MODELING THE IMPACT OF THE CURB RADIUS ON OPERATING SPEEDS AND OTHER SURROGATE SAFETY MEASURES USING VIDEO AND GPS TRAJECTORY DATA

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ABSTRACT

Motor-vehicle turning maneuvers at intersections are often involved in crashes and serious injuries, in particular collisions involving vulnerable road users. In Canada alone, 30% of fatalities and 40% of serious injuries took place in intersections. In Montreal, a total of 21.2% accidents included a left or right turning vehicle with vulnerable users (17.5%) or against through traffic (3.7%). Thus, to improve intersection safety, geometric design related treatments have been implemented and studied in past literature. These include curb radius reduction and curb extensions which aim to reduce turning speeds and crossing distances. The radius effects and treatments have been investigated for large intersections and road curves in rural areas using observed crash and point-speed measures, with limited studies examining small urban intersections. The limitations of crash data are known in the literature, these include long periods of observation to investigate low-volume intersections, underreporting, and misclassification, among others. On the other hand, studies that utilized operating speed models to examine design consistency have used point-speed measures. With the help of modern data collection techniques (video footage and GPS data), this study aims to fill the gaps presented in the literature on the investigation of the safety of curb radii and other geometric elements in local urban intersections using surrogate safety measures derived from vehicle trajectories and statistical regression models. More specifically, this research aims at: (1) develop a methodology to evaluate the impact of the curb radius on the speed of vehicle turning maneuvers in local intersections with small radius using Montreal video trajectory data and a cross-sectional approach. (2) To evaluate the safety effectiveness of curb radius reduction as a traffic calming treatment using a naïve before-after study and video data collected from two intersections in Toronto, Canada. In addition to speeds, post-encroachment time is used as a surrogate indicator, (3) To expand on the use of GPS smartphone data for establishing a methodology for evaluating

the safety of turning movements to overcome the shortcomings of video cameras. For this purpose, GPS-based surrogate safety measures (85th percentile, median speeds, and deceleration) were extracted and modeled using mixed-effect regression models for a large data set from Quebec City.

Among other results, a statistically positive and significant association between the radius and speed measures was observed for the video trajectory data. For instance, in the cross-sectional analysis, an increase of 1-meter in the curb radius results in an increase of 0.775 kph for the 85^{th} speed and 1.208 kph for the median speed for all turns. For the before-after study, an average decrease was witnessed for all speed measurements for both intersections studied after the curb reduction treatment implementation. The countermeasure contributed to 1.6 kph and 0.783 kph decrease for 85^{th} percentile and median speed, respectively, for both intersections when examined using the mixed-effects linear regression models. Lastly, using GPS smartphone data, the findings also support the relation between exhibited speeds and the measured corner curb radius. Using regression models of speeds, for every 1-meter increase in the measured curb radius, a statistically significant increase of 0.4 kph in both 85^{th} percentile and median speeds was observed. Other intersections attributes, like the signalization, had an influence on the speed measures. As for the deceleration models, an increase of 1-meter in the radius resulted in a 0.01 m/s^2 increase in the severity, thus, decreasing the safety of the intersection. Overall, the effectiveness of curb radius and reduction treatment was confirmed in the three different case studies. Despite the modest impacts in most of the cases, the importance of radius reductions is implied. Also, future work is required to address the limitations presented by the filtering techniques for the GPS data. Moreover, cross-calibration of the models can be used to evaluate the means of data collection by collecting GPS data for the video trajectory models and vise-versa.

RESUME

Les manœuvres de virage des véhicules à moteur aux intersections sont souvent impliquées dans des collisions et des blessures graves, en particulier, les collisions impliquant les usagers vulnérables de la route. Au Canada seulement, 30% des décès et 40% des blessures graves sont survenus aux intersections. À Montréal, un total de 21,2% des accidents impliquaient un véhicule tournant à gauche ou à droite. En effet, 17,5 % impliquaient des utilisateurs vulnérables et 3,7% impliquaient la circulation tout droit en direction opposée. Pour améliorer la sécurité des intersections, des traitements liés à la conception géométrique ont été mis en œuvre et étudiés dans la littérature. Il s'agit notamment de la réduction du rayon de bordure et des extensions de bordure qui visent à réduire les vitesses de virage et les distances de traverse. Les effets de rayon de bordure et les traitements ont été étudiés pour les grandes intersections et les courbes de route dans les zones rurales en utilisant des mesures de collisions observées et de vitesse ponctuelle, avec des études limitées examinant les petites intersections urbaines. Les limites des données sur les collisions sont connues dans la littérature, notamment les longues périodes d'observation pour enquêter sur les intersections à faible volume, la sous-déclaration et les erreurs de classification, entre autres. D'un autre côté, les études qui ont utilisé des modèles de vitesse pratiquée pour examiner la cohérence de la conception ont utilisé des mesures de vitesse ponctuelle. À l'aide de techniques modernes de collecte de données tel que les séquences vidéo et les données GPS), cette étude vise à combler les lacunes présentées dans la littérature sur l'étude de la sécurité des rayons de bordure et d'autres éléments géométriques dans les intersections urbaines locales en utilisant des mesures de sécurité de substitution dérivées de trajectoires des véhicules et des modèles de régression statistique. Plus spécifiquement, cette recherche vise à: (1) développer une méthodologie pour évaluer l'impact du rayon de trottoir sur la vitesse des manœuvres de virage

des véhicules dans les intersections locales à petit rayon en utilisant les données de trajectoire vidéo de Montréal et une approche transversale. (2) évaluer l'efficacité en matière de sécurité de la réduction du rayon de bordure de trottoir en tant que traitement d'apaisement de la circulation à l'aide d'une étude naïve avant-après et de données vidéo recueillies à partir de deux intersections à Toronto, au Canada. En plus des vitesses, le temps post-empiètement est utilisé comme indicateur de substitution. (3) Pour étendre l'utilisation des données GPS des téléphones intelligents afin d'établir une méthodologie pour évaluer la sécurité des mouvements de virage pour surmonter les lacunes des caméras vidéo. À cette fin, des mesures de sécurité de substitution basées sur le GPS (85^e centile, vitesses médianes et décélération) ont été extraites et modélisées à l'aide de modèles de régression à effets mixtes pour un grand ensemble de données de la ville de Québec.

Parmi les résultats, une association statistiquement positive et significative entre les mesures de rayon de bordure et de vitesse pratiquée a été observée pour les données de trajectoire vidéo. Par exemple, dans l'analyse transversale, une augmentation de 1 mètre dans le rayon du trottoir entraîne une augmentation de 0,775 km/h de la 85^e vitesse et de 1,208 km/h de la vitesse médiane pour tous les virages. Pour l'étude avant-après, une diminution moyenne a été observée pour toutes les mesures de vitesse aux deux intersections étudiées après la mise en œuvre du traitement de réduction du trottoir. La contre-mesure a contribué à une diminution de 1,6 km/h et de 0,783 km/h pour le 85^e centile et la vitesse médiane, respectivement, pour les deux intersections lors de l'examen à l'aide des modèles de régression linéaire à effets mixtes. Enfin, en utilisant les données GPS, les résultats soutiennent la relation entre les vitesses pratiquées et le rayon de bordure de coin mesuré. En utilisant des modèles de régression des vitesses, pour chaque augmentation de 1 mètre du rayon de trottoir mesuré, une augmentation statistiquement significative de 0,4 km/h dans les vitesses du 85^e centile et médian a été observée. D'autres attributs d'intersections, comme la signalisation, ont eu une influence sur les mesures de vitesse. Quant aux modèles de décélération, une augmentation de 1 mètre dans le rayon de bordure de trottoir a entraîné une augmentation de 0,01 m/s^2 de la gravité, diminuant ainsi la sécurité de l'intersection. Dans l'ensemble, l'efficacité du rayon de courbure et du traitement de réduction a été confirmée dans les trois études de cas différentes. Malgré les impacts modestes dans la plupart des cas, l'importance des réductions de rayon est implicite. En outre, des travaux futurs supplémentaires sont nécessaires pour remédier aux limitations présentées par les techniques de filtrage des données GPS. De plus, l'étalonnage croisé des modèles peut être utilisé pour évaluer les moyens de collecte de données en collectant des données GPS pour les modèles de trajectoire vidéo et vice-versa.

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CONTRIBUTION OF AUTHORS

This thesis is the combination of papers written for conference presentations and journal review. The first has been presented and the second is intended to be submitted to the *Accident Analysis Prevention (AAP)* journal. My contributions to this research include conducting the collecting a portion of the data, preparing, and analyzing it, and writing the manuscript. My supervisor, Prof. Luis Miranda-Moreno, provided guidance, comments, and editorial revisions throughout the entire process. The co-authors of the publications helped in data collection and providing comments. Additional members of the IMATs Lab at McGill university assisted with data collection as well.

Chapter 3

Bocktor, Y., Ledezma-Navarro, B., Miranda-Moreno, L.; 2020. The effect of the geometric turning radius on the vehicle speeds at urban non-signalized intersections.

Presented at the *Transportation Research Board (TRB) 99th Annual Meeting*; Washington DC, USA – January 2020

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Chapter 5

Bocktor, Y., Miranda-Moreno, L.; 2020. Evaluating the safety of turning maneuvers in local urban-suburban intersection using GPS data: A case study in Quebec, Canada

In preparation for submission to *Accident Analysis Prevention (AAP)* journal

I am the sole author of all additional chapters.

CHAPTER 1 INTRODUCTION

1.1 CONTEXT

Vehicle turning movements pose a threat to the safety of road users at intersections, in particular to vulnerable road users (pedestrians and cyclists) when vehicles travel at high speeds. According to the *National Motor Vehicle Crash Causation Survey* done by the United States (U.S) Department of Transport, 26.7% of crashes involved a turning vehicle (Highway Traffic Safety Administration, 2008). Another survey showed that 1.9% of the crashes were due to the geometric design (Highway Traffic Safety Administration, 2018). In Canada, 30% of fatalities and 40% of serious injuries took place in intersections (Transport Canada, 2011) from a total of 1,922 fatalities and 9,492 serious injuries. Pedestrians make up for 17.7% of fatalities and 15.5% of serious injuries with most crashes occurring in urban environments (speed limit less that 60 kph) (Transport Canada, 2018). Based on the crashes in the City of Montreal from the year 2011 to 2016, the most common collision scenario included a turning vehicle with a vulnerable road user. From the total, 16.2% of collisions involved a left turning vehicle with pedestrians crossing (10.6%), with cyclists (1.9%), or against through traffic (3.7%). On the other hand, right turning vehicles were only involved in 5% of collisions (pedestrians: 3% and cyclists: 2%) (City of Montreal, 2019). With "Vision Zero" gaining more momentum worldwide, constant efforts have been put forth to improve the safety of intersections through the identification of geometric design contributing factors and implementation of traffic calming measures.

Countermeasures and traffic calming treatments are implemented abundantly to improve the safety of intersections, urban or rural, in Canadian cities. These include improved markings, curb extensions (**Figure 1-1**), designated right and left turn channels (Yan et al., 2007), etc. Most of the previously mentioned treatments involve an indirect change in the curb radius, increasing it in most cases, which is overlooked most of the time as a safety contributing factor. A more recent intersection treatment which has been commonly implemented in North American cities is curb radius reduction. However, its implications are underreported in journals. As seen in **Figure 1-2**, radius reduction (marked in purple) compromises a pavement extension in each corner resulting in a smaller radius. This decreases the turning comfort of drivers, their speeds, and thus the potential for severe conflicts. Both curb radius reduction and curb extension decrease the crosswalk distance, the pedestrian exposure, and the likelihood of injuries or crashes.

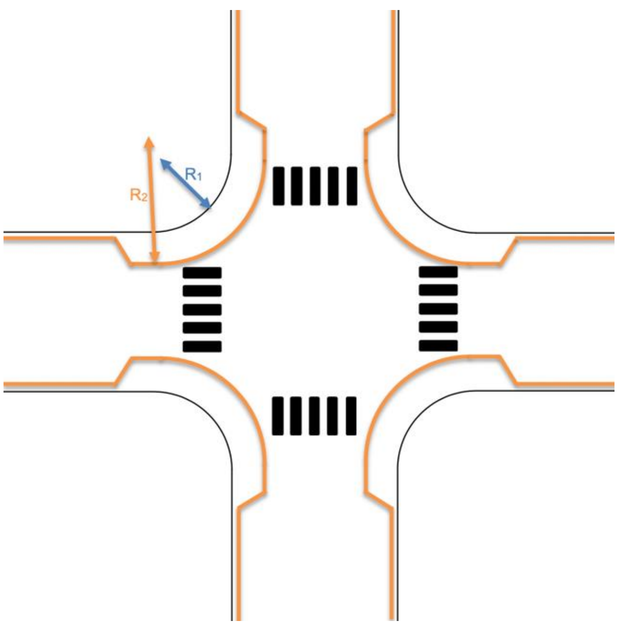

Figure 1-1 Curb extension with R_1 as the initial radius and R_2 is the increased radius after treatment

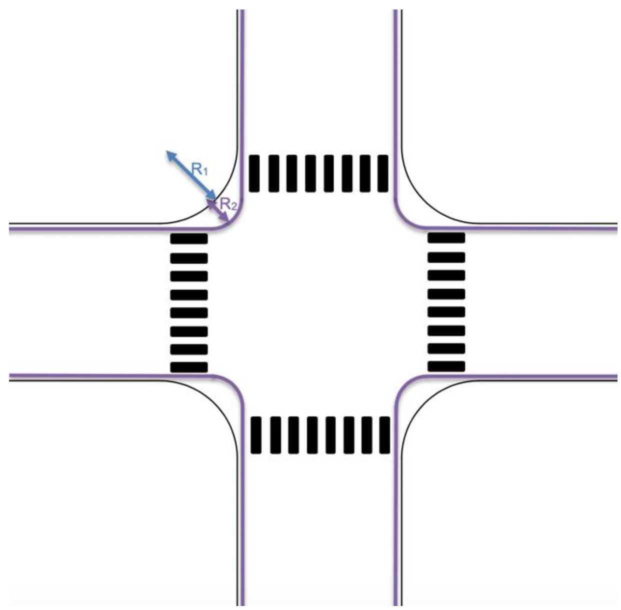

Figure 1-2 Curb radius reduction extension with R_1 as the initial radius and R_2 is the decreased radius after treatment

To investigate the link between the geometric design features or countermeasures such as curb radius and the safety outcomes, alternative road safety approaches and indicators have been used including the traditional approach of observed crash data. For instance, O'cinneide (1998) studied the effect of lane width, minimum stopping sight distance, and horizontal curve radius for rural roads and highways using crash rates. More studies have indicated that large curb radii had more crashes, thus, are less safe (Othman et al., 2009). More recently, Stipancic et al. (2020) examined the safety of intersection geometric features, including the presence of curb extensions, in Montreal using a cross-sectional regression analysis of pedestrian-vehicle crash data. It was found that curb extensions reduced pedestrian injuries by 24%.

As an alternative to the traditional approach, surrogate safety measures (SSMs) have been gaining popularity as a more proactive technique. Among the advantages, SSMs do not require crashes to take place, thus, reducing the diagnosis and evaluation periods. The SSMs indicators include proximity-based and event severity approximations. Proximity based SSMs include measures such as time to collision (TTC) and post-encroachment time (PET). From its name, PET is the time difference from the exit of the first road user from the conflict zone to the moment of entrance of the second road user (Shekhar Babu and Vedagiri, 2018). Severity approximations, however, include the use of operating speeds, acceleration, hard breaking events, etc. Studies have commonly used speed for the evaluation of design compliance of posted speed limits and influencing geometric factors. The geometric attributes, including the horizontal curve of the road as the main contributor, were evaluated with operating speed models for rural two-lane highways, with very few studies on urban local roads (Wang et al., 2004, 2005). As previously mentioned, highways and freeways have higher traffic volumes and speeds, hence, are studies more often (Jiang, 2009). However, local roads and intersections, the focus of this research, have less volume and speed but higher access to property (Wang et al., 2013). When using SSMs, trajectory data is necessary. This can be derived from video sensors using computer-vision algorithms (Fu et al., 2019; Mussone et al., 2011; Zheng et al., 2018) or Global positioning systems (GPS) (Käfer et al., 2010a; Langford et al., 2015; Stipancic et al., 2018). GPS data can be obtained from different sources including GPS-enabled vehicles like taxis and private vehicle fleet or smartphone apps. These data sources are advantageous, stand-alone or combined, as they open the door to in-depth analysis using speed profiles and trajectories given that the frequency of the measure (every second) (Kieć et al., 2019).

This study takes a step back and examines the effect of the curb radius as a safety influencing factor. In current practice, the choice of the curb radius is decided using the swept path, which is "the envelope swept out by the sides of the vehicle body, or any other part of the structure of the design vehicle" (Transoft Solutions Inc., 2019). These guidelines are presented in manuals like AASHTO. Initially in 1940, swept paths were generated base on equations, then plastic templates were used (Leisch et al., 2014). With software developments, swept path can be determined from CAD environments and others 3D applications (**Figure 1-3**). Despite the advancements in the design of intersections, evidence show that there is a gap between the design criteria and the expected effect. For instance, Stover (2008) studied the deviation of trajectories of the turning vehicles compared to the design vehicles swept paths which resulted in curb damage. Older studies questioned the design speeds on horizontal curves and suggested improvements based on data collected from five states using Highway Safety Design Model that incorporates a consistency module (Krammes et al., 1995). Thus, this thesis revisits the topic by studying vehicle speeds and other SSMs measures and their link to the curb radius.

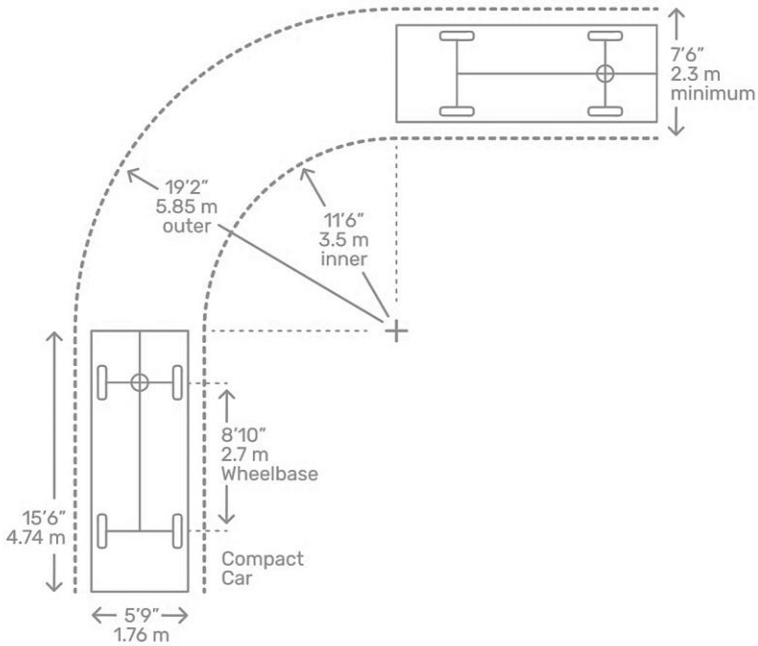

Figure 1-3 Swept path for a 90 degree turn of a passenger vehicles (Dimensions Guide, 2020)

1.2 RESEARCH GAP

Based on the literature review, this research identifies some gaps on the evaluation of the safety of the curb radius. Firstly, turning vehicle speeds and safety have been mainly investigated using simulated trajectory data - Alhajyaseen et al., (2013b). Other studies which have successfully estimated the safety of the curb radius using empirical data have a limited sample size and use point-speed measured data collected using radar guns, pneumatic tubes, etc. Some of the studies which use more automated data collection methodology, for instance video data, have used small samples (the study by Alhajyaseen et al. have only studies data from 8 intersections).

Research that utilized GPS data focus mostly on rural intersections, and those which studied urban intersections did not examine the curb radius. Furthermore, they tend to use floating cars which introduce a bias in the results. Not only this, but the filtering of GPS data using map matching treats intersections as points of the intersection of two lines, hence, overlooking details in the trajectories.

In conclusion, the literature falls short in estimating the safety of curb radii in urban local intersections. Given the common use of crash rates, more focus has been given to rural large horizonal curves with a higher susceptibility for observed crashes. However, studies that used SSMs from video footage (processed using computer vision) and GPS data for intersection evaluations tend to ignore the direct effect of the curb radius on the safety of intersections or have only evaluated a limited amount of intersections. Furthermore, studies have depended heavily on microsimulations for intersection safety evaluation rather than field collected empirical data. Moreover, despite the often-used intersections treatments, very few studies have examined the safety implications of curb radius reduction using observational studies.

1.3 OBJECTIVES

The overarching objective of this thesis is to fill in a gap presented by the literature on the safety effect of the curb radius on motorized vehicles in urban local intersections using trajectory data. This is achieved through the following specific objectives:

- To develop a methodology to evaluate the impact of the curb radius on the safety of turning maneuvers in local intersections with relatively small radii. Using the setting of Montreal, Canada, the data is collected from video cameras in a set of local urban intersections, computer vision commercial software is used to extract 85th percentile and median speeds which are the main safety indicators. Furthermore, operating speed (85th percentile and median speeds for non-car-following vehicles) models are developed using Maximum

Likelihood random-effects linear regression models for each turn type along with other geometric factors to understand the turning behavior of vehicles

- To evaluate the safety implications of curb radius reduction as an intersection traffic calming treatment using a naïve before and after study. Similarly, using trajectory data collected from video cameras, two intersections are studied in Toronto, Canada. Using surrogate safety measure obtained using a computer vision commercial software, Maximum Likelihood random-effects and standard linear regression models are computed using PET, 85th percentile, and median speeds for vehicle not exhibiting car-following behavior. Furthermore, the trajectories of speeds are studied over five areas to compare the change in the turning behavior.
- To expand on the existing use of GPS smartphone data for establishing an automated methodology for evaluating the safety of turning movements. Using open source packages and libraries, GPS-based surrogate safety measures (85th percentile, median speeds, and deceleration) are computed and extracted from the large data set. The obtained trip attributes from GPS data are later merged with manually collected geometric attributes for a set of local urban intersections in Quebec City, Canada. Maximum Likelihood random-effects and standard linear regression models of the operating speeds and decelerations are developed. Moreover, speed profiles for select intersections of varying radii categories are examined using polynomial regression models. In order to obtain trips in intersections, less filtering was done, thus, the results do not omit car-following behavior nor noisy trips.

1.4 CONTRIBUTIONS

The contributions of this thesis are as follows:

- Investigate the relationship between safety outcomes and curb radius using different metrics and empirical studies.
- Develop and evaluate operating speed models with regards to the curb radius and other geometric attributes in Canadian urban local intersections with small radii using emerging data collection techniques (video footage automatically processed and GPS smartphone data).
- Demonstrate the effects of understudied traffic calming measure, the curb radius reduction treatment, along with other influencing factors using surrogate safety measures (speed and PET) in a Canadian urban context. This work provides important empirical evidences using both a cross-sectional and a before-after study in an area with limited reported work.
- Develop an automated methodology for extracting and evaluating safety of intersections using big (GPS) data for intersections which tend to be overlooked through data filtering.

1.5 ORGANIZATION

This thesis is organized in six chapters, including the introduction. Chapter 2 presents an extensive literature review on the design of intersections and curb radii and the evaluation techniques used. Chapter 3 presents the first case study in Montreal, Canada. Using video data analysis, this study evaluated the safety of curb radii and other geometric factors for 35 local urban/suburban intersections. The analysis is done through Maximum Likelihood (ML) random-effects linear regression models using operating speeds as a safety indicator. Chapter 4 evaluates an understudied traffic calming treatment for curb radii in Toronto, Canada. Known as curb radius reduction, a before and after study is evaluated using random effects and linear regression models for SSMs (speeds and PET) collected from video data. Chapter 5 further investigates the effects curb radii using GPS smartphone data of 2 million data points. From the data set, turning trips are obtained for 76 intersections in Quebec City, Canada. The evaluation is done using operating speeds and deceleration random effects and linear regression models. Moreover, a detailed analysis of the turning trajectory is studied using 6th degree polynomials. Lastly, chapter 6 concludes the main findings of this thesis, its limitations, and the potential of further research on this topic.

