reduction in traffic conflicts due to an engineering safety countermeasure using a before and after approach.

The increased complexity of video-based analysis does not preclude the ability for video to substitute or compliment traditional traffic detectors. Along with trajectories, video has the ability to extract traditional traffic parameters including flow, speed, headway, and density at both the microscopic, or individual vehicle level (Coifman et al., 1998) and the macroscopic, or corridor level (Cho & Rice, 2006). This type of vehicle data is potentially useful to traffic flow modeling (Coifman et al., 1998), but is especially important for applications related to safety and conflict analysis. As detecting and extracting the position and speed of vehicles provides the basis for conflict analysis, verifying the parameters themselves will lend additional support to the technique.

In order to determine vehicle speeds, vehicles must first be successfully detected and tracked. In a study of video-based vehicle classification, Gupte et al. (Gupte, Masoud, Martin, & Papanikolopoulos, 2002) achieved a detection rate of 90%. Of the vehicles detected, 70% were classified successfully. Messolodi et al. (Messelodi, Modena, & Zanin, 2005) implemented a vehicle tracking system that operated in real time. A ground truth data set was compiled manually for 1325 vehicle records and was compared to the automated results. Over all records, the system exhibited an average count error of -5.2%. For the detected vehicles and 88% classification rate was achieved.

The analysis of speed data, especially at the microscopic or individual level has been limited. This is potentially due to the amount of video that must be processed and the resources required to perform the analyses (Cho & Rice, 2006). Even when the speed of individual vehicles has been extracted, the methods used to validate this data have left much to be desired. Coifman (Coifman et al., 1998) extracted data for velocity, flow, and density collected by video in real-time on a freeway facility. Data was temporally aggregated to 5-minute intervals, resulting in 514 comparison samples. When compared to ground truth from calibrated inductive loops, 100% of the samples exhibited error less than 10%, while 95% exhibited error less than 5%. Errors for flow and density were much higher than for speed. Presenting results from the same study, Malik et al. (Malik & Russell, 1997) showed improvements when post-processing was used in place of real time analysis. Across the study, detection rates varied between 75% and 95%. In daylight conditions and using 5-minute aggregation periods, nearly all samples showed speed error of 5% or less. Variation in speed accuracy was observed due to a vehicles lane position. Other analysis techniques have also fallen short of the evaluation and quantification of microscopic speed error. MacCarley et al. did not strictly consider the error of each video-extracted speed. Instead, it was claimed that 95% of all extracted speeds were "reasonable" when compared to speeds determined manually (MacCarley & Slonaker, 2007).

Dailey (Dailey, Cathey, & Pumrin, 2000) actually considered individual vehicle data, but considered only 190 vehicles from 40 seconds of video data. Dailey was able to demonstrate that the mean of the speed detection error across all observations was 0. However, if disaggregate records are considered, the individual mean error varied between -40% and 80%. Recognizing these large errors, it was suggested that the methodology was sound as long as a large number of vehicles was used to estimate mean traffic speed. The authors recommend using aggregation periods of at least 20 seconds. Schoepflin (Schoepflin & Dailey, 2004) utilized a comparison of speed distributions created manually and by video data, noting that the distributions were approximately equal in mean and distribution. The authors claimed this indicates a "certain equivalence" between the video data and actual events. Although errors of up to 20% were possible, averaging individual speeds over 20 second intervals was observed to reduce variability by a factor of 10. These studies, in particular, exemplify the issues with using aggregated data. Using temporally aggregated data for speed analysis effectively eliminates the influence of higher and lower speed vehicles on the mean speed value and aggregation can obscure the performance of a device exhibiting compensating errors (Kranig, Minge, & Jones, 1997). The reduction in error due to aggregation clearly demonstrates that video-based detection may exhibit compensating errors. Furthermore, the use of temporally aggregated data for safety analysis represents an ecological fallacy, and should be avoided if disaggregate data is available.

Existing literature documents several issues associated with extracting vehicle speeds from video. In terms of vehicle detection, perhaps the biggest issue is with false and missed detections. False detections involve the tracking of any object that is not a road user. Shadows cast by vehicles in adjacent lanes are particularly problematic (MacCarley & Slonaker, 2007). Vehicles can be missed if they are partially or fully occluded by other vehicles. Occlusions can also disrupt feature tracks, creating inaccurate trajectories and speed estimations (Saunier & Sayed, 2007). The vehicle position in the roadway may also have an effect on the accuracy of speed. Accuracy is affected by the lane position of a vehicle (MacCarley & Slonaker, 2007). Vehicles that are further from the camera occupy a smaller number of pixels than vehicles that are close. Distant vehicles may not show distinctive features and may be difficult to identify and track, leading to potential variability in speed data (Cho & Rice, 2006). Laureshyn demonstrates the issue of overestimation of derivative values. Tracking inaccuracy means that the "distance between two measured points is systematically biased towards longer distances, which results in speed overestimation" (Laureshyn & Ardö, 2006).

Regardless of the success of existing video-based systems, if video detection is to be considered a reasonable alternative to other ground truth methods, the accuracy of the data must meet the same requirements used for other traffic detection devices. Bahler (Bahler, Kranig, & Minge, 1998) utilized inductive loops for ground truth, which exhibited count errors between 1% and 4%, calculated, based on 5 and 15-minute counts aggregated to 1 hour intervals (Kranig et al., 1997). The same study demonstrated that most commercially available non-intrusive traffic detectors were able to provide counts within 3% of ground truth, and speeds within 8% error (Bahler et al., 1998). Several issues exist with regards to existing literature on ground truth data. Existing literature provides little guidance on acceptable speed accuracy for ground truth data. Most attempts to data have quantified error based on aggregated data, with little research focused on reasonable accuracy for microscopic vehicle data. Finally, there has been no consideration for evaluating device precision and accuracy separately. It these issues considered, researchers should endeavor to find detectors that "approach the ideal, but fall within some level of tolerance that may vary from application to application" (Coifman, 2006).

HOV facility microsimulation calibration methods

A literature review has found a limited number of papers related to this subject. While there are many publications that focus on the calibration of traffic microsimulation software there are few that discuss data collection methods. Furthermore, little has been written on the calibration of public transit networks or HOV facilities within microsimulation software and, to the best of my knowledge, video-tracking software has not been used in calibration studies.

In (Toledo & Koutsopoulos, 2004), the importance of calibrating microsimulation models is presented. The authors demonstrate a number of statistical methods that can be applied to traffic models, notably goodness-of-fit and hypothesis tests. Statistical methods are then applied in a freeway case study where traffic speeds collected using sensors are compared to simulated outputs. In (Hollander & Liu, 2008), the authors present the methodologies developed by a large number of traffic microsimulation calibration studies. The authors outline the importance of identifying key parameters when calibrating a microsimulation as well as the importance of applying the proper goodness-of-fit measures to the calibration scenario. In (Gomes, May, & Horowitz, 2004), the authors provide a detailed process to accurately simulate urban freeway facilities that include HOV lanes using the VISSIM microsimulation platform. They conclude that the VISSIM platform can be used to accurately calibrate freeway facilities with complex geometrical features. The authors in (Yang, Wang, Wang, Chen, & Zhou, 2012) present an implementation of control strategies in a microsimulation program for bus rapid transit (BRT) networks and analyze the results using travel speed and average delay measures. They conclude that the application of the microsimulation software leads to accurate results and is useful for the planning and management of transit networks. In (Abdelghany, Mahmassani, & Abdelghany, 2007), a dynamic traffic assignment-simulation modeling framework (DYNASMART-P) that can plan and analyze a BRT network is presented. The primary operational attributes of the BRT are evaluated by running a number of simulation experiments with the objective to assess the potential change in transit ridership and overall traffic interactions within the network. The authors conducted five sets of experiments with respect to the following operational elements: right-of-way separation, prioritization at certain intersections, higher service frequency, stop-skipping and shorter dwell times. The work presented in (Cortés, Burgos, & Fernández, 2010) provides guidelines for incorporating certain elements of public transportation into microsimulation programs in order to properly model the interactions between general traffic and public transportation. The study looks at examples of software being developed specifically for public transportation simulation including the interaction of buses at stops and in networks. In (Yu, Yu, Chen, Wan, & Guo, 2006), the authors present a method to calibrate a microsimulation software BRT model using GPS data. The performance index is calculated as the Sum of Squared Error (SSE) between the collected speeds and the simulated speeds. A Genetic Algorithm is used to minimize the SSE by adjusting a number of the microsimulation software parameters. The author of (Fernández, 2010) outlines a method to calibrate and validate bus stop modeling within microsimulation software and concludes that current software does not represent bus stops and their capacity properly, which may lead to the unrealistic simulation of bus networks and their performance. The authors in (Zhang, Hounsell, & Shrestha, 2012) used microsimulation software to calibrate bus acceleration, deceleration and speed based on GPS data. They concluded that the default parameters used in microsimulation software differ significantly from the actual values and hypothesized that it would affect the outcome of emissions modeling.

In (Abou-Senna, Radwan, Westerlund, & Cooper, 2013) the authors present a procedure that integrated vehicle parameters from microsimulation software into the Environmental Protection Agency (EPA) emission modeling software MOVES. They compare four different methods of microsimulation parameter inputs and conclude that second-by-second inputs provide the most accurate emission models. In (Xie, Chowdhury, Bhavsar, & Zhou, 2011) the authors discuss the implementation of MOVES using the PARAMICS microsimulation platform and compare the emissions along a network that included highway facilities based on varying market shares for alternate fuel types. The authors conclude that the integration of the microsimulation platform allowed for a more accurate emission model due to the vehicle level measures. In terms of tracking software applications, (Jackson, Miranda-Moreno, St-Aubin, & Saunier, 2013) presents a video data collection methodology based on feature-tracking algorithms. The authors also discuss the video data processing and present some of its applications. The authors in (P. St-Aubin, Miranda-Moreno, & Saunier, 2012) outline a method for safety analysis at freeway ramps using automated trajectory measurements and surrogate measures of safety. The video-collection method is proposed as an alternative to traditional methods including historical accident data analysis.

HOV performance and safety

The study conducted by (Bauer, Harwood, Hughes, & Richard, 2004) investigates the safety effects related to the addition of a travel lane by using the shoulder and/or narrowing the general traffic lanes. A before-after analysis is undertaken using facilities within the California freeway system where HOV lanes were added to deal with congestion issues. The accident frequencies increased between 3 and 11% along the treated facilities, with no significant change along the control sites. The study concludes that one of the likely reasons for the increase in accident rates is due to speed differentials between the HOV and GP lanes. The safety effects regarding the addition of a concurrent HOV lane along existing freeways facilities are also investigated in the study undertaken by (Cooner & Ranft, 2006). A before-after crash frequency analysis is performed along two freeway systems in Texas over 10 years. The conclusions of the analysis are similar to the Bauer study, with accident rates roughly doubling, specifically between the HOV and adjacent lanes due to speed differentials. The authors recommend increasing the total HOV lane width, including a painted buffer. The study performed by (Jang et al., 2009) evaluates the safety differences between continuous and limited access HOV facilities. The authors were able to conclude that limited access facilities display higher collision rates compared to continuous access lanes due to the high concentration of weaving movements occurring at defined locations. Additionally, it was concluded that both types of facilities display significantly reduced collision rates when shoulder widths are greater than 8 ft. (2.4 m.) In (Hughes, 1999), the author explores the relationship between congestion and speed differences with respect to collisions. The data for the study was collected using inductive loops along a highway facility with an HOV lane while the crashes had been previously mapped along the segment. The author concludes that the change in average speed due to congestion at given times was related to the recorded crash data from the same time period. The study conducted by (Cothron, Ranft, Walters, Fenno, & Lord, 2004) investigates the reasons behind some of the safety issues affecting HOV lanes by investigating the network in Texas. One of the major reasons for increased crash occurrence along selected corridors is most likely related to the speed differential present between the HOV lanes and the adjacent GP lane with average speed differentials along highway segments of 30 mph (48 km/h.) The increased speed differential present during HOV operations is due to the large difference in congestion levels between the different lane groups.

The study conducted by (Guin, Hunter, & Guensler, 2008) focuses on the performance of HOV lanes with respect to the adjacent GP lanes. In order to evaluate the differences, the study investigates the effective capacity of the HOV lane using speed-flow relations, speed differentials and lane densities. The authors conclude that there are significant links between

HOV lane operating speeds and GP congestion levels, with HOV drivers slowing down due to increased perception of collision risk due to the large speed differential. In (Thomson, Liu, Wang, Schroeder, & Rouphail, 2012), a study is undertaken with the goal of evaluating the difference in capacities between various HOV facilities. The authors focused on five distinct facility types, analyzed their capacities using speed-flow relationships and discovered that they all displayed varying speed-flow patterns. These findings led the authors to conclude that the capacity levels of a freeway system need to be evaluated before implementation in order to choose the most effective HOV type. The study performed by (Kwon & Varaiya, 2008) investigates the performance of the entire HOV network in the state of California. The authors evaluate the travel time, capacity and congestion effects related to HOV lanes by analyzing the speed and flow values collected using inductive loop systems over a six-month period. They conclude that roughly 80% of facilities are underutilized (flows below 1400 veh/pl/h) and that four lane GP systems carry the same number of passengers as a system with one HOV and three GP. The research in (Schofer & Czepiel, 2000) investigates the performance characteristics currently being used by transport agencies and researchers to evaluate HOV facilities. The authors look at the average volumes in the HOV and GP lanes along a number of facilities and investigate the relationship between the two volumes with respect to HOV lanes that have succeeded or failed. The authors conclude that the most important factor regarding HOV lane success is the utilization of the lane, with minimum values between 800-1000 veh/pl/h.

Chapter 2:

Verification of the accuracy of the data collection method

2.1 INTRODUCTION

The collection and analysis of vehicular traffic data is an essential component of any urban transportation system. The ability of systems to collect accurate and consistent data directly affects the ability of engineering decisions and treatments to create positive impacts in the planning, construction, and operations phases (Bahler et al., 1998). In any data collection campaign or large-scale test, the greatest challenge is the creation of the “ground truth” data, or the “reference data set that represents the actual history of the traffic” (MacCarley & Slonaker, 2007). The need for accurate data is so acute, because any errors in the ground truth data will directly impact study outcomes and ultimately decision making (Coifman, 2006).

It should therefore be clear that sensors used to collect traffic data sufficiently accurate according to the specific data needs of any given project (Coifman, 2006). Traditionally, the method for collecting data was limited to the use of inductive loops at fixed locations (Bahler et al., 1998). In fact, inductive loops became the “de facto standard” in many jurisdictions and are still used widely today (Coifman, 2005). Despite the performance of these systems, it is impractical and costly to maintain an adequate network of permanent collection locations in urban streets, collectors, and arterials (Kranig et al., 1997). Accordingly, the use of non-intrusive traffic data collection technologies has become increasingly popular. Non-intrusive technologies do not require access to the travel lane for installation. They are often installed outside the right of way, making their operations an installation much safer when compared to other technologies (Bahler et al., 1998).

Of the available technologies, video-based traffic sensors are some of the most promising. Evidence already exists showing that cameras have the ability to substitute conventional detection devices (Cho & Rice, 2006). Cameras provide additional flexibility in mountain locations an enable multiple lane detection (Bahler et al., 1998). Laureshyn (Laureshyn & Ardö, 2006) states that as “the manual processing of video data is very resource demanding work, there is a high demand for automation of this task”. This demand has led to the development of numerous systems for the automated extraction of traffic data from video footage using computer vision techniques. A video-based detection system is able to provide a wide variety of data, include conventional traffic parameters such as flow and velocity (Bahler et al., 1998; Coifman et al., 1998). In addition to conventional parameters, computer vision systems are able to extract new parameters including vehicle trajectories, which can lead to information on vehicle manoeuvring and traffic conflicts (Coifman et al., 1998; Saunier & Sayed, 2007). Perhaps the most unique attribute of video data is the preservation a complete record of events. Unlike other detectors, video captures the entire series of events as they occurred during data collection. As new measures are developed, or as data needs evolve, video footage can be reanalyzed and data extraction can be refined.

While video-based detection systems appear to have many advantages, before any system is implemented for the collection of ground truth data, the collected data must first be comprehensively verified to ensure accuracy is maintained. The purpose of this chapter is to evaluate the accuracy of a video-based detection system, comprised of commercially available video cameras and the Traffic Intelligence video analysis software system. The system will be evaluated with regards to the accuracy of extracted vehicular speeds, recognizing that a vehicle must first be detected before its speed can be evaluated. As part of this study, a technique for evaluating separately the precision and accuracy of collected data is proposed. Finally, the required accuracy of ground truth video detectors is considered.

2.2 METHODOLOGY

Site Selection

Two road types were selected to ensure a robust evaluation of video-based data collection methods. It was determined that an adequate study would contain, at a minimum, an evaluation of the technology in both an arterial and freeway environment. Arterials and highways not only provide different geometric conditions, but more importantly demonstrate varying traffic parameters, including speed and volume.

Autoroute 15 (A15) in Montreal, Quebec, Canada was the selected freeway facility. The A15 is a major north-south corridor within the island of Montreal and is one of the most heavily travelled highways in Montreal, with an AADT of approximately 90,000 (COMB, 2013). At the testing location, the geometry consists of four lanes in each direction, though certain sections feature between three and five lanes. The speed limit at the testing location is posted at 100 km/h.

Boulevard Taschereau in Brossard, Quebec, Canada was selected as the arterial facility for this study. The 17.5 km arterial runs east west on the South Shore of Montreal, connecting two major bridges and servicing important highway connections to the island of Montreal. The arterial is made up of sections with 3 to 6 lanes in each direction depending on the location with speed limits ranging from 50-70 km/h. The section chosen for this study was made up of 6 lanes in the westbound direction with a speed limit of 50 km/h.

Instrumentation and Data Collection

The same camera system was used at both sites. The selected camera was a GoPro Hero 3 video camera, set to record 720p video at 30 frames per second. The camera is capable of recording up to 6 hours of video on a single battery charge. The Go Pro camera is highly portable, allowing for extremely versatile installations, which was useful for this study.

One important criterion for site selection is the presence of existing roadside infrastructure to facilitate the mounting of the camera system. At the A15 location, a pedestrian overpass structure was used for mounting. This configuration allowed the camera to be mounted much closer to the roadway compared to other potential locations. The video camera was attached to the guardrail on the overpass using a specialized mounting system, shown in Figure 3. At Taschereau, existing luminaire poles were used to support the collection equipment. A pole system, developed by the transportation research group at McGill University, was utilized at this site. The mounting system is made up of a 20-foot telescoping pole with a bracket at its base that attaches to the base of the luminaire pole, shown in Figure 3. The close proximity of adjacent poles also allowed for the collection of simultaneous video data from multiple orientations.

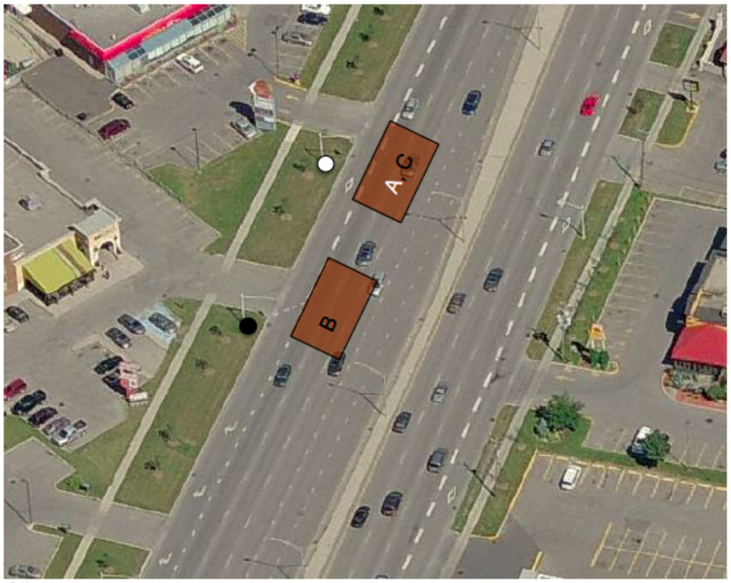
(a)

(b)

Figure 3 Mounting configurations for freeway (a) and arterial (b) environments

The objectives of this study were not only to verify the performance of video-based data collection across multiple sites, but also to test for the effect of camera orientation on reported accuracy. Knowledge of accuracy with respect to orientation is important because the ability to utilize multiple orientations during data collection improves flexibility and provides more mounting options, which may be highly beneficial in the urban environment. Messolodi et al. (Messelodi et al., 2005) demonstrated that cameras pointing downward would reduce vehicle occlusion, which could improve accuracy. Cho and Rice (Cho & Rice, 2006) discuss the issues with extracting speeds from vehicles distant from the camera. When a vehicle is at a distance, it occupies fewer pixels in the video frame, and "its features may be hard to identify and furthermore can change as the precise position of the vehicle within the pixel grid changes" (Cho & Rice, 2006).

To address these issues, three camera orientations were used at each site. The first was a perpendicular orientation, were the camera was positioned over the roadway looking directly across the lanes of travel. A perpendicular orientation enables speeds to be extracted when vehicles are closest to the camera. Two parallel orientations were also tested. A parallel orientation, were the camera is positioned looking down the roadway, is beneficial if more information, such as vehicle trajectory, is required. This orientation was used with a speed extraction zone approximately 10 m from the camera, known as "parallel close". The third orientation used a parallel camera with a speed extraction zone approximately 20 m from the camera, known as "parallel far". At least 30 consecutive minutes of video was recorded for every orientation at each site. The following Figure 4 presents the locations of the cameras and their respective study areas for both sites based on the different orientations. The black and white dots are the camera locations, and the orange boxes define the study area captured by the cameras using the three orientations (defined by the A,B and C).



(a)

(b)

Figure 4 Camera orientations and study areas for (a) arterial and (b) highway locations

Feature-Based Tracking Algorithm

The computer vision-based analysis was undertaken using an open source project called Traffic Intelligence (Saunier, 2013) developed at Ecole Polytechnique in Montreal, Canada. The program consists of several tools to analyze the video, extract vehicle trajectories, and evaluate trajectory data. The primary tool is a feature-based tracking algorithm that outputs trajectories for all moving objects in the video frame. In order to translate trajectories from the video frame to real-world measurements, a homography matrix is defined to convert object positions from the image level (pixels) to a surface (meters). A homography relates two images of the same planar surface taken from different angles by defining the pixels from one image using the warped pixels of the other image. The following equation defines the effect of a homography:

$$M = \begin{matrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{matrix}$$

where M is a 2x2 homography matrix (1)

Points x – (u,v,1) and x' = (u',v',1) are from 2 different images

The pixel coordinates are related through the homography if:

$$x' = Mx$$

The extraction and grouping of trajectories into corresponding vehicles is a crucial step. First, moving points, or features, within a defined frame are identified and tracked. These features are then grouped into objects based on their relative position and speed with respect to each other. The resulting objects are stored in a database with their two-dimensional coordinates and instantaneous velocity values for each video frame. Figure 5 shows the tracking process in action.

Figure 5 Trajectories being tracked along a lane (left) with the visible features appearing on the mask (right)

The main issues related to Traffic Intelligence are the over-segmentation and over-grouping of trajectories. Over-segmentation occurs when a single vehicle is given multiple trajectories. This primarily occurs when features are too far from each other due to the geometry of the vehicle. Over-segmentation can lead to inflated vehicle volumes but does not affect the speed values since the correct features are being grouped together. Over-grouping occurs when multiple vehicles are defined by a single trajectory, due to the proximity of neighbouring features. The over-grouping of objects will lead to inaccurate speed calculations and false volume counts (Saunier, Sayed, & Ismail, 2009). Given these issues, the most important parameters within Traffic Intelligence are related to the definition of objects with respect to the location and number of features being tracked. In order to accurately apply Traffic Intelligence, the key parameters needed to be calibrated. The calibration was done by manually counting the vehicles within a video over a specified time period. The algorithm was then applied to the video segment and the outputted volumes were compared to the actual values.

Semi-Automated Data Extraction

Data was extracted following a semi-automated approach. The extraction of speeds was completely automatically through the computer-vision software. Virtual speed boxes are added to the video frame. The extracted trajectories are evaluated over the speed box, with the instantaneous object speeds being averaged to obtain a single speed value for each object. While the extracted speeds were extracted automatically, the ground truth data set was determined manually. Vehicles were tracked through the road segment corresponding to the virtual speed box. Using the length of the box and the video frame rate, the speed of the vehicles could be calculated. As some objects are missed through over-segmentation or over-grouping, both the extracted and manual speeds need to be matched accordingly in order to analyze the results. The video output provides an object number and trajectory overlaid on the corresponding vehicle. This allowed for manual speeds to be matched one-to-one with corresponding extracted speeds for each object.

Data Analysis

To begin, analysis involved the simple calculation of the mean error in the extracted speeds at every site, as demonstrated previously within existing detector testing literature. To fully understand the behavior within the error present in the extracted data, additional analysis was completed to divide the total error into both precision and accuracy error, as described in the results below. Figure 6 presents the differences between precision and accuracy error for the speed data and is further explained in the following section.

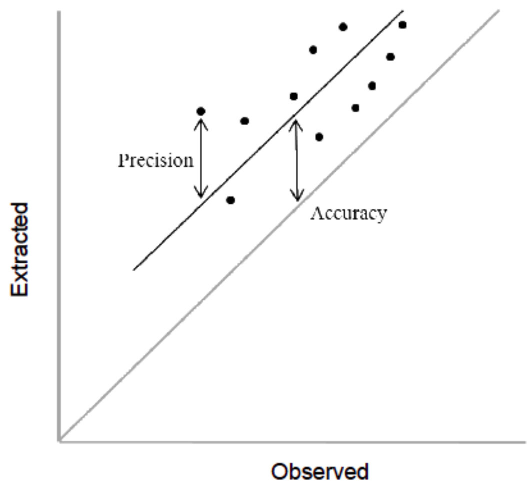


Figure 6 Demonstration of error segregation

2.3 RESULTS

Traditional Mean Error Approach

The mean error for extracted speeds was calculated at each of the 12 study areas. The mean speed error was calculated by determining the normalized error in extracted speed for each individual vehicle, and then averaging the errors across the entire sample.

$$Mean\ Error\ = \left|\frac{Extracted\ speed - Observed\ speed}{Observed\ speed}\right| \quad (2)$$

A sample of 100 consecutive vehicles was selected in each study area. The results of the mean error calculations are presented in

Table 1. It can be observed that for many of the study areas, the extracted speeds exhibit significant difference when compared to the true vehicle speeds that were calculated manually. At Taschereau, the mean error in five of the six cases exceeds 10%, with the sixth case exhibiting an error of 8%. Some variation between the lanes is also observed for the same camera orientation. For the A15, the mean error values are consistently lower with less variation

between the lanes (between 3% and 12%). The results from this conventional approach indicate that the video extracted data does not fall within acceptable limits established in the literature review for any of the study areas along Taschereau. For the A15, the video data would be acceptable as ground truth in exactly half of the study areas. In general, it would be concluded from this analysis that video extracted speed data is not within an acceptable accuracy for use in microscopic calibration and surrogate analysis.

Table 1 Mean Error Values for Video-Extracted Speeds

	Mean Error	
	Lane 2	Lane 3
Taschereau		
Perpendicular	0.16	0.08
Parallel close	0.22	0.12
Parallel far	0.15	0.15
A15		
Perpendicular	0.08	0.03
Parallel close	0.05	0.05
Parallel far	0.10	0.12

Error Evaluation

To better understand the characteristics of the present errors and in the hope of observing trends across lanes and orientations, the extracted speeds were plotted against the ground truth speeds. These plots utilize a diagonal line to indicate the ideal detector performance (that is an ideal detector would show data falling directly along the diagonal line). Data points over the line indicate overestimation of speed, while points below the line indicate underestimation. The true speeds are separated into various bins because manual calculations are limited to full frames. This data visualization is potentially powerful in identifying general trends within the results. In Figure 7 and Figure 8, the results are presented for all camera orientations over two lanes at both sites.

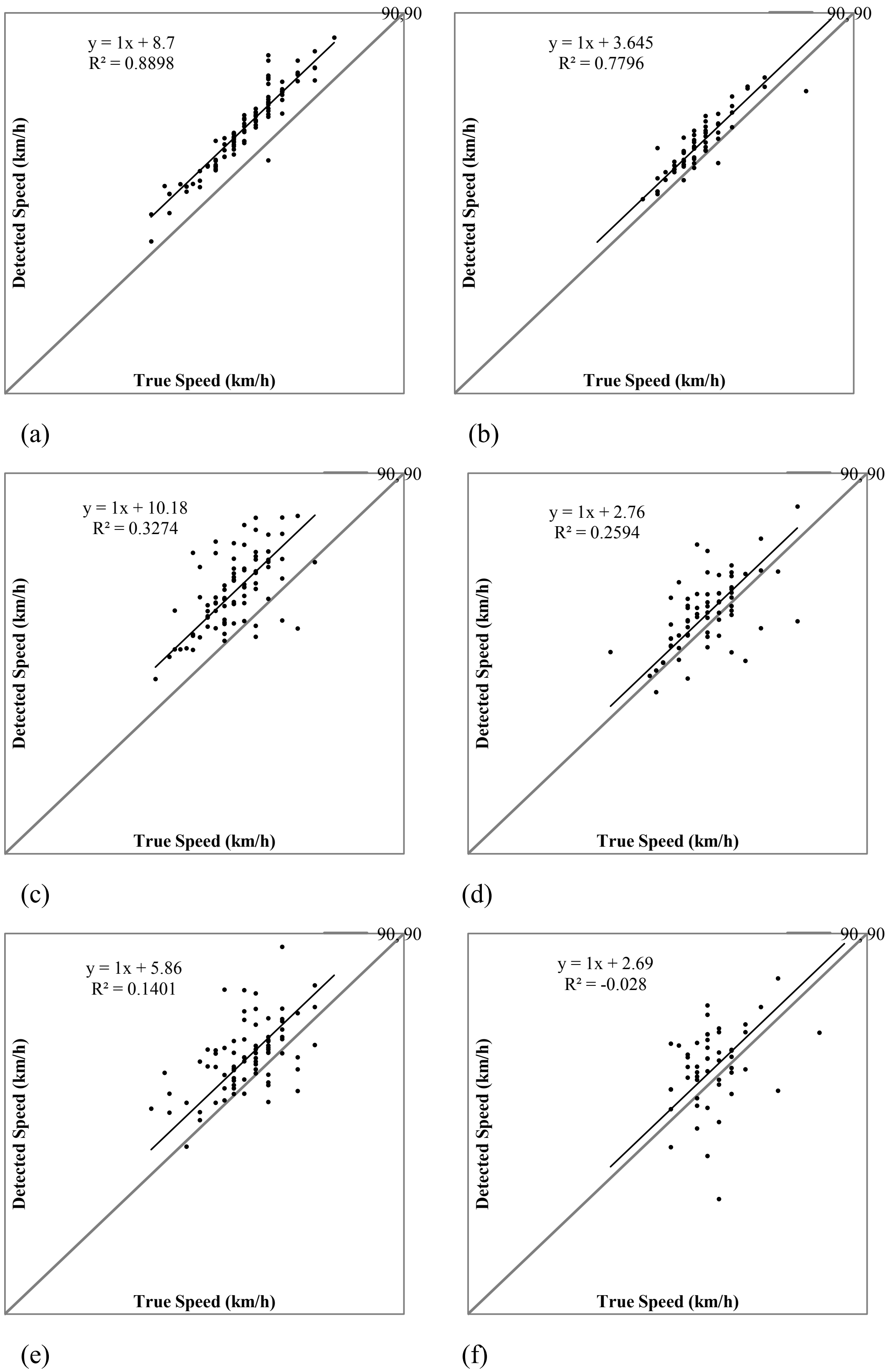


Figure 7 Detected and true speed for Taschereau, perpendicular Lane 2 (a) and Lane 3 (b), parallel close Lane 2 (c) and Lane 3 (d), and parallel far Lane 2 (e) and Lane 3 (f).

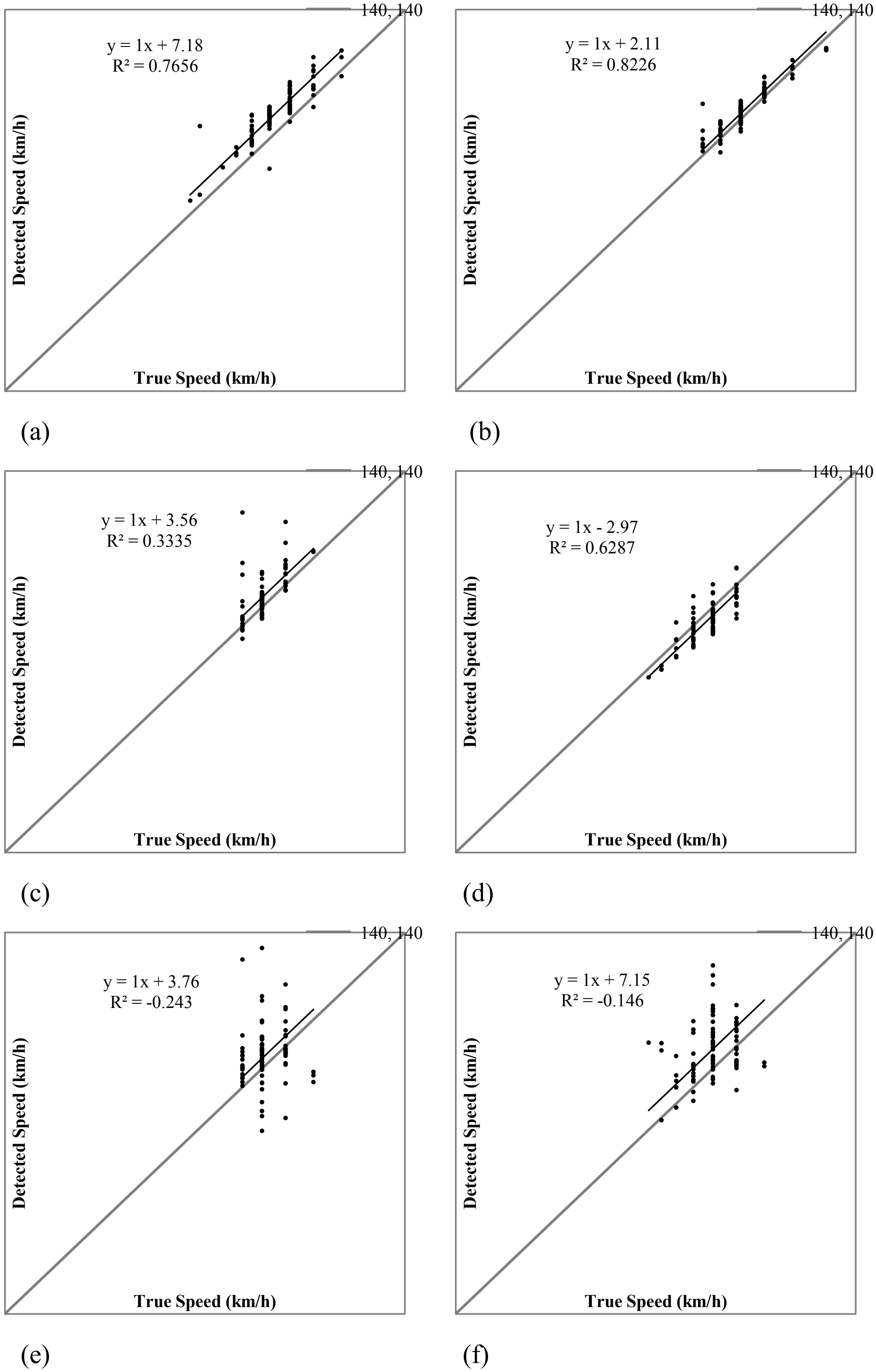


Figure 8 Detected and true speed for Autoroute 15, perpendicular Lane 2 (a) and Lane 3 (b), parallel close Lane 2 (c) and Lane 3 (d), and parallel far Lane 2 (e) and Lane 3 (f).

Visually, it was determined from these plots that the cloud of data points tended to sit above the diagonal line, indicating a general overestimation problem, consistent with (Laureshyn & Ardö, 2006). To formally investigate this, a trend line was added to the plots. The slope of the trend line was held to be 1, such that it would be parallel with the ideal line already present. Using this technique, the intercept of the trend line can indicate the direction and magnitude of the general estimation error, while the R-squared value can indicate the precision of the extracted speeds independent of any over- or under-estimation. Based on the intercept values alone, 11 of the 12 study areas exhibit overestimation trends.

While the intercept provides insight into the accuracy of the extracted speeds, the R-squared value for each trend line reveals the precision, or repeatability of each extracted speed measurement, with a higher R-squared indicating a higher degree of repeatability. In general, the R-squared values for the perpendicular camera orientation were the highest in all cases, ranging between 0.77 and 0.89. The parallel orientation with a close speed box had the second highest repeatability, with R-squared values between 0.26 and 0.63. The worst results were for the parallel orientation with a far speed box, with R-square values near zero. Fixing the slope to be equal to 1 indicates an assumption that over- or underestimation is independent of vehicle operating speed. In most cases, this assumption appears to hold, as the lines appear to be a sufficient fit of the data.

Proposed Segregated Error Approach

The visualization exercise proved to be powerful by allowing observation of both precision (repeatability) and accuracy as separate phenomenon through the use of the R-squared and intercept values. However, it would be extremely beneficial to transform these values into mean values of precision and accuracy error. Utilizing mean error values maintains the notation utilized in existing literature, and provides an intuitive and communicable comparison between sites and camera orientations. The intercept in the formulas on the figures above quantifies the difference between the line-of-best-fit and the ideal detector line. This value is indicative of the magnitude of the difference between the mean of extracted speeds and the mean of the true speeds. This accuracy error can be determined by averaging the normalized error between the line-of-best fit and the ideal line at every data point. The remaining portion of the total mean error can be attributed to precision error and is the difference between the corrected extracted speeds based on the intercept and the line of best fit. The segregated errors for all sites and orientations are presented in Table 2.

$$Precison\ error\ = \left|\frac{(Extracted\ speed \pm y\ intercept) - Observed\ speed}{Observed\ speed}\right| \quad (3)$$

$$Accuracy\ error = Total\ mean\ error - Precision\ error$$

Table 2 Segregated Error Values for Video-Extracted Speeds

	Lane 2 Error			Lane 3 Error		
	Mean	Precision	Accuracy	Mean	Precision	Accuracy
Taschereau						
Perpendicular	0.16	0.04	0.12	0.08	0.04	0.04
Parallel close	0.22	0.10	0.12	0.12	0.10	0.02
Parallel far	0.15	0.12	0.03	0.15	0.13	0.02
A15						
Perpendicular	0.08	0.03	0.05	0.03	0.03	0.00
Parallel close	0.05	0.05	0.00	0.05	0.05	0.00
Parallel far	0.10	0.09	0.01	0.12	0.10	0.02

If the mean error values from Table 2 are considered, patterns in the data are difficult to observe. For Lane 3 at both sites, the perpendicular orientation produced the lowest error, the parallel close exhibiting more error, and parallel far exhibiting the most. However, this pattern does not hold for Lane 2 at either site. Based only on the mean error, there are no emergent patterns, and the video extraction technology would likely be rejected for collection of ground truth speed data. However, when the error is segregated, patterns in the data do emerge. For example, the perpendicular camera orientation consistently produced the lowest precision error, followed by the parallel close orientation and the parallel far orientation with the highest precision error. Additionally, the precision error is observed to be nearly equal for both lanes within each orientation. Consistently, a single orientation produced equal or nearly equal values of precision error across both lanes at the same site.