CHAPTER 2 LITERATURE REVIEW

Given the complexity of intersections in urban areas, their safety has been a question. Therefore, traffic calming treatments and geometric countermeasures have been implemented extensively in North American cities. Among the alternatives, curb extensions, roundabouts, and channelized turning lanes, which include an indirect change in the curb radius at intersections, are popular. The purpose of these treatments is to reduce vehicle operating speeds. To study the effectiveness of these countermeasures, studies have utilized various safety indicators including crash data (e.g., crash rates before and after implementation), surrogate safety measures (e.g., Post Encroachment Time (PET)), which also include operating speed models or projected trajectory data (e.g., 85th percentile, median speeds, speed differential, etc.). Not only are these speed measures used to assess treatments, but they also evaluate geometric design consistency. These studies utilize different data collection methods like sensor and GPS data. Despite the abundant literature, there are some gaps when evaluating curb radius and its related treatments as an important influencer on the turning movements at local urban/suburban intersections. Therefore, the literature review examines the following topics: (1) intersection design, (2) intersection safety, (3) safety measures, (4) data collection methods, and the (5) literature shortcomings.

2.1 INTERSECTION DESIGN

The design of intersection is mostly done following the *AASHTO Green Book* (AASHTO, 2011). The design manual includes guidelines and warrants for all design elements, geometric and operational. The geometric elements include curb radius, curb extensions, number of lanes, presence of median, and stopping sight distance. On the other hand, operational criteria involve signal light phasing and signalization type. The effectiveness of geometric and signalization design criteria has been widely explored by research; however, limited literature evaluates the direct effect of the curb radius in smaller local urban/suburban intersections using modern data collection techniques.

2.1.1 **Curb Radius Design**

A well-designed curb radius ensures the safety of vehicles and vulnerable users, specifically pedestrians. According to the *National Association of City Transportation* (*NACTO) Urban Street Design Guide*, a smaller curb radius entails a safer environment for pedestrians as it reduces their exposure to vehicles by reducing the crossing distance. It is also associated with a slower vehicular speed (NACTO, 2012). However, it could have an adverse effect on the larger vehicles using the facilities, thus, damaging the curb (Stover, 2008).

The *AASHTO Green Book* is the basis to the standards used in North America (AASHTO, 2011). The AASHTO curb radius recommendation starts with the choice of the right design vehicle including the swept path associated with the AADT of the intersection in Chapter 2 of AASHTO. Chapter 9 of AASHTO states in detail the design elements of at-grade intersections. A radius of 3.0 to 4.5 meters is recommended for low turning traffic conditions. The Canadian design guidelines for turning radii at intersections (TAC, 1999) follows that of AASHTO's. These guidelines have been adapted to provincial and city levels, in some cases. For instance, The *Road Engineering Design Guidelines* of the City of Toronto uses a minimum turning radius for a local street (design vehicle name: P in reference to passenger car) of 4.0 meter and maximum of 15.0 meters unless there is a pedestrian clearway limitation (City of Toronto, 2017). Another example in the province of Ontario is the City of London with a minimum of 6.0 meters and a maximum of 9.0 meters in a residential land use area (City of London, 2015).

2.2 INTERSECTION SAFETY

Research has been conducted to study the numerous effects of geometric designs at intersections using crash data. O'cinneide (1998) has related various geometric design elements to accidents and developed predictive models using each component. These elements included: lane width, shoulder width, minimum stopping and passing sight distances, and horizontal curve radius. However, these studied developed models focusing on highway and rural roads intersections. Bauer and Harwood developed statistical models using crash data in relation to highway geometric elements for at-grade intersections (Bauer and Harwood, 2000). Using a regression model, it was found that the geometric effect was only between 5% and 14%. Also, using crash data and a tree-based regression, Karlaftis and Golias (2002) exhibited the effects of lane width, pavements serviceability, and volume counts on the safety of the rural roads.

Other treatments include changes to the existing intersection. That would include: improving the visibility of the road marking and signs, changing the level of signalization, addition of signs and visual cues, in-roadway warning lights, the addition of median refugee islands, turn restrictions, and curb ramps (Turner et al., 2006). More specific countermeasures have been implemented for turning maneuvers which highly contribute to the crash rate at intersections. An operational treatment for the signalization by Maze and Henderson (1994) studied the safety effect of including a left turning phase using crash data. Another technique included the use of traditional exclusive right turning lanes (Roefaro, 2011). Moreover, to improve the safety of these channelized right turn lanes, more pedestrian friendly design have been proposed by Zageer et al. (2002). This new design, termed as “Smart right-turn channels” reduced the turning angle, hence easing the merging to the traffic stream upon turning. Countermeasures like smart right-turn channels include an indirect change of radius which is not accounted for directly given the before-after nature of the study and the limited sample size.

Various operating measures are used to examine the safety specific to turning maneuvers (left- and right-turning vehicles). However, these measures and studies focus on large intersections or highway/expressway intersections. This is due to the extensive use of crash and injury data that is biased towards higher risk intersections. Fitzpatrick investigated the safety of right turn channels for nine intersections with exclusive right-turn lanes of radii between 8.2 and 26.0 meters using crash data (Fitzpatrick and Schneider H, 2005). It was found that large turning radii used increased the speed, thus, they had an adverse effect on pedestrian safety. Using 85^{th} percentile speed collected with the help of pneumatic tubes, operating speed models were developed for free-flowing vehicles for the beginning of the turn, middle of the curve, and the exit of the turn. In a later study, speed data was collected using pneumatic tubes and video cameras for right turning lanes in an urban setting in Texas. Regression models were developed for the 85^{th} percentile speed at each site (Fitzpatrick et al., 2006). The model included statistically significant variables like the lane length, lane width, measured radius, and island size. Another study by Othman et al. (2009) indicated that large right turning radii were less safe compared to left curves based on the crash rates of rural roads of Western Sweden.

Other measures, gap acceptance time, for instance, was studied for pedestrians crossing for 8 signalized intersections in Japan (Alhajyaseen et al., 2013a). Great attention was given to left turning traffic at left turn lanes (left traffic in japan is equivalent to right traffic in North America) using modeled scenarios, empirical data, or a combination of both. The data was collected using video data and the results were modelled using a Euler Spiral Curve to model the trajectory. The results show that the curb radius has an effect on the trajectory. Ale et al. (2014) developed volume-based safety warrants for right turn lanes at uncontrolled intersections of two-lane roadways and major-road approaches using 350 VISSIM scenarios for conflicts and crash data collected. The models were calibrated using spot-speeds and volumes collected from the field. Another study looks into the driver's perception when using right turn lanes to change from a major to a minor road using a logit model (Yu et al., 2016). However, Archer concluded that the behavior of the drivers in response to the intersection layout is not properly captured by the simulated scenarios (Archer, 2004).

Levine (2012) stressed the importance of the curb radius and its relation to injuries at intersection while pinpointing the lack of studies done in that field. 2,043 non-signalized intersection in Florida were studied and several crash injury severities ordered probit models were developed. The models included the traffic volume at minor and major approaches (surrogate measure for traffic volume), lighting conditions and other geometric factors, including the number of lanes, skew angle, distance to the nearest intersection, and the presence of left and right shoulders. The results highlighted the importance of speed enforcement, a 90-degree intersection design, and road markings which reduced severity of injuries (Haleem and Abdel-Aty, 2010). Research on the safety of intersections in Quebec using pedestrian injuries has shown a relation of traffic and pedestrian volumes with the number of lanes but the curb radius was not considered (Morency et al., 2015). Another study examined pedestrian safety with regards to the intersection geometry in Montreal using injury data and exposure measures obtained from AADT (Stipancic et al., 2020). It was found using Integrated Nested Laplace Approximation (INLA) modeling techniques for

1864 intersections that treatments like curb extensions, raised medians and exclusive left turns reduce injuries.

2.3 SAFETY MEASURES

From the previously discussed treatments and evaluations, the most prevalent methodology of analysis and assessment is that based on available crash data. However, a shift towards surrogate safety measures and speeds have been witnessed in the last years.

2.3.1 **Surrogate Safety Measures**

Surrogate safety measures (SSMs) are a more proactive way of assessing the safety of intersections and potential hotspots without the occurrence of crashes or injuries (Shekhar Babu and Vedagiri, 2018). Not only are they predictors for crashes, they also require a shorter period of time to be collected as compared to crash data which can take many years, especially in low volume areas. SSMs focus on the use of vehicle conflicts that can be involved in near-crashes. Defined as "an observable situation in which two or more road users approach each other in time and space to such an extent that there is risk of collision if their movements remain unchanged", conflicts become indicators of potential crashes (Hydén, 1977). This is further explained by the Hydén pyramid of conflicts and crashes (Hydén, 1987). Time to collision (TTC), post encroachment time (PET), speeds (85^{th} percentile, 95^{th} percentile, and median speed), speed profiles (Moreno and García, 2013; Pei et al., 2012), acceleration and deceleration rate (AR and DR) are example indicators of safety measures used. TTC and PET are event-based time approximations; while speed, acceleration, and deceleration rates are severity approximation. PET requires vehicles to cross paths; hence, it could be disadvantageous when considering high volume intersections. However, this makes PET an accurate estimator for turning vehicles safety, especially in intersections, as conflicts occur between different road users (vehicle-vehicle or vehicle-pedestrian).

2.3.2 Speed as a Safety Indicator

When evaluating risk of conflicts, speed plays a role as an indicator of the severity of the near-crashes. Various studies have been conducted to relate speed and its association with crashes and injuries. Pei et al. (2012) has found a positive correlation between high speeds and increased injury severity.

2.3.2.1 Operating Speed Studies

Operating speed models have been widely used to investigate design consistency and driver's compliance with speed limit (Hassan et al., 2001). Most operating speed models focus on rural two-lane highways, segments, and curvature. Those that examine urban setting, focus on road segments (Dinh and Kubota, 2013). A study on suburban arterials in Texas with speed limits between 64 to 81 km/h found that approach density and horizontal radius to be most significant for the model (Fitzpatrick et al., 1997). Operating speed models follow linear regressions or linear mixed-effect models to capture the effect of road geometric characteristics (Wang et al., 2006).

Early models were developed by Emmerson in 1970 for the average speeds measured at the center of a horizontal curve on two-lane roads in rural areas in relation to the curve radii ranging from 25.0 to 457.2 meters (Emmerson, 1970). It was concluded that curves with radii greater than 200 m curvature had negligible influence on speed, whereas radii less than 100 m are accompanied with a substantial reduction in speed. A few decades later, Krammes et al. (1995) deduced a model linking the 85th percentile speed to the degree of curvature, length of the curve, and deflection angle based on data from low- to moderate-volume rural collectors or minor arterials in level to rolling terrain to evaluate design consistency between successive geometric features. Radii used in that study are greater than 145 meters.

2.3.2.2 Speed Trajectories and Profiles

Recently, speed along the curb radii of urban or rural intersections are studied through trajectory was made possible by the revolution in transportation simulation. Such studies give a deeper understanding of the microscopic vehicle behavior when traversing intersections. For instance, a study predicted the trajectory of vehicles at urban intersections based on geometric measures and simulated scenarios. The results were later compared to 65 left turning vehicles at an intersection for calibration (Kawasaki and Tasaki, 2018). However, other work used an Euler-spiral-based model, showed a shift in trajectory depending on the intersection angle, number of exit lanes and vehicle type (Asano et al., 2010). A following study developed a model for left turning traffic (which in Japan is equivalent to that of right turning traffic in North America) using a gap acceptance model and the effect on pedestrians (Alhajyaseen et al., 2012). Also, speed modelled using simulations along the trajectory used third-degree polynomial to capture the behavior of the drivers. This behavior includes an initial phase where the drivers slows down as they approach the curve, then go around the curve in a slowed down manner, and then accelerate again to a high speed as they leave the intersection. This study looked at radii between 9.7 and 21.0 meters of big intersections. Cafiso & Cerni (2012) studied continuous speed profiles of rural two-lane roadways using GPS data. Using light detection and LIDAR guns, Boonsiripant (2009) collected vehicle speeds for highway intersections to develop speed profiles. Likewise, Distefano & Leonardi (2019) developed speed profiles to study the effect traffic calming for urban setting. Lastly, Moreno &

García (2013) used speed profiles developed from GPS data collected for 12 scenarios for traffic calming in urban setting for as a surrogate safety measure as it provides an in-depth perspective on the driving behavior.

2.4 Data Collection Methods

The previously mentioned data-driven non-simulated studies utilize various data collection methods for surrogate safety and operating speed models. Some of the studies aimed for operating speed analysis use more traditional point-speed methods like radars, laser speed guns, pneumatic tubes, and location traffic analyzer. While these methods are very helpful, they are limited as they only examine one location of the turn rather than the entire trajectory. Thus, more recent studies utilize methods like lidars, thermal cameras, video footage, and global positioning system (GPS) data. These methods or a combination of them allow for the collection of speed profiles and surrogate safety measures.

2.4.1 **Video Data**

With the current development of computer vision in the field of transportation, the use of video camera collected footage has provided an easy mean of data collection. The use of video data and computer vision has been particularly popular in evaluating road safety of all users using surrogate safety measures (SSMs). These SSMs are used for evaluating existing infrastructure or before-after studies for road treatments and traffic calming measures. St-Aubin (2011) examined the safety of highway ramps and lane-changing. A before-after study was done for a lane-changing ban using video data collected from surveillance cameras and mobile video to obtain SSMs (St-Aubin et al., 2013). Another study focused on the safety of pedestrians in intersections during night time using SSMs computed from thermal camera video data (Fu et al., 2016). The results show that thermal cameras can be effectively used to solve the issue of low visibility. Due to its accurate classification of users, video data was used to study the safety of cyclists, especially in intersections (Zangenehpour et al., 2015, 2013). More studies have utilized multiple measure to study the same attributes. A paper by Kieć et al. (2019) used both video and GPS data to study the safety of turbo-roundabout with speeds as a function of radii.

2.4.2 **GPS Data**

The Global Positioning System (GPS) data has been used in a wide array of studies on intersections and turning movements. Korpilo et al. (2017) used GPS data to locate hotspots for runners and cyclists based on number of trips. The ease of data collection and its frequency makes it a powerful tool for various applications. Some studies have used GPS data to generate automatic algorithm to detect road characteristics like complex highway intersections and crossovers using longest common subsequence clustering method (Huang et al., 2017), or to measure horizonal curves ranging from 200 to 1800 meters (Ai and Tsai, 2015). To further understand the turning behavior, Phondeenana et al. (2013) detected turning movements using the heading angle calculated using the mathematical function “arctan”. Similarly, Käfer et al. (2010b) developed an algorithm to detect turning movement 2-4 seconds before its occurance. This study used data collected using a test drive vehicle for 10 km on three road intersections.

GPS data, collected using floating vehicles or smartphones, has been utilized in safety assessment of various road types, segments, and intersections. While some studies have derived safety measures using the data, some have related it to crash data. Xu et al. (2019) studied the safety of urban expressways used the variance speed (from the GPS data) and compared it to the crash data.

The relationship of the two measures was examined using a Poisson Gamma model. A similar study on urban road segments in Hong Kong applied a full Bayesian method (Pei et al., 2012). Another study evaluated the safety of intersections using crash data and GPS data for speed variance for 195 intersections, in relation to their geometric attributes. These attributes include number of lanes, volumes of movements, cycle lengths, angle of intersecting road, and signal phasing. The results show a safety issue with 4-legged intersections with more lanes (Xie et al., 2013). Strauss & Miranda-Moreno (2017) examined intersection geometric design and built environment characteristics affecting cyclists in Montreal. Using GPS smartphone data, they have formulated a linear regression relating speed and these measures for road segments and intersections. Furthermore, some have studied the safety of intersections using SSM of behavioral related like hard breaking events, acceleration, and deceleration (Stipancic et al., 2018, 2016).

The aforementioned speed studies in **section 2.3.2** have been made more compreshensive because of the frequency of GPS data and their ease of collection. While a lot of studies have been carried out on the topic, a scarce amount examin the curb radius, especially for local urban/suburban intersections. Studies either focus on urban segments or highway curves. An example study is on two-way rural road with 13 tangent-curve configerations using GPS devices installed in a car. The study successfully generated an operating speed predictive model for radii between 200 to 500 m (Bella et al., 2013). Similarly, Cafiso & Cerni (2012) studied speed profiles with regards to geometric features of two-lane rural highways, as well as acceleration and deceleration for horizontal curvature. Using in-vehicle GPS data for more than 200 vehicles, Wang et al. used maximum deceleration in comparison with speed for urban stop-controlled intersections (Wang et al., 2005). This study mimics an earlier one using acceleration rates (Wang et al., 2004). A more recent publication examines the geometric influence on drivers' speed choice in urban setting using in-vehicle GPS data, however, it only examines road segments (Wang et al., 2006).

2.5 LITERATURE SHORTCOMINGS

Based on the findings of existing literature, the following shortcomings have been noted:

- Design manuals, especially with regards to curb radius, fall short in estimating the actual turning behavior of vehicles in intersections.
- Most studies which evaluate the safety of intersection geometric attributes tend to use crash data and rates. Crash data tends to show a bias towards larger intersections and curb radii because of the increased potential of collisions presented by higher speeds and volumes. Not only do they focus on larger intersections, but they also require a longer duration to collect and are not as proactive as surrogate safety measures.
- Operating speed models have been computed to study the effectiveness of the design manuals and posted speed limits, especially for on rural arterial two-lane roads. These studies focus on, both, road segments and horizontal curves. However, very few studies examine urban local roads and intersections.
- Most of the existing operating speed models used point-speeds which do not capture the full turning trajectories. Those which have used more advance techniques like Video and GPS data investigate either investigate the safety of rural horizonal curves or other geometric attributes of intersections. The use of these data sources provides an easier automated method for larger data sets.
- Various traffic calming treatments have been implemented by municipalities to improve the safety of intersections for all road users. These include exclusive turning lanes,

roundabouts, curb extension, radius reduction, etc. All of which include an adjustment to the curb radius. Nonetheless, very few studies examine the direct effect of the curb radius on the vehicle safety. Furthermore, limited research examined the implications of the curb radius reduction treatment.

Thereupon, this study aims to fill in a literature gap focusing on the safety of curb radii less than 30.0 meters (a focus on 2.0 -10.0 meters) in urban local intersections of a speed limit of 50km/hr. This is done in the Canadian context using data collected from video cameras and GPS application.

CHAPTER 3 THE EFFECT OF THE GEOMETRIC CURB RADIUS ON VEHICLE SAFETY USING SPEEDS MEASURED AT URBAN NON-SIGNALIZED INTERSECTIONS: A CASE STUDY IN MONTREAL, CANADA

3.1 Introduction

Intersections are known to be a safety concern because of the complexity of road user interactions and various design elements integrated (Shirazi and Morris, 2017). It is believed that the curb radius, also known as turning radius or curve radius, has an influence on the speed and hence on the overall safety of intersections. Thus, constant efforts have been made in improving the safety of intersections through various geometric design treatments that aim to reduce turning vehicle speeds, improve visibility, or reduce pedestrian crossing distances. These improvements to the intersection geometry entail an indirect change to the radius of the curb. For instance, right turn channels increase the curb radius at the intersection while a smart right turn decreases the radius. Nonetheless, very few studies have looked at the direct impact of the curb radius on the speed of turning vehicles given the nature of before-after studies.

Given the archaic nature of the topic, the studies conducted on the safety of curb radii, utilize rather traditional evaluation techniques. Studies conducted use crash data, however, such data has a bias towards highways because more crashes are likely to happen at larger curves with higher speeds (Roudsari et al., 2006). Other studies use injuries and their severity as measures of safety (Haleem and Abdel-Aty, 2010). In recent years, there has been a shift in quantifying the safety at intersections through the use of surrogate safety measures such as time to collision (TTC), post encroachment time (PET), and various speed measures. One study collected point-speed data using pneumatic tubes and evaluated the safety of right turn lanes (Fitzpatrick et al., 2006), while one recent study used 85th percentile speed collected from video data (Fu et al., 2019). Simulations are also utilized to predict the trajectory of vehicles at urban intersections based on geometric measures (Kawasaki and Tasaki, 2018). From the literature, studies which mainly focus on mathematical models and simulations, lack the use of real trajectories and mostly target highways and arterials.

This chapter takes a step back and investigates the link between curb radius and turning (left or right) operating speeds of vehicles at non-signalized intersections with stop controls in minor or in all approaches. The objective of this research is to fill in a gap in the literature on the effect of the curb radius on the turning speeds of vehicles using observational video trajectory data. Using data from a large set of intersections in Montreal, Canada as an example of a North American city; a statistical model was generated to help understand the implications of the curb radii on vehicle operating speeds. These speed measures are used as safety indicators.

3.2 METHODOLOGY

As mentioned, video data collection was done for 35 intersections and manual data collection of geometric attributes followed. Later, the data was processed, variables were generated accordingly, and statistical models were generated to test the effect of the quantified measured curb radius on the turning speeds along the curve. The breakdown of these steps is seen in **Figure 3-1.**

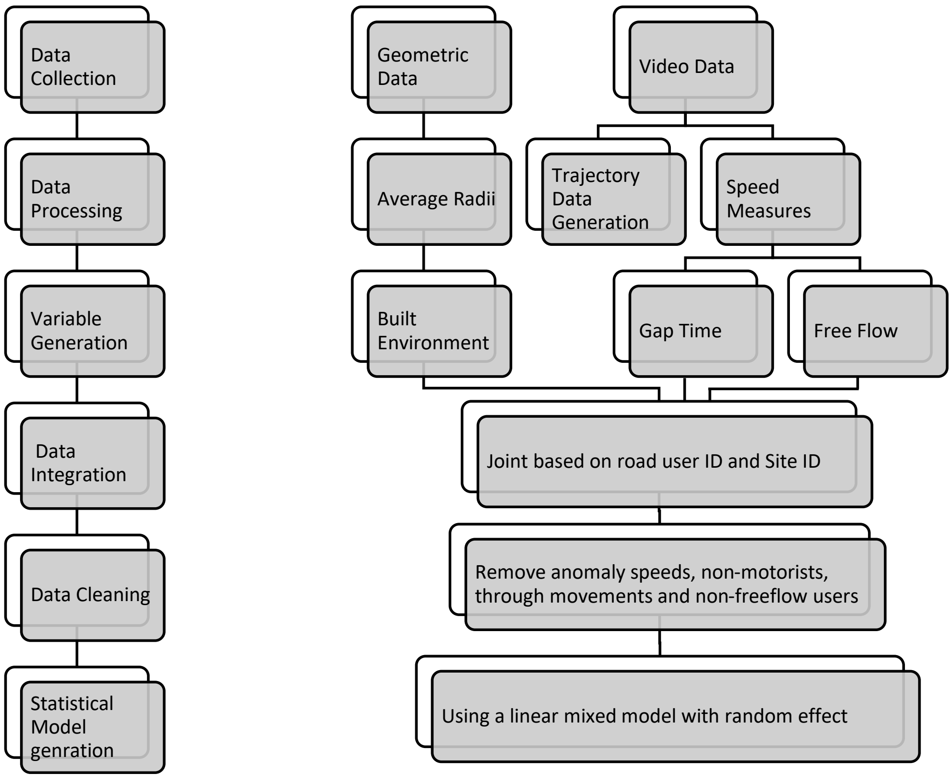

Figure 3-1 Flow chart of the outline of the study

The framework of the methodology of the collected empirical data measures is discussed in the following sections: site selection, video data collection and processing, curb radius and geometric attributes, statistical equations, and assumptions.

3.2.1 **Site Selection**

Using GIS maps, the selection criteria for the intersection was based on street types and the number of lanes for each approach (Ville de Montreal, 2018). This study focuses on local streets with one to two lanes per approach. The speed limit for the local streets of Montreal is 40 kph except in the areas surrounding schools where this speed limit is reduced to 30 kph. A total of 35 non-signalized intersections with stop controls in the minor or all approaches were selected at random from six boroughs (Ahuntsic-Cartierville: 6, Lasalle: 4, Plateau-Mont-Royal: 3, Pointe-aux-Trembles-

Rivières-des-Prairies: 6, Rosemont-La-Petite-Patrie: 2, and Villeray-Saint-Michel-Parc-Extension: 14). The areas are either urban, urban suburban, inner suburban or outer suburban.

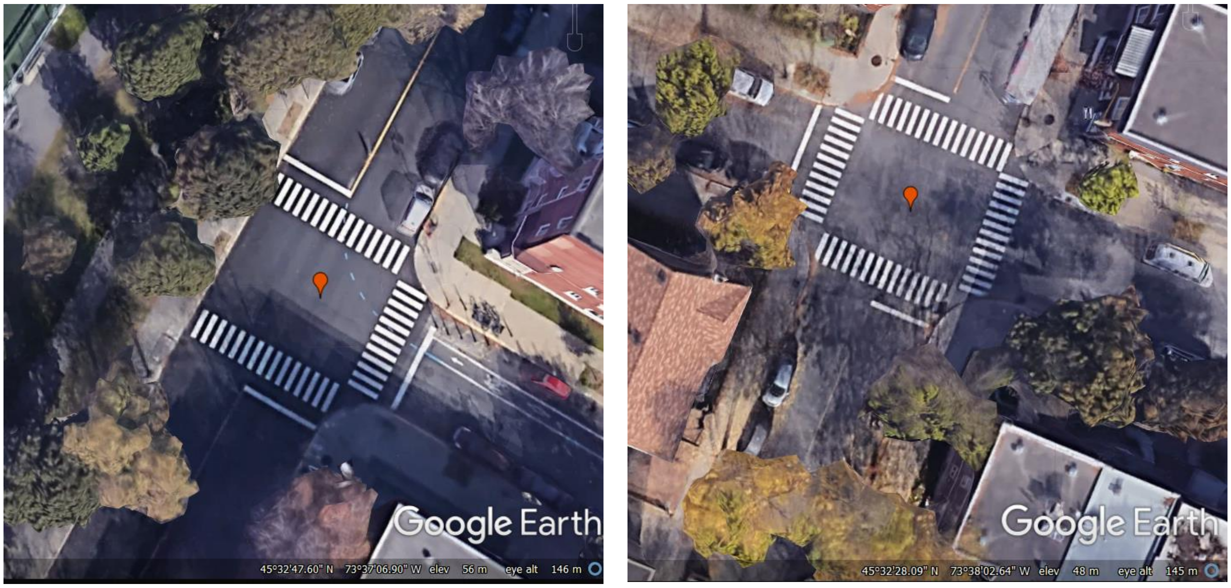

Figure 3-2 Google Earth aerial view of a 3-legged/ T-intersection (left) and 4-legged/ X-intersection

The sites include both T-intersections, which refer to three-leg intersections, and X-intersections, which are the common four-leg intersections as seen in **Figure 3-2**. As previously mentioned, the sites used are either minor-only-stop intersections or all-way stop intersections. Minor-only-stop intersections or partially stop-controlled intersections entail the presence of a stop sign at one of the approaches, while all-way stop intersections or fully stop-controlled are intersections with stop signs for all approaches. For the purpose of this study, each approach was assigned an approach level stop control attribute.

3.2.2 **Video Data Collection and Processing**

Video cameras (1080×720 pixels resolution and 30 frames per second) were installed at the intersections at a height varying between 6 to 8 meters; with an orientation set to capture all users: pedestrians, cyclists, and motorists (cars, trucks, buses and motorcyclists) from all directions of the site. The data was collected for periods of two days. The video footage was processed by computer vision software, *Brisk Lumina* (Brisk Synergies, 2017), which integrates and utilizes deep and machine learning algorithms for traffic safety analysis. The video footage was processed in three main stages: (1) definition of scenarios, (2) video calibration, and (3) trajectory generation. Firstly, scenarios of the various traffic maneuvers' interactions with road users of all approaches were defined. Secondly, the videos were calibrated through the adjustment of homography, defined as two related images which share the same planar surface in space. The homography, in the premise of this research, was used to match the points on the video footage to the coordinates of the street. Based on the aforementioned step, conflict zones are outlined, and the pre-trained deep learning methods are applied (St-Aubin, Paul and Ledezma-Navarro, Bismarck and Labbe, Aurélie and Fu, Ting and Saunier, Nicolas and Miranda-Moreno, 2018). Lastly, the trajectories of the road users were tracked for every frame of the footage along the path as seen in **Figure 3-3** which are used for various speed measure generations.

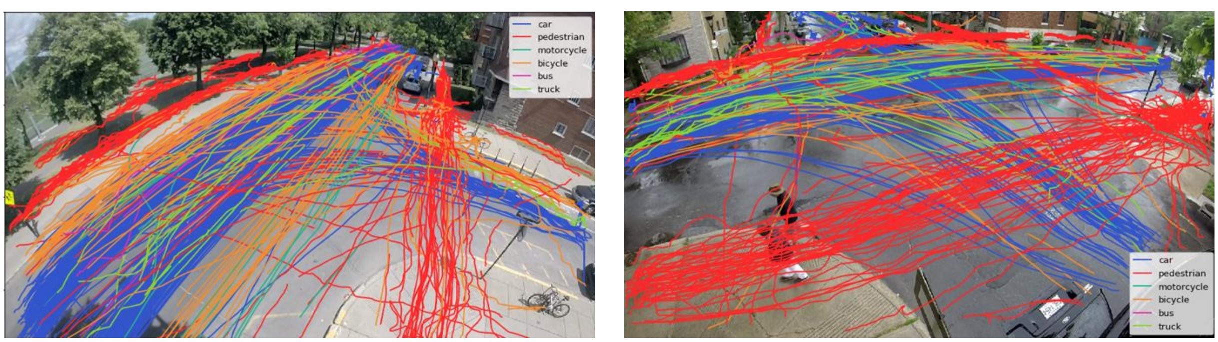

Figure 3-3 Trajectories tracked by computer vision of the commercial software corresponding to the intersections in Figure 3-2

3.2.3 Curb Radius and Geometric Attributes

From the chosen 35 intersections, there are 12 T-intersections and 23 X-intersections which adds up to 120 curbs in total. An aerial satellite map of Montreal from *Google Earth Pro* (Google Inc., 2019) was obtained, and the intersections were pinned to it. Each side was numbered according to the quadrant system with reference to the north of Montreal which is a true northwest. The radii were measured using the tools available on *Google Earth Pro* (Google Inc., 2019) by two different people, and an average of 3 readings were recorded per person. Thus, the radius noted for each curb is an average of 6 readings to normalize personal bias.

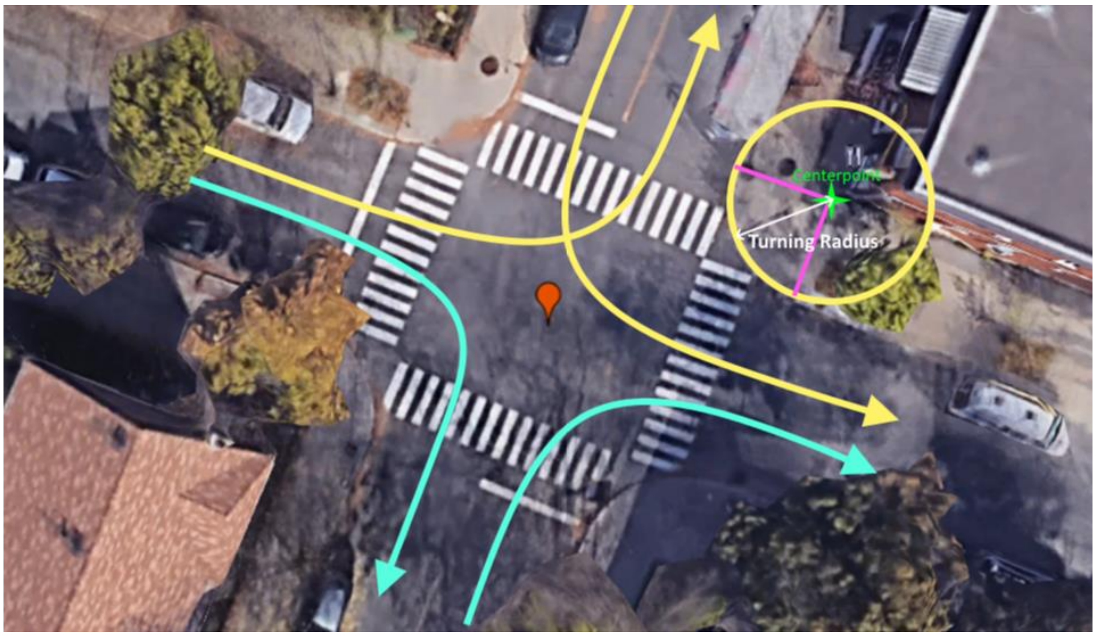

Figure 3-4 Defining of turning (curb) radius and the right and left turning movements detected for this intersection

Each intersection side was identified, zoomed into and the center point of the curb was established. The measuring tool "Ruler-Circle" was utilized where the center of the ruler was superimposed on the center point (**Figure 3-4**), then the measurements were allocated to each road user. Since the selected intersections are from local streets, the radii measured are less than 10 m (from 2.58 m to 9.33 m). **Figure 3-5** shows the distribution of the radii measured.

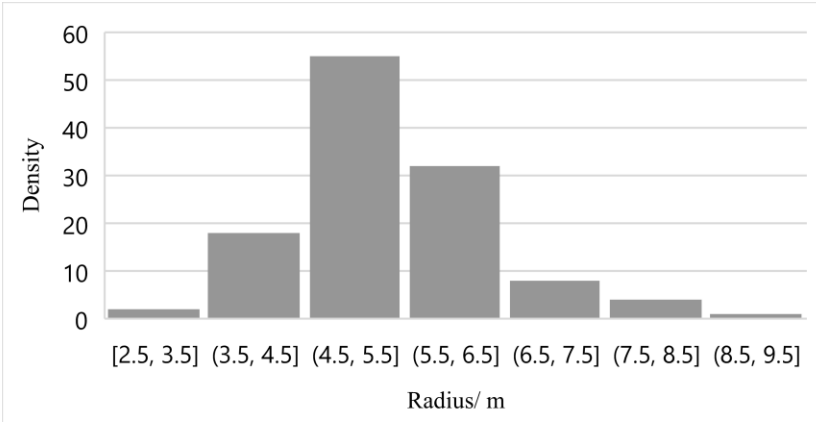

Figure 3-5 Distribution of the curb radii measurements of the intersections

Other attributes of the geometric identity of the intersection that are believed to influence the turning behavior of vehicles were also noted and measured. These include: the presence of crosswalks, bike paths, stop signs, number of lanes for each direction, the distance to the nearest intersection, and number of legs of the intersection. The intersections used for this study were assumed to be at-grade and of simple radii (non-compound radii). The built environment of the intersection was also a contributing factor. Using a grid approach of 500m x 500m for the Montreal census metropolitan area (CMA), population density was obtained from the census track level from Statistics Canada for eight surrounding cells (Zahabi et al., 2016).

3.2.4 **Statistical Equations**

The data presented in this study are geometric factors recorded at the approach or the intersection level for each road user in the database. The individual 85th percentile speed and median speed along the curve were observed at the road-user level. Thus, a linear mixed model with random effects which utilizes a Maximum Likelihood (ML) estimator was used with an error factor on the intersection level using STATA 13. This model helps to accommodate unobserved factors at the intersection level that could affect observations nested in the same location. Considering y_{ij} the outcome of interest, the model takes the following form:

$$y_{ij} = \beta_0 + \beta_1 x_1 + \cdots + \beta_k x_k + u_i + \epsilon_{ij}$$

where y_{ij} in this case is the median speed or 85$^{\text{th}}$ percentile speed, i = 1, …, n sites (with n = 35) and j stands for approaching vehicle. β_0 is the intercept of the model and $\beta_{(k)}$ represents the coefficients for the k factors $x_{(k)}$taken into consideration. ϵ_{ij} is the random error of the regression estimate and u_i is the random error factor specific to the intersection i. Both errors are assumed to be normally distributed. The errors follow the conditions:

$$\epsilon_{ij} \sim N\ (0{,}1) \text{ and } Cov\ (u_i, u_j) \neq 0.$$

3.2.5 **Assumptions**

For the purposes of this study, it was assumed that car following behavior was omitted by discarding the road users with gap time cut offs of 10s and 5s for stop-controlled approaches and no-stop-controlled approaches, respectively. This provides a better understanding of the actual relation between speed and the curb radius. Furthermore, it was assumed that the trajectories of the vehicles tracked were complete. This might have been a source of error given the occasional cut offs in the trajectories and their re-recognition. However, because of the sole concern of the effect of the curb radius on the average speed of the full trajectory, this would not affect the results significantly. To account for this error, however, anomalous data of speeds higher than 150 kph were discarded. Furthermore, the intersections were assumed to have simple curb radii, on a regular terrain and an angle between 60 to 120 degrees. 30 out of the 35 intersections are proper

90-degree intersections. This chapter aims to find a direct relationship between the speed of turning vehicles and the curb radius measured. Even though the turning radius of the vehicle's movement is different from the curb radius, this study explores the possible link between the speed of the vehicle and the measured turning radius of the curb.

3.3 VARIABLE GENERATION AND INTEGRATION

The results obtained from the commercial software are in the form of speeds (15^{th} and 85^{th} percentiles, median, and mean speeds) along each trajectory of each road user (pedestrian, cyclist, or motorists) and the time stamps of detection and departure from the site. Along with the geometric attributes mentioned above, the data was compiled for each road user to complete the dataset. This dataset was then used to compute and generate variables like free flow and approximate gap time between vehicles using Python. The free flow in this case is defined by the presence of any vulnerable road users at the time of the turn of the motorist within a buffer of 5 seconds of the motorist's trajectory that would affect normal free flow conditions. The selection of the criteria of 5 seconds was based on the estimated time it would take a pedestrian to be able to get off the sidewalk and interfere with the vehicle. Also, using the time stamps of the road users, an approximate gap time was calculated using the average of the time the vehicle was first seen and last seen. This is due to one of the limitations of video tracking technologies as the trajectories do not necessarily start from the same location, thus, an exact gap time could not be obtained. Gap time, therefore, is used as an indicator of the presence of other vehicles affecting the speed along the turning movement causing exhibited car-following behavior. Accepted average gap times for stop-controlled approaches and no-stop-controlled approaches are 10 s and 5 s, respectively. The selection of gap time was based on the recommendations of Troutbeck, R.J. and Brilon (2002).

The last step in the data generation was the integration of all the information to the users of interests. For the purposes of this study, only turning motorists (cars, buses and trucks) are included. Data cleaning was done through the following steps. Firstly, motorcycles were disregarded given their small percentage. An aggregation was therefore done for buses and trucks, while cars were a stand-alone category. Furthermore, only right- and left-turning motorists were considered to examine the effect of the curb radius of the intersection. Also, vehicles turning to driveways and parking lots at 3-leg intersections were manually detected and removed from the data set.

For this chapter, various information was collected on the road user and intersection levels, then tested using regression models to check their significance. It was found that only a handful of variables had a statistically significant effect on the speed of the turning road user. All variables, however, are defined in **Table 3-1**. Dummy variables are used for stop controlled, bike path, crosswalk, and pedestrian crossing present. Categorical variables, which are similar to the dummy variables, but with more than two categories, are also used for the intersection and the movement type. Measurements like speeds, radii, and distances are continuous. Other measures of speed like the 15^{th} percentile speed and mean speed were also obtained. In spite of that, only the 85^{th} percentile speed and median speeds were used in this study. The 85^{th} percentile speed has been used as a measure of safety in other studies (Zangenehpour, 2017) (Fitzpatrick et al., 2006) (Fu et al., 2019). The median speed is used as an indicator of the speed around the middle of the curb since it reflects on the measure of speed approximately midway of the trajectory (median of the point speeds).

Table 3-1 The description and units (or categories) for variables used for statistical models

Variable	Description	Categories / Units
X85th	85th percentile of the vehicle speed	Continuous measured in kph
Median	Median speed of the vehicle along the trajectory	Continuous measured in kph
TRadius	The radius of curvature measured at the curb of the approach	Continuous measured in m
Stop Controlled	Stop Sign is present at the approach	0 = no stop sign and 1 = stop sign present
Bikepath_Approach	If a bike path is present at the vehicle's approach	0 = no bike path and 1 = bike path present
Bikepath_Exit	If a bike path is present at the vehicle's exit after the turn	0 = no bike path and 1 = bike path present
Crosswalk_ Approach	If a crosswalk is present at the vehicle's approach	0 = no crosswalk and 1 = crosswalk present
Crosswalk_ Exit	If a crosswalk is present at the vehicle's exit after the turn	0 = no crosswalk and 1 = crosswalk present
Inter Distance_approach	Distance to the closest Intersection from approach	Continuous measured in m
Inter Distance_Exit	Distance to the closest Intersection from Exit	Continuous measured in m
Free flow	If a pedestrian is present within a 5 sec buffer	0 = no pedestrian and 1= pedestrian present
Movement Type	Right turn or left turn at intersection	0 = right turn and 1 = left turn
Intersection Type	Intersection type based on the number of branches	Categorical variable with two sets: (1) 3-legged intersection and (2) 4-legged intersection
Vehicle Type	The type of vehicle involved in the interaction.	Categorical variable with two sets: (1) cars and (2) buses and trucks
Intersection Complexity	Number of lanes of the approach and exit of the vehicle	Continuous count of lanes
Population	Cluster population from 2006 census	Continuous measured in number of people/million

3.4 RESULTS AND ANALYSIS

The results are explained in three subsections. The first presents the analysis of the summary statistics of the data in aggregated and disaggregated approaches, followed by a preliminary analysis of the speed in relation to the curb radii collected. Lastly, a discussion of the random-effects regression models examining the effect curb radius and other geometric factors on the speed measures is presented.

3.4.1 Summary Statistics

The data obtained were examined on two levels. Firstly, all road users were studied together in an aggregated approach and summary statistics obtained are shown in **Table 3-2**. Then, the data was disaggregated based on the direction of the turn (right and left turn) in **Table 3-3**. The average of the 85th percentile speed is 22.33 kph for the full dataset with a standard deviation of 10.75 kph for a total of 6,909 observations. Compared to the disaggregated data, the right turn decreased the average 85th percentile speed by 0.93 kph (average of 21.4) while a left turn increased it by 1.02 kph (average of 23.35).

Table 3-2 Aggregated data summary statistics for both turns

Variable	Mean	Std Dev	Min	Max
X85th	22.33	10.75	0.11	134.89
Median	14.26	8.93	0	90.94
TRadius	5.40	0.94	2.58	9.12
Stop Controlled	0.46	0.50	0	1
Inter Distance_approach	129.34	92.97	60	690
Inter Distance_Exit	165.8	104.89	60	690
Population	79.95	110.03	16	135.86
Observations	6909			

Table 3-3 Disaggregated data summary statistics

	RIGHT TURNING VEHICLES				LEFT TURNING VEHICLES			
Variable	Mean	Std Dev	Min	Max	Mean	Std Dev	Min	Max
X85th	21.4	10.98	0.11	134.89	23.35	10.40	0.36	123.29
Median	13.66	7.73	0	90.94	14.93	10.04	0	59.03
TRadius	5.33	0.89	2.58	9.12	5.47	0.98	2.58	9.12
Stop Controlled	0.54	0.50	0	1	0.50	0.50	0	1
Inter Distance _approach	133.00	102.05	60	690	125.53	81.94	60	380
Inter Distance_ Exit	165.40	100.52	60	380	167.30	110.83	60	690
Population	82.09	28.27	16	135.86	77.61	27.78	16	135.86
Observations	3620				3289			

The distribution of the stop-controlled users was around 54% as compared to 46% of non-controlled, hence, showing balanced distribution. **Figure 3-6** shows the distribution for both 85th percentile speed and median speeds for the combination of both turns, right turn, and left turn. It can be observed that the 85th percentile peaks around 20 kph for all turns. However, the median speed peaks at 12 kph for right turns and 18 kph for left turns.

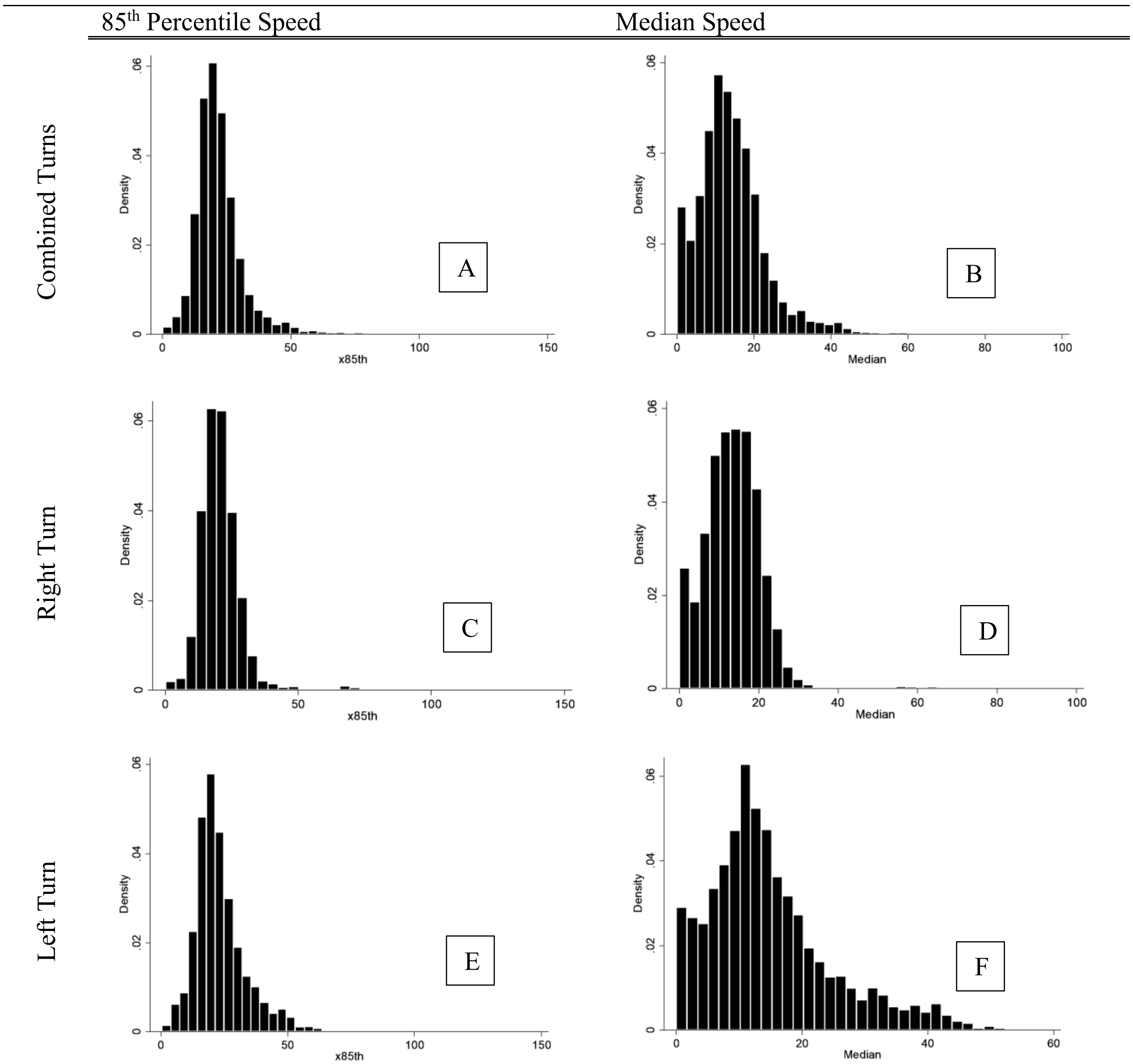

Figure 3-6 Histogram for speeds of vehicle users based on turning movements (speeds in kph)

3.4.1 **Preliminary Analysis of Operating Speed**

Based on the existing literature, higher speeds in intersections are indicators of increased risk, hence, decreasing the overall safety. Therefore, to study the effect of the curb radii on speed, the radii were divided into four main categories for a preliminary analysis using a box plot (**Figure 3-7**).

By examining all sets, it can be observed that for every increase the radius, the average median speed increases. The highest increase is seen from categories of 2.0-4.0 m to 4.0-6.0 m. This increase can be explained by the driver's comfort of driving. Curb radii of less than 4 m are very sharp and much lower speeds are required. Also, such small curb radii are present in residential areas or older parts of town which are touristic and lead to more pedestrian volumes, thus, decreasing the turning speeds. The smaller increase in the speed in higher radii groups can be attributed to the likelihood of higher volumes of vehicles given that the intersection is bigger.