Interestingly, the patterns for accuracy error are not as clear. The accuracy error is typically not equal across lanes at a single site. When considering camera orientation, it is clear that the parallel far orientation typically produced the lowest accuracy error. This indicates that the repeatability of speed measurements is much better when the speed extraction zone is close to the camera (i.e. either the perpendicular or parallel close orientations). However, the speed that is averaged across multiple consecutive vehicles will be much closer to the true mean speed when the parallel far orientation is utilized.

2.4 DISCUSSION

Video data collected using a perpendicular orientation results in the most precise speed estimations using the feature-tracking software. At Taschereau, the speed boxes for the perpendicular and parallel far orientation were at the same location, and data was collected simultaneously. Furthermore, data for the parallel close were collected immediately upstream. This means that the samples at Taschereau generally contain the same vehicles travelling at a constant speed. As the error results indicate, the precision error at Taschereau is lowest for the perpendicular orientation (4%), followed by parallel close (10%), and parallel far (12% and 13%). Collecting data simultaneously and using the same vehicles across each sample data set further validated the results.

The difference in precision error for the same orientation at the different sites is noteworthy. Consistently, the precision error reported at the A15 was lower than corresponding error values at Taschereau. While the errors for the perpendicular orientation were approximately equal, the errors for both parallel configurations at Taschereau were between 3% and 5% higher. Some of the variation can most likely be explained by difference in camera setup and distance to speed extraction zone. At Taschereau, the camera's location on the side of the road limited the camera's parallel orientation to being slightly less than 180 degrees. At the A15 study site, the location of the overpass structure allowed for true parallel orientations using the adapted video recording setup. These small differences may have contributed to the variation in precision error.

In addition to camera angle, the height at which the video data was captured varied slightly between the sites. The pole used along Taschereau has a maximum height of 20 feet whereas the overpass height along the A15 was approximately 25 feet above the road surface.

From the results above, it appears that precision error is highly dependent on camera orientation, while accuracy error is more independent. Although a weak trend of decreasing accuracy error with increasing distance was observed, the trend did not hold for each site or across all lanes. Precision is predominantly related to the ability of the software to consistently track and detect features. Even if errors are made in the programming or calibration or the feature tracking and speed extraction, those errors will appear across all objects. This means that even inaccurate speeds will be consistently inaccurate. Precision is highest when objects are close to the camera, where their features can easily be identified and tracked. Objects further from the camera have smaller features, which may appear or disappear in certain frames due to low pixel resolution. For these reasons, the pattern in precision error can be explained. Accuracy error is highly dependent on the parameters of the tracking and extraction modules, as well as the created homography. As parameterization and homography were completed for each camera orientation, variability was introduced that can be attributed to the software and not to the orientation.

Although the perpendicular orientation yields more precise vehicle speeds compared to the parallel close angle, both orientations serve a purpose in different data collection applications. The availability of roadside structures suitable for video data collection is a deciding factor in many situations. One of the most important issues that arises with the perpendicular orientation is the occlusion that occurs when vehicles in separate lanes travel through the extraction zone simultaneously. If the recording system cannot be installed high enough above the road surface, a substantial number of vehicles can be missed, resulting in a false representation of the traffic environment. Alternately, the parallel orientation is necessary when vehicle interactions and lateral movements need to be observed. Ideally, both orientations should be used to complement the data, providing researchers with a more detailed picture of the traffic environment within a study area.

2.5 CHAPTER CONCLUSIONS

This study was developed to evaluate the potential use of feature-tracking software and video data as ground truth for the collection of disaggregate vehicle speeds. Multiple camera orientations were tested along arterial and freeway facilities. The individual speed values were compared to manually collected results across 12 study areas. Although the traditional mean error approach did not lead to acceptable results, a new approach was proposed for the evaluation of traffic detection technologies. The proposed segregated error approach divides the mean error values into separate values representing accuracy and precision (repeatability) errors. In doing so, several of the camera orientations exhibited precision error values within the accepted range for ground truth speed calculations (5%). Even with large accuracy errors, video data can be calibrated for use as ground truth data, so long as precision error is minimized through appropriate selection of camera position and orientation.

The biggest benefit of the segregated error approach is that it allows for ground truth data collection by devices that might be dismissed by traditional approaches. Although video data displays a total mean error much greater than 5% in most cases, the precision, or repeatability, of video extracted speeds is often within reasonable limits for ground truth data. This method provides the ability to compensate for the over-estimation problem present in many video-based detection systems. Importantly, even devices exhibiting a high accuracy error can be calibrated to provide consistent and accurate speed measurements. The same cannot be said about devices with high precision errors. The segregated error approach can allow practitioners to select devices with high levels of precision regardless of the level of accuracy. This result has implications for the testing of new traffic detection technologies and the selection of technologies for the process of traffic data collection.

In future studies, the validity of calibrating detection devices using this approach will be considered. Importantly, more testing sites should be utilized to ensure that the patterns demonstrated herein apply universally. Finally, the behaviour of more detection technologies should be evaluated with respect to the segregated error approach.

Chapter 3:

Microsimulation calibration study

3.1 INTRODUCTION

Traffic microsimulation software has become an essential modeling tool in transportation research and practice. Many applications of traffic microsimulations are being used to analyze and evaluate transit projects and issues. However, the reliability and accuracy of these models relies on how precisely the field conditions are represented by the software parameters. Typical traffic microsimulation software such as VISSIM, PARAMICS and AMSUM has a number of parameters that can be calibrated for specific traffic environments and situations. Calibrating parameters from microscopic data such as acceleration, speed distribution and driver behaviour as well as dwell time for bus transit in a bus corridor or roadway section are vital to the proper use of microsimulation software. A careful calibration is required to properly validate simulation output on a microscopic scale if one is to use simulation results to study microscopic behaviours, safety or emissions. The challenge is to adjust or calibrate the set of vehicle parameters for the local conditions. This issue has attracted some attention in the past; for instance we can refer to the studies presented in (Toledo & Koutsopoulos, 2004; Yu et al., 2006; Zhang et al., 2012) that use GPS data and sensors to obtain speeds within corridors. Despite these advances, these studies do not adjust for other parameters such as speed distributions, vehicle characteristics and bus dwell times. As well, GPS data only provides speed profiles for a given vehicle, not for the whole population of motor vehicles in a given link. Getting a representative sample of GPS data for all vehicles in a specific facility can be difficult and costly. Moreover, alternative sources of data have emerged in the transportation literature such as the video-based trajectories from which microscopic data can be obtained for all road users. Despite that, no applications have been documented in the literature taking its advantages.

This chapter proposes methods to calibrate essential parameters for the microsimulation of specific roadway facilities, some with bus transit traffic. These parameters are motor-vehicle speed profiles and bus arrival and departure times. These methods uses microscopic data generated from automatic video-based trajectories using computing vision techniques. Notably, a new method is developed to detect bus dwell times thereby expanding the capabilities of the tracking software. The advantages of video-based trajectory data for microsimulation model calibration are demonstrated using case studies in Montreal, Canada of a major bus corridor with an exclusive bus lane and articulated buses, and a highway corridor with a High Occupancy

Vehicle (HOV) lane. Furthermore, an emissions model is applied to the microsimulation scenarios and the emission rates of the default and calibrated models are compared. This research also illustrates the advantages of the use of mobile video data collection systems.

3.2 METHODOLOGY

The following section introduces the methods developed for this study. Figure 9 presents the steps involved in the microscopic calibration that includes video data collection, video processing, calibration and post-processing:

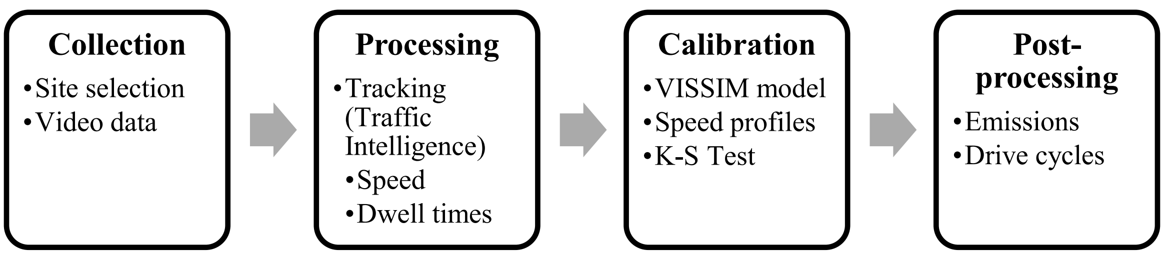


Figure 9 Steps involved in the proposed methods

Collection

The facilities of interest in this study are exclusive bus lanes and HOV lanes. Accordingly, two important corridors of each type are selected from which different roadway sections are identified for data collection using mobile video cameras. The mobile video cameras are installed on adjacent infrastructure using a mast with a max height of 10 m (30 ft). After collection sites have been chosen, video camera equipment is installed along the facilities for several hours in each location. (Jackson et al., 2013)

Video Processing

This work relies on an open source project under active development called Traffic Intelligence (bitbucket.org/Nicolas/trafficintelligence) *Saunier (2013)* that consists of several tools for video analysis and the interpretation of the resulting trajectory data. A feature-based tracking algorithm *Saunier and Sayed (2006)* is used that yields the trajectories of all moving objects in the camera view or a user-defined zone. In order to obtain measurements in real world coordinates, e.g.

meters, a homography matrix is needed to project the vehicle positions in the image space (in pixels) to the road plane (e.g. in meters).

The video tracking process begins with the extraction and grouping of feature trajectories into each moving vehicle. The program detects and tracks distinctive moving points called features within the frame that are then grouped together based on their proximity to one another and their relative motion. The main issues are over-segmentation (several trajectories for the same vehicle) and over-grouping (one trajectory for several vehicles). In order to minimize these issues, the parameters of the program are tuned by trial and error and consider the effect of factors such as the positioning of the video camera. Once the tracking parameters are properly set and the program analyzes the video, the vehicles are stored in a database that includes the vehicle unique number and the two-dimensional coordinates of the object at each time step, i.e. for each image frame in the video. Velocity data is also stored in the database by differentiating the positions over time. This process can be tailored to extract a number of traffic parameters. In this study, speed distributions and bus dwell times are the target parameters.

Speed Distributions

The tracking software collects trajectory and velocity data for all the vehicles at each frame in the video. Filters are applied to the trajectories in order to collect measurements for all of the motor vehicle types. The presence of an exclusive lane in the study area means that vehicle types are segregated by lane for most sites. Areas or “speed boxes” are drawn manually for each zone where speed data is desired, e.g. for each lane of traffic. These speed boxes are similar to virtual loops. Running through the trajectory database, the average velocities of the vehicles passing through the boxes are collected and outputted using the frame rate and the mean and standard deviation are calculated from the speed distribution.

Dwell Times

A new method was developed to detect the times of arrival and departure of the buses. The analysis could not rely on the fact that the lane was exclusive to buses because it was not respected by all road users and data was collected at one site when the exclusive lane was not in effect. The video-tracking algorithm was run on a specific window drawn in the image space in the bus lane before and after the bus stop. This allows for the detection of movement specifically in this zone. The rules to filter only buses were based on the object’s consistent heading and its maximum size. The angle of the instantaneous speed vector with a reference vector was computed in each frame to filter out vehicles turning at intersections if there was one in the field of view. The buses in the area under study are all articulated and therefore longer than other vehicles. Their size is the maximum distance between any pair of features on it. To identify stopping and departing buses, the sign of the speed difference between the beginning and end of the bus trajectory was used.

Microsimulation Calibration

VISSIM has a number of parameters that can be calibrated. The controlling processes within the software include a psychophysical model for longitudinal movements and an algorithm for lateral movements. The following list presents the most important VISSIM parameters that involve components of vehicle interactions and driver behaviour (Gomes et al., 2004; Lownes & Machemehl, 2006).

- Speed Distribution: Cumulative distribution that is focused around the median value.
- Acceleration/Deceleration: Maximum and minimum values for accepted acceleration/deceleration within the network
- Dwell Times: The time a bus spent at a transit stop. Boarding and alighting rates can then be measured accordingly.

In order to calibrate VISSIM for this study, the following parameters had to be measured in the field using specific measurement processes. First, the speed distribution of all the vehicles travelling along the corridor was collected using the video tracking software applied to the raw footage collected in the field. Second, bus dwell times were calculated by a semi-automated method using the tracking software. The number of passengers alighting and boarding were counted manually by studying the video footage. Average boarding and alighting rates were then calculated based on the dwell times.

The vehicle models and performance characteristics used in VISSIM are based on European vehicles (PTV, 2011). A North American template was inputted into VISSIM in order to simulate a more accurate traffic environment. The template included vehicle dimensions, features and acceleration and deceleration profiles for passenger vehicles.

The speed profiles are the focus of the calibration in this study because the dwell times and acceleration profiles are set parameters in the microsimulation environment. The speed profile in

VISSIM is a cumulative distribution function for the desired speeds assigned to the vehicles when generated by the simulation. Each vehicle's desired speed is fixed. The vehicle tries to reach it but may not depending on traffic conditions which is why the calibration of the default profiles is necessary in order to accurately, simulate the observed driving environment. For this study a semi-automated iterative process was designed with the objective of minimizing the error between the observed speed profiles and the simulated speed profiles. First, the observed speed profiles are extracted using the tracking software and inputted into VISSIM. Second, the scenarios are run using the observed profiles while simulated speed collection sensors placed in VISSIM according to the actual data collection sites then captured the simulated speed profiles. The speed profiles are exported to MATLAB and a two-tailed Kolmogorov-Smirnov test is applied in order to test the fit of the simulated profiles with respect to the observed values. The Kolmogorov-Smirnov test (K-S test) is a non-parametric test that has been used successfully in previous calibration studies (Hollander & Liu, 2008; Kim, Kim, & Rilett, 2005; Zhang et al., 2012) and compares the overall fit of two samples by quantifying the distance between them. Formally, the two-tailed K-S test is given by:

$$D_{stat} = sup|F_1(x) - F_2(x)| \qquad (4)$$

F_1 *and* F_2 are empirical distribution functions

The null hypothesis (H_0: $F_1 = F_2$) is rejected when the D_{stat} is larger than the critical value for a defined alpha value. The results of the K-S test are analyzed based on the p-values at an alpha of 5%. The VISSIM speed profiles are automatically adjusted based on the previous K-S test results and are analyzed using this process, until a statistically relevant threshold was achieved for all of the data collection locations within the scenarios

Emissions Modeling

The next step involves the modelling of emissions along the facilities using the MOVES emission modeling software. The objective of the emissions analysis is to quantify the importance of calibrating microsimulation parameters by comparing the emission rates of the default and calibrated VISSIM scenarios. The emissions software requires the following inputs. (Koupal, Cumberworth, Michaels, Beardsley, & Brzezinski, 2002; Koupal, Michaels, Cumberworth, Bailey, & Brzezinski, 2002)

- Temporal and meteorological data: using weather data from weather stations for temperature and relative humidity.
- Traffic volume: using both the calibrated and default scenarios from VISSIM data collection points.
- Fuel type: using gasoline as the fuel type for the passenger vehicles.
- Age distribution: using a typical age distribution for cars ranging from 0 to 20 years.
- Vehicle drive cycles: inputting link-level drive cycles from VISSIM were inputted into MOVES.

3.3 CASE STUDIES

Côte-des-Neiges bus corridor, Montreal, Canada

The Côte-des-Neiges is one of the main bus corridors with an 8 km (4.97 mi) section that includes bi-directional exclusive bus and taxi lanes that are active during the morning peak (southbound) and the evening peak (northbound). The test location for this study was chosen based on a number of factors. First, the sites had to have appropriate utility poles along the roadway in order to properly install the camera equipment. Second, the site had to be free of any obstacles such as trees and overhanging structures that may affect the tracking algorithm. Third, the section had to be relatively straight in the horizontal and vertical axes in order to measure the vehicle trajectories as accurately as possible. Based on these factors, the study area was located along chemin de la Côte-des-Neiges between avenue Decelles and the Boulevard in the southbound direction. The Côte-des-Neiges corridor has operating speeds of 50 kph (31mph) in both the reserved and general lanes.

For this study, ten hours of video data was collected at four separate locations along the corridor, shown in Figure 10. The bus dwell times and speed data were collected at all four locations, however the VISSIM speed calibrations were done using two of the study areas (Armoury and Decelles) due to the presence of signalized intersections at the other locations. The speed profiles and dwell times were collected using the Traffic Intelligence software and inputted into VISSIM. The following sections present the results of the calibration of the microsimulation scenario.

(a)

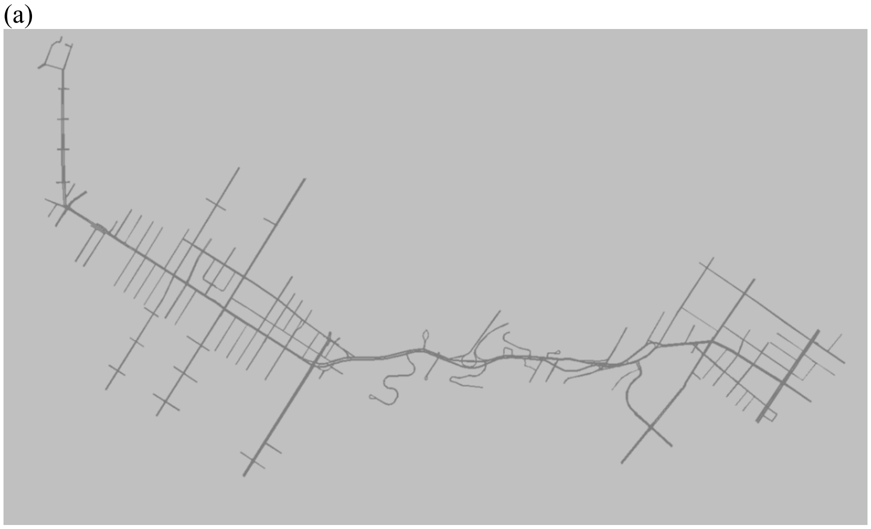

(b)

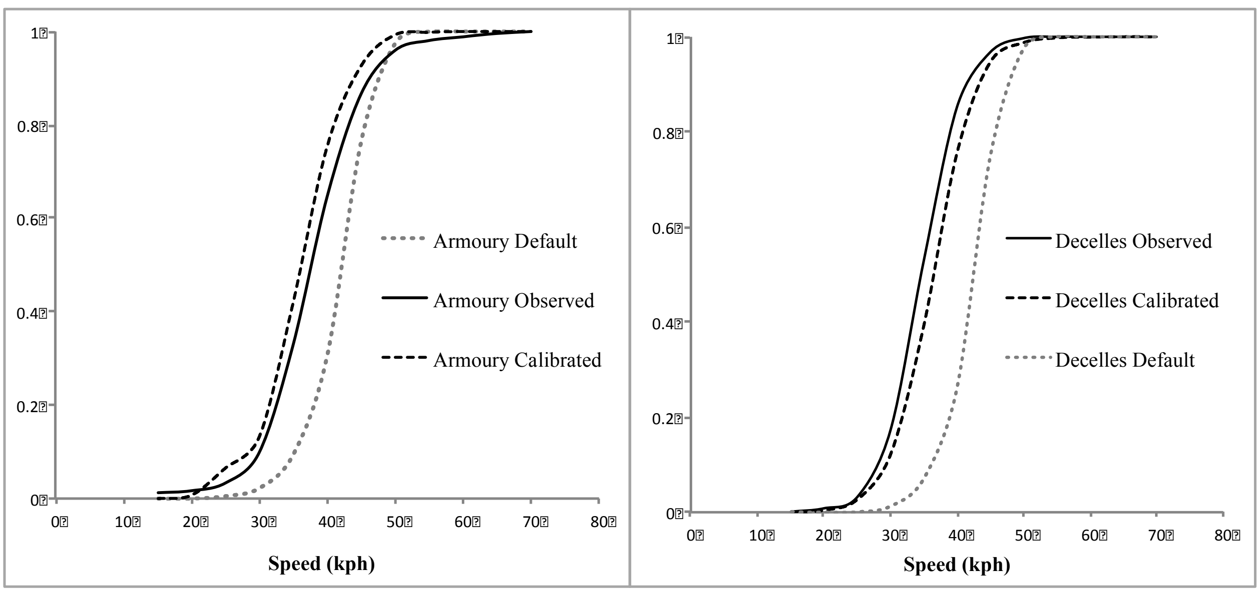
Figure 10 (a) The Côte-des-Neiges study area with markers indicating the four video data collection sites and (b) The VISSIM network of the Cote-des-Neiges corridor

Dwell times

The results of the methods are satisfactory for arrivals, as all were successfully detected without any false alarms. The results are mixed for departures since, depending on the sites, few features can be tracked so far away from the camera, and the perspective makes it difficult to measure how the speed is changing (the homography loses accuracy as the distance from the camera increases and, combined with some lens distortion, measured speeds tend to "naturally" diminish as vehicles move further away from the camera). It follows that many dwell times cannot be measured automatically. For those, the departing time for the buses was manually collected. The dwell times that could be automatically measured were validated by comparing them to the manually recorded times (recorded in-field using a stopwatch). The percent difference between the two methods based on data from all four locations was 1%. This difference is mainly due to rounding and mechanical errors since the software measures in frames (1/30th of a second) while the stopwatch measured in tenths of seconds.