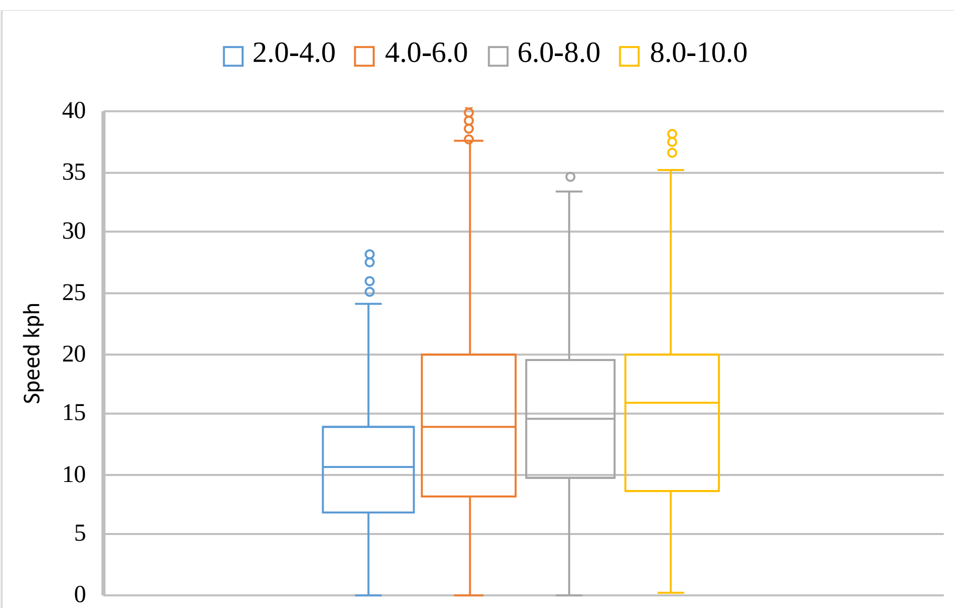

Figure 3-7 Distribution of median speed of trips based on the curb radius category measured in meters

The software was able to produce speed heatmaps from the trajectories of the motorized road users for randomly selected intersections. From **Figures 3-8** and **3-9**, it can be observed that for the detected turning vehicle trajectories, the motorist reached their lowest speed (darkest purple) right before the curve and then the speed increases as they merge to the stream. The highest speeds are attained by through vehicles. Unfortunately, these heatmaps are missing the left turning vehicles marked in the red arrow because of the incomplete trajectories as the diagram is produced for 15-min intervals only.

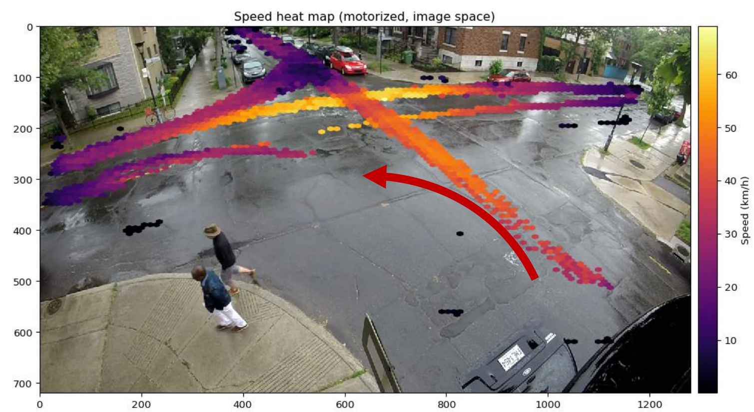

Figure 3-8 Speed heatmap of a 4-legged intersection

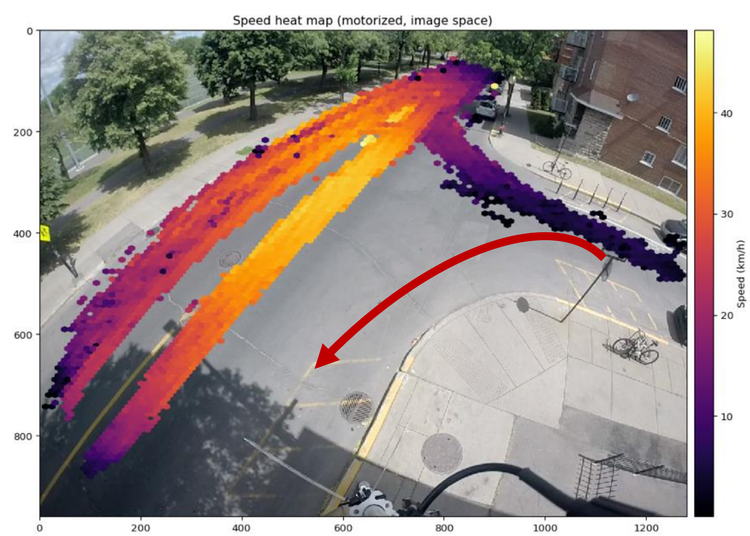

Figure 3-9 Speed heatmap of a 3-legged intersection

3.4.2 Regression Model Analysis and Discussion

As previously mentioned, a random effects linear model with an error factor on the intersection level was used to evaluate the significant factors affecting speeds at the intersection with a focus on the curb radius. The models were evaluated for both 85th percentile and median speeds using only significant factors. Insignificant factors like number of lanes, complexity of intersection (combination of the number of lanes of approach and exit of turn), distance to the nearest intersection, and the presence of a crosswalk at the approach or the merging side were eliminated from the models. Other factors like width and length of crosswalks, the classification of the neighborhood cluster, and land use of the area were also removed as they were insignificant at a 90% confidence level.

Curb radius, presence of a bike path at the exit, free flow conditions, and stop-controlled approaches were the most significant for the combined turns (aggregated) model. Starting with the aggregated data model analysis, it is shown that for every meter increase in the radius, an increase of 0.778 kph and 1.208 kph is witnessed for the 85th percentile and the median speeds, respectively. In other words, a vehicle turning in an approach with a curb radius of 10 meters would be travelling with a speed of 9.5% more than that of the vehicle in an approach with a curb radius of 5 meters. Based on this part of the statistical model, it can be concluded that the curb radius increases the lowest speed reached by the vehicle while turning. Left turns had a higher 85th percentile speed compared to right turning (with turning as a dummy variable). However, the movement type has no effect on the median speed. The heavier vehicle type has higher speeds for the right turning models and combined but it was not significant for left turns when compared to cars. This could be because of the sample bias; as around 400 heavy vehicles were captured during data collection.

Table 3-4 Random Effects ML Regression Models for aggregate and disaggregate data

	85th Percentile Speed			**Median Speed**		
	Combined	**Right Turn**	**Left Turn**	**Combined**	**Right Turn**	**Left Turn**
	b/se	b/se	b/se	b/se	b/se	b/se
TRadius	0.778***	-0.142	2.568***	1.208***	0.643**	2.708***
	(0.210)	(0.402)	(0.299)	(0.157)	(0.258)	(0.270)
Bikepath_approach	-1.703*	-2.904**	0.096	-0.495	-0.389	0.391
	(0.925)	(1.314)	(1.028)	(0.799)	(0.843)	(1.132)
Bikepath_exit	-2.046**	-0.481	-2.870***	-1.898**	-1.921**	-0.767
	(0.912)	(1.254)	(1.011)	(0.791)	(0.804)	(1.121)
Free flow	2.222***	0.816	3.719***	2.700***	1.540***	3.929***
	(0.629)	(0.775)	(0.908)	(0.464)	(0.498)	(0.797)
Stop Controlled	-4.876***	-5.300***	-5.589***	-5.881***	-5.302***	-5.637***
	(0.266)	(0.386)	(0.330)	(0.197)	(0.248)	(0.359)
Movement Type	0.851***			0.150		
	(0.234)			(0.173)		
Intersection Type	1.536	0.919	3.057**	2.907**	1.787	4.739***
	(1.381)	(1.948)	(1.498)	(1.204)	(1.249)	(1.687)
Vehicle Type	2.072***	2.486***	0.769	1.040***	1.257***	-0.088
	(0.532)	(0.710)	(0.682)	(0.392)	(0.456)	(0.598)
Population	-0.041*	-0.028	-0.059***	-0.069***	-0.073***	-0.065**
	(0.021)	(0.029)	(0.023)	(0.019)	(0.019)	(0.026)
Constant	20.249***	25.693***	8.433***	11.218***	16.355***	-1.006
	(2.242)	(3.580)	(2.786)	(1.827)	(2.297)	(2.775)
u_i	3.359***	4.624***	3.575***	2.966***	2.963***	4.128***
Constant	(0.423)	(0.577)	(0.456)	(0.368)	(0.375)	(0.518)
ϵ_{ij}	9.179***	9.068***	7.730***	6.775***	5.827***	6.778***
Constant	(0.078)	(0.107)	(0.096)	(0.058)	(0.069)	(0.084)
AIC	50,366	26,360	22,900	46,182	23,156	**22,054**
Observations	6,909	3,620	3,289	6,909	3,620	3,289

Note: The table presents the coefficients of the mixed-effect linear regression model, using intersection level random effect and an independent covariant structure.
Statistical significance is indicated as follows * p<0.10 ** p<0.05 *** p<0.01. Standard errors of regression coefficients are reported in parentheses.

Based on these findings, a disaggregate model was necessary to further investigate the effect of the curb radius on each turn type. From the AIC values, median speed models were more accurate with lower AIC values. The most accurate is that of left-turning motorists. When examining the attributes, the curb radius was significant for all models which confirms the hypothesis of this chapter. However, the curb radius has a negative coefficient and was deemed insignificant for the right turn and 85^{th} speed model implying no direct correlation between the right turning movement and the curb radius. This could be due to the influence of other factors like the cautiousness of most drivers while turning right as bikes can appear from their blind spots. From a statistical point of view, this can be explained by the limitation of the sample size when examining the turn specific models and the bounded variability of the measured radii, or the possibility of a reduced speed at a higher curb radius as drivers are more aware at "less" safe environments.

The intersection type seemed to be the most significant for the left turning movements. With a 3-legged intersection used as a base category, thus omitted from the model, a 4-leg intersection increases the median speed by 4.739 kph and the 85^{th} percentile speed by 3.057 kph. Also, a higher population decreased the speeds. While the aggregated models agree on most of the significant variables for both speed measures, those obtained from the right turn disaggregate model did not. This could be explained through a variable which was not accounted for.

3.5 CONCLUSION

This chapter aims to investigate the effect of the curb radius, with respect to vehicle speeds at non-signalized intersections of local-local intersections. This research fills in a gap presented in the literature of speed safety studies on the curb radius at urban non-signalized intersections with a curb radius under 10.0 meters to quantitively evaluate the existing design criteria and assess its safety.

For the purposes of this study, 35 urban/suburban intersections were selected, video data was collected, and processed using commercial software to obtain speed measures for over 75,000 users. The data was later filtered to only motorized vehicles and an approximate gap time was used to remove any car following effects. A random effects linear regression model was used with an error factor on the intersection level to account for the separate behavior at each intersection. Based on the statistical model, it was found that the curb radius had a significant effect on the aggregation of right and left turning movements for both the 85th percentile and the median speed measures. For the aggregate models, an increase of 0.778 kph and 1.208 kph is witnessed for the 85th percentile and the median speeds for every 1-meter increase in the radius. An increase in the curb radius resulted in an increase of speed implying reduced safety. However, the curb radius was not of significance for the 85th speed of right turning vehicles but significant to a 95% confidence interval for median speed. The average observed speeds for the left turn were higher compared to the right turn. This is because there is a greater distance associated with a left turn, thus, allowing for a higher speed to be reached. Other factors like the presence of a bike path, stop sign or pedestrian at approach, and population were also significant.

Most of the studies have been done on the effect of the curb radius have only examined the crash rates and injury severities as safety indicators. Furthermore, those which look at other measures like speed, have used simulation generated trajectories. However, this study does not use crash data because of its scarcity, especially for local intersections as less crashes are likely to happen due to the lower speeds. Thus, the use of speed as a safety indicator is more appropriate.

Nonetheless, a few limitations are presented by its use. For instance, this study does not take into account the complexity of the curb (combined curb design) which could be of an effect. While the statistical model provided a general correlation of safety and curb design, a detailed understanding along every meter of the trajectory would give a better insight.

This study establishes a relation between the existing design with its safety by presenting a novel perspective on the design of the curb radii of urban intersections. While other geometric elements were examined as part of the models, like the width of crosswalk and the number of lanes were insignificant and hence omitted from the models. Thus, the established operating speed models help further study the design consistency for small curb radii in urban local intersections. While this study advocates for smaller curb radii, this would cause a problem for larger vehicles using the intersections.

Future work on this topic would include the incorporation of the turning angle, as well as PET based statistical model to see the effect of the curb radius on the conflicts at intersections. Further validation can be done using crash data or injuries. Also, to account for the randomness of the start of the detection of the vehicle and its end, speeds will be measured for every meter starting at least 5 meters before the turn to get trajectory speed data to better capture the turning behavior of drivers.

CHAPTER 4 A NAÏVE BEFORE AND AFTER SAFETY EVALUATION OF CURB RADIUS ADJUSTMENT USING SPEED AND SURROGATE SAFETY MEASURES: A CASE STUDY IN TORONTO, CANADA

4.1 INTRODUCTION

This chapter takes the investigation of the impact of the curb radius on the operating speeds a step further; more specifically, the use of curb radius treatments as a speed reduction measure for turning vehicles at urban intersections. Similar to the previous chapter, video trajectory data is used. Instead of a cross-sectional study approach, this chapter implements a before-after approach.

This chapter looks into the radius reduction modification done for two intersections in Toronto, Canada. These intersections were selected in response to safety concerns voiced by the residents in the areas adjacent to the two intersections. These include unsafe driving behavior around the intersection showing little or no respect of stop sign or signalization. Moreover, there has been two serious injuries reported because of vehicle-pedestrian collisions in the preceding five years. Thus, as part of the constant effort put forth by the municipality, the suggested treatment was curb radius reduction as per the new guidelines. The treatment was done for all the sides of the intersections.

In recent years, countermeasures have been done to improve the safety of intersections. These include the use of road medians and refugee islands, smart right turn channels (Autey et al., 2012; Sacchi et al., 2013), and curb extensions (Bella and Silvestri, 2015; Johnson, 2005). Nonetheless, very few studies have looked at the impact of changing the curb radius despite its acquired popularity as a countermeasure. On the other hand, the City of Toronto has introduced refined guidelines for design and treatments focusing on the curb radius design. These guidelines, issued in 2016, examine curb radius reduction as a treatment to decrease speed and pedestrian crossing distance (City of Toronto, 2016).

In summary, the objective of this work is to evaluate the effectiveness of a curb radius reduction treatment using a naïve before-after study and automated video-trajectory data collected with video cameras temporarily installed in the proximity of two study intersections. In addition to the speed indicators, conflicts identified based on post-encroachment time (PET) are integrated in the before-after safety analysis. Random-effects regression models are used to quantify the effect of the countermeasure.

4.2 METHODOLOGY

The typical methodology for a before-after study consists of the following steps: (1) identification and selection of sites, (2) treatment design and implementations, (3) video data collection before and after the treatment, (4) data processing and cross-sectional statistical study, and (5) assumptions. The selected sites were defined by the city. Brisk Synergies – Transoft, carried on data collection and processing. For this research, we got access to the raw data for investigating the intervention effects.

4.2.1 **Identification and Selection of Sites**

As previously mentioned, the sites were selected based on residents' concerns after the occurrences of injuries at the two intersections examined in this study. The first intersection selected is Christie Street and Davenport Road (referred to as *Intersection 1* in this study) and the second intersection is Driftwood Avenue and Yorkwoods Gate (referred to as *Intersection 2*). *Intersection 1* was modified in 2016 and is a signalized 4-legged intersection with a bike lane in each direction of traffic flow. It should be noted that in Toronto right turning is permitted on red light with priority given to crossing pedestrians. The intersection is between minor arterial – minor arterial roads (City of Toronto, 2018). *Intersection 2* is between collector – collector roads and is a 3-legged intersection with an all-way stop controlled signalization. The curb radius adjustment was done in 2017 for this site.

4.2.2 **Treatment Design and Implementations**

The treatment selected and implemented by the city for the study intersections was the reduction of the curb radii. This is shown in **Figure 4-1**. The treatment includes a pavement extension to the existing curb (the extension is shaded in yellow). By doing so, the curb radius is reduced which has many benefits. Firstly, it reduces the turning speed as vehicles are less comfortable executing the turn and improved the angle of sight. Secondly, it lessens the pedestrian exposure to traffic as it extends the crosswalk length.

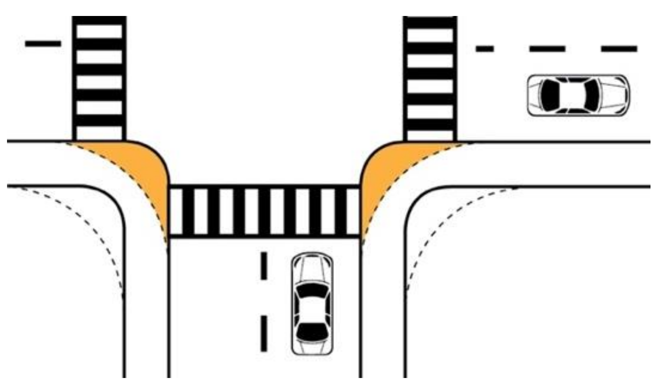

Figure 4-1 Curb radius reduction concept illustration with yellow shading depicting the added pavement (City of Newmarket, 2020)

As previously mentioned, the treatment was first executed in the intersection of Christie Street and Davenport Road in 2016. The radius reduction was done to all sides of the intersection as seen in

Figure 4-2 with markings for the bike lanes inside the conflict area of the intersection. Because of the adjustment, there was a change in the pedestrian crossing distance from 21.5 meters to 17 meters only on the north side while a 2 meters decrease was brought about in the west approach to around 17 meters as well. While all sides were adjusted, this study only looks at the northwest corner radius which was changed from 14 meters to 4 meters.

Figure 4-2 Aerial view of before (left image) and after (right image) the treatment for Intersection 1 (Christie Street and Davenport Road) obtained from Google Earth (Google Inc., 2019)

For the intersection of Driftwood Avenue and Yorkwoods Gate in **Figure 4-3**, the curb radius was reduced from 24 meters to 4 meters for both, the northwest and southwest, corners. However, for the purpose of this study and limitation of the camera placement, data was collected only for the northwest corner. The crosswalk of the north approach decreased from 12 meters to 8.25 meters while the west approach changed from 17.25 meters to 8.75 meters. Markings for cyclists were added to the intersection as well. There is a slight curvature in both intersection alignments, however, it is assumed to have a negligible effect on the obtained results.

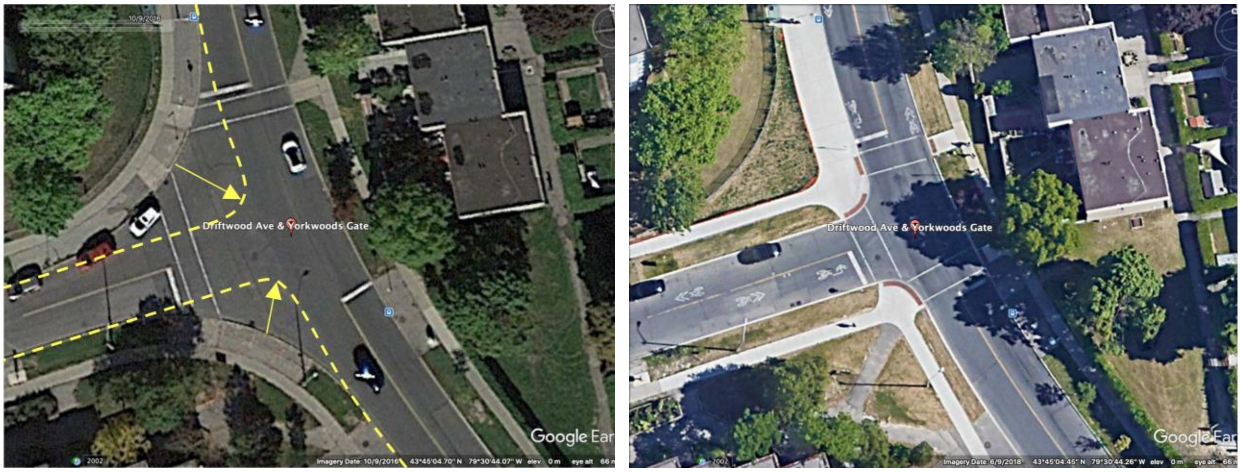

Figure 4-3 Aerial view of before (left image) and after (right image) the treatment for Intersection 2 (Driftwood Avenue and Yorkwoods Gate) obtained from Google Earth (Google Inc., 2019)

4.2.3 **Video Data Collection and Processing**

Video data was collected for the northwest corner for both intersections. This was carried out by Brisk Synergies – Transoft, the deciding party, by mounting video cameras on light poles around 7 meters high. A 720-pixels video camera resolution was used for the before treatment data of *Intersection 1* while a lower resolution of 480-pixels was used for data collection after the adjustment. However, the same resolution of 720-pixels was used for recording the videos for *Intersection 2* before and after the treatment. Around 80 hours of video footage was obtained for each intersection with 40 hours before and 40 hours after the radius reduction. This was collected over 3 days. For Christie St and Davenport Rd, data was collected form August 2nd to the 4th 2016 before the reduction and from November 8th till the 10th 2016 for the after study. On the other hand, the video recording was done from September 13th to the 15th before the adjustment and November 8th till the 10th afterwards for the intersection of Driftwood Av and Yorkwoods Gt.

The collected video footage is then processed using a computer vision commercial software, *Brisk Lumina* provided by Brisk Synergies - Transoft (2017). Using deep learning algorithms, different roads users were generated, and various measures of their interactions are measured (which will be discussed in section **4.3**). Firstly, scenarios are defined, which in this study is the interaction between vehicles and crossing pedestrians. Follows that a homography adjustment for video calibration achieved through matching points from the video footage to their corresponding street coordinates. Lastly, road user specific output details were obtained, for example: road user type, speed, and conflict data like Post Encroachment Time (PET). Explained in **Figure 4-4**, PET is the time between the exit of the first road user from the conflict zone (t_1) and the instance of the entrance of the second road user to the conflict zone (t_2). Thus, the equation for PET is:

$$PET = t_2 - t_1$$

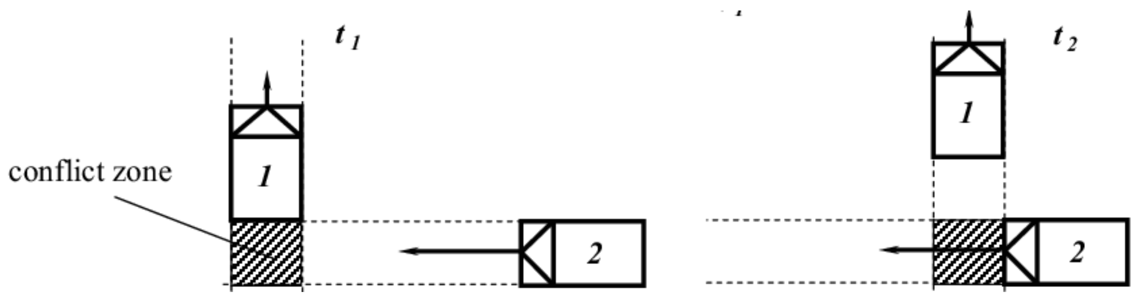

Figure 4-4 Post Encroachment Time (PET) with t1 where the first road user leaves conflict zone and t2 when the second road user first enters the conflict zone (Laureshyn, 2010)

4.2.4 Statistical Analysis and Modelling

The evaluation of the effect of the curb radius reduction is done through regression statistical models using STATA 13, namely, Maximum Likelihood (ML) random mixed-effects regression models. In addition to the speed measures (85th percentile speed and median speed), PET is used as a proximity indicator. In addition, a simple index (risk) combining both is defined as the ratio of speed and PET (defined in section **4.3**).

The random mixed-effects regression estimator used for this research is as follows:

$$y_{ij} = \beta_0 + \beta_1 x_1 + \cdots + \beta_k x_k + u_i + \epsilon_{ij}$$

Where:

y_{ij} – speed indicators (85th percentile speed or median Speed) or surrogate safety indices (1/PET, 85th percentile speed, or ln (Risk)) for road user *j* in intersection *i = 1 or 2*

β_0 – model intercept

β_k – coefficients for the *k* factors of x_k vectors taken into consideration

u_i – random error factor specific to the intersection *i*

ϵ_{ij} – normally distributed regression random error term.

Both errors are assumed to be normally distributed with non-zero error covariance as follows:

$$\epsilon_{ij} \sim N\ (0,1) \text{ and } Cov\left(u_i, u_j\right) \neq 0.$$

4.2.5 Assumptions

To better understand the direct effect of the curb radius on the vehicle speeds, non-conflict data were filtered out using the free flow coefficient which is assumed to capture car following behavior. This is done through the approximation of the gap time between travelling vehicles.

Furthermore, both intersections in this study show some skew in their geometry as *Intersection 1*'s crosswalks are not parallel. *Intersection 2*, on the other hand, has a curvature along the long side of Driftwood Avenue. These two abnormalities are expected to affect all road users the same way, thus, will be accounted for by the "Intersection Type" variable in linear regression models and the additional error factor in the random effects ML regression models. This also would account for the different placements of the bike lanes for both intersections. Moreover, the radius measurement assumes a simple radius (not compound) and does not take into account the turning radius of the maneuver of the vehicles.

Lastly, the variation in the resolution and placement of the cameras used minimal effect on the results is taken into consideration when evaluating the outputs of the speed analysis. However, as seen in the summary statistics (presented above), the maximum speed reached by the vehicles turning did not exceed 60 kph which is a good indicator of the accuracy of the results obtained.

4.3 DATA DESCRIPTION

The measures generated from the commercial software can be divided into two categories: non-conflict related and conflict related data. The hierarchy of the data is shown in **Figure 4-5**. Non-conflict data is gathered for all road users in the intersection where they could or could not have had an interaction with another (conflict). The measures of interest in this case are 85th percentile speed and median speed which are used as safety indicators which measure the anticipated risk potential (De Ceunynck, 2017). Similarly, for conflict data, 85th percentile speed and Post Encroachment Time (PET) are used.

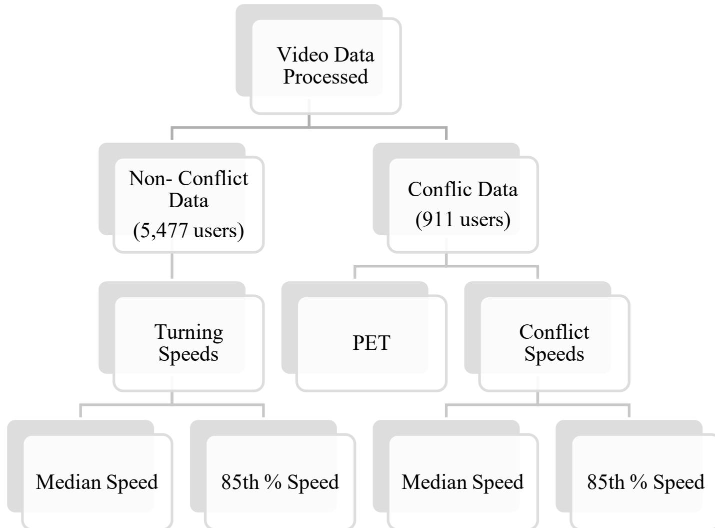

Figure 4-5 Hierarchy of data collected

Lower values of PET correspond to a higher probability of collision as the time between the two vehicles is less. Therefore, higher values of 1/PET or speed result in an increased risk. Thus, to further understand the risk of each conflict, a variable, referred to as risk, combines both in the format speed/PET. Consequently, a positive coefficient indicates a less safe situation.

The variables used are shown in **Table 4-1** which includes both dependent and independent variables. The dependent variables, as mentioned previously, are speed, PET, and risk which are the indicators of the probability of collision (PET) and its severity (speed). Various factors are believed to affect these variables. For instance, the main hypothesis of this project is that the variable "Treated" (referring to the radius adjustment treatment) should yield less severe interactions if equals to one. On the other hand, if "Pedestrian" arrives "First" in an interaction, it would be a more dangerous situation. Other variables like "Heavy Vehicle", "Peak Hour", and "Night Time" are believed to be contributing to the safety of the road users. The intersection type compares the 4-legged to the 3-legged types, however, this variable essentially is a place holder for *intersection 1* compared to *intersection 2*. Lastly, free flow is an indicator for car following conditions based on the gap time between the vehicle with a cut-off of 10 seconds which is used for stop-controlled intersections. This is calculated using the difference of the average times between when the vehicle was first and last seen. The variable was used for data cleaning purposes as only non-car following vehicles were used from the non-conflict data in this study.

Table 4-1 The description and units (or categories) for the variables used

Variable	Description	Categories / Units
X85th	85th percentile of the vehicle speed	Continuous measured in kph
Median	Median speed of the vehicle along the trajectory	Continuous measured in kph
PET	Post Encroachment time	Continuous measured in seconds (used as 1/PET)
Risk	The ratio of X85th/PET	Continuous (used as ln(risk))
Pedestrian First	If the pedestrian arrived before the vehicle to the conflict area	Categorical variable with two sets: (0) vehicle arrived first & (1) Pedestrian arrived firsts
Heavy Vehicle	The type of vehicle involved in the interaction	Categorical variable with two sets: (1) cars & (2) buses and trucks
Treated	If an adjustment has been done to the radius for the before and after study	0 = before & 1 = after
Peak Hour	If the vehicle crosses the intersection during peak hour times	Categorical with peak=1, hours for AM Peak Hours from 7 AM to 8 AM and PM Peak Hours from 3 PM to 4 PM
Night Time	If the vehicle is driving under dark conditions	Categorical with night= 1, hours from 7 PM to 6 AM inclusive
Intersection Type	Intersection type based on the number of branches	Categorical variable with two sets: (1) 4-legged intersection & (2) 3-legged intersection
Free Flow	Car following experienced	0=cars within 10s & 1=no cars

Tables 4-2 and **4-3** present the summary statistics for both sets of data obtained from the processing of the video footage. For non-conflict data, there's a total of 5,864 detected vehicles with a distribution of 51% treated observations. The average 85th percentile speed is 21.59 kph before and 20.85 kph after the treatment. Additionally, 915 observations were made for conflict

data. The average conflict 85th percentile speed is 12.50 kph before and 13.24 kph after. The average PET value for before is 5.42 s and 5.35 s after the treatment.

Table 4-2 Summary statistics for all vehicles observed during the time of data collection

	BEFORE				AFTER			
Variable	Mean	Std Dev	Min	Max	Mean	Std Dev	Min	Max
Mean Speed	15.66	5.83	0.92	34.11	15.00	5.76	0.97	35.49
Median Speed	15.59	6.81	0.05	35.72	14.69	6.28	0.07	34.05
X15th Speed	8.67	5.88	0	31.37	8.99	5.74	0	27.93
X85th Speed	22.59	6.62	0.29	43.56	20.85	6.65	1.21	49.02
Hour	12.90	3.63	7	19	12.83	3.59	6	19
Intersection Type	1.57	0.49	1	2	1.02	0.15	1	2
Observations	2676				2801			

Table 4-3 Summary statistics for all observations of road users involved in conflict

	BEFORE				AFTER			
Variable	Mean	Std Dev	Min	Max	Mean	Std Dev	Min	Max
PET	5.42	1.89	0	9.73	5.35	2.00	0.90	9.87
Ln(Risk)	0.43	1.68	-6.18	2.66	0.58	1.37	-4.93	2.71
Vehicle Median Speed	7.10	6.41	0.02	35.48	7.38	5.60	0.06	24.56
Vehicle X85th Speed	12.50	8.77	0	35.67	13.24	8.33	0	40.71
Vehicle Conflict Speed	11.31	7.09	0.02	31.30	11.79	6.21	0	29.09
Hour	13.85	3.48	7	19	13.15	3.35	6	18
Pedestrian First	1.75	0.44	1	2	1.73	0.45	1	2
Intersection Type	1.63	0.48	1	2	1.57	0.50	1	2
Observations	440				475			

4.4 Before and After Study Results and Analysis

This section looks at the results of the before and after of the implementation of the radius reduction treatment in Toronto. This is done thoroughly by the analysis of conflict and non-conflict data through the examination of statistical models and summaries.

4.4.1 **Non-Conflict Speed Analysis**

This part of the analysis looks at all the turning vehicles in the intersection, both, involved in a conflict or not by considering 85th percentile speed and median speed as the main indicators.

4.4.1.1 Summary Statistics

In this section, the summary statistics and histograms for each intersection before and after the treatment were analyzed. From **Tables 4-4** and **4-5**, it can be seen that the free flow has a mean of 0.93 and 0.96, respectively, which is closer to 1. This entails that most of the vehicles captured in this study show no car-following behavior and those that did were dropped for the regression models discussed in the following subsection. The average value for median and 85th percentile speed showed a decrease for both intersections. However, the decrease in speed for *Intersection 1* was much greater than that of *Intersection 2*.

Table 4-4 Summary statistics of non-conflict data of Intersection 1

	BEFORE				AFTER			
Variable	Mean	Std Dev	Min	Max	Mean	Std Dev	Min	Max
Mean Speed	14.00	6.85	0.96	38.16	12.74	6.06	1	36.01
Median Speed	13.44	7.48	0.05	34.44	12.01	6.32	0.07	35.17
X15th Speed	8.79	6.47	0	33.84	8.74	5.98	0	30.61
X85th Speed	19.75	7.56	0.29	43.45	17.45	7.08	1.46	55.47
Hour (used for Peak Hour and Night time)	12.26	3.47	7	18	12.18	3.42	6	19
Free Flow	0.93	0.25	0	1	0.93	0.27	0	1
Observations	1230				2726			

Table 4-5 Summary statistics of non-conflict data of Intersection 2

Variable	BEFORE				AFTER			
	Mean	Std Dev	Min	Max	Mean	Std Dev	Min	Max
Mean Speed	17.03	4.45	0.92	34.11	17.35	4.79	0.97	34.40
Median Speed	17.36	5.62	0.28	35.72	17.33	5.15	0.25	34.05
X15th Speed	8.68	5.43	0	31.37	9.58	5.70	0.06	27.55
X85th Speed	24.87	4.73	1.14	43.56	24.34	5.06	1.21	43.60
Hour (used for Peak Hour and Night time)	13.38	3.69	7	19	13.28	3.66	6	19
Free Flow	0.96	0.21	0	1	0.96	0.20	0	1
Observations	1628				1604			

The distribution for the median speed of both intersections before and after is illustrated in **Figure 4-6**. When comparing A and B of the figure, an increase in zero speed vehicles was seen and a decrease in those of speed greater than 20 mph. Thus, an overall shift towards smaller speeds was witnessed. C and D, however, show an increased density of speeds less than 20 mph while the rest remain almost unchanged.

Figure 4-7 shows a shift towards higher speeds for both intersections post treatment. However, the highest reached speed was less post-radius adjustment (B and D) in comparison to the before condition (A and C).

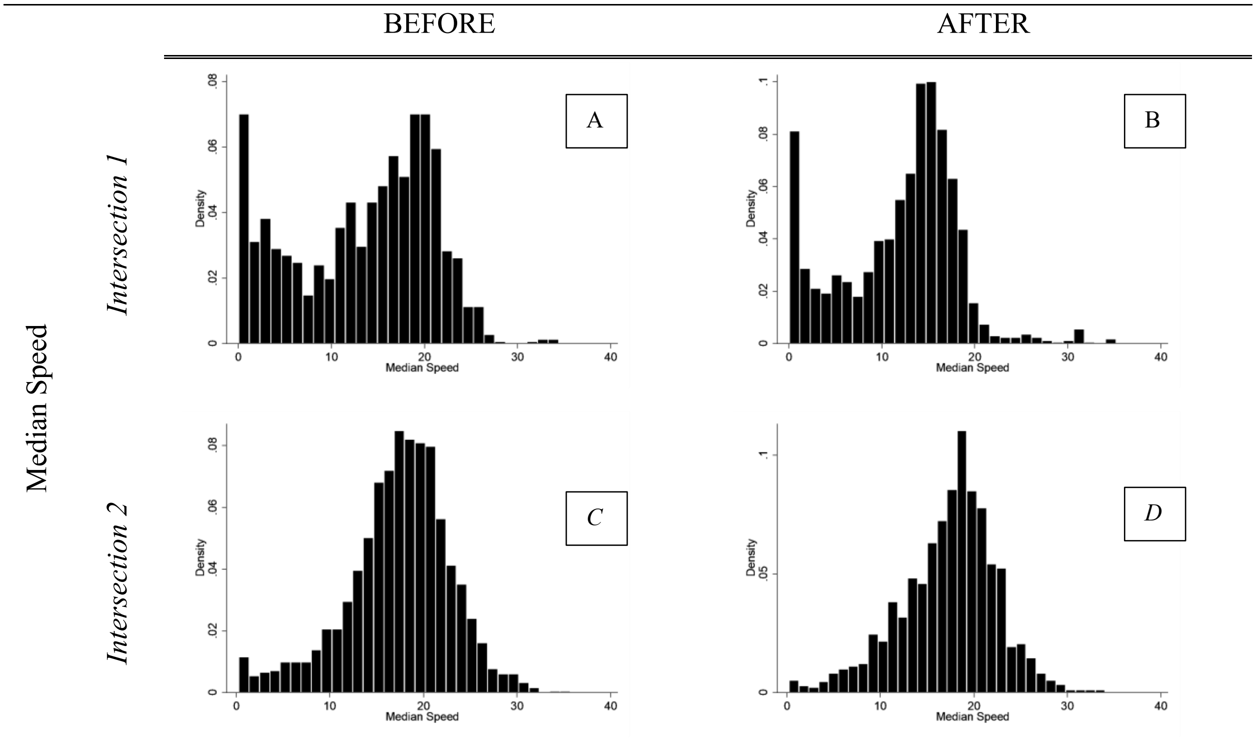

Figure 4-6 Distribution of Median speed of non-conflict vehicles of Intersection 1 (A & B) and Intersection 2 (C & D)

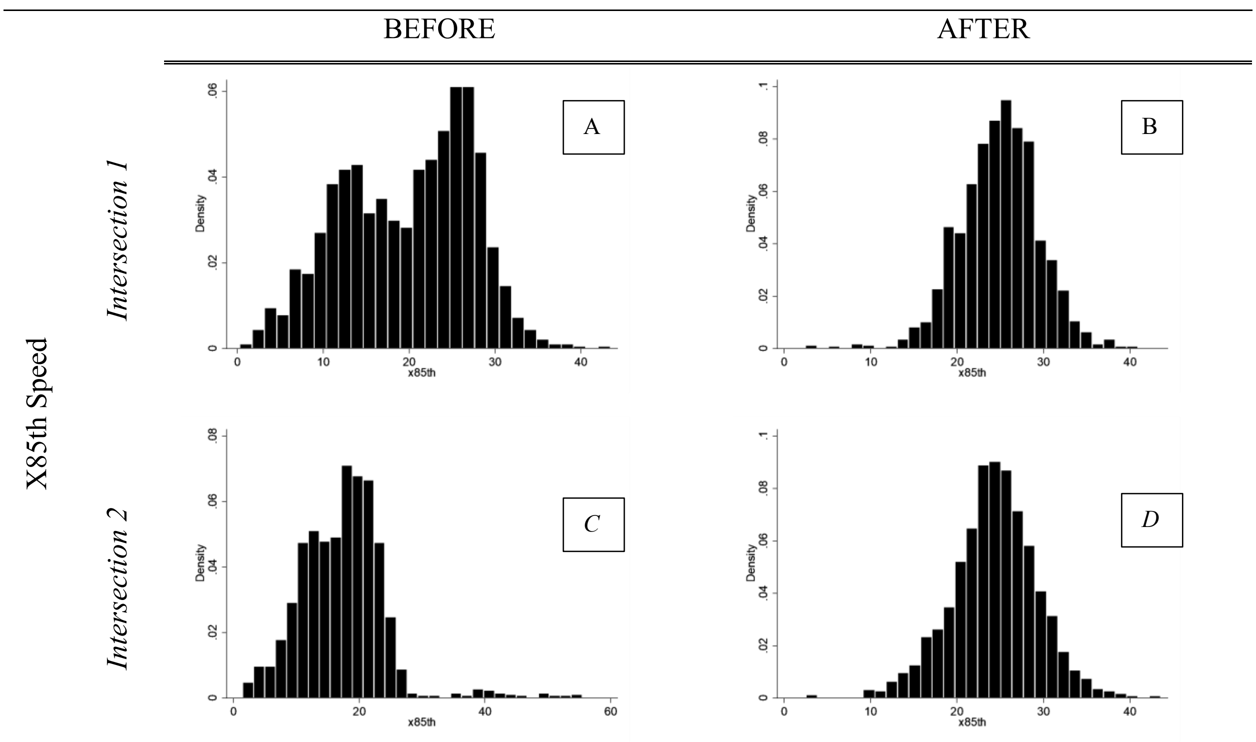

Figure 4-7 Distribution of 85th percentile speed of non-conflict vehicles of Intersection 1 (A & B) and Intersection 2 (C & D)

4.4.1.2 Linear and Random Effects ML Regression Models

The regression models used for this study show that the type of vehicle and treatment were statistically significant with a p-value less than 0.01 for both the 85th percentile and median speed models. ML models has shown to be superior to linear regression models based on literature. The treatment has contributed to a decrease of a 1.577 kph and 0.783 kph for 85th percentile and median speed, respectively. The intersection specific regression models show that the treatment resulted in a 3.39 kph decrease in the 85th percentile speed for intersection 1, while intersection 2 has a decrease of only 0.46 kph. The heavy vehicle factor had no effect on the intersection models.

Table 4-6 Random Effects and linear regression models for 85th percentile speed and median speed for non-conflict motorists

	ML Regression Models		**Linear Regression Models**			
	Both Intersections		**Inter 1: Christie and Davenport**		**Inter 2: Driftwood and Yorkwoods**	
	X85th	**Median**	**X85th**	**Median**	**X85th**	**Median**
Heavy Vehicle	-0.580*	-1.943***	0.000	0.000	0.000	0.000
	(0.333)	(0.347)	(.)	(.)	(.)	(.)
Treated	-1.577***	-0.783***	-3.369***	-2.139***	-0.458**	0.108
	(0.156)	(0.163)	(0.276)	(0.278)	(0.179)	(0.198)
Peak Hour	-0.107	-0.263	0.497*	0.317	-0.485***	-0.645***
	(0.165)	(0.172)	(0.298)	(0.301)	(0.187)	(0.206)
Night Time	1.928***	0.972	2.696	2.354	1.938***	1.033
	(0.704)	(0.734)	(2.467)	(2.488)	(0.646)	(0.713)
Constant	22.143***	15.407***	19.758***	13.591***	24.903***	17.497***
	(2.320)	(1.796)	(0.220)	(0.222)	(0.144)	(0.159)
u_i	3.276**	2.533**				
Constant	(1.640)	(1.269)				
ϵ_{ij}	5.771***	6.016***				
Constant	(0.055)	(0.057)				
R^2			0.063	0.026	0.0080	0.0046
AIC	34,764	35,218				
Observations	5477	5477	2236	2236	2919	2919

Note: The table presents the coefficients of the mixed-effect linear regression model, using intersection level random effect and an independent covariant structure.
Statistical significance is indicated as follows * p<0.10 ** p<0.05 *** p<0.01. Standard errors of regression coefficients are reported in parentheses.

4.4.1.3 Speed Trajectory Analysis

To further understand the effect of the treatment on a closer level, the average speed is obtained for five areas in each intersection before and after the treatment. For the same intersection, the area placement was done in the same location when analyzing for before and after the radius reduction.

The images in **Figures 4-8** and **4-9** show the camera orientation for collecting the video footage for before and after the treatment. Areas 1 to 5 capture the vehicles movement from the slowest speed at the beginning of the turn (as the driver slows down to check for the opposing stream), increasing around the curb, to slow down again upon merging with the traffic stream.

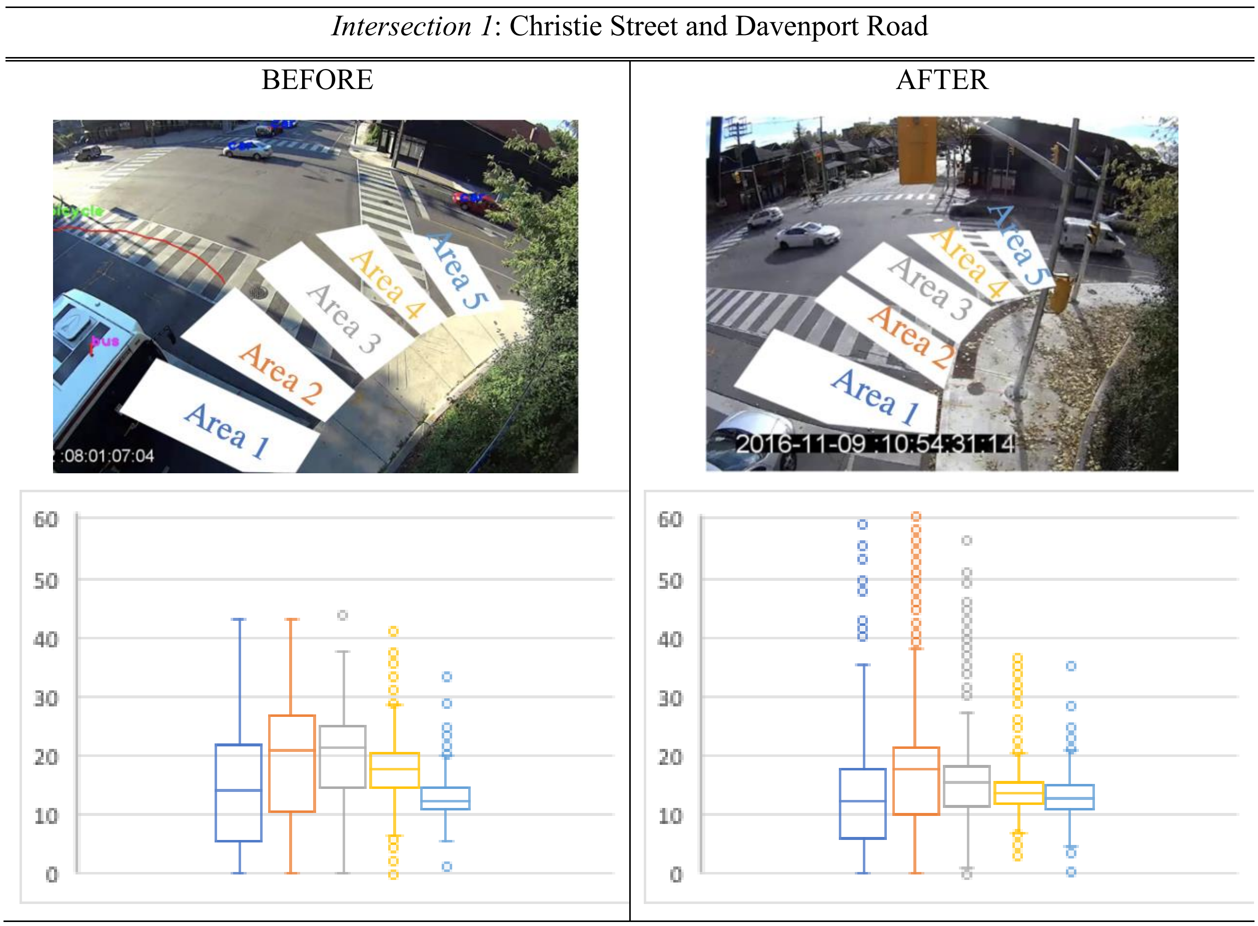

Figure 4-8 Representation of speed trajectory of turning vehicles using speed box for the treatment of Intersection 1

By comparing the box plot for the before and after scenarios for *Intersection 1*, it can be noticed that the speeds for all areas have decreased. Not only this, but the variation of speed a log the curve is much less with a smaller curb radius causing a sharper turn. The anomaly encountered post treatment are more due to the use of lower resolution camera.