<u>Speed profiles</u>

In order to calibrate the speed profiles of the vehicles travelling along the corridor, the speeds collected at two sites were extracted from Traffic Intelligence and inputted into VISSIM. The following figures present the differences between the observed speeds, the VISSIM default speeds and the calibrated speed profiles for the locations during a typical peak hour period.



	Armoury			Decelles		
	Observed	Default	Calibrated	Observed	Default	Calibrated
N	1289	1234	1276	1329	1264	1197
Mean (kph)	47.7	46.5	43.5	42.3	47.1	43.9
Standard Deviation (kph)	17.3	5.1	6.2	5.2	4.3	5.6
p-value (two-tailed K-S test)		0	0.79		0	0.66

Figure 11 Speed profiles for sites (a) Armoury and (b) Decelles and the final iteration of the K-S test

Based on visual inspection, the differences between the default and calibrated speed profiles are noticeable. For instance, in Decelles, the observed mean speed is 42.3 kph, which is much lower (about 5kph differences) than the default parameter. In order to quantify these observations in Figure 11 presents the results of the K-S tests for the Côte-des-Neiges corridor. Both calibrated profiles exhibit strong relationships with the observed speed profiles (p-values of 0.79 and 0.66 for Armoury and Decelles respectively).

Significant improvement when using calibrated speeds is measurable in other parameters such as travel time and delay. For instance the difference between the default and calibrated travel times along the corridor averaged 10% (i.e. higher calibrated travel times).

Emissions Modeling

The drive cycles were extracted from the default and calibrated VISSIM scenarios in order to model the emissions along the corridor. The drive cycles are defined as the average speed of all vehicles per time interval along each link of the corridor. In this case, six links within VISSIM are being analyzed measuring a total of 1.45 km (0.9 mi). As the other MOVES parameters remain constant for both scenarios, the different drive cycles are inputted into the model and the emission rates in g/mi are compared in Figure 12.

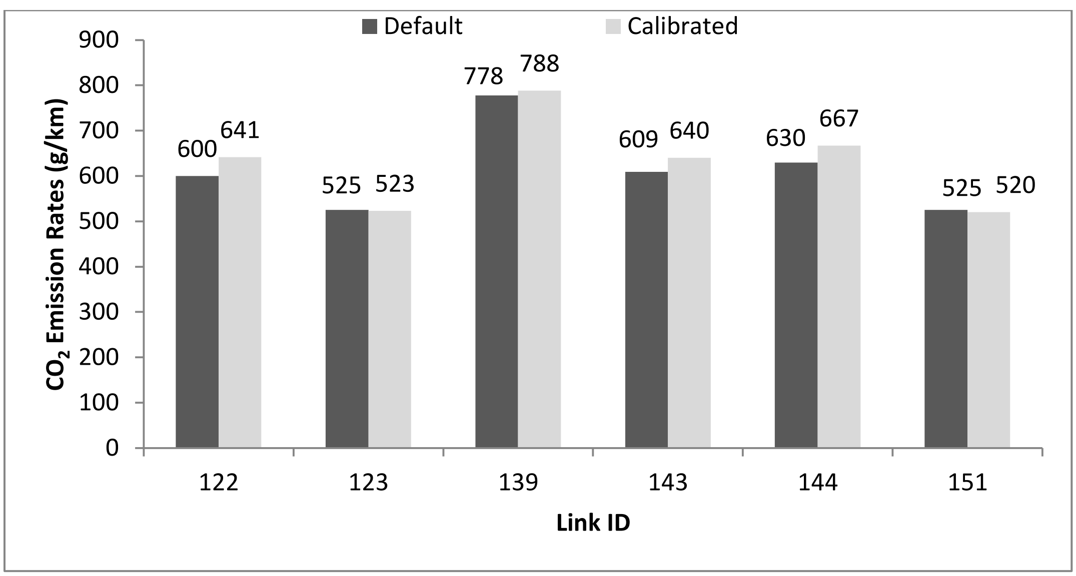


Figure 12 CO_2 emission rates for the default and calibrated scenarios at the link level as well as the relationship with the calibrated average speeds for the Côte-des-Neiges case study

The results from the emissions model validate the observed differences between the calibrated and default microsimulation scenarios. Although the differences are marginal for some of the microsimulation links, these rates represent the average values during the peak period. This is supported by the difference in the emission rates for the default and calibrated profiles. According to emissions studies *(Alessandrini, Cattivera, Filippi, & Ortenzi, 2012; Barth & Boriboonsomsin, 2008)*, CO_2 emissions as a function of speed exhibit the following relationship as displayed in Figure 13. Moreover, the outputted emission rates are all within the range of observed values as displayed in Figure 13.

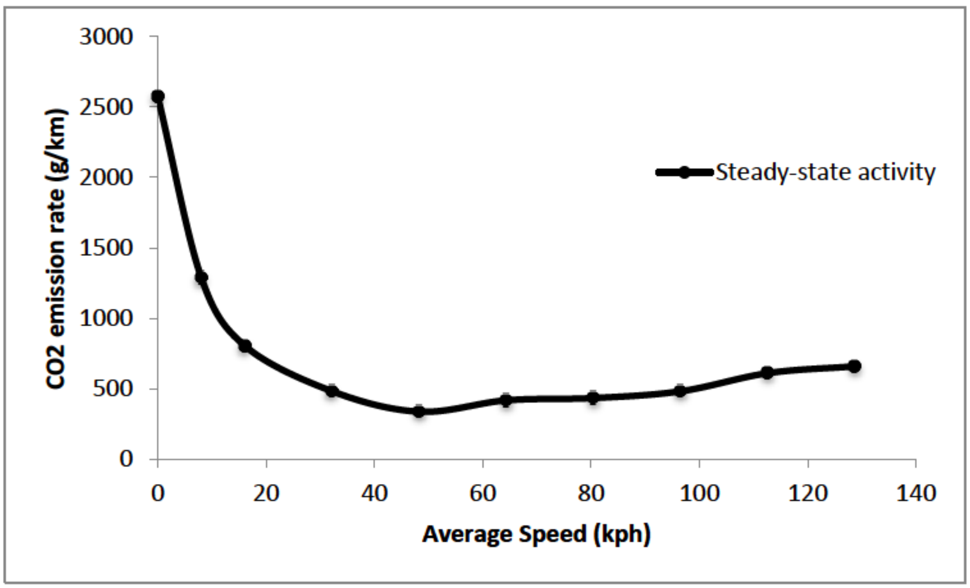


Figure 13 CO_2 emission rates as a function of speed

The Côte-des-Neiges corridor exhibits speeds in the 15-50 kph (10-30 mph) range. At this level of the curve, a decrease in average speed would lead to an increase in emissions. In summary, the speeds are overestimated by 5% when using the default parameters, which results in a 3% average difference in CO_2 emissions between the calibrated scenario and the default scenario. Furthermore, the average speed for each link presented in Figure 13 also follows the inverse relationship between speed and emission rates.

Highway A15, Montreal, Canada

The A15 is the major north-south highway on the island of Montreal. In order to try and curb the congestion and promote car pooling on the A15, the Ministère des Transports du Quebec (MTQ) implemented a 9 km (5.5 mi) HOV facility in the northbound direction during the weekday afternoon peak period of 3pm-7pm.

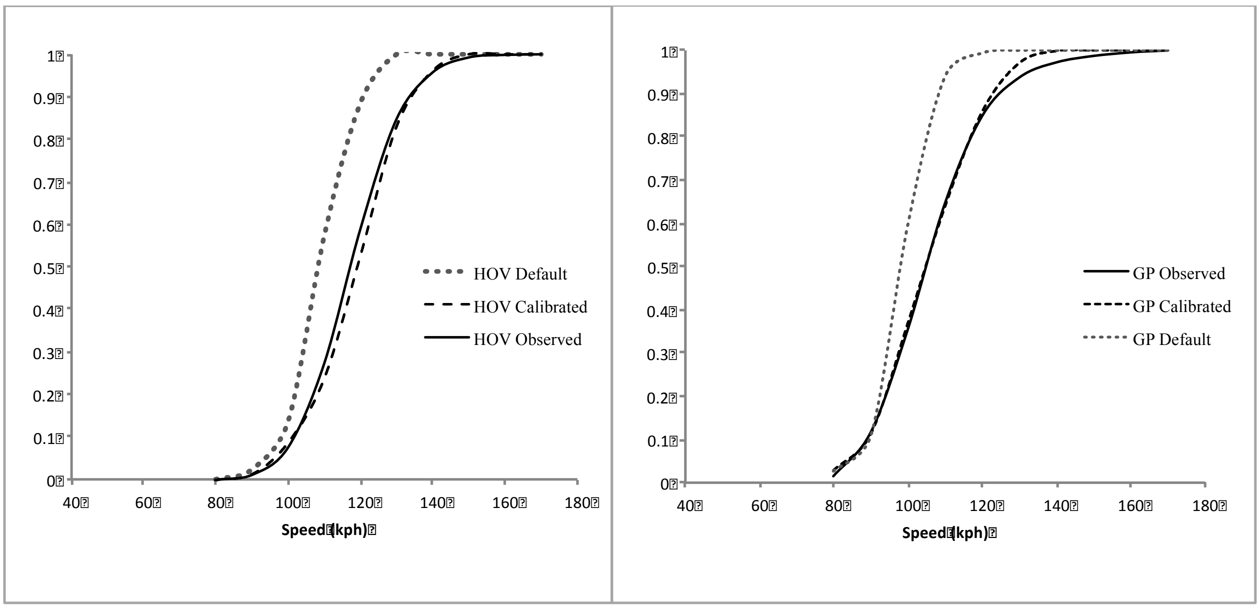
Figure 14 displays a map of the area, highlighting data collection sites. The lane is never cut off from the general purpose facilities, allowing vehicles to get on and off of the HOV facility freely. The highway is made up of 4 lanes in each direction (including the HOV) along this stretch, with certain sections going down to 3 and up to 5 depending on the road geometry. The posted speed limits for both the HOV and general purpose (GP) lanes along the corridor is 60-100 kph (37-62 mph).

For this study, eight hours of video data was collected at two sites along the facility during the weekday rush hour periods. The speed data and volumes were extracted using the tracking software and the speed profiles were obtained for the HOV and GP lanes.

Figure 14 The A15 highway study area with the markers indicating the two video data collection sites

Speed Profiles

The VISSIM microsimulation was developed using the collected traffic characteristics and the calibrated speed profiles were obtained using the methods described in the previous section. The study area includes 5 links in VISSIM measuring a total of 2 km (1.2 mi). A link is defined as section of road usually between intersections. The following Figure 15 presents the observed, calibrated and default speed profiles for both the GP and HOV lanes for a typical peak hour traffic environment.



	HOV			GP		
	Observed	Default	Simulated	Observed	Default	Simulated
N	572	387	415	6432	6256	6317
Mean (kph)	122.6	113.7	124.7	111.6	103.2	110.2
Standard Deviation (kph)	12.6	8.2	12.1	16.1	7.7	13
p-value (two-tailed K-S test)		0	0.74		0	0.68

Figure 15 Speed profiles for (a) GP and (b) HOV lanes and the final iteration of the K-S test

The K-S test for the A15 corridor also presents statistically relevant results for the calibration of the speed profiles for the HOV and GP lanes (p-values of 0.74 and 0.68 respectively). Moreover, the differences between observed and default mean speeds are more important than in the previous case study, with an underestimation of approximately 8%. This again highlights the significant benefits that can be obtained from an appropriate calibration – default calibration can lead to inaccurate speeds, travel times and delays.

Emissions modeling

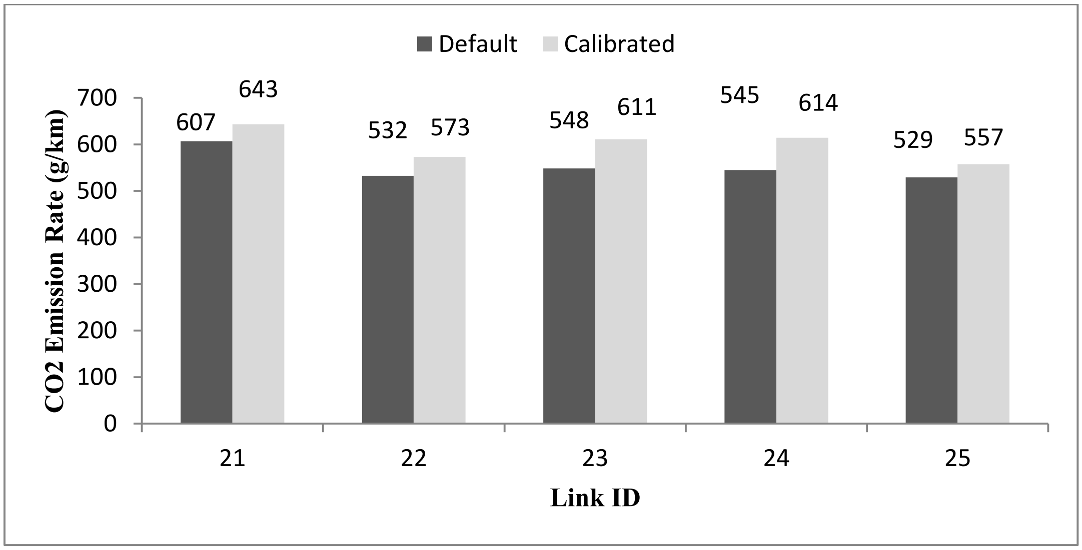


Figure 16 CO_2 emission rates for the default and calibrated scenarios at the link level as well as the relationship with the calibrated average speeds for the A15 case study

The emissions model for the A15 differs from the Côte-des-Neiges corridor because the facility has operating speeds in the 100-110 kph (60-65 mph) range. The calibrated and default scenarios have measurable speed differences and these are reflected in the emission rates. The results indicate that the calibrated model has emissions rates that are on average 8% higher than that of the default model. It is worth noting that both the emission rates as a function of speed are well within the accepted range based on *(Alessandrini et al., 2012; Barth & Boriboonsomsin, 2008).* Moreover, the average speeds for each link of the highway presented in Figure 16 are positively related to the emission rates, further validating the results of parameter calibration and emission modeling.

3.4 CHAPTER CONCLUSIONS

This chapter presents and demonstrates the application and reliability of methods for calibrating microsimulation models using video-based trajectory data. The methods are developed using

VISSIM and MOVES software. Using a mobile video-camera system, video data is collected and processed to obtain important microscopic parameters such as speed distributions and bus dwell times in two roadway sections, one with bus transit facilities. This study demonstrates the potential that this method of data collection and trajectory analysis can have on the calibration of microsimulation software. The proposed approach allows for the collection of individual vehicle speed distributions and bus dwell time data in the field. With video collection, the entire traffic environment can be recorded along with the interactions between vehicles. The experimental results indicate that both the speed distribution and the vehicle characteristics are key factors within VISSIM scenarios involving bus corridors and HOV facilities. Important biases were observed (up to 8%) between the calibrated and default average speeds. Significant improvements in the accuracy of the models are achieved when using calibrated microscopic data. Results from modeling the emissions in two distinct traffic environments were promising. The calibrated and default models for speed and CO_2 emission rates were positively related and were well within acceptable ranges. Furthermore, differences between the calibrated and default speed profiles, as well as between the calibrated and default emissions followed comparable patterns.

Future work will include the collection of data at more sites within the networks as well as the collection of additional data at each site in order to preserve data for validation and decrease the risk of over fitting the model. Both case studies reveal a difference between the collected and simulated speed profiles. This may have resulted from the following factors. First, the collected samples may not represent the typical behavior of the network. Second, the speed measurements in the simulation result from several factors, in particular the driver behavior parameters, and from the complex interaction of the vehicles that may prevent them from reaching their desired speed. In all likelihood, the reason for the discrepancy is a combination of both factors. Further research and more advanced analyses along with the additional data collection will likely elucidate this issue.

Future work will also include the collection and measurements of lane changing behavior, gaps, vehicle classification and accelerations. Furthermore, the algorithm for the detection of arrivals and departures needs to be validated on other datasets. The method of tracking in specific areas or virtual loops is promising. A more advanced automatic calibration system will lead to a more efficient and accurate calibration process and more precise simulations. Subsequent activities will also involve the application of this method within other traffic environments. Moreover, the collection of other traffic parameters could lead to the application of the calibration process in the analysis of traffic safety. The continual advances exhibited in intelligent transportation systems (ITS) will also allow for the development of additional applications for automated feature-based tracking and video data collection.

Chapter 4:

Performance And Safety Evaluation Using Surrogate Analysis

4.1 INTRODUCTION

The following chapter presents methods to evaluate the performance and safety of HOV facilities using a video-data collection processing system tested in the previous chapters of this document. The methods are illustrated using two case studies. The first case study investigates the performance and safety of a part-time highway HOV lane in Montreal, Canada. By using data recorded at multiple sites along the segment both before and after the installation of the HOV facility, the average hourly throughputs, travel times, violation rates and speed differentials are analyzed and compared, and these are referred to as performance indicators. The second case study explores the use of trajectory data for an arterial segment in Brossard, Canada with a reserved bus lane. With this data, this case study investigates the lane change violation rates and time-to-collision (TTC) measurements at entry and exit points at two sites along the arterial.

It is worth mentioning that although a number of technologies have been used to collect data and evaluate HOV lanes, including inductive loops, radar and detectors (Shaw, 2003), the feature-based tracking approach supported by video data are relatively new options in practice and research and provide a rich source of microscopic information. With the development of HOV and HOT facilities across North America, the integration of non-intrusive technologies for toll payment and enforcement activities is a primary objective for facility operators. The use of video-based sensors (mobile or fixed) could then help increase the overall effectiveness of the lanes while reducing safety issues along the entire network. Additionally, the video-based mobile systems allow for the collection of microscopic traffic data for all vehicles traveling along a facility in a given period of interest, which is essential during a diagnostic study on operations and safety.