Intersection 2: Driftwood Avenue and Yorkwoods Gate

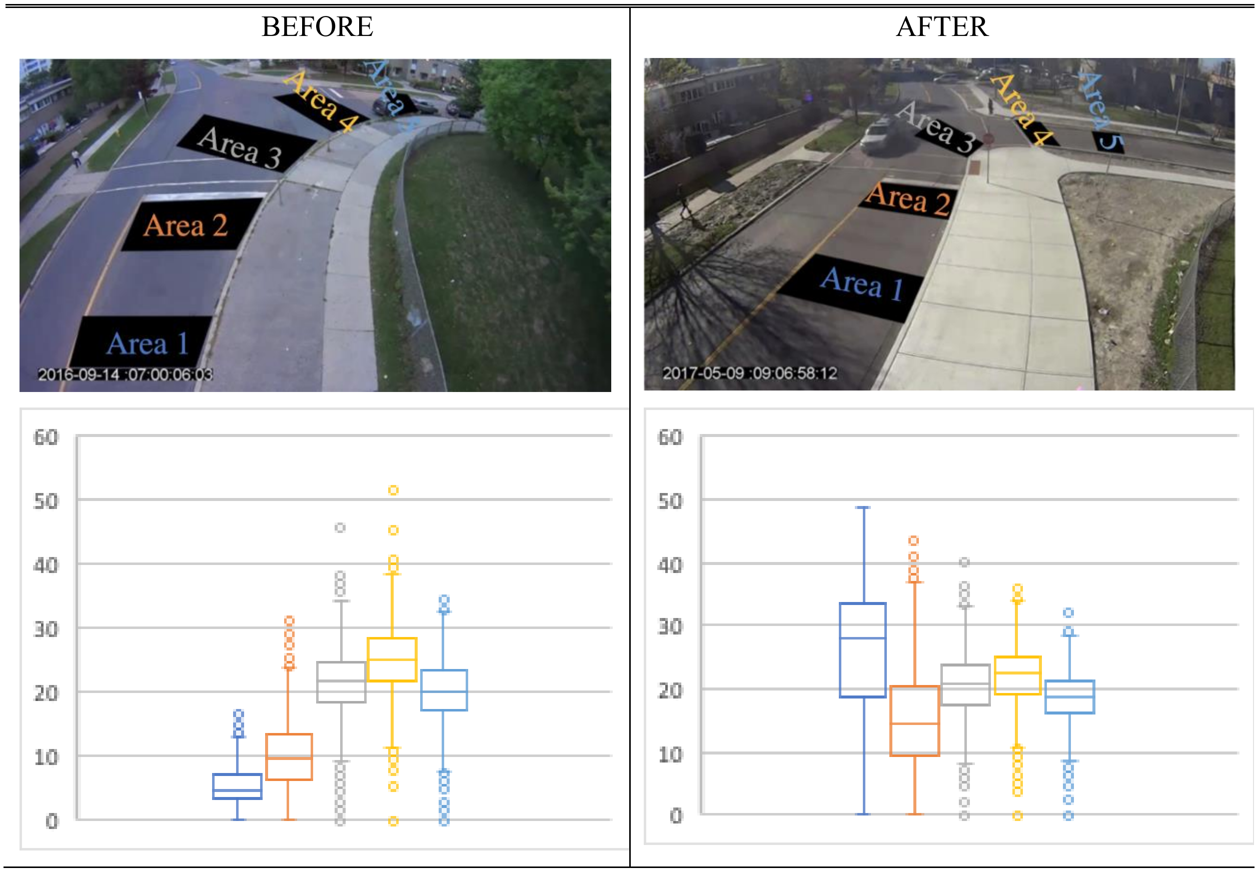

Figure 4-9 Representation of speed trajectory of turning vehicles using speed box for the treatment of Intersection 2

The curb radius modification for *Intersection 2* was a sizable change from 24 meters to four meters. By keeping area 1 in the same location, the speed has multiplied almost 5 times. This is mainly due to the fact of the driver's perspective of the fact that this part of the road is non-curved. This also could be due to the fact that area 1 also captures the speed of through traffic not only those which are turning. Areas 3, 4 and 5 show a decrease in speed which can be attributed to the decrease in the curb radius. It should be noted that the decrease in speed is less for *Intersection 2* because of the intersection control. *Intersection 1* is a signalized intersection while *Intersection 2* is only stop-controlled, thus, allowing for cars to speed up in the absence of flowing traffic.

4.4.2 **Conflict Analysis**

The conflict data is that which is collected from road users involved in an encounter of interaction between two road users. PET is the main indicator for the probability of the interaction to become an accident while the speed provides an understanding of the severity of the risk posed. The evaluation of these measures was examined statistically in the following two subsections.

4.4.2.1 Summary Statistics

The histograms of the data distribution for before and after the implementation of the treatment gives an insight to the increased safety. As shown in **Figure 4-10 A** & **B**, there has been an increased density for PET greater than 4 which is a good indicator given that these are low risk interactions. **Figure 4-10 C** & **D** show a shift towards a slower speed for after the treatment whilst the before curve is more spread out. A few readings were measured towards 40 kph in the after study which can be explained by the decreased resolution of the camera used for video collection.

Summary statistics were produced for both intersections independently. The data from *Intersection 1* shows a total of 163 vehicles involved in conflict before the radius while 197 were involved after the treatment as presented in **Table 4-7**. While this indicates an increased number of conflicts, this increase could mean that more cars were stopping for pedestrians to cross. While the average PET decreased by 0.41 seconds which could mean a higher likelihood of collision, the vehicle 85th percentile speed decreased by 3.14 kph indicating lowered risk and severity. *Intersection 2*, on the other hand, showed an increase in the average PET by 0.21 seconds but an increase of 2.85 kph with the same number of interactions before and after the treatment (**Table 4-8**).

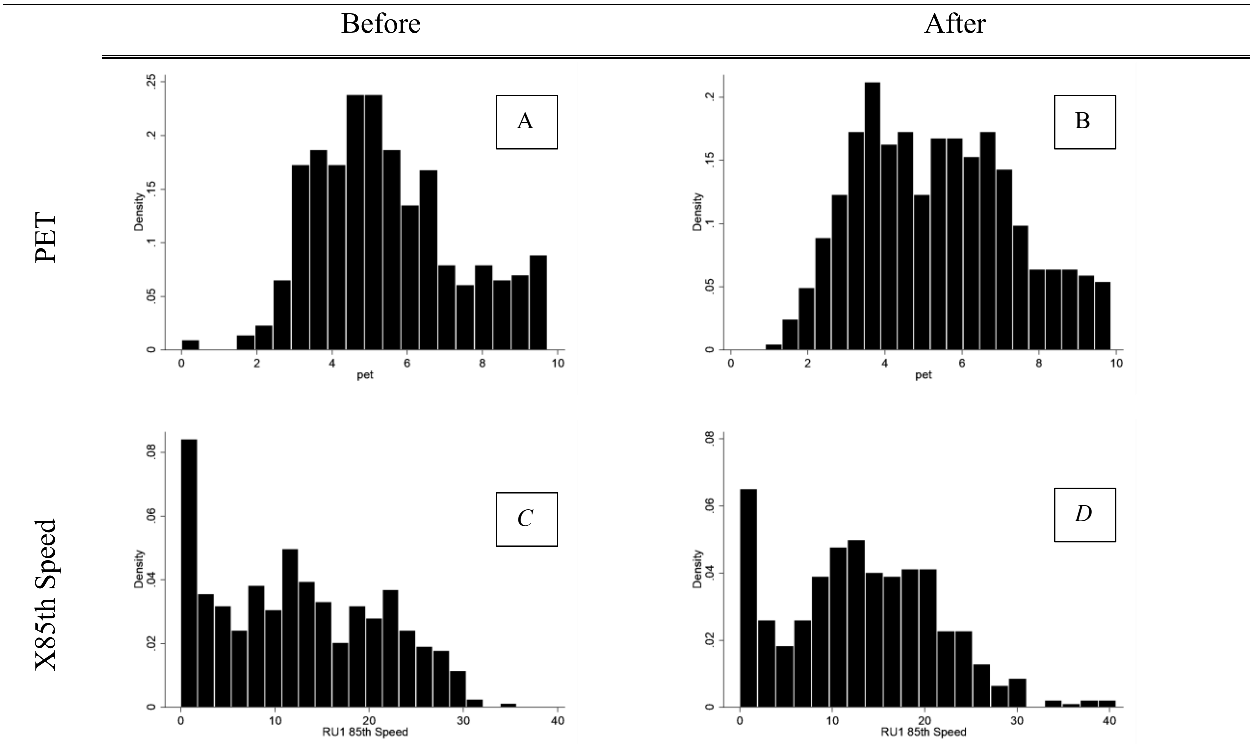

Figure 4-10 Distribution of PET (A & B) and 85th percentile speed (C & D) for both intersections before and after the treatment

Table 4-7 Summary statistics of conflict data of Intersection 1 before and after treatment

	BEFORE				AFTER			
Variable	Mean	Std Dev	Min	Max	Mean	Std Dev	Min	Max
PET	4.89	1.72	1.87	9.60	4.48	1.69	0.90	9.71
Ln(risk)	1.25	0.58	-0.99	2.53	1.17	0.52	-0.64	2.50
Vehicle Median Speed	10.97	6.96	0.14	23.83	9.55	5.13	0.10	19.09
Vehicle X85th Speed	17.48	6.72	2.39	35.67	14.34	4.76	3.17	25.98
Vehicle Conflict Speed	8.59	7.02	0.02	31.30	8.63	5.40	0	23.79
Pedestrian Median Speed	4.19	2.39	0.15	12.47	4.44	1.79	0.25	11.93
Pedestrian X85th Speed	8.34	2.48	2.90	18.88	7.33	1.83	3.66	17.67
Pedestrian Conflict Speed	6.68	3.04	0.05	17.21	6.30	2.58	0.04	14.75
Hour	13.39	3.36	7	18	12.51	3.24	7	18
Pedestrian First	1.80	0.40	1	2	1.75	0.43	1	2
Observations	163				197			

Table 4-8 Summary statistics of conflict data of Intersection 2 before and after treatment

Variable	BEFORE Mean	Std Dev	Min	Max	AFTER Mean	Std Dev	Min	Max
PET	5.75	1.93	0	9.73	5.96	1.98	1.40	9.87
Ln(risk)	-0.31	1.85	-6.18	2.66	0.15	1.62	-4.93	2.71
Vehicle Median Speed	4.83	4.79	0.05	21.13	5.85	5.42	0.06	24.56
Vehicle X85th Speed	9.57	8.51	0	31.93	12.42	10.06	0	40.71
Vehicle Conflict Speed	12.91	6.65	0.66	26.46	14.03	5.77	0.40	29.09
Pedestrian Median Speed	3.31	1.28	0.14	7.91	3.27	1.53	0.23	10.66
Pedestrian X85th Speed	7.58	4.19	0	26.91	7.82	4.48	0.65	37.79
Pedestrian Conflict Speed	5.45	1.23	1.69	11.28	5.88	1.78	2.15	11.83
Hour (used for Peak Hour and Night time)	14.12	3.54	7	19	13.60	3.37	6	18
Pedestrian First	1.71	0.45	1	2	1.71	0.46	1	2
Observations	277				278			

The histograms of both intersections for before and after the treatment for PET and 85th percentile speed for the conflict vehicles are presented in the following figures. **Figure 4-11 (A & B)** show a decrease in the density of the PET values less than 3 seconds and an increase for those with a value greater than 5.5 seconds. This shift in PET represents a redistribution in the probability of collision as less PET represents high risk interactions. When comparing the histograms for *Intersection 2* (**C & D** of the figure), D shows an increase in PET greater than 7 seconds. Also, the minimum PET increased from 0 seconds to 1.4 seconds which indicates a shift in the curve towards higher PET values.

Figure 4-12 (A & B) for *Intersection 1* show a smaller range of speed for after treatment with the highest speed of 25 kph in comparison to 35 kph. *Intersection 2*, on the contrary, showed an increase in speed which is due to much greater decrease in the curb radius in comparison to *Intersection 1* (explained in the prior section).

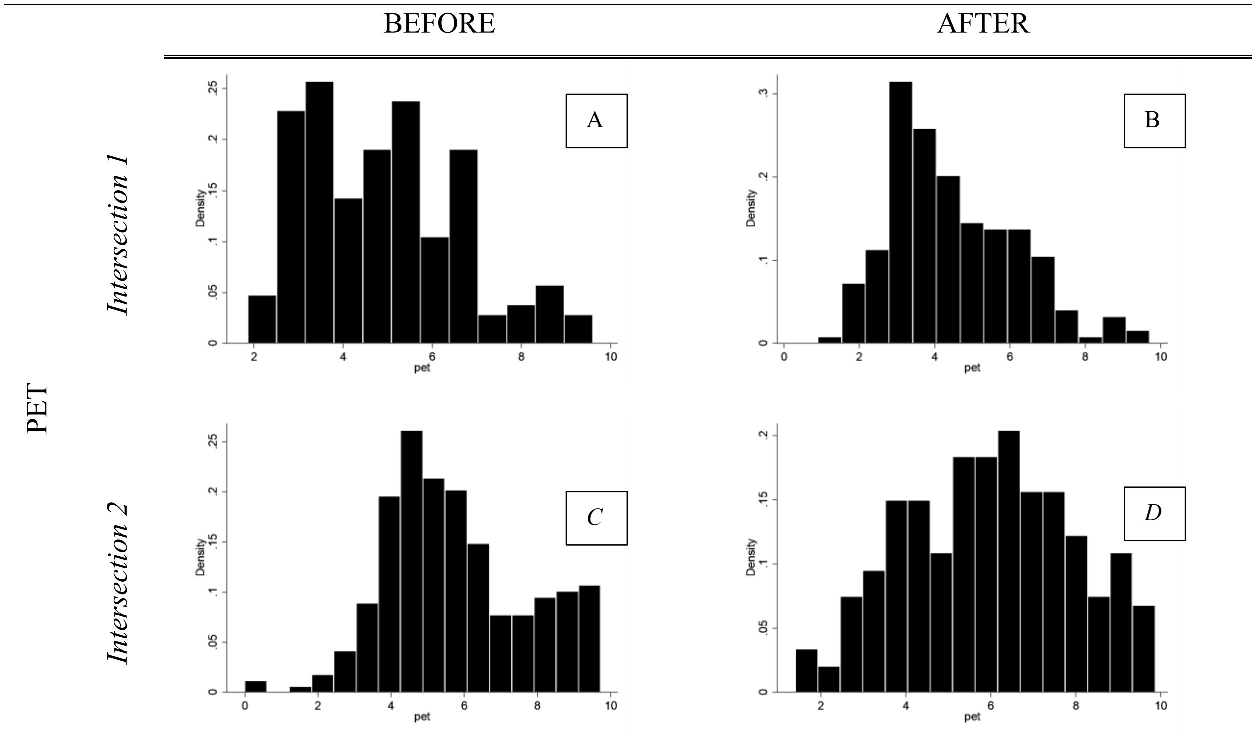

Figure 4-11 Distribution of PET for Intersection 1 (A & B) and Intersection 2 (C & D) for before and after the treatment

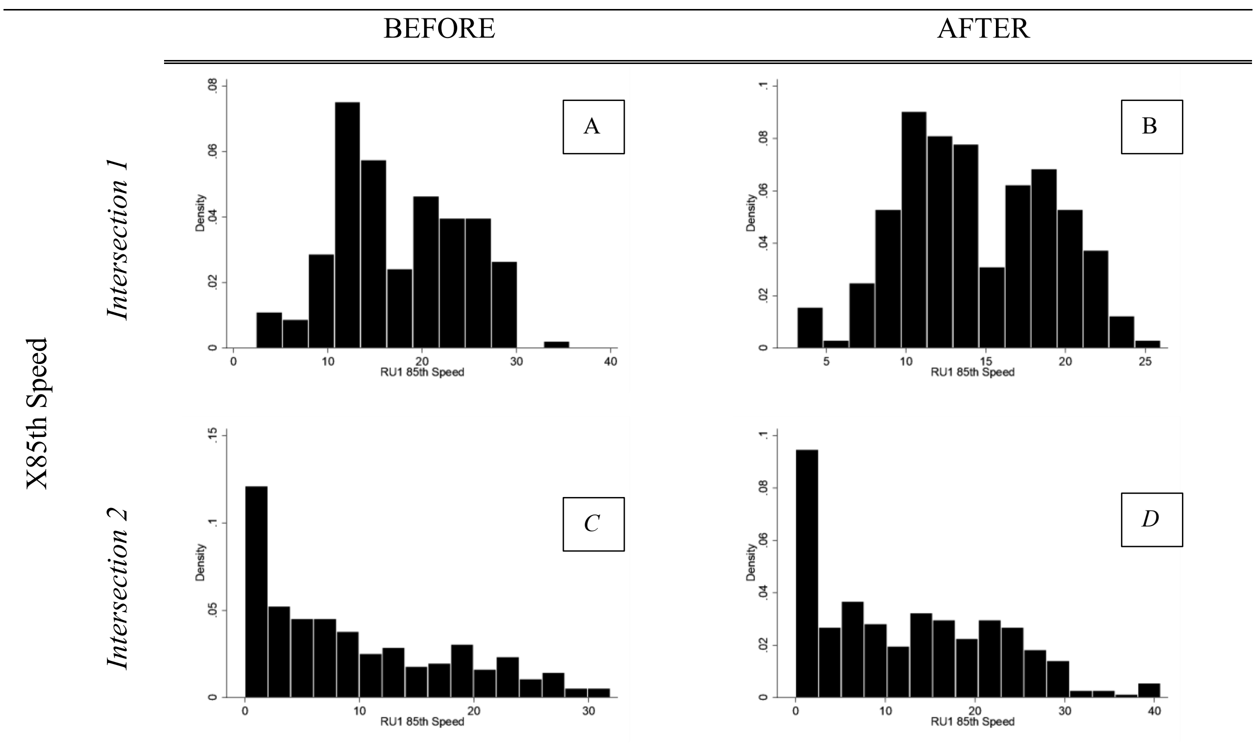

Figure 4-12 Distribution of 85th percentile speed of conflict involved vehicles for Intersection 1 (A & B) and Intersection 2 (C & D) for before and after the treatment

4.4.2.2 Regression Models Analysis

For the three safety indicators (85th percentile speed, inverse PET, and natural logarithm of risk), random mixed-effects and linear regression models were computed using the same variables. Both models of all observed interactions showed very similar coefficients as seen in **Table 4-9**. The linear regression model illustrated a significant effect of when comparing the "Intersection Type" variable. It shows that *Intersection 2* is relatively safer than *Intersection 1* with 5.3 kph less in speed. The same applies to the PET and risk models. Night time hours, show an increase in speed by 9.405 kph which is statistically significant but the decrease inverse PET (increase PET value) is not significant. Therefore, showing an increased risk during night time which is expected. The variable of main interest, the treatment, did not have a significant effect on the speed of the overall data. Thus, models were done for *Intersections 1* and *2* separately.

In the intersection specific model, it can be seen that the treatment variable decreased speed and the overall risk for *Intersection 1*. However, statistical significance was presented in the speed and inverse PET models. While PET shows an increase, the overall risk is affected mostly by speed, thus, affirming the assumption that the curb radius reduction improves the safety of the intersections. The models for *Intersection 2*, on the other hand, shows a statistically significant increase in speed and risk when examining the treatment. The PET model for *Intersection 2* has shown no significant variables.

Table 4-9 Random Effect ML and Linear regression models for conflict vehicle 85^{th} percentile speed, PET, and the natural logarithm of risk (combined and for each intersection)

	ML Regression Models			**Linear Regression Models**					
	Both Intersections			**Inter 1: Christie and Davenport**			**Inter 2: Driftwood and Yorkwoods**		
	X85th	**1/PET**	**Ln(risk)**	**X85th**	**1/PET**	**Ln(risk)**	**X85th**	**1/PET**	**Ln(risk)**
Pedestrian First	-8.826***	-0.018***	-1.264***	-0.546	-0.033***	-0.087	-13.485***	-0.009	-1.920***
	(0.544)	(0.007)	(0.097)	(0.132)	(0.013)	(0.069)	(0.656)	(0.008)	(0.142)
Heavy Vehicle	1.254	-0.023	-0.016	-0.031	-0.056**	-0.398***	1.143	-0.002	0.122
	(1.143)	(0.014)	(0.203)	(1.575)	(0.027)	(0.148)	(1.373)	(0.016)	(0.296)
Treated	0.274	0.012**	0.220**	-3.047***	0.025**	-0.080	2.570***	0.001	0.423***
	(0.478)	(0.006)	(0.085)	(0.619)	(0.011)	(0.058)	(0.596)	(0.007)	(0.129)
Peak Hour	-1.241**	0.002	-0.190**	-0.351	0.006	-0.019	-1.303**	-0.003	-0.254*
	(0.489)	(0.006)	(0.087)	(0.637)	(0.011)	(0.060)	(0.608)	(0.007)	(0.132)
Night Time	9.363***	-0.049	0.251	0.000	0.000	0.000	9.554***	-0.049	0.281
	(2.964)	(0.037)	(0.528)	(.)	(.)	(.)	(2.881)	(0.034)	(0.621)
Constant	20.20***	0.227***	1.460***	17.988***	0.258***	1.336***	19.760***	0.202***	1.176***
	(1.946)	(0.020)	(0.483)	(0.778)	(0.014)	(0.073)	(0.691)	(0.008)	(0.149)
u_i	2.628**	0.026*	0.668**						
Constant	(1.337)	(0.013)	(0.337)						
ϵ_{ij}	7.195***	0.090***	1.281***						
Constant	(0.169)	(0.002)	(0.030)						
R^2				0.068	0.051	0.028	0.46	0.0066	0.27
AIC	6,200	-1,766	3,112						
Observations	911	911	904	358	358	358	553	553	546

Statistical significance is indicated as follows * p<0.10 ** p<0.05 *** p<0.01. Standard errors of regression coefficients are reported in parentheses.

4.5 CONCLUSION

Chapter 4 studied the effect of the treatment of the reduction of curb radii for two intersections in Toronto, Canada. The first intersection selected is Christie Street and Davenport Road and the second intersection is Driftwood Avenue and Yorkwoods Gate. Video footage was collected for both intersections before and after the adjustments to evaluate its effect using empirical data. The collected video data was then processed using a computer vision commercial software which generates measures like speed and PET.

An average decrease of 1.6 kph and 0.783 kph for 85th percentile speed and median speed, respectively for both intersections based on the computed mixed-effects model. To further investigate the results, speeds were obtained about each curve, before and after the adjustment, in five main areas. The speed was then plotted as a box plot. It can be noticed that an overall decrease was brought about for both intersections. However, because of limitations of space and camera placement, the placement of the five areas differed for the intersections. While the plot for intersection of Christie Street and Davenport Road focused primarily on the speed around the curved part of the curb, that of Driftwood Avenue and Yorkwoods Gate examined the trajectory as it captured cars earlier from the curve showing a trajectory like pattern as the camera placement is further from the curve. Due to this placement, the speeds measured show higher values as it captures non-turning vehicles. This also explains the overall increase in risk in the conflict data.

After running linear regression models for the conflict data both intersections combined, it was important to run separate models given the different natures of each intersections in terms of road hierarchy and design. It was found for the intersection of Christie Street and Davenport Road that the speed showed a statistically significance decrease of 3 kph after the modification. While the probability of a conflict increased, the overall risk after treatment decreased showing a negative coefficient, however, not statistically significant. Contrarily, the intersection of Driftwood Avenue and Yorkwoods Gate showed an increase in the conflict speed by 2.6 kph and an overall increased risk.

With these findings, more investigation is required to study the turning behavior of drivers using more frequent attainable measures. While the goal of this chapter was to obtain speed for every meter, that was a limitation of the used software. Furthermore, for future video collection, cameras would be mounted on buildings for a wider view and a more consistency.

CHAPTER 5 EXAMINING THE BEHAVIOR AND SAFETY OF TURNING VEHICLES IN LOCAL URBAN INTERSECTIONS USING SPEEDS OBTAINED FROM GPS DATA: A CASE STUDY IN QUEBEC CITY, CANADA

5.1 INTRODUCTION

Studies have utilized Global Positioning System (GPS) data to investigate driving behavior and overall network safety. The collection methods vary from smartphone collected GPS data to floating vehicles and GPS-enabled taxis. While GPS-enabled vehicles collect more accurate data and have been more widely used in the literature, they introduce a bias due to the driver's awareness and limited sample sizes obtained. On the other hand, smartphone GPS data is easy to set up, inexpensive, and provides a large coverage for the area of study.

Using the frequent speed measures obtained almost every second, operating speed models were developed to examine the effect of posted speed limits and road geometry with a focus on two lane rural roads (Cafiso & Cerni, 2012). These road geometric attributes include the horizontal curvature, number of lanes, etc. Only a few studies have examined urban roadways or intersections (Wang et al., 2005). Thus, this study continues to investigate the safety of intersections in an urban local setting through modern automated techniques of data collection. While the previous chapters utilize video trajectories, this chapter addresses the safety of the curb radius with the aid of smartphone GPS data, instead. Video data has a higher penetration rate (all vehicles in the intersection are observed), however, it has a lower coverage of the network. In other words, the use of GPS data provides an opportunity to study a larger intersection sample. Furthermore, the granularity of the data (every 1 second as compared to the continuous measure of video footage) has aided in the processing and the mapping of the data.

In this Chapter, the effect of the curb radius on the turning behavior is investigated using a large GPS dataset collected through a smartphone application. Data was collected in *City of Quebec* through *Mon Trajet,* a mobile application where drivers voluntarily log their travel trips. A total of 19.7 million data points were processed in this study. Using this smartphone GPS data and collected intersection geometrical attributes; linear regression models, mixed-effects linear regression models, and polynomial regressions were used to evaluate the safety of the intersections with speed and deceleration as indicators. Using python geographic packages and libraries, this data was processed through joining and intersecting based on coordinate system data (longitude and latitude of each intersection midpoint and vehicle locations throughout the trip). This information was then filtered, and data analysis was done through the aforementioned models. Based on the previous chapters, the curb radius is expected to have positive statistically significant effect in which an increase in the radius would result in higher speeds, hence, more dangerous driving behavior and decreased intersection safety.