4.2 CASE STUDY 1: HIGHWAY HOV LANE

The proposed methods consist of the following steps: site selection and identification of performance measures, video data collection and processing and the analysis and identification of issues. These methods are designed to evaluate the performance, safety and adoption of a highway HOV facility using alternative data collection and processing applications. This involves using a before and after approach, in which data is collected prior to and after the HOV facility is installed. The methods are based on the guidelines described in the "HOV Systems Manual" presented in the NCHRP Report 414 (Institute, Parsons, Douglas, Pacific Rim Resources, & Board, 1998):

- Definition of project objectives
- Identification of measures of effectiveness
- Collection of Before data
- Collection of After data
- Analysis of Before and After data

To determine the performance of the study highway sections, different traffic parameters and infractions are quantified including speeds, volumes and violation rates along the segment, before and after the implementation of the HOV lane. The analysis will take into consideration the average speeds per lane, the speed differential between adjacent lanes, the hourly flow rates per lane and the violation rates along the HOV lane during operational hours.

Site selection and description

The most important feature of the site selection is the identification of sites at which traffic data can be collected both before and after the construction of an HOV facility or before ad after the temporary closure of an HOV facility. The latter scenario meets the time parameters of this study and a single opportunity presented itself with a temporary shutdown of the HOV facility along the A15 highway in Montreal, Canada. Between August and November 2013, the HOV lane, which had operated during peak hours on weekdays, was decommissioned due to construction on an overpass crossing the highway. The construction did not affect the geometry of the highway segment in any way. The highway continued to operate the four northbound lanes as GP lanes during the afternoon peak period traveling northbound. In summary, for approximately three months the A15 segment had reverted to a non-HOV highway. Since the HOV lane on the A15 is continuous access and separated by normal broken lines, the highway segment looks and performs like a typical four-lane highway facility. In order to shut down the part-time HOV facility, the overhead signs reminding drivers of the presence of the HOV lane were covered.

Two sites along the A15 highway were selected for data collection in order to evaluate the overall performance of the segment. The following criteria were used in order to select useful data collection sites. First, the site had to have the presence of structures above or adjacent to the highway facility in order to properly collect video data using the recording system. Second, the site could not contain objects that may obstruct the video frame due to the nature of the tracking software. Third, the site had to be relatively flat in the horizontal and vertical planes in order to achieve the most accurate values from the tracking software. Based on these criteria, the following sites were chosen for data collection along the A15 highway. Figure 17 presents the highway segment with markers defining both study areas.

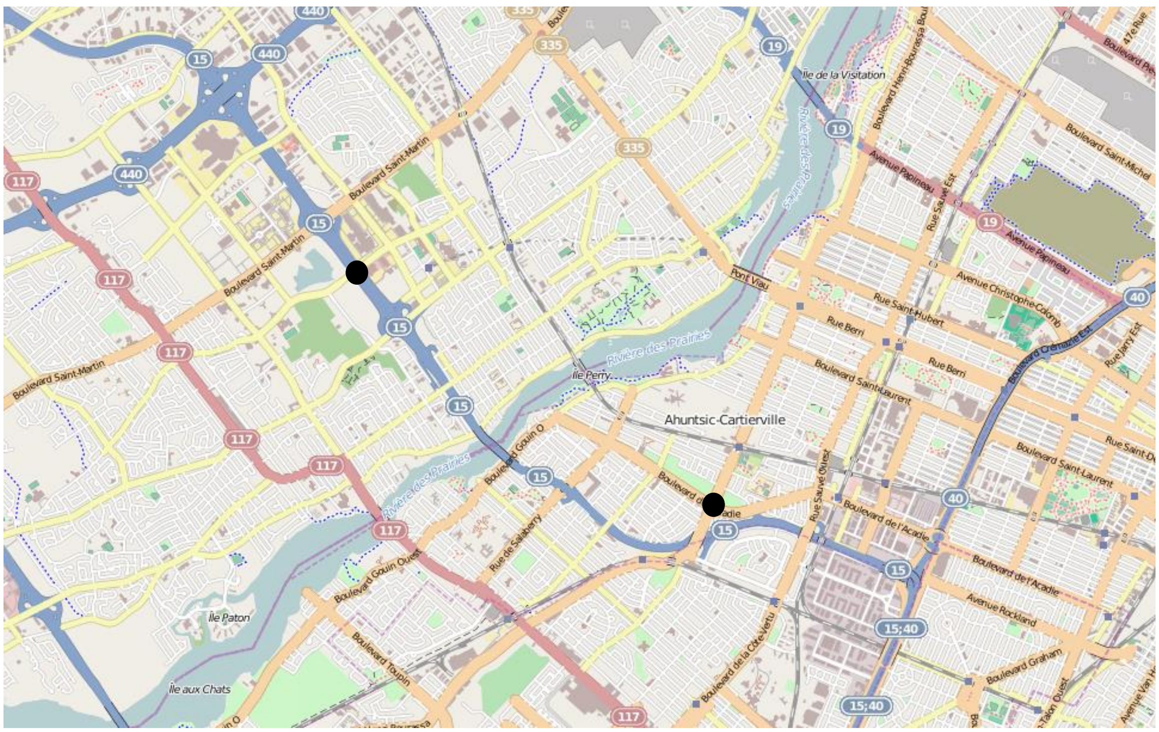


Figure 17 Map of the highway corridor with the locations of the collection sites

Henri-Bourassa overpass

This site is located just north of the A40/A15 interchange, at the beginning of the HOV facility. Due to the presence of an overpass above the A15, the video recording system can be attached directly above the vehicles, providing excellent video footage of the entire highway for the feature-tracking software. The speed limit along this section is set at a maximum of 100 km/h and a minimum of 60 km/h. Additionally, the site is located right before an entrance onto the highway as can be seen in the satellite image presented in Figure 18.

Figure 18 Aerial view of the Henri-Bourassa site (Site 1)

Boulevard Souvenir overpass

The second site is located 5 km north of Boulevard Henri-Bourassa, just south of the A440/A15 interchange in Laval, Canada where the HOV lane ends. The overpass crossing the highway was also used as the mounting structure for the recording system, with the camera installed directly above the four lanes of traffic facing downstream. The speed limit for this segment was also between 60 km/h and 100 km/h. Figure 19 presents an aerial view of the site with the location of the recording system.

Figure 19 Aerial view of the Souvenir site (Site 2)

Data collection

The data for this study was collected using the GoPro recording system described previously in this document. The GoPro was attached to the overpass structure using a specialized mount and pointed downstream. One of the main advantages of this recording system is its near invisibility, allowing for the collection of unaltered traffic data.

In order to properly compare the before and after video data along the highway, the data was collected between 3pm-5pm on weekdays. This time period was chosen for two reasons; (a) the HOV facility is active between 3 pm and 7 pm and (b) to maximize the amount of daylight during data collection for both collection periods because night data collection is not as effective in terms of the tracking software's capabilities. Video data was collected on three separated occasions at both sites for before and after data collection periods, adding up to 24 hours of peak hour video footage along the A15 highway.

The only data that was collected manually during the study are the violation rates along the HOV facility. During operating hours, the HOV lane is open to vehicles with 2 or more occupants. Although there are technologies being used that can identify occupancy rates in vehicles, they were not part of the scope of the study. The occupancy rates were therefore collected manually from the overpass during the video collection periods. It is important to note that the manual collection was performed with utmost discretion to minimize any alterations in behaviour along the highway segment.

Data processing

The data collected was processed using the Traffic Intelligence feature-based tracking software, which has been described in detail in Chapters 2 and 3 of this document. The following section will describe the steps undertaken to extract the traffic volumes per lane as well as the individual vehicle speeds.

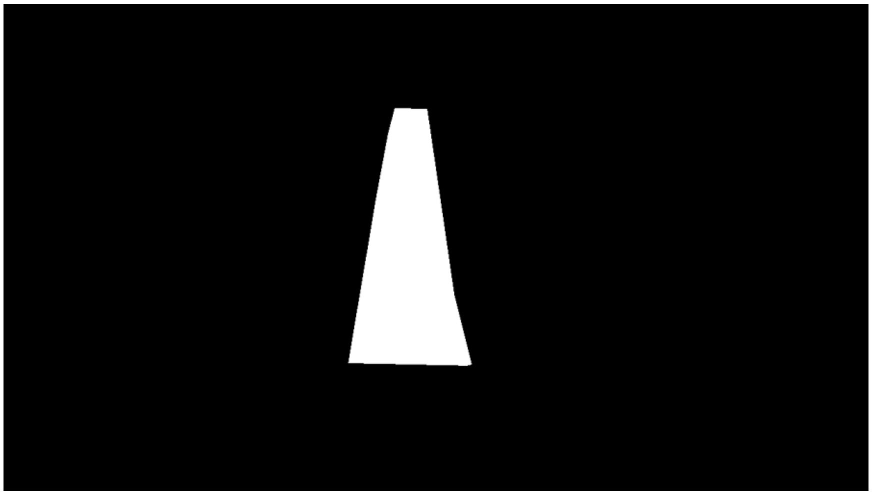
Video editing

The outputted GoPro video files are 26 minutes in length. In order to accurately compare the performance of the highway facility across both collection periods the videos are merged together and then cut into 10-minute segments. This allows for greater resolution of the resulting volume and speed values.

Lane analysis

In order to break the traffic data down into individual lanes, masks were applied to the video frame prior to the feature tracking process. A mask is a filter that forces the software to only analyze data within the highlighted areas of the video frame. The following Figure 20 presents a video frame and its respective lane mask for the second lane from the inside.

(a)



(b)
Figure 20 (a) video image of the highway facility with (b) the mask applied over lane 2 (in white)

Once the masks are applied to the video, the feature-tracking algorithm processes all of the video files for each site using a batch script. First, the individual features are tracked throughout the area of the mask. Second, the features are grouped together based on their respective speeds and distances from one another. Figure 5 in Chapter 1 presents the features of a vehicle being tracked across the video frames from a specific lane. From the figure, the features making up a vehicle can be seen in the mask while the trajectory of each feature is tracked across time and presented using the blue lines. The resulting volumes and speeds are outputted into databases and then transferred to Excel worksheets for further analyses.

Calibration
The calibration of Traffic Intelligence is discussed in detail in Chapter 2 of this document. For the A15 highway segment, the traffic flows were calibrated manually by counting the vehicles from randomly selected videos and then comparing the results to the automatically processed values. In general, the volumes were overestimated by 5% for both sites and were adjusted accordingly. As for the speeds, Chapter 2 concluded that the parallel recording orientation resulted in acceptable mean errors. Additionally, because the speeds are being evaluated relative to one another, the overestimation is not a factor in this study.

Measures of performance

The following measures are used in the analysis to evaluate the overall performance and safety of the HOV facility.

Average speed per lane

The average speed per lane is aggregated over ten minute periods for all four lanes of the highway segment. The speeds are calculated using the trajectories collected using Traffic Intelligence.

Average hourly flow per lane

The hourly flows are calculated by expanding the volumes per lane aggregated over ten minute periods. The hourly flow rates at ten minute intervals allows for finer resolution of the data.

Travel time

The travel time is calculated by measuring the driving distance between both sites (5.2 km) and applying the average speed per lane to determine the average travel time along the segment in minutes.

Violation rates

The violation rates are calculated by dividing the number of violations observed over a set time period by the total flow of vehicles in the HOV lane. The violations were collected manually from the roadside at ten-minute periods.

4.3 DATA OUTCOMES

The volume, speed and violation values are presented for both sites along the A15 in the following section.

Site 1: Henri-Bourassa overpass

The following figures exhibit the change in vehicle flows and speed with respect to time per lane per hour in the "before" scenario (i.e. no HOV lane) and "after" scenario for the Henri-Bourassa site.

No HOV collection period

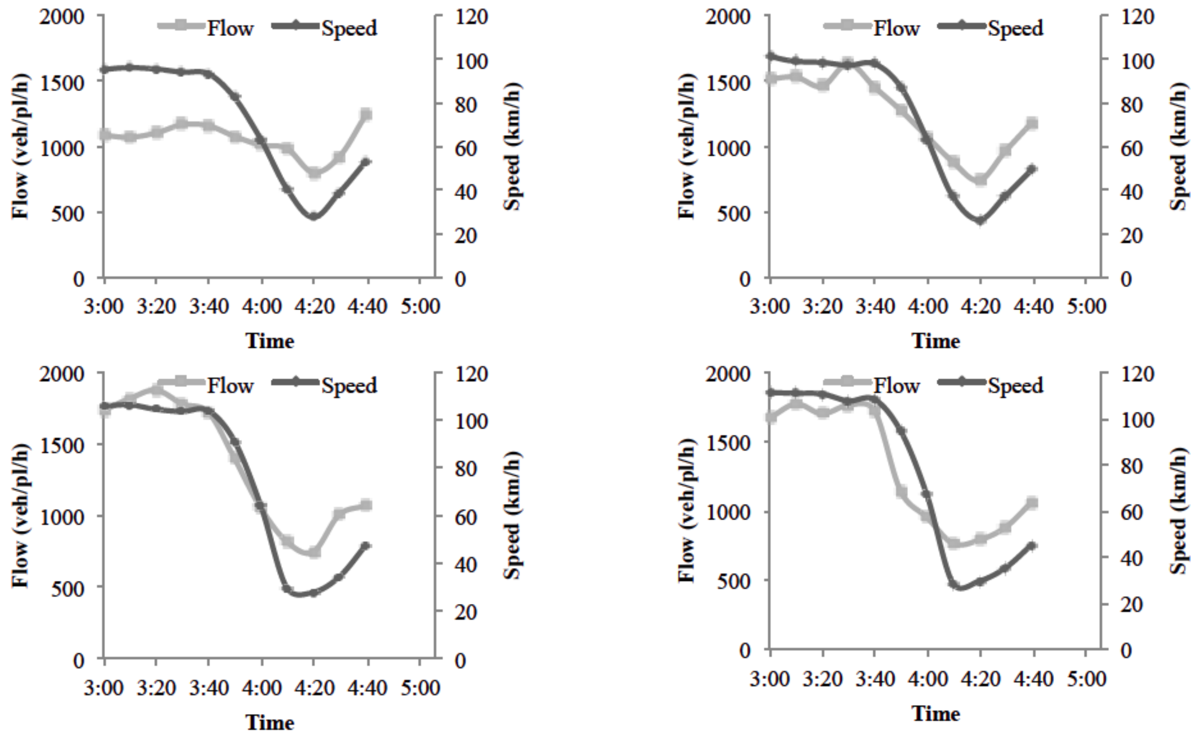


Figure 21 Speed and flow per lane without the presence of the HOV lane

Table 3 Summary table for Site 1 without the presence of the HOV lane (standard deviation in brackets)

Site 1 - No HOV

	Lane 4	Lane 3	Lane 2	Lane 1
Average Speed (km/h)	70.9 *(26.9)*	72.2 *(29.8)*	74.4 *(33.9)*	77.2 *(36.2)*
Average Hourly Volume	1055 (*122*)	1247 (*299*)	1364 (*436*)	1292 (*428*)
Travel time (min)	4.40	4.32	4.20	4.04

Based on the Figure 21, it can be concluded that the A15 highway displays typical congestion issues. Between 3 pm and 4 pm, the highway displays regular operating speeds in the 100km/h range with flows ranging between 1100-1800 veh/pl/h. As expected, increased demand starting at 4 pm begins to lower the operating speeds and in effect lowers the flow. All four lanes of traffic display this speed-flow relationship and follow the same trend throughout the data collection period.

Additionally, the table above presents the average speed and volume over the entire collection period for Henri-Bourassa. Typically, the outside lane (Lane 4) has the lowest speeds due to entrance and exit ramps. Because the inside lane is designated as a passing lane, speeds typically increase as one moves towards the inside. This speed relationship is observed at the Henri-Bourassa site based on Table 3**,** with speeds incrementally increasing from lane 4 to lane 1. Furthermore, volumes follow the same trend, further reinforcing the results displayed in the figures above

With HOV collection period

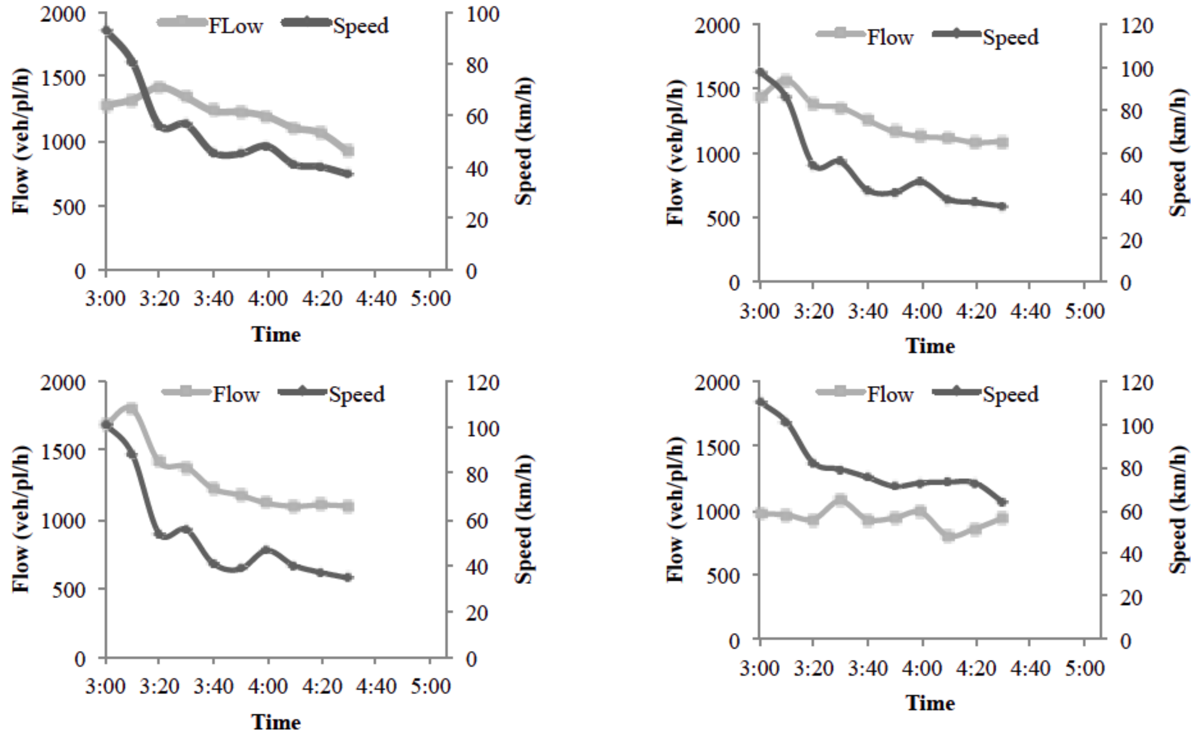


Figure 22 Speed and flow per lane with the presence of the HOV lane

Table 4 Summary table for site 1 with the presence of the HOV lane

Site 1 - HOV

	Lane 4	Lane 3	Lane 2	Lane 1
Average Speed (km/h)	52.1 *(19)*	51.4 *(21.4)*	52.0 (*22.6*)	78.3 *(15)*
Average Hourly Volume	1201 *(142)*	1224 (*190*)	1277 *(268)*	934 *(70.8)*
Travel time (min)	5.99	6.07	6.00	3.98

Figure 22 present the relationship between operating speeds and flows along the A15 highway during the "after" collection period (i.e. operational HOV lane.) Lanes 2-4 display a similar relationship found in the “before” figures, where the speed and flow fluctuate with one another. However, the HOV lane is the only one that seems to exhibit a different association. Throughout the entire collection period the flow and speed are not being affected by their fluctuations to the same effect as the other lanes. The data presented in the Table 4 also indicates that lane 1 cannot be classified with the rest of the highway due to the significant difference between the average speed and hourly volume values.