5.2 METHODOLOGY

The framework of this study is divided into the following main sections: data collection, data processing, data filtering and generation, cross-sectional statistical studies, and assumptions. The methodology is illustrated in **Figure 5-1.**

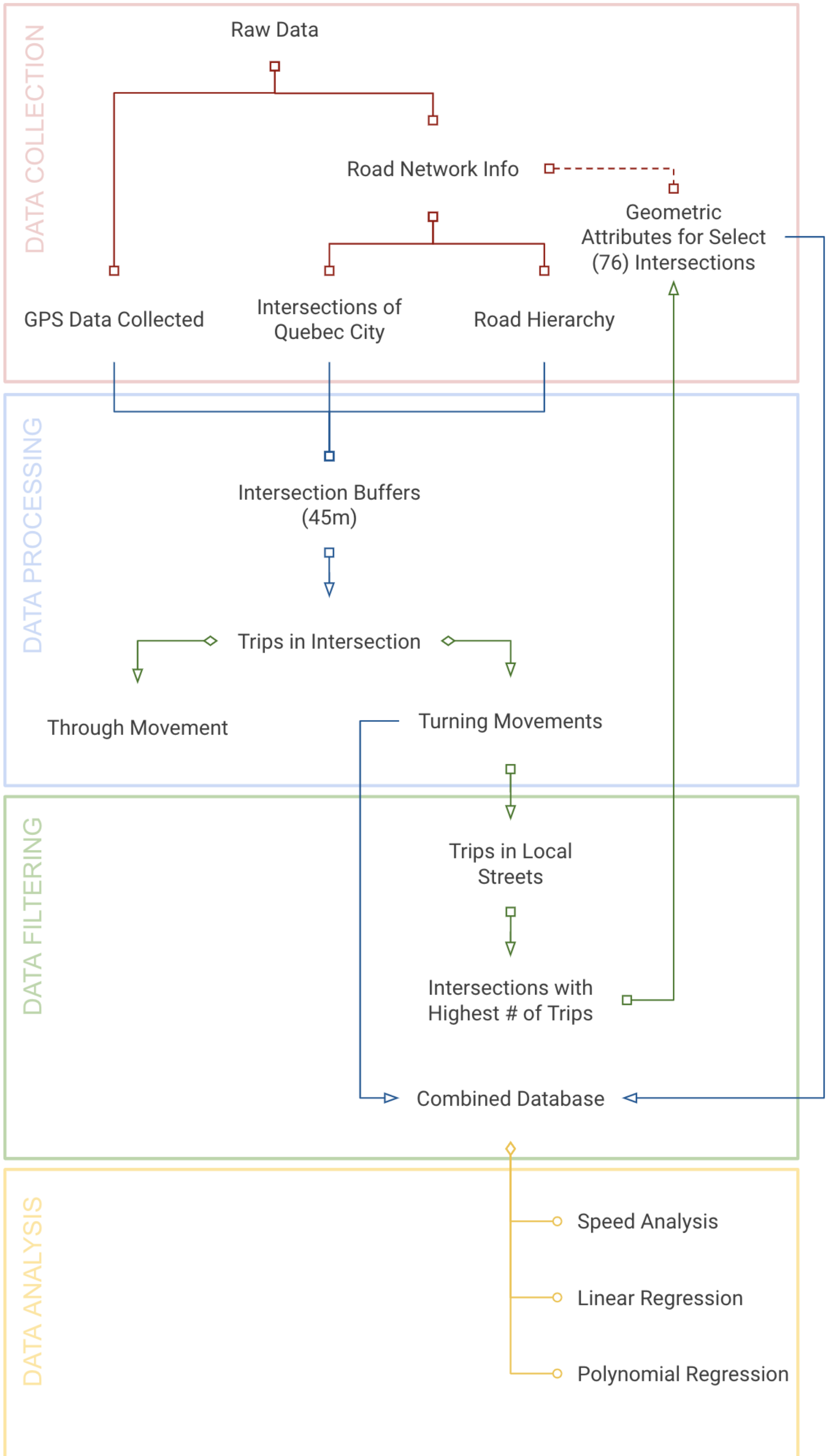

Figure 5-1 Breakdown of the methodology used in chapter

5.2.1 **Data Collection**

The data collected are of two types: (1) GPS data obtained from Mon Trajet application and (2) road network information obtained using governmental databases or measured from Google Earth.

5.2.1.1 GPS Data Collection

In efforts of collecting GPS smartphone data, the City of Quebec had started the phone application Mon Trajet developed by Brisk Synergies (Ville de Quebec, 2015). The application was installed by the drivers in which they were able to log in their trip with anonymity guaranteed. The trip information was then stored in a database which was later obtained for this study. A total of 50,000 trips for 5,000 drivers were stored in the database, however, for the purpose of this chapter only a sample of 21,939 trips for 4,000 drivers was examined. The data collected for one day was mapped as shown in the following figure.

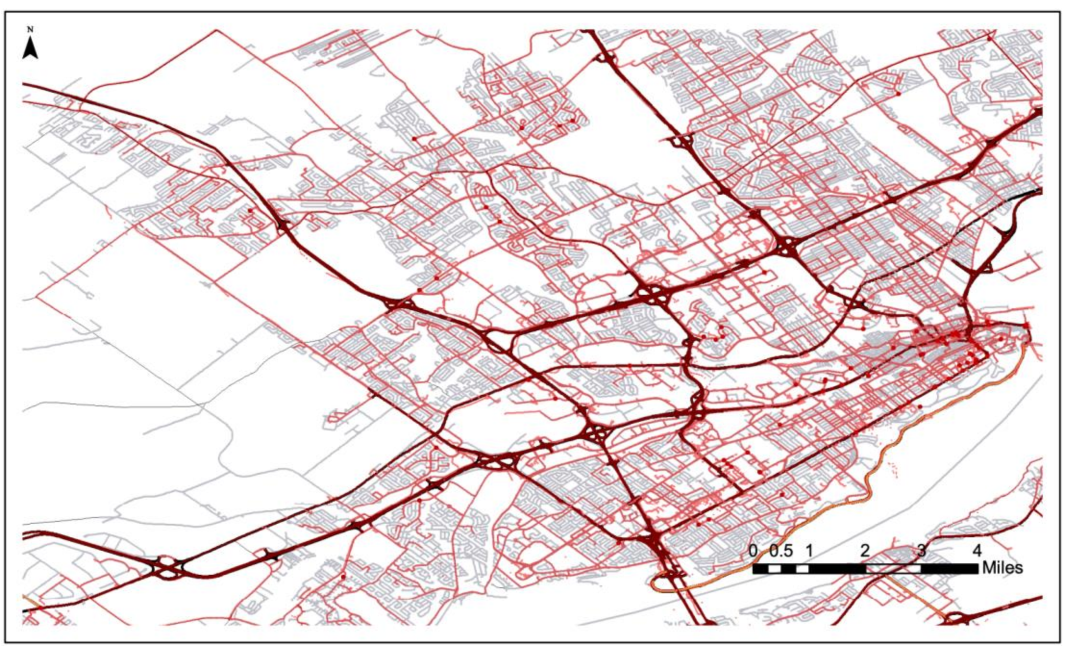

Figure 5-2 GPS points coverage on the level of Quebec City for one day

These 4,000 drivers represent 19,7 million individual data points collected over 21 days from April 28 until May 18, 2014. For each $trip_i$ logged, the attributes i, a_{ij}, t_{ij}, x_{ij}, y_{ij}, and v_{ij} are collected which are trip number, point identifier, time stamp, longitude, latitude, and speed; respectively (Stipancic et al., 2018).

$$trip_i = \left\{ \begin{matrix} i, a_{i0}, t_{i0}, x_{i0}, y_{i0}, v_{i0} \\ i, a_{i1}, t_{i1}, x_{i1}, y_{i1}, v_{i1} \\ \vdots \\ i, a_{ij}, t_{ij}, x_{ij}, y_{ij}, v_{ij} \\ \vdots \\ i, a_{in_i}, t_{in_i}, x_{in_i}, y_{in_i}, v_{in_i} \end{matrix} \right\}$$

5.2.1.2 Road Network and Intersection Attributes Measurement

Road network information was obtained from the available shape files made available online by *Ville de Quebec* (*City of Quebec*). Firstly, the information for the road hierarchy for Quebec was obtained from Données Québec (2019a) in the form of a shape file. The intersections database of Quebec city was retrieved (Données Québec, 2019b). The used local streets have a speed limit of 50km/hr. The database contains information like name, signalization, and location (longitude and latitude) for a total of 11,416 intersections.

Using ArcGIS, the data was matched spatially to obtain the road hierarchy information for each intersection (Esri Inc., 2019). After data processing and filtering (discussed in **sections 5.2.2** and **5.2.3**), 76 local urban/suburban intersections with the highest trip count were selected at random and geometric data was collected using Google Earth (Google Inc., 2019).

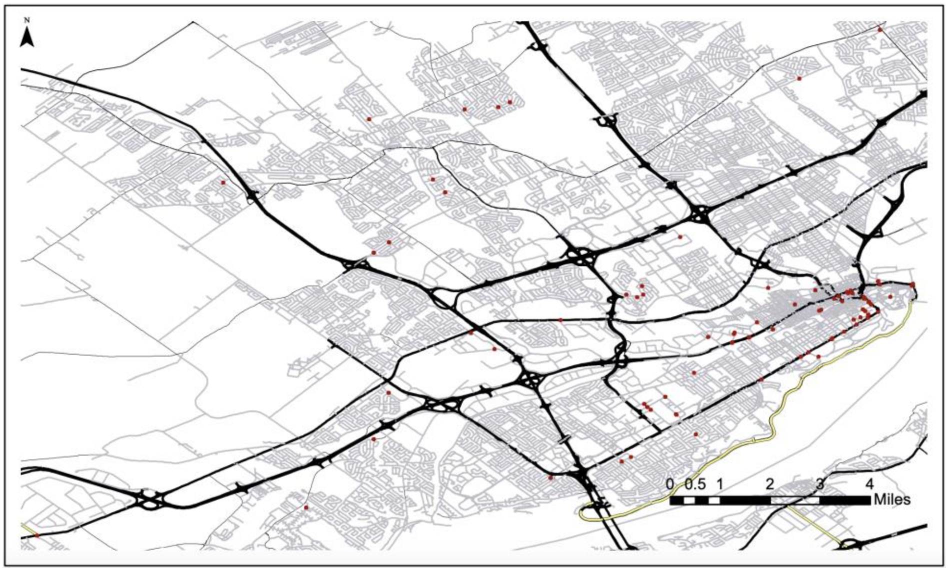

Figure 5-3 76 local urban intersections in Quebec City

For each of these intersections, information collected include: intersection type, number of lanes, curb radii, the presence of crosswalks, curb extensions, road median in each approach. The technique used for curb radii measurement is similar to that discussed in **section 3.2.3**. 220 curb radii were measured and used for this chapter. The distribution of the curb radii measured ranged from 0.56 to 27 meters for larger intersections (**Figure 5-4**).

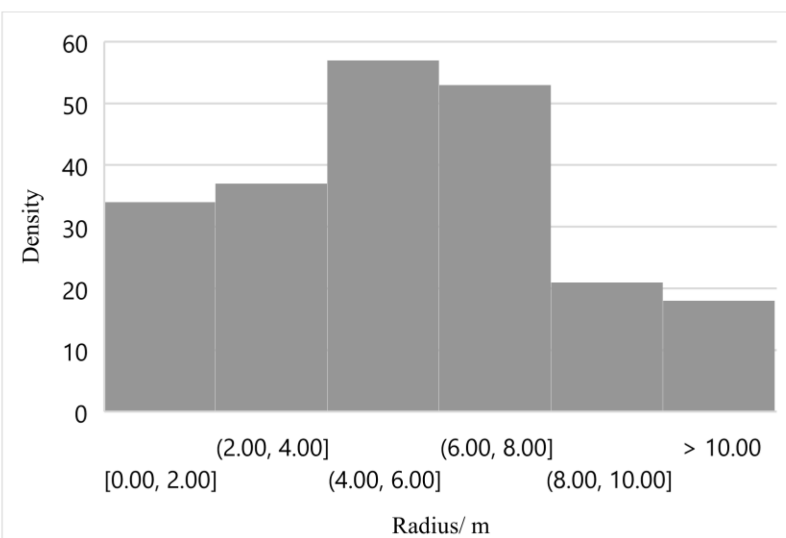

Figure 5-4 Distribution of 220 curb radii used in study

5.2.2 **Data Processing**

Given the spatiotemporal nature of the data, processing was based on the coordinates of the points and intersections. Firstly, a 1-meter buffer was created for each intersection and spatially joint with the road information layer to obtain the hierarchy of the roads for each intersection using ArcGIS. With a total of the 21,939 trips, the use of ArcGIS was not feasible, time wise nor with the data size. Thus, the processing of the data was automized using python packages and libraries. These include the use of Geo-Pandas data frames which were utilized to create 45-meter buffers for each intersection. To validate these radii, the results obtained were fed into ArcGIS for visualization. Traditionally, 20 to 30-meters buffers are used to evaluate safety of intersections, however, an extra 15 meters were added to capture the behavior of the driver before arriving at the curved part of the intersection. With these buffers, trips within the intersections were captured and turning movements were allocated.

Figure 5-5 shows an example of one turning trip within the intersection's 45-meter buffer. The location in which the vehicle first entered was labelled as point "a" and the last as point "c". The midpoint "b" was obtained by dividing the number of observations within the buffer by two which has proved to be a decent approximated assumption. Angles were computed for vectors **A** and **C** and then the turn angle was calculated by subtracting angle A from C.

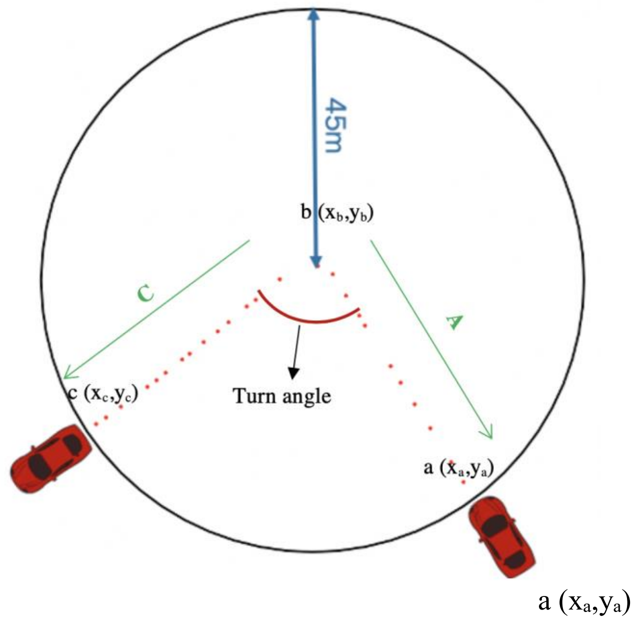

Figure 5-5 Example turning trip in intersection (GPS points presented by red dots)

The angle was calculated using arctan2 which stands for 2-argument arctangent. Based on the magnitude of the angle and the direction of the vectors, the type of movement (right or left turn), and the bounds of the movements (north east, north west, south east, southwest, east north, east south, west north, and west south) were determined (algorithm explained further in the appendix). The arctan2 function follows the shown mathematical reasoning.

$$atan2(y_{a,c}, x_{a,c}) = \begin{cases} \arctan\left(\frac{y_{a,c}}{x_{a,c}}\right) & if\ x_{a,c} > 0, \\ \arctan\left(\frac{y_{a,c}}{x_{a,c}}\right) + \pi & if\ x_{a,c} < 0\ and\ y_{a,c} \geq 0, \\ \arctan\left(\frac{y_{a,c}}{x_{a,c}}\right) - \pi & if\ x_{a,c} < 0\ and\ y_{a,c} < 0, \\ +\frac{\pi}{2} & if\ x_{a,c} = 0\ and\ y_{a,c} > 0, \\ -\frac{\pi}{2} & if\ x_{a,c} = 0\ and\ y_{a,c} < 0, \\ undefined & if\ x_{a,c} = 0\ and\ y_{a,c} = 0. \end{cases}$$

Where $x_{a,c}$ and $y_{a,c}$ are the coordinates for either vector A or C.

Upon classification of each turning trip, speeds like 85th percentile, 15th percentile, median and mean were computed. Also, deceleration was found between each consecutive point in the trip and the highest deceleration (most negative) was appended to the trip database which was used for the statistical analysis using STATA 13.

5.2.3 **Data Filtering and Generation**

As the trip information is logged into the application and saved in the database, some data filtering technique was applied to clean up some of the noise caused by the urban canyon effect (Kalman filter). Upon retrieval of the data, trips with less than 5 point were dropped. The second level of filtering focused on obtaining the turning portions of the trips (explained in the previous section). Turning trips of less than 5 points were discarded, as well as those with speeds of less than zero. Based on the turning trips database, 76 intersections were selected at random given a local hierarchical definition to measure the curb radius and other geometric attributes. Based on the intersection ID and the movement direction, the turning trip database was joint with the intersection's geometric attributes to create a complete database of 199,867 turning events from 18,820 vehicle trips.

5.2.4 **Cross-Sectional Statistical Studies**

To evaluate the relationship of the curb radius and other geometric factors with the safety of turning behavior represented by the turning speed, various models were utilized. These include two types of regression statistical models using STATA 13: Linear regression and Maximum Likelihood (ML) random mixed-effects regression estimators. The dependent variables used for speed indicators are 85th percentile speed, median speed, and deceleration of each trip. The models are presented in chapters 3 and 4. Furthermore, generalized polynomial regressions were used to estimate turning trajectories using speed and cumulative distance . Maximum Likelihood (ML) random-effects regression estimator used are explained in chapters 3 and 4.

Polynomial regression models are used in this chapter to capture the turning behavior along the curb radius. This is due to the models' ability to capture inflection points presented by the slowing down and speeding up of vehicles (fluctuations in speeds). The claim is supported with literature presented in chapter 2. The model follows:

$$y = c_0 + c_1 x^1 + c_2 x^2 + \cdots + c_{\mathrm{n}} x^n$$

Where:

n – degree of the polynomial

y – speed measured

x – cumulative distance in intersection buffer

c_0 – model intercept

c_n – coefficients for the *n* factor of x^n vector.

5.2.5 **Assumptions**

Given the limitations of the data type and available resources, some assumptions were made in order to capture the effect of the curb radius on the turning speed and the overall safety of the turning behavior. Firstly, GPS data is known to be noisy, especially, because of the obstruction of buildings (Shirazi and Morris, 2017) . However, for the purpose of this chapter, no additional filtering was done on the data, like map matching, as it tends to treat intersections as points

(Stipancic et al., 2018). With intersections being the focal point of this chapter, these techniques were not considered. Using a five-point filter and a minimum speed of zero m/s, the data is assumed to be complete trajectories and representative the behavior of the general public. Also, the results assume no car following effects as compared to chapters 3 and 4. With a sensitivity analysis done for the tuning angle, a turning movement is acknowledged if between 65 degrees to 150 degrees. Using a sample of results, manual validation has found that these results have a 95% accuracy, thus, no further filtering was required.

Moreover, intersections are assumed to have simple curb radii (as compared to compound radii design). The angle of the intersections (3- or 4-legged) are proper 90-degree angles on regular terrain. This is not the case for four intersections as Quebec City is located on a slope, however, it is assumed to be of negligible effect. Also, radii measured are as low as 0.59 meters which is due to the fact that some of the downtown locations are in the old town where the design guidelines are not followed. This chapter assumes a direct relation between the measured curb radius and the vehicle turning radius.

5.3 DESCRIPTIVE DATA

The safety of 76 intersections in Quebec City was evaluated in this chapter. These correspond to a total of 220 curb radii measured. The speed distributions of the median and 85th percentile speeds are shown in **Figure 5-6**. On the other hands, **Figure 5-7** shows the distribution of the measurements of the 220 curb radii based on the road hierarchy and the signalization. Based on the design manuals, a larger curb radius is designed for higher volumes. Also, a higher level of signalization is expected for greater volumes and hence the hierarchy of the road. This correlation is illustrated below. Local streets are associated with lower curb radii as compared to larger intersections of local/regional/national junctions. Similarly, intersections with no signalization have lower curb radii as compared to stop controlled and signalized intersections.

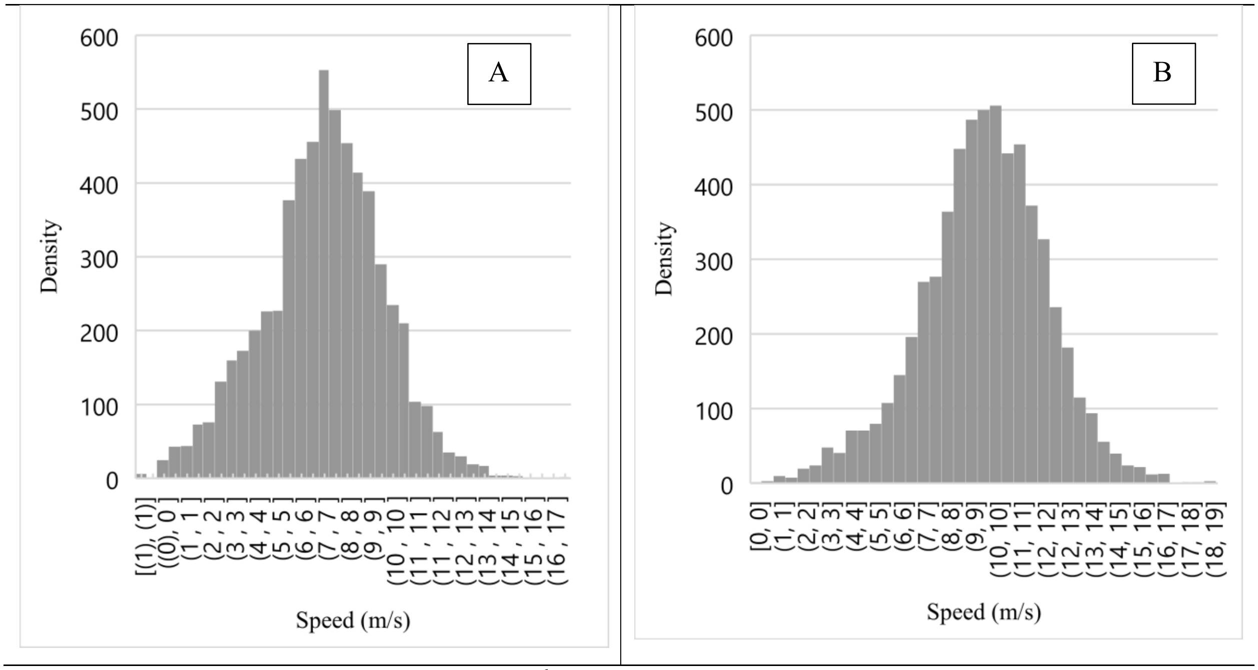

Figure 5-6 Distribution of the median speed (A) and 85th percentile speed (B) of the entire trajectory within the intersection

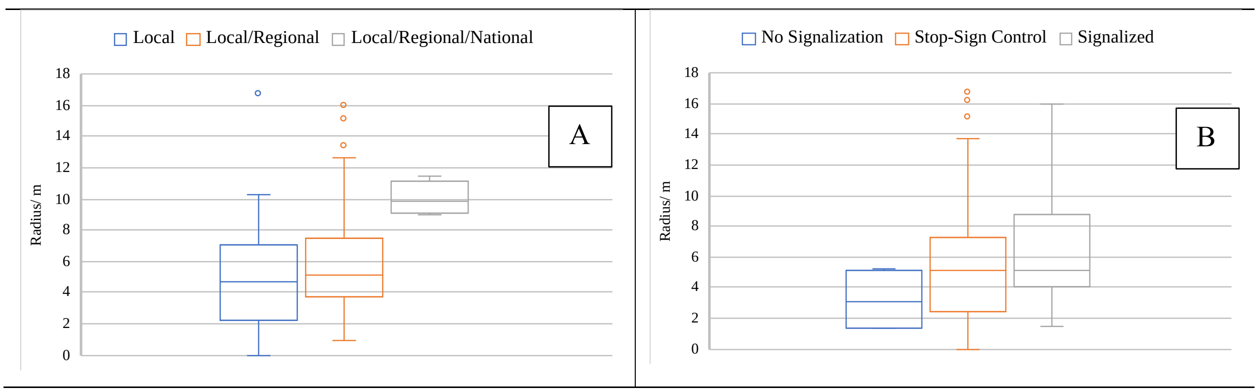

Figure 5-7 Distribution of the curb radius based on road hierarchy (A) and signalization (B)

The variables studied in this chapter were categorized into trip attributes, road characteristics, and intersection geometry. Trip attributes refers to speed measures of the GPS trips collected, for instance: 85th percentile speed, median speed, hour, movement type, turn angle, peak hour, and night time. The intersection characteristics include the road hierarchy, signalization, and the intersection type being 3-legged or 4-legged. Lastly, the intersection geometric attributes focus on aspects like the curb radius, number of lanes, presence of crosswalks, and medians. The aforementioned attributes like 85th percentile, median speeds and deceleration are dependent continuous variables in m/s and m/s^2, respectively. Independent variables are either continuous, categorical, or boolean variables.