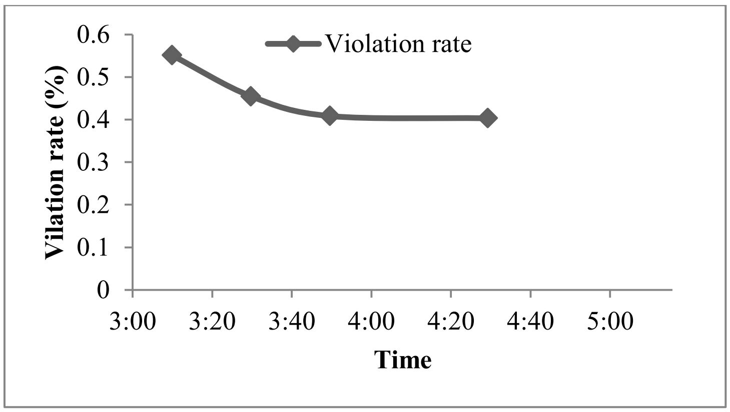


Figure 23 Violation rates at site 1

The manually collected violation rates are presented in Figure 23. A violation was defined as a vehicle driving in the HOV lane with less than 2 occupants.

Site 2: Souvenir overpass

The speed-flow graphs are presented in the following section for both the before and after collection periods at the Souvenir overpass site.

No HOV collection period

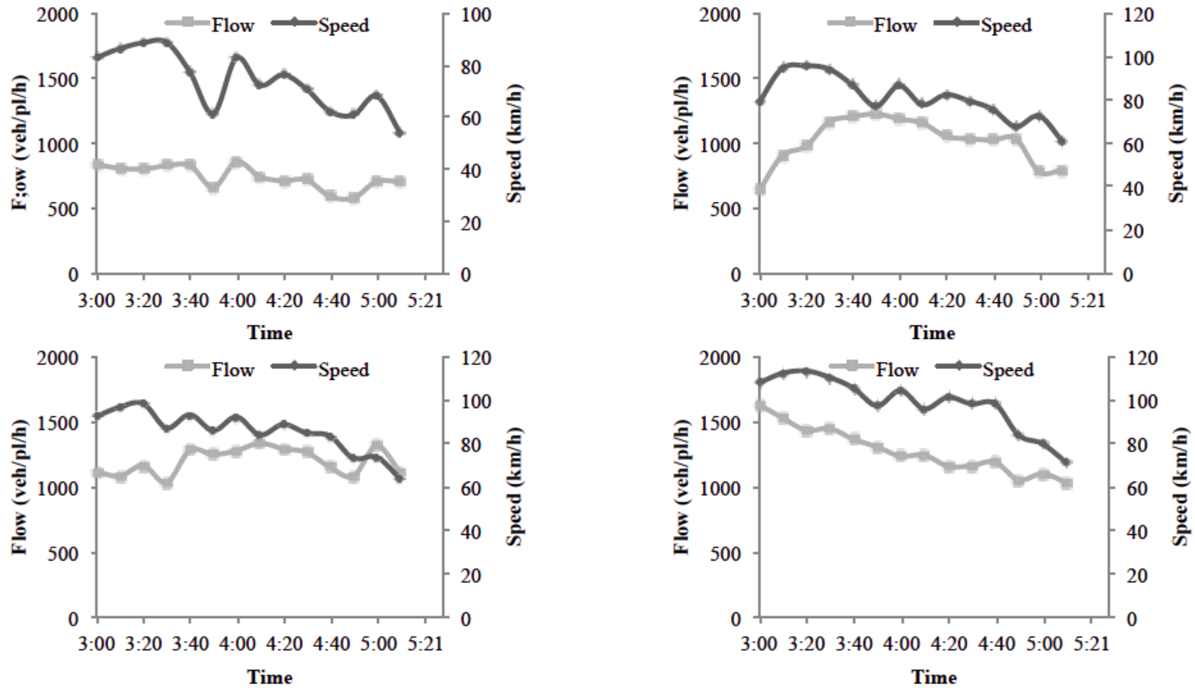


Figure 24 Speed and flow per lane at site 2 without the presence of the HOV lane

Table 5 Summary table for site 2 without the presence of the HOV lane

	Site 2 - No HOV			
	Lane 4	Lane 3	Lane 2	Lane 1
Average Speed (km/h)	73.8 *(11.4)*	80.8 (*10.2*)	85.6 *(9.7)*	98.7 *(12.53)*
Average Hourly Volume	741 (*90*)	1013 (*178*)	1198 (*101*)	1279 (*182*)

The Souvenir site exhibits the same trend found at Henri-Bourassa with respect to the congestion pattern and the speed progression from the outside lane towards the inside. Overall, the traffic flows are approximately 20% lower than at the first site, which also explains the less significant dip in both flow and operating speeds presented in the Figure 24 and Table 5.

With HOV collection period

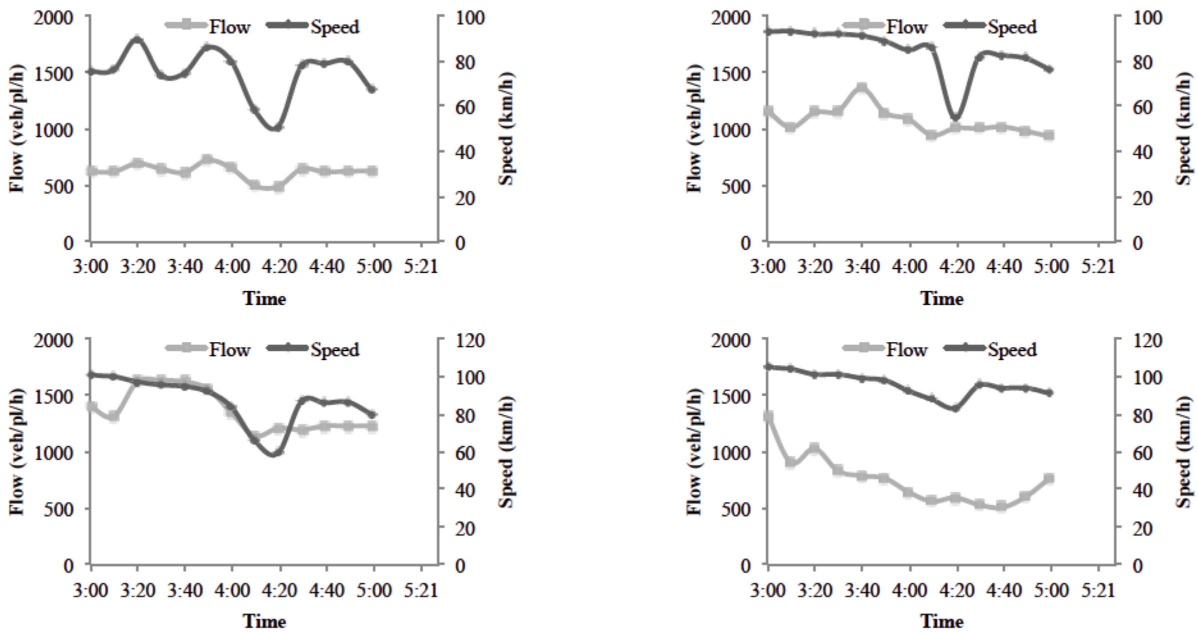


Figure 25 Speed and flow per lane at site 2 with the presence of the HOV lane

Table 6 Summary table for site 2 with the presence of the HOV lane

	Site 2 - HOV			
	Lane 4	Lane 3	Lane 2	Lane 1
Average Speed (km/h)	75.1 *(10.5)*	85.1 *(10.4)*	87.4 *(12.5)*	96.3 *(6.3)*
Average Hourly Volume	619 *(65)*	1084 *(118)*	1375 *(183)*	755 *(226)*

The data collected at the Souvenir site with the presence of the HOV lane (Figure 25 and Table 6) also follows the congested highway trend between 3 pm and 5 pm. The major difference between the two data collection periods is the significant drop in volume traveling within the HOV lane (lane 1.) This is discussed in more detail in the following section of the study.

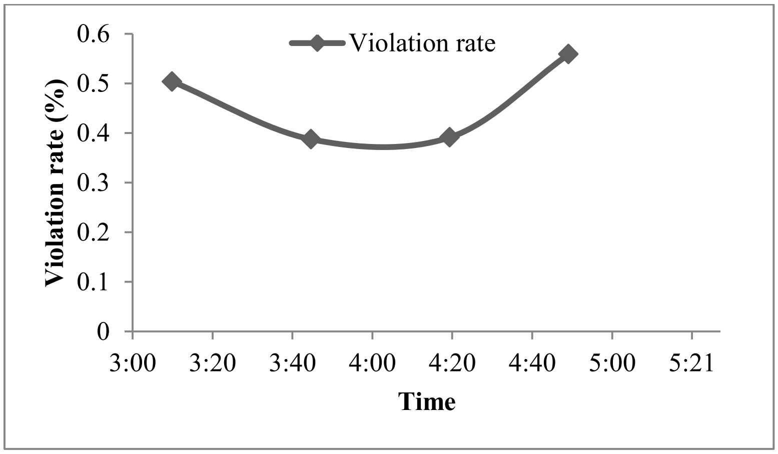


Figure 26 Violation rates at site 2

The violation rates presented in the Figure 26 were collected over 10 minute periods throughout the data collection sessions from the overpass at the Souvenir site along the A15 highway. The average violation rate for the entire collection period is around 50%, meaning half of all vehicles using the HOV lane have less than two occupants.

4.4 ANALYSIS AND DISCUSSION

The following section will present the volume, travel time and speed measures that help quantify the effects of the HOV facility based on the results in the previous section.

Volume

Figure 27 presents the average volumes traveling across both sites on the A15 over the entire collection period of 3 pm-5 pm.

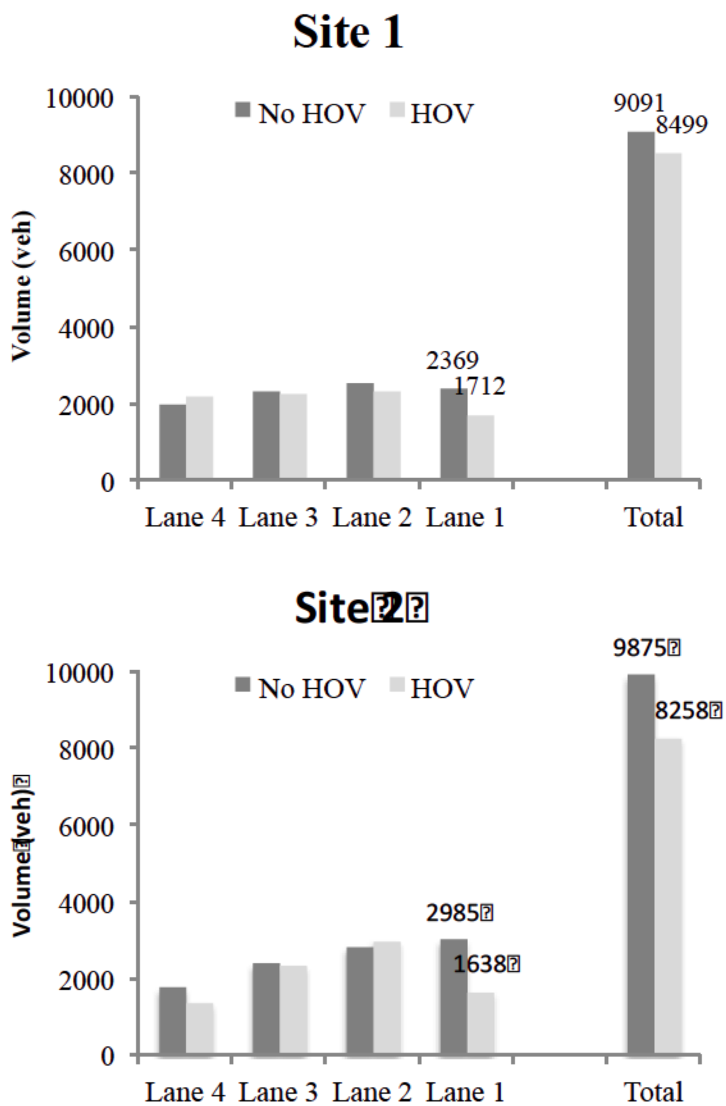


Figure 27 Total volumes per lane at both sites

Based on Figure 27, it can be observed that the average volume traveling through both sites is lower with the presence of the HOV lane. For the Henri-Bourassa site, the total volume across the four lanes is approximately 7% higher without the presence of the HOV facility operating along Lane 1. For the Souvenir site, the total volume is approximately 20% higher without the presence of the HOV facility. The lane-by-lane breakdown indicates that the majority of the difference stems from the notable difference in vehicles traveling along Lane 1. Additionally the average hourly volume for the HOV lane is 934 veh/pl/h and 755 veh/pl/h for sites 1 and 2 respectively.

According to the HOV Guidelines for Planning, Design and Operations (Operations, 2003)**,** a highway HOV lane should have a minimum volume of 800 cars per hour and 1800 passengers per hour. Based on the volumes, the lane seems to satisfy these requirements. However, by applying the violation rates at both sites (approximately 45% at both), the passengers per hour value drops considerably to around 1500 passengers per hour. Performing a sensitivity analysis on site 1 reveals that the violation rate would have to drop to at least 20% in order to achieve acceptable performance measures as can be seen in Figure 28. Additionally the drop in violation rates would have to coincide with an increase in eligible users along the HOV lane to keep the minimum threshold value in hourly volume.

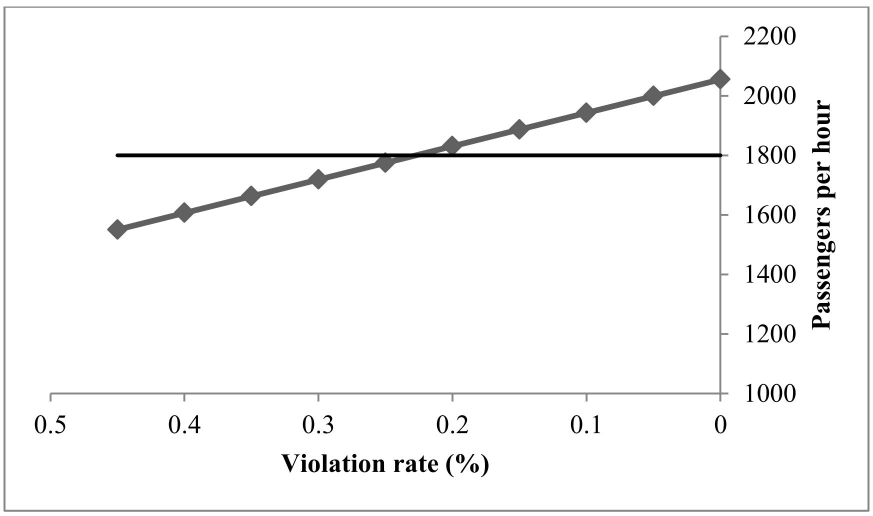


Figure 28 Sensitivity analysis for violation rates and passenger throughput

Speed

One of the most important safety issues regarding HOV facilities is the speed differential between adjacent lanes, as discussed in the literature review. The difference in operating speed generally results from the decrease in volume along an HOV lane with respect to the adjacent GP lanes. The potential speed differential can result in the increase in crash severity and likelihood due to vehicles entering and exiting HOV lanes. Using the results collected in this study, the speed differentials between the HOV lane and the GP lanes have been calculated and are presented in Figure 29. The average operating speeds per lane was collected over ten minute intervals.

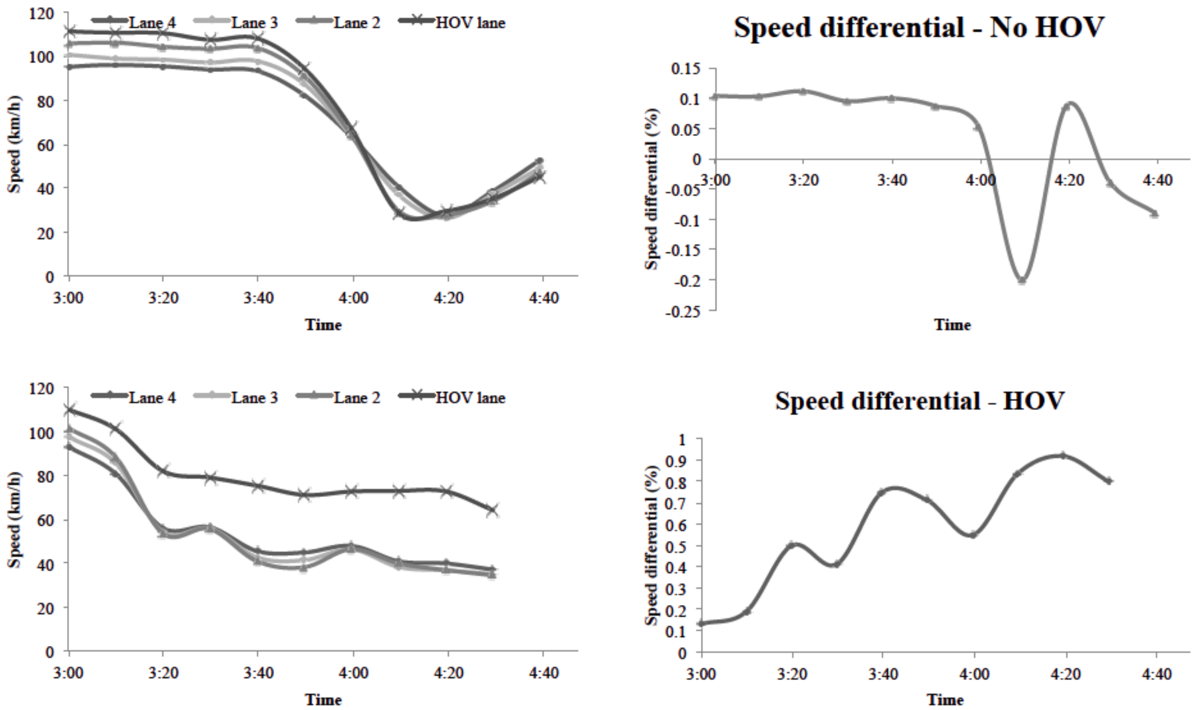


Figure 29 Speed differential at site 1

Figure 29 presents the speed differential between the HOV and GP lanes at the Henri-Bourassa site. The data in (a) was collected without the presence of the HOV lane and the results are indicative of normal operating behaviour. As previously mentioned, the speeds should increase from the outside lane towards the inside. Additionally, the speeds follow the same pattern throughout the collection period and at no point is there a large speed differential between any lanes. The speeds exhibited in (b) were collected during the operation of the HOV lane. Although the four lanes follow the same pattern across time, there is an important difference between the HOV lane and the adjacent GP lanes. The average percent difference between the HOV lane and Lane 2 is 62% or 26 km/h.

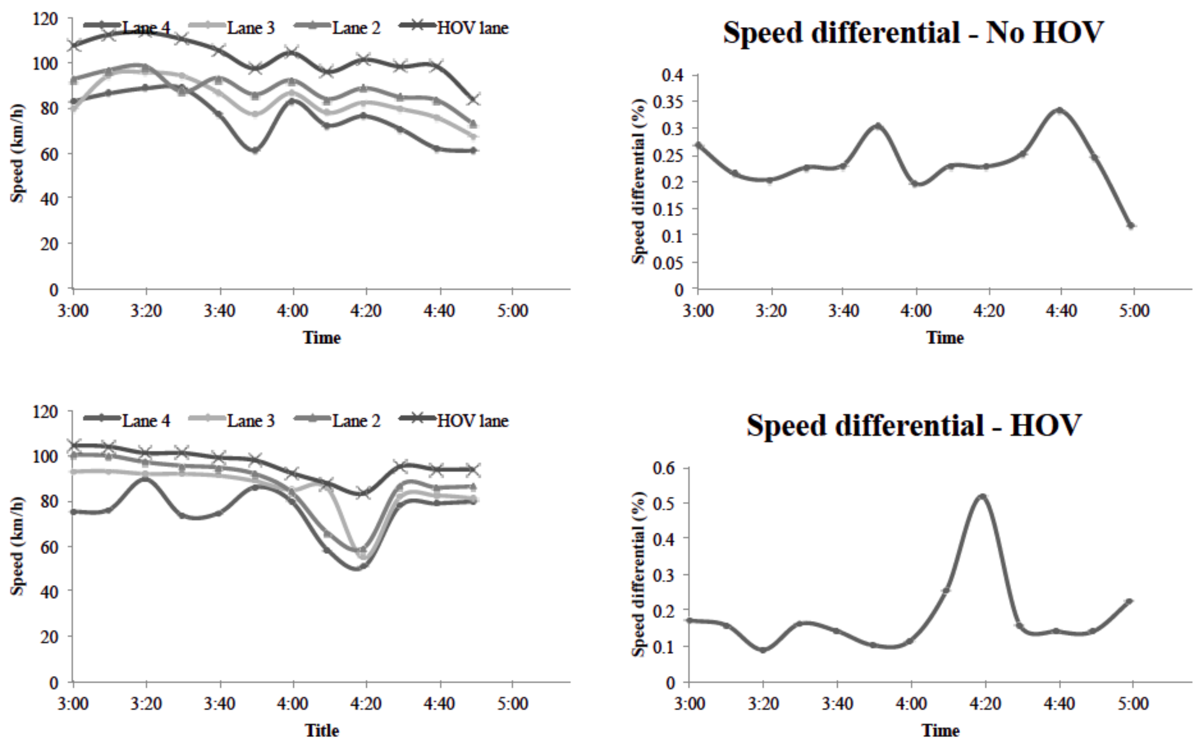


Figure 30 Speed differential at site 2

At the Souvenir overpass the speed differentials are slightly different. The speed data in Figure 30 (top) was collected without the HOV lane and shows all four lanes in following the same pattern. Although the different lane speeds are more spread out, there is less concern regarding speed differentials because the average hourly flows never exceed 1300 vehicles. The data presented in Figure 30 (bottom) shows the speeds along the highway during the operation of the HOV lane in the inside lane. The average speed differential is only 12% or 9km/h between 3pm and 5pm. However, during the facilities most congested period between 4:00-4:30pm, the average speed differential is 28% or 18 km/h. Because the overall congestion level at the second site was not as high as the first, fewer safety issues were observed. This is most likely due to the decrease in volume traveling along the highway near the end of the HOV facility.

Travel Time

According to the HOV Guidelines for Planning, Design and Operations (Operations, 2003), HOV lanes should cut travel times relative to the GP lanes by 1 minute per mile along the segment. The travel times at the first site are not within the threshold, with the average trip lasting approximately 90 seconds more over 3.25 miles. This threshold is the least indicative due to the limited data collection points along the segment, but it does help validate the underperformance of the HOV facility. Additionally, an approximate travel time impact indicator (TTI) was calculated for the segment to quantify the effect of the HOV lane on travel time. The following equation was developed and applied to each lane, with the final indicator being the sum of the individual lanes.

$$TTI = (Travel\ time\ * Volume\ )after - (Travel\ time * Volume)before \qquad (5)$$

The final indicator is found to be 5032 min/h for the highway segment between the two data collection sites. This indicates that the scenario with an HOV lane adds approximately 80 hours of delay to the corridor per hour of operation, an increase of 25 % when compared to the scenario without HOV.

HOV recommendations

The results from the study reveal a number of shortcomings in terms of the performance and safety of the A15 highway HOV facility. In order to solve the issue of low volumes along the facility during peak periods, the governing body must invest time and funds to grow participation. An example is the use of awareness campaigns presenting the advantages of HOV lanes and carpooling, such as reduced congestion, travel time and emissions. Second, carpool programs must be more effective and attractive to users in order to increase the volume along the HOV lane.

The second issue affecting the performance of the HOV lane is related to the violation rates. Because the observed violation rates are approximately four times higher than the maximum allowed of 10%, there is a need to address the situation. The most straightforward countermeasure would be the increase in enforcement present along the highway segment. The A15 highway is perceived to have less police enforcement relative to other segments, which likely leads to an increase in violations. Because of the layout of the highway, there is not much room for stationary police surveillance along the median. Therefore, an increase in police routes along the highway would help dissuade single occupant vehicles from using the HOV lane.

Although the violation rates are too high to be acceptable, the violators are inadvertently helping with congestion as they are filling the underutilized lane, reducing the congestion of the GP lanes. Because of the powerful draw created by the empty lane syndrome, an increase in participation along the HOV would both increase performance and curb violation rates simultaneously. An additional countermeasure would be the installation of infrared systems placed along the HOV facility. The system can detect occupancy rates and hand out fines based on the vehicle license plate. The issue with this countermeasure is its high cost to build and operate.

The third issue related to the HOV facility along the A15 is the speed differential present between the HOV lane and the GP lanes during congested periods. The 20-25 km/h speed difference is very large and can lead to increases in conflict occurrence and severity along the highway segment (Hughes, 1999). A potential countermeasure would be the installation of a larger buffer between the lanes in order to minimize the interactions between the lanes. The main problem with this solution is the lack of room available along the highway. Alternatively, the HOV facility could be switched from continuous access to limited access with the goal of decreasing movements between lanes. As previously mentioned, studies have shown that limited access HOV facilities do not necessarily decrease conflicts due to the increase in density surrounding the weaving zones.

Based on the assumption that the transportation agency will keep the HOV lane in operation the following recommendations are put forward. First, increase the awareness of the HOV facility by promoting carpooling and the existence of the lane. Install more signs and symbols before and along the facility to ensure that drivers are aware of the lane. Second, increase enforcement along the lane by scaling up the police presence on the A15 highway in the short term. If the network does expand due to congestion reduction and other benefits, there may be more motivation to invest in occupancy monitoring systems along the lane. Third, in order to properly utilize the HOV lane, a more flexible approach could potentially be implemented as follows. Recording systems should be installed along the segment and volumes and speeds can be extracted nearly instantaneously using the process described in this chapter. The HOV lane would only be opened when the volume and speed values reach a certain threshold. The lane can be outfitted with dynamic signage that indicates its current designation, allowing for it to be opened and closed at will throughout the peak period. This would therefore ensure the optimal allocation of the highway facilities limited resources and potentially decrease speed differentials between the inside and adjacent lanes due to the potential decrease in congestion along the GP lanes. The implementation of a flexible HOV facility could help stabilize the performance along the A15 highway as well as decrease the risk of collisions due to large speed differentials. Finally, the installation of a monitoring system would be a potential opportunity to convert the HOV lane into a High Occupancy Toll (HOT) lane in the future. HOT lanes are open for vehicles with a minimum number of occupants as well as SOV’s that pay a toll using transponders installed in the vehicle. The large violation rates may be an indication of the willingness of drivers to pay for the use of a reserved lane on the A15 highway segment.

Data collection recommendations

The study has demonstrated the applicability of feature-based tracking and video-based data collection methods for the evaluation of HOV facility performance. In order to further validate the process and the results, the system should be installed at additional sites along the segment. Additional sites would validate the performance of the HOV facility and give more insight into the traffic environment on a microscopic level. One of the advantages of this system is its flexible and unobtrusive setup. Furthermore, its cost relative to traditional data collection systems is much lower. For example, inductive loops are placed permanently into roadways and amount to approximately 6,000 CAD $ just in installation costs per unit (Mimbela et al., 2003).

4.5 CASE STUDY 2: RESERVED BUS LANE

This second case study adapts the same methods that the previous one; however, alternative safety indicators are used.

Study type

The current study is designed to evaluate the effectiveness of an operational exclusive bus lane (XBL) using alternative collection and processing methods. In order to quantify the performance of the lane, a number of microscopic indicators are calculated based on the collected data.

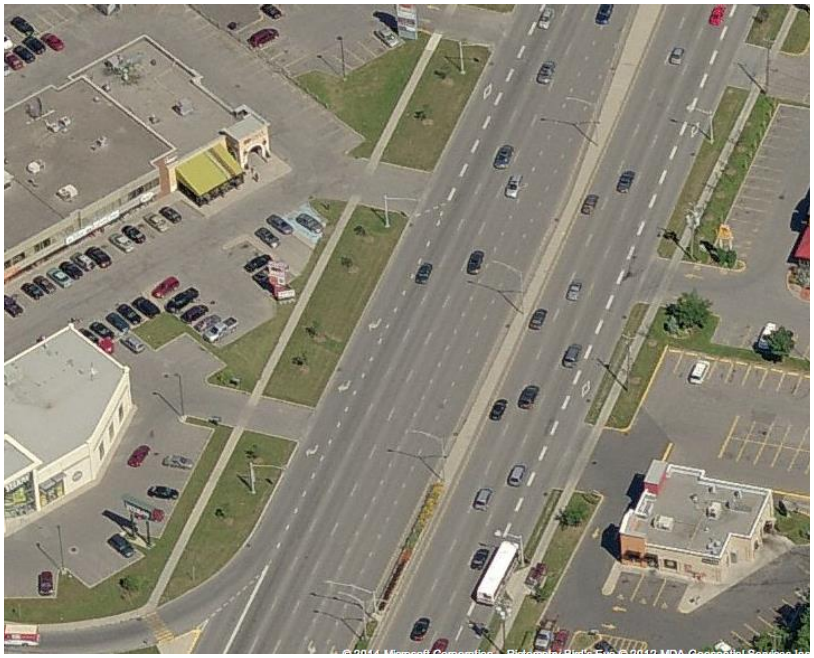
Site selection and description

The primary objective of this study is to observe the traffic environment within and adjacent to an XBL installed on the outside lane along an arterial. Specifically, the manoeuvres being undertaken by vehicles having to cross the lane due to the presence of entrance and exit driveways along the roadway are the primary objective of this study. As mentioned in the previous section, the availability of roadside structures is a requirement for the study area due to the data collection system being tested. Based on these factors, the XBL along the Taschereau Boulevard in Brossard, Canada was chosen as the study site. The Taschereau Boulevard has a 2 km long XBL in both the northbound and southbound direction. The facility is a permanent reserved lane for buses and taxis that operates 24 hours a day. The objective of the lane is to curb the vehicular traffic crossing the limited number of bridges between the South Shore of Montreal and the downtown core by increasing transit passengers. Because the major bus terminal on the South Shore (Panama terminal) is located at the southern end of the reserved lane, the main purpose of the XBL is as a feeder lane for all of the transit buses travelling between the terminal and other locations along the South Shore of Montreal.

Data collection

Data was collected along Boulevard Taschereau using the same video recording system described previously in this chapter. The difference between the two facilities is that the recording system was attached to roadside poles along the reserved lane because of the lack of overpass structures overhead. The recording system was at an approximate height of twenty feet and angled parallel to the arterial looking both upstream and downstream.

The first site is located right before a major intersection along the facility with traffic heading southbound. Figure 31 presents the collection site. The video data was collected looking downstream, with a focus on the vehicles changing lanes from the fourth lane into the outside lane. Figure 31 also displays a still image from the video recording at the site, with the reserved lane closest to the camera and a taxi traveling along the reserved lane.

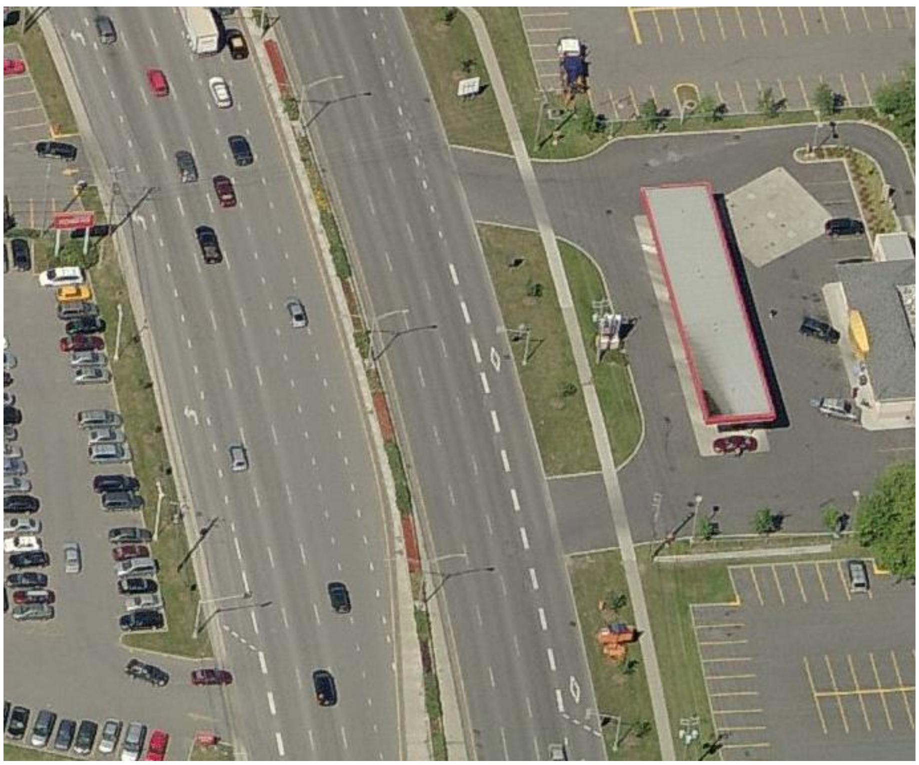


(a)

(b)

Figure 31 Aerial view of site 1 (a) and a video image taken at site 1 (b)

The second site is located just downstream of the first between two major intersections. The primary purpose for data collection at this site is to capture the movements in and out of the parking area and crossing through the reserved bus facility on the outside lane. Figure 32 also presents an image still from the video data, showing vehicles exiting the parking area and entering the arterial.



(a)

(b)
Figure 32 Aerial view of site 2 (a) and a video image taken at site 1 (b)

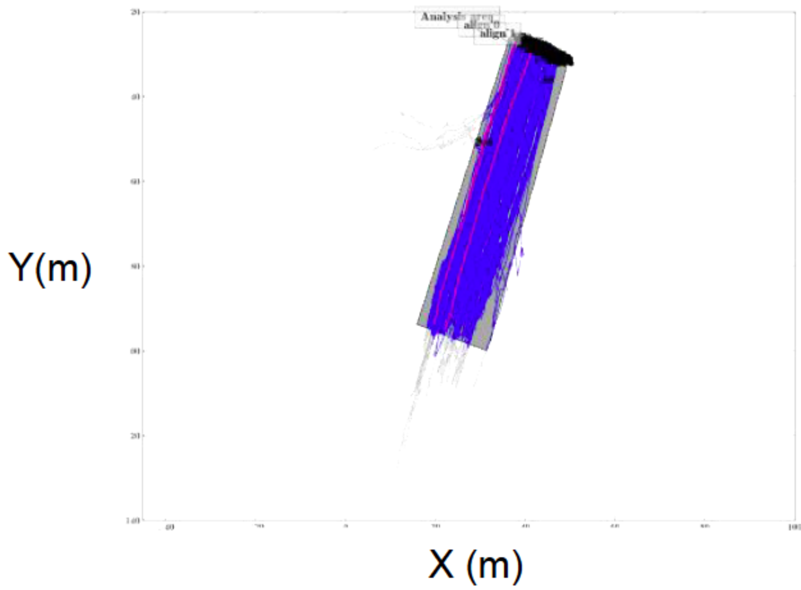
Data processing

This study uses the same data processing methods as the one found earlier in the chapter as a foundation and then builds on it using more advanced processes. The additional processing is done using another open source tracking software called pvaTools (python vision analysis toolbox) developed by researchers at Ecole Polytechnique in Montreal, Canada (P. St-Aubin, 2014). This tool takes the processed trajectories from Traffic Intelligence and calculates a number of indicators related to traffic interactions and safety. The primary objective of this study is to investigate two indicators using pvaTools. First, methods were developed to evaluate the number of lane change violations recorded by the collection system along the facility. Second, the time-to-collision (TTC) values along the arterial are calculated in order to analyze the safety at the entrance and exit points along the arterial. Both of these indicators are described in further detail in the following section.

Lane change violations

One of the issues being observed in this study is the effectiveness of the lane markings along the arterial and how vehicles interact with the reserved lane. The primary issue related to lane change violations is the fact that vehicles traveling in the reserved lane are less likely to expect an interaction with a vehicle in the adjacent lane when the lane change occurs outside of the authorized areas. Therefore, conflict severity and likelihood can rise along corridors where lane change and other pavement marking violations occur frequently. The pvaTools software is able to define lane changes within a study area. A process is developed for this study looking at the lane change violation rates along the arterial. A violation involves a non-authorized vehicle entering the reserved lane before it is allowed entry. Figure 31 showing the first site along Taschereau includes a section of the road where vehicles are allowed to cross into the reserved lane due to an upcoming intersection. The process involves filtering lane changes occurring in the disallowed zone and comparing them to the overall lane changes occurring within the site.

Figure 33 (left) shows the trajectories in blue along the arterial at the first site. The pink lines are the manually designated lanes for the reserved lane and the adjacent GP lane. After running pvaTools for this specific database of trajectories and lanes, the lane changes between lanes 1 and 2 are calculated and outputted as a total value.



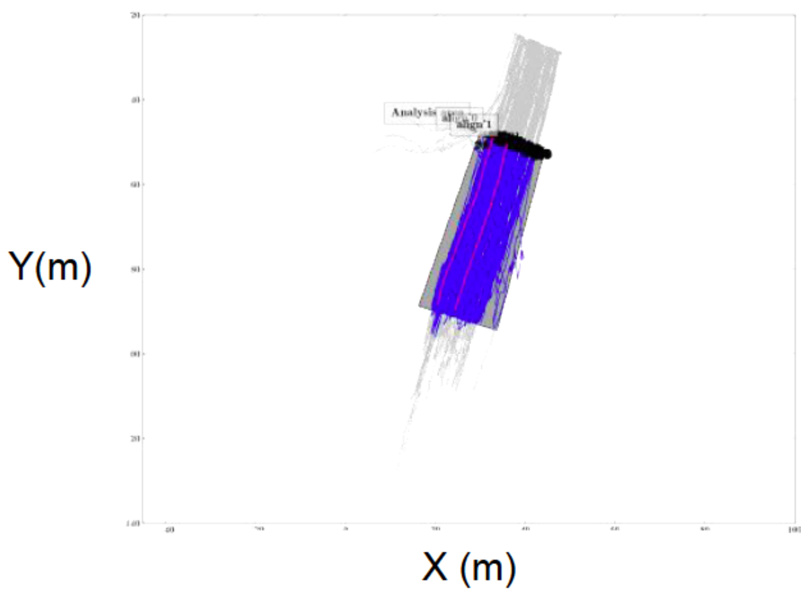


Figure 33 Trajectories at site 1 for the entire study area (left) and the accepted weaving area (right)

The end of the reserved lane and the beginning of the right turn lane occurs at the midpoint of the tracked area presented in the figure above. Although the majority of vehicles will respect the lane markings, the visual observation of the video data pointed out a number of violations. In order to automatically calculate the lane change violation rates, the disallowed zone is exclusively targeted using the following method. With the smaller analysis area shown in Figure 33 (right), the non-authorized lane changing violations are determined to be the difference between the large and small analysis areas. Therefore, the lane change violation rate is calculated by dividing the violations by the total lane changes from Lane 2 to 1.

TTC

Time-to-collision (TTC) is a surrogate safety indicator that is applied to a variety of safety studies. TTC is defined as the time until two objects will collide assuming that their velocities and paths remain constant (P. G. St-Aubin, 2011). Figure 34 presents two typical scenarios in which TTC can be measured: a) diagonal and from behind and b) a perpendicular TTC scenario. The pvaTools software has incorporated TTC calculations into its process and allows users to set the threshold TTC value in seconds as well as the desired analysis area. Once those parameters are defined, the software will output a "heat" map of the TTC occurrences, with higher concentration points highlighted within the analysis area. Additionally, a database is created with all of the TTC occurrences with their respective TTC values and coordinates within the study area. Based on these outputs, various traffic environments can be evaluated and potentially compared based on their TTC values and concentrations. For this study, the TTC measurements due to entering and exiting vehicles interacting with both reserved lane and GP lane vehicles are analyzed along the Taschereau Boulevard arterial.

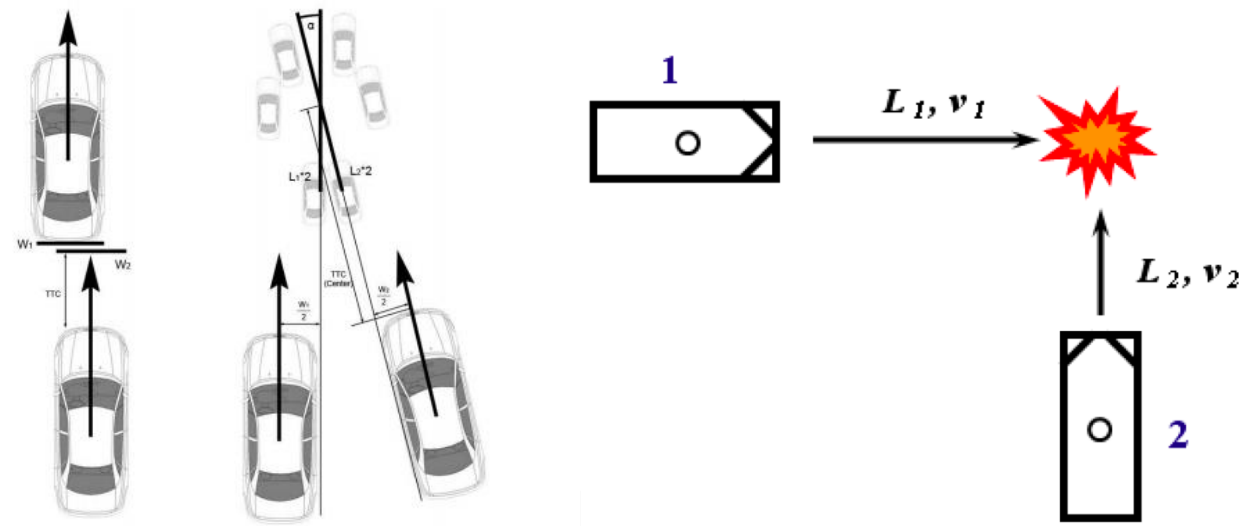


Figure 34 Diagonal and rear end TTC examples (P. G. St-Aubin, 2011) (left) and perpendicular TTC situation (Laureshyn, Svensson, & Hydén, 2010) (right)

4.6 RESULTS AND ANALYSIS

Lane change violations

The lane change violations are calculated at the first site along Taschereau. Video data was collected over a three-hour period and processed using the Traffic Intelligence software. The pvaTools is then applied to the trajectories database using the process developed in this chapter and described in the previous section. Data is aggregated into thirty-minute periods, and the lane changes occurring within the authorized area are filtered out. The lane changes that are left over therefore occur within the unauthorized area and are considered violations. Figure 35 shows the lane change violation rates over the entire collection period along with the total volumes traveling southbound along the arterial’s five lanes.

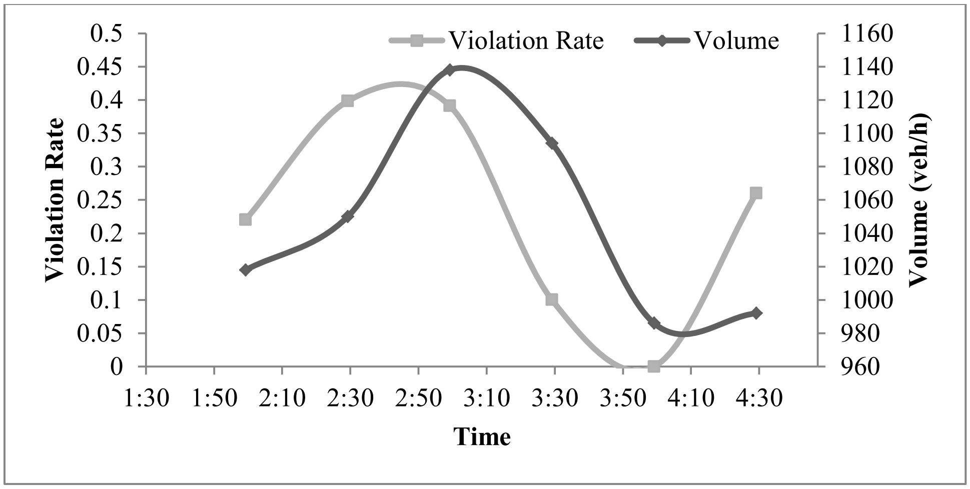


Figure 35 Violation rates and arterial volumes during collection period

The lane change violation rates along Taschereau vary between 0% and 40% over thirty minute data collection periods between 2 pm and 4:30 pm on a weekday. The lane changes are measured over a 70 m length of road in which the first 30 m do not allow lane changes and the last 40 m are part of the weaving section for non-HOV vehicles making right turns at the upcoming intersection. The volumes were extracted using the feature-based tracking algorithm built into the Traffic Intelligence software and expanded into hourly volumes. Based on the figure, there seems to be a relationship between lane volumes and violation rates at the study area. As volumes increase along the GP lanes, vehicles may begin their lane change early because of the presence of queues due to the downstream intersection. Figure 36 presents a common occurrence during the data collection where a queue in the adjacent GP lane influences vehicles to change lanes before the authorized area.

Figure 36 Typical behaviour during queuing, with a vehicle cross the pavement marking early

TTC

The TTC measurements are calculated using pvaTools at the second site along Taschereau Boulevard. The pvaTools software allows for the setting of a threshold TTC value. Based on past studies (P. G. St-Aubin, 2011; P. St-Aubin et al., 2012)**,** a threshold value of 1.5 seconds was set prior to the processing of the trajectory data because it is considered the threshold for meaningful safety and collision impacts. The data was collected over a three-hour period during a weekday. The software calculates the TTC measurements and defines X and Y coordinates along the road plane where the event occurs. After processing the data, the TTC values are plotted onto the road plane as shown in Figure 37.

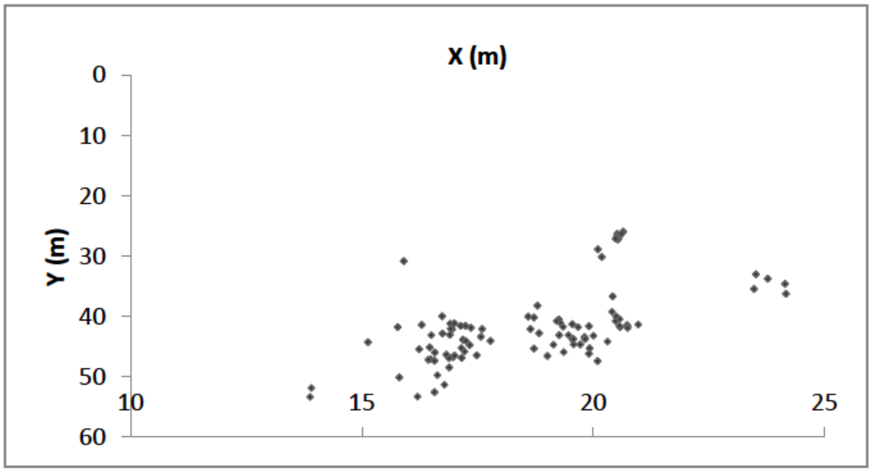


Figure 37 TTC collision points (< 1.5 s) plotted onto study area

The four lanes of the arterial can be defined based on the clustering of collision points. By adding a layer representing the lanes of the arterial as well as the vehicle entry point, the scattered collision points become meaningful as seen in Figure 38.

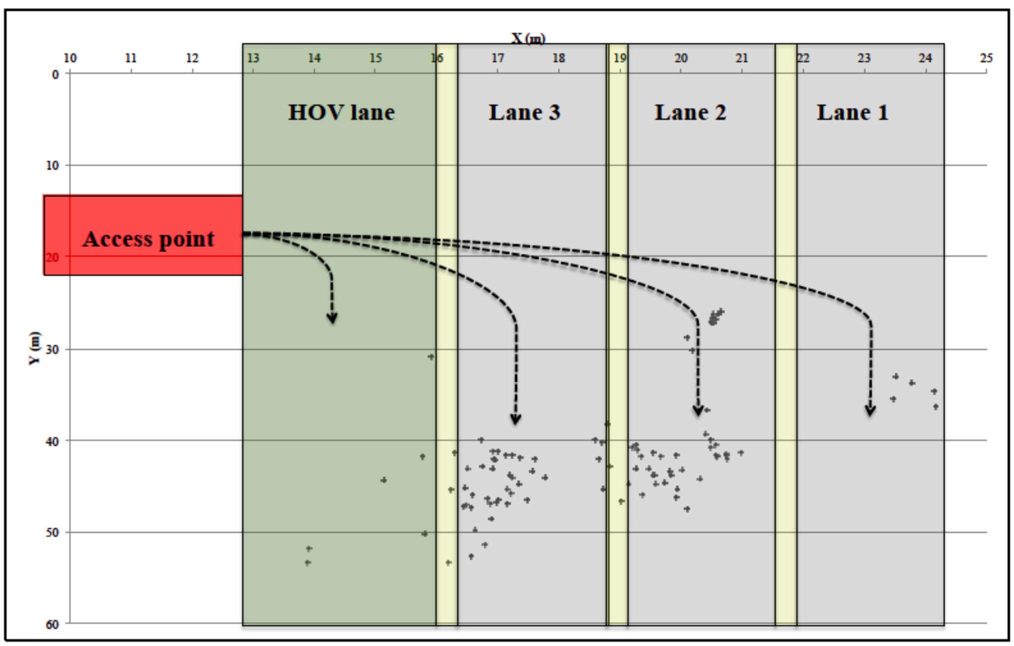


Figure 38 Overlay of the road surface and the access point, with the typical vehicle turning patterns

The vehicles are moving downstream from the camera location. Because vehicles are not authorized to enter the reserved lane they theoretically enter the arterial via lanes 3, 2 and 1 respectively. However according to the video data many vehicles enter via the reserved lane before merging into the GP lanes further downstream. This entry movement is reflected in the figure based on the collision points occurring downstream between lanes 4 and 3. Additionally, the collision points downstream of the access point are primarily clustered between lanes 3 and 2. This supports the assumption that most vehicles enter via lanes 3 or 2 and cross the predicted paths of the vehicles moving downstream. The general location of the collision points also supports the theory that the access point is creating safety issues because nearly all of the instances occur downstream from it.

4.7 DISCUSSION

HOV recommendations

This case study was designed to present the multiple uses of video data and trajectory data extracted in terms of safety issues along an arterial HOV facility. Because of the limited data collection it is difficult to recommend countermeasures for the Taschereau Boulevard segment. However, based on the results of the lane change violation rates and TTC measurements, certain measures can be recommended as possible solutions. The large concentration of lane changing violations near the end of the reserved lane can be indicative of two situations. First, the geometric design may not reflect the traffic environment and could this could be leading the to early lane changes which in turn could be affecting collision frequencies and severity between buses and passenger vehicles. To address this issue additional data can be collected along the arterial to evaluate the current pavement markings relative to the geometric design and traffic volumes. Second, the psychological aspect of changing lanes early regardless of its relative location could be the controlling factor. This issue can be potentially addressed through increased police enforcement along the arterial with a specific focus on lane changing violations.

The potential conflicts due to the vehicles entering and exiting the arterial from access points can be evaluated using video data and TTC conflict analysis. The main conflict issues based on the exploratory analysis done in this case study are found in the lanes adjacent to the reserved lane based on the number of TTC measurements recorded within these lanes downstream of the access point. These results are supported by the fact that the volumes in the adjacent GP lanes are much higher than the reserved lane, leading to greater chances of interactions. Due to the relatively long headways between buses, most vehicles exiting the access points use the reserved lane as a buffer zone for the GP lanes. However, the location of the access points can be lead to difficult merging movements due to extensive queuing along the arterial close to major intersections. This scenario can influence vehicles to merge dangerously into the GP lanes or travel along the reserved lane illegally. One countermeasure that may be effective along the Taschereau Boulevard arterial due to its geometric layout would be the construction of a collector lane running parallel to the arterial channelling all entering and exiting vehicles to a single access point between the intersections. The aerial image presented in Figure 39 exhibits the typical layout along the arterial. The significant offset between the commercial spaces and the arterial could be used to install a feeder lane connecting the parking areas throughout a block. This would lead to fewer interactions at access points between both the reserved and GP lanes and entering and exiting vehicles. Additionally, the current signal cycles lead to large gaps between fleets, theoretically allowing for the addition of short actuated signals at the access points to remove any potential interactions.

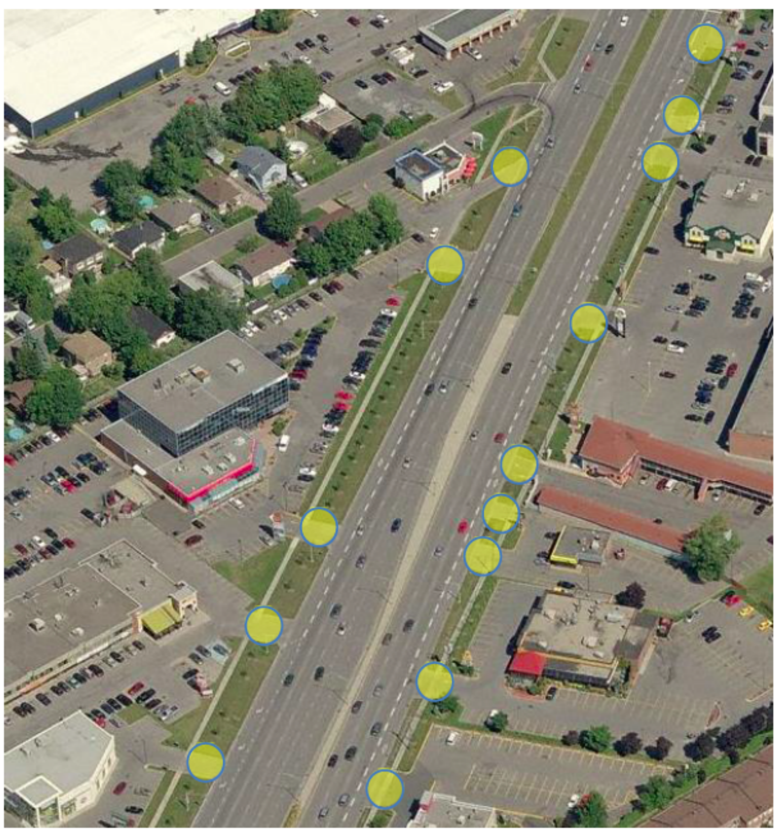


Figure 39 Aerial photo displaying the typical spacing of access points along arterial

4.8 CHAPTER CONCLUSIONS

The objective in this chapter was to present methods to evaluate the performance and safety of HOV facilities using video data and alternative measures. The methods are based on an inexpensive and flexible monitoring system that can be installed along highway HOV facilities and analyze traffic volumes and speeds automatically. The potential benefits of the proposed methods includes a more interactive approach to evaluate the efficiency of HOV lanes due to immediate adjustments throughout the operating hours, increased understanding of the traffic environment at the microscopic level and the potential implementation of automatic enforcement systems. The methods are illustrated using two case studies. The first case study uses video data from a HOV lane in a highway section. In the second case study, the exploratory investigation along an arterial with a reserved bus lane attempts to present the application of vehicle trajectory analyses. The effectiveness of pavement marking and road design are examined through lane change violation rates with respect to congestion levels. The safety issues regarding interactions between vehicles entering and exiting the arterial are evaluated using TTC measurements based on trajectories.

The results from both case studies seem to indicate that the video-based analysis methods are feasible and can be applied to various HOV facilities. Because of the exploratory nature of these case studies, additional data can be collected along the current facilities and others in order to further validate the results collected in this chapter. Furthermore, the proposed methods will have to be streamlined in order to install permanent monitoring systems that can automatically evaluate HOV lane effectiveness and safety in real time.

Chapter 5:

Final Conclusions and Future Work

The purpose of this thesis was to develop methods to evaluate the safety and effectiveness of HOV facilities using video-based data collection and existing (open source) tracking algorithms. Chapter 2 tests the accuracy of the video data collection system used in this research. This is compared to traditional approaches, including measures obtained manually. The development of an error segregation process led to the validation of the data collection method used in this research, with precision levels within the accepted ranges. The third chapter proposed methods for the application of video-based data in the calibration of HOV microsimulation models. The statistically significant difference between the default and calibrated scenarios underlined the importance of calibrations with respect to HOV facilities. This research found that the proposed calibration methods can significantly improve the outcomes of microsimulation models, which can then be used to test HOV countermeasures. Finally, the last chapter presents methods that were developed to analyze the safety and performance impacts along HOV lanes using the alternative collection and processing tools. The methods are built and illustrated using two case studies. The results of the research suggest that the tools can successfully calculate performance and safety indicators within highway and arterial HOV facilities. This is expected to help in the development and implementation of a more proactive approach to detect issues along HOV facilities. As a general conclusion, the results presented in this thesis indicate that the video-based data collection and processing tools can be applied to the diagnosis of operational and safety problems at HOV facilities. The literature review of various empirical studies and guidelines suggests that one of the most effective ways of evaluating HOV facilities is through monitoring programs.

Future work should include the design of a permanent real-time recording system as well as a streamlined version of the software used to extract the vehicle trajectories and calculate the traffic indicators. Because of the underutilization of the HOV facility along the A15 highway, the application of this monitoring system can potentially increase the operating effectiveness of the entire facility through the integration of a variable HOV lane. Additionally, the large speed differentials between the HOV and GP lanes can be addressed using two approaches. First, a calibrated microsimulation network can be designed in order to evaluate changes in driver behaviour due to geometric changes including physical buffers and limited access pavement markings. Second, the most promising designs can then be implemented and evaluated using the video-based collection and processing tool.

The arterial HOV facility pilot study also has the potential of being expanded across the corridor and along other arterial reserved lanes. Instead of installing permanent collection stations, it may be more effective to collect video data at various sites in order to properly build a microsimulation scenario of the corridor. The calibrated microsimulation can be used to predict changes in driver behaviour due to changes in geometric design as well as different bus headways travelling along the arterial. Furthermore, the potential addition of a collector lane running parallel to the arterial can be evaluated before any physical changes are implemented. Future work should focus on the collection of surrogate safety indicators along busier arterials in order to build a more complete record of the potential safety issues at arterial reserved bus lanes.

Based on the research conducted in this thesis and the results collected in numerous empirical studies and guidelines, HOV facilities need to be evaluated individually and on an on-going basis. There is no ideal set of initial traffic parameters that can guarantee the success of an HOV facility. Two highway corridors with identical traffic environments can have markedly different HOV results due to the wide variety of factors that affect both the performance and the safety along the facilities. Although guidelines have been put in place to help transportation planners with their attempts at curbing congestion by increasing passenger throughput, the HOV lanes under consideration need to be evaluated and monitored once they are operational. The video-based collection and analysis methods presented in this thesis can be used as a new way to measure the performance and safety impacts related to the implementation of HOV facilities.

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