Dependent attributes were used to test the hypothesis of this chapter. For instance, an increase in the “curb radius” (continuous measure) is believed to increase the speed and deceleration rate, thus, decreasing the safety of intersection. Peak hour, on the other hand, is a boolean variable which indicates whether a trip took place during the hours of 7-8 AM or 3-4 PM, inclusive. During these hours the speeds are expected to go down as more car following behavior can be witnessed. The number of lanes were categorized to two categories: equal of less than 2 or higher than 2. The selection of the categories is based on the expected complexity of intersections with 1 or 2 lanes being the norm of local urban intersections.

Table 5-2 shows the statistical summary for the trip attributes. The average speed of turning trips in intersections was 6.62 m/s which is 24 kph with a maximum of 60 kph which is an acceptable limit for turning speed. Moreover, median speed was found to be around 24 kph, as well. 85th percentile speed obtained had a higher average, as anticipated, of 32kph. The deceleration rate averaged to the value of -1.6 m/s^2 (-5.76 km/hr^2) which indicates a generally safe breaking behavior as dangerous breaking is defined to be higher (more negative) than -3 m/s^2 (Wang et al., 2005). The distribution of the categorical variables and their percentages is shown in **Table 5-3**.

Table 5-1 Description and the categories or units used for variables used

	Variable	Description	Categories / Units
Trip Attributes	X85th	85th percentile of the vehicle speed measured along the trajectory	Continuous measured in m/s
	X15th	15th percentile of the vehicle speed measured along the trajectory	Continuous measured in m/s
	Median	Median of the vehicle speed measured along the trajectory	Continuous measured in m/s
	Mean	Mean of the vehicle speed measured along the trajectory	Continuous measured in m/s
	Decel	Deceleration of the lowest value from the consecutive points of the trajectory	Continuous measured in m/s^2
	Turn Angle	Angle of the turn	Continuous measured in degrees
	# Trips in Inter	Number of trips detected in buffer	Continuous count of trips
	Movement Type	Right turn or left turn at intersection	Boolean variable: 0 = right turn 1 = left turn
	Peak hour	If the trip took place during peak hour with AM Peak Hours between 7-8 AM and PM Peak Hours between 3-4 PM	Boolean variable: 0 = not peak 1 = during peak
	Night Time	Refers to driving during dark light conditions of 7 PM to 6 AM inclusive	Boolean variable:0 = not night time 1 = night time
Intersection Characteristics	Road Hierarchy	Type of road hierarchy of the intersection	Categorical variable with 3 sets: 1 = Local 2 = Local/National 3 = Local/National/Regional
	Signalization	The level of signalization of the intersection	Categorical variable with 2 sets: 1 = No signalization 2 = Stop-sign controlled 2 = Signalized intersection
	Intersection Type	Intersection type based on the number of branches	Categorical variable with 2 sets: 3 = 3-legged intersection 4 = 4-legged intersection
Intersection Geometry	Curb Radius	The radius of curvature measured at the curb of the approach	Continuous measured in m
	Road Median	If there is a road median at any of the approaches of the intersection	Boolean variable: 0 = no road median 1 = road median present
	Lanes_Approach	The number of lanes in the approach is equal to or less than 2	Boolean variable: 0 = 2 ≥ lanes 1 = 2 < lanes
	Lanes_ Exit	The number of lanes in the exit is equal to or less than 2	Boolean variable: 0 = 2 ≥ lanes 1 = 2 < lanes
	Crosswalk_ Approach	If a crosswalk is present from the vehicle's approach	Boolean variable: 0 = no crosswalk 1 = crosswalk present
	Crosswalk_ Exit	If a crosswalk is present from the vehicle's exit after the turn	Boolean variable: 0 = no crosswalk 1 = crosswalk present

Table 5-2 GPS trip attributes statistical summary

	Variable	Mean	Std Dev	Min	Max
Trip Attributes	Mean Speed	6.62	2.61	0	16.43
	Median Speed	6.61	2.84	0	17.18
	X15th Speed	4.23	2.71	0	16.16
	X85th Speed	9.04	2.96	0	18.69
	Deceleration	-1.60	1.04	-11.08	1.29
	Hour (used for Peak Hour and Night time)	11.35	4.5	0	23
	Turn Angle	14.65	166.53	-294.54	294.83
	Number of Trips in Inter	142.67	107.65	31	437
	Observations	6410			

Table 5-3 Categorical distribution of variables used

	Variable		Categories	Freq	Percent%	% cum.
Trip Attributes	Turn Type	0	Right turn	3,753	58.55	58.55
		1	Left turn	2,657	41.45	100.00
	Peak Hour	0	Trip was not during peak hour	1,951	30.44	30.44
		1	Trip was during peak hour	4,459	69.56	100.00
	Night Time	0	Trip was not during night time	5,918	93.32	93.32
		1	Trip was during night time	492	7.68	100.00
Intersection Characteristics	Hierarchy	1	Local	3,679	57.39	57.39
		2	Local/ National	2,609	40.70	98.10
		2	Local/ National/ Regional	122	1.90	100.00
	Signalization	1	No signalization	73	1.14	1.14
		2	Stop-sign control	3,905	60.92	62.06
		3	Signalized intersection	2,432	37.94	100.00
	Intersection Type	3	3-legged intersection	2,737	42.70	42.70
		4	4-legged intersection	3,673	57.30	100.00
Intersection Geometry	Road Median	0	Median absent in intersection	4,838	75.48	75.48
		1	Median absent in intersection	1,572	24.52	100.00
	Lanes_Approach	0	Number of lanes at trip approach (2 ≥)	3,488	54.41	54.41
		1	Number of lanes at trip approach (2 <)	2,922	45.59	100.00
	Lanes_Exit	0	Number of lanes at trip exit (2 ≥)	3,424	53.42	53.42
		1	Number of lanes at trip exit (2 <)	2,986	46.58	100.00
	Crosswalk_Approach	0	Crosswalk is absent at trip approach	3,813	59.49	59.49
		1	Crosswalk is present at trip approach	2,597	10.51	100.00
	Crosswalk_Exit	0	Crosswalk is absent at trip exit	3,988	62.22	62.22
		1	Crosswalk is present at trip exit	2,422	37.78	100.00
	Observations			6410		

5.4 Results and Analysis

The results for this chapter present a preliminary analysis of speed, linear regression analyses of speeds and deceleration, and polynomial analysis of speed trajectories.

5.4.1 Preliminary Analysis of Speed

This initial analysis examines the effect of road characteristics and intersection geometry on speed.

5.4.1.1 Speed and Road Characteristics

Figure 5-8(A) shows that the speed decreased with the higher hierarchal classification of the intersection. Local/Local intersection had the highest speeds as it is less likely to have signalization control and cars are less likely to stop while turning. Local/National intersection showed lower speeds as they are more likely to be signalized. Local/National/Regional showed a greater average as compared to Local/National because regional roads have higher operating speeds.

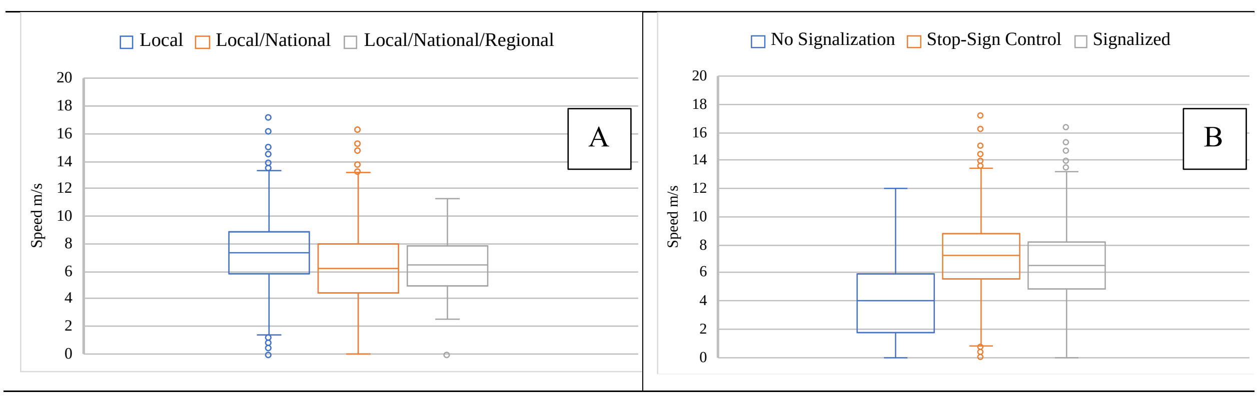

Figure 5-8 Median speed distribution of trips according to the road hierarchy (A) and intersection signalization level (B)

Non-signalized intersections in Figure **5-8(B)** showed the lowest speeds as vehicles approach the intersection more carefully. False safety perception for stop-sign controlled intersections explain the highest speeds, while signalized intersections showed a similar average median speed.

5.4.1.2 Speed and Curb Radius

Higher speeds are indicators of increased risk severity of crashes and injuries. Larger curb radii increase the turning speed of the vehicles, thus, decreasing the safety of the driver and the intersection overall. This is seen in **Figure 5-9** where the 220 curb radii measures were categorized and a box plot of median speeds of all trips for right and left turns was plotted. Generally, an increase in the turning radius was correlated with an increased average median speed for the category. However, a decrease was seen from 6-8 meters to 8-10 meters curb radii. This can be explained given a smaller sample size of trips in this category. Also, 8-10 meters curb radii were associated with signalized intersections, thus, vehicles were expected to slow down at these intersections. The maximum increase in speed was seen between 4-6 meters to 6-8 meters.

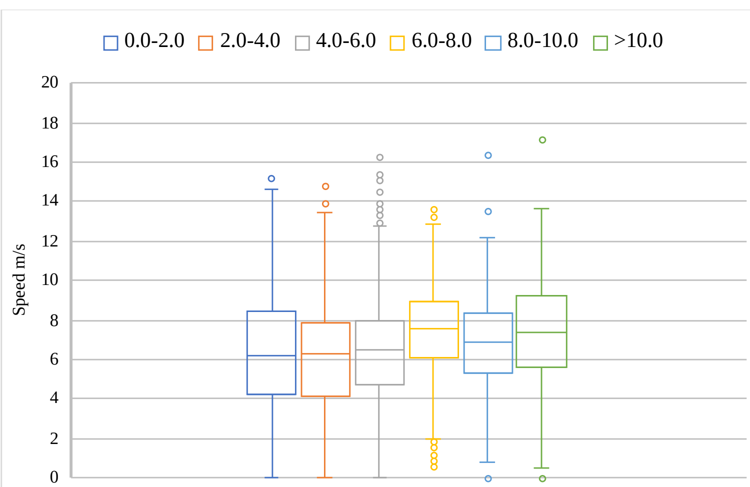

Figure 5-9 Distribution of median speed of trips based on the curb radius category measured in meters

The 76 intersections used in this study were mapped below in **Figure 5-10** using ArcGIS (Esri Inc., 2019). Using all turns in each of the intersections, the average median speed was found. The diagram below assumed that for any 3-legged or 4-legged intersection, the 2 or 4 curb radii should be of a similar measure given the same volume of vehicles passing and road characteristics. Therefore, the average of the curb radii was found based on the frequency of trip with respect to each side. Intersections in downtown (upper right corner of the purple box) showed lower speeds which can be explained by higher control and volumes. Larger radii, represented by bigger circles, are of a higher speed category of 7-8.6 m/s. Smaller radii further from the city also experienced higher speeds as the drivers are less likely to abide by the rules in residential areas.

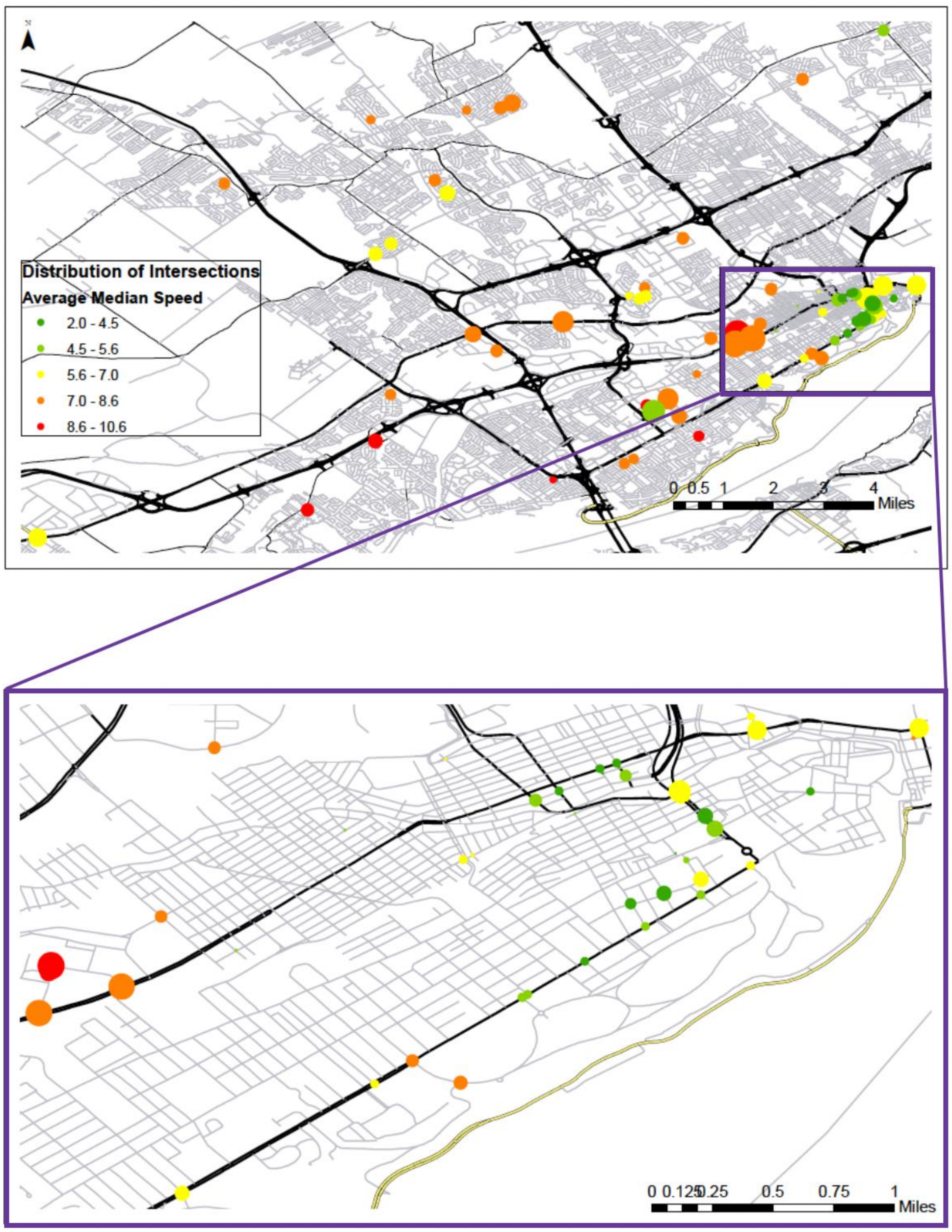

Figure 5-10 Mapping of median speed of trips in intersections (size of circle represents the average curb radii of intersection)

5.4.2 **Linear Regression Analysis**

In order to investigate the effect of the curb radius, linear regression models and Maximum Likelihood (ML) random-effects regression models were run. The models' dependent variables were 85^{th} percentile speed, median speed, and deceleration. For the speed measures, positive coefficients indicate a decrease in safety. However, a negative coefficient refers to decreased safety for the deceleration models. The models include other independent variables which represent trip attributes, road characteristics, and intersection geometry of statistical significance.

From the speed models, the curb radius had positive coefficients as hypothesized. The regression model speeds experienced an increase of 0.1 m/s while the ML regression models showed an increase of 0.6 m/s. Therefore, an increase in the curb radius by 5 meters would result in a higher speed by 0.5 m/s. Other geometric factors, for instance, the presence of a median increase the speed as it provides a false sense of safety. Higher number of lanes in the exit of the trip's trajectory decreased the speeds as cars show more cautious driving at a more complex merging road stream.

As discussed earlier, trips during peak hours experienced lower speeds and higher decelerations. Night time increased the speeds, however, it had no statistically significant effect on deceleration. A more complex road hierarchy decreased speeds and increased deceleration. Factors like road hierarchy, signalization, and intersection type median are insignificant since mixed-effects regression creates another error term on the intersection level capturing local factors.

The most representable linear regression model was that of the median speed with the highest R^2 value of 0.1318. As for the ML random effects models, the deceleration model with the lowest AIC of 18,053, thus, proving to be of a better fit.

Table 5-4 Linear regression and random effects ML regression models using 85th percentile, median speed, and deceleration

	Regression Models			ML Regression Models		
	X85th	**Median**	**Decel**	**X85th**	**Median**	**Decel**
Curb Radius	0.102***	0.107***	-0.011***	0.060***	0.058***	-0.009**
	(0.007)	(0.007)	(0.003)	(0.010)	(0.010)	(0.004)
Turn Type	0.060	-0.107	-0.041	0.288***	0.124**	-0.056**
	(0.072)	(0.069)	(0.027)	(0.066)	(0.063)	(0.026)
Road Hierarchy	-1.466***	-1.475***	0.183***	-0.774	-1.410***	0.131
	(0.107)	(0.101)	(0.039)	(0.576)	(0.535)	(0.126)
Signalization = 2	2.322***	2.319***	-0.322**	0.368	0.670	-0.092
	(0.355)	(0.338)	(0.130)	(0.739)	(0.691)	(0.202)
Signalization = 3	2.394***	2.246***	-0.364***	0.552	0.414	-0.024
	(0.335)	(0.319)	(0.123)	(0.383)	(0.365)	(0.148)
Intersection Type	-0.300***	-0.253***	-0.023	-0.489	-0.258	-0.110
	(0.086)	(0.082)	(0.032)	(0.473)	(0.439)	(0.102)
Road Median	0.403***	0.495***	-0.125***	1.430**	1.212**	-0.256**
	(0.095)	(0.090)	(0.035)	(0.595)	(0.552)	(0.127)
Lanes_Approach	0.362***	0.375***	0.128***	-0.865***	-0.047	0.227***
	(0.114)	(0.109)	(0.042)	(0.218)	(0.206)	(0.077)
Lanes_Exit	-0.247**	-0.213*	0.211***	-1.278***	-0.585***	0.242***
	(0.119)	(0.113)	(0.044)	(0.223)	(0.211)	(0.079)
Crosswalk_Approach	-0.190**	-0.183**	-0.067*	0.246	0.059	-0.055
	(0.095)	(0.090)	(0.035)	(0.162)	(0.154)	(0.054)
Crosswalk_Exit	0.186**	0.270***	-0.104***	0.606***	0.350**	-0.130**
	(0.092)	(0.088)	(0.034)	(0.165)	(0.156)	(0.055)
Peak Hour	-0.713***	-0.636***	0.187***	-0.599***	-0.513***	0.198***
	(0.084)	(0.080)	(0.031)	(0.074)	(0.071)	(0.030)
Night Time	0.253*	0.356**	-0.048	0.330**	0.423***	-0.026
	(0.146)	(0.139)	(0.054)	(0.128)	(0.123)	(0.052)
Constant	7.041***	4.529***	-1.377***	8.857***	6.159***	-1.587***
	(0.375)	(0.357)	(0.138)	(0.826)	(0.772)	(0.221)
$\boldsymbol{u_i}$				1.842***	1.707***	0.372***
Constant				(0.160)	(0.148)	(0.036)
$\boldsymbol{\epsilon_{ij}}$				2.406***	2.297***	0.973***
Constant				(0.021)	(0.020)	(0.009)
R^2	0.1170	**0.1318**	0.0312			
AIC	31,333	30,694	18,498	29,759	29,161	**18,053**
Observations	6410	6410	6410	6410	6410	6410

Note: The table presents the coefficients of the mixed-effect linear regression models, using intersection level random effect and an independent covariant structure and linear regression models. Statistical significance is indicated as follows * p<0.10 ** p<0.05 *** p<0.01. Standard errors of regression coefficients are reported in parentheses.

5.4.3 **Polynomial Analysis**

Given the literature on the topic, polynomials were used to estimate the trajectory deviation from that expected from the swept path and estimating deceleration (Wang et al., 2005). This section of the chapter utilized polynomial functions of varying degrees to estimate the speed based on the cumulative distance measured from the first point detected within the intersection buffer. In order to minimize noise in the models, only right turning vehicles were considered. A generic polynomial regression was modelled, and intersection specific polynomials were later computed.

5.4.3.1 Generic Polynomial Regression

In order to investigate the best fit polynomial model, a total of five models were computed. Starting from a 3rd degree to a 7th degree polynomial. The results are shown in **Table 5-5**. Based on the R^2 results obtained, the higher the polynomial degree, the higher the R^2 value. However, the coefficient of x^5 in the 7th degree polynomial is insignificant, thus, the 6th degree polynomial is selected to be the most representative for this data set.

5.4.3.2 Intersection Specific Polynomial

Given the results in **Section 5.4.3.1**, 6th degree polynomials were run for right turning vehicle trips in selected intersections based on the radius category and the results are shown in **Figure 5-11**. For each of these intersections, a separate model was fitted. For curb radii between 4-7 meters, a bin was created every meter instead of two meters.

The results show that the curb radii from 5-9 meters exhibited the least noise based on the data filtering technique used in this study. Specifically, Intersections of radii between 7-9 meters claimed the highest R^2 value of 0.75. The colored lines show the smooth curve of the measured points and the black dashed line represents the estimated 6th degree polynomial for the select intersections. For all curves, the average starting speed for vehicles is almost the same as the exiting speed with the minimum speed at a distance of 40 to 42 meters from the start of the buffer. The plotted graphs show that the minimum speed reached was rarely zero, hence, indicating rolling stops in most cases.

Table 5-5 Polynomial models to estimate the spatial trajectory of turning vehicles

	Generic Polynomial linear Regression				
	3rd Degree	4th Degree	5th Degree	6th Degree	7th Degree
Distance	-0.021***	-0.075***	-0.154***	-0.209***	-0.191***
	(0.001)	(0.002)	(0.003)	(0.004)	(0.006)
$Distance^2$	1.94×10^{-4}***	0.001***	0.003***	0.005***	0.004***
	(1.22×10^{-5})	(3.11×10^{-5})	(6.50×10^{-5})	(1.23×10^{-4})	(2.18x10-4)
$Distance^3$	-4.99×10^{-7}***	-5.05×10^{-6}***	-2.15×10^{-5}***	-4.49×10^{-5}***	-3.14×10^{-5}***
	(2.73×10^{-8})	(1.48×10^{-7})	(5.09×10^{-7})	(1.40×10^{-6})	(3.31x10-6)
$Distance^4$		6.64×10^{-9}***	6.10×10^{-8}***	1.88×10^{-7}***	8.27×10^{-8}***
		(2.13×10^{-10})	(1.62×10^{-9})	(7.23×10^{-9})	(2.44x10-8)
$Distance^5$			-5.92×10^{-11}***	-3.63×10^{-10}***	4.31×10^{-11}
			(01.75×10^{-12})	(1.70×10^{-11})	(9.18×10^{-11})
$Distance^6$				2.63×10^{-13}***	-4.94×10^{-13}***
				(1.46×10^{-14})	(1.69×10^{-13})
$Distance^7$					5.40×10^{-16}
					(1.20×10^{-16})
Constant	6.839***	7.473***	8.100***	8.398***	8.328***
	(0.039)	(0.043)	(0.047)	(0.049)	(0.052)
R^2	0.0117	0.0328	0.0569	0.0637	0.0642
Observations	44604	44604	44604	44604	44604
Statistical significance is indicated as follows * p<0.10 ** p<0.05 *** p<0.01. Standard errors of coefficients are reported in parentheses.					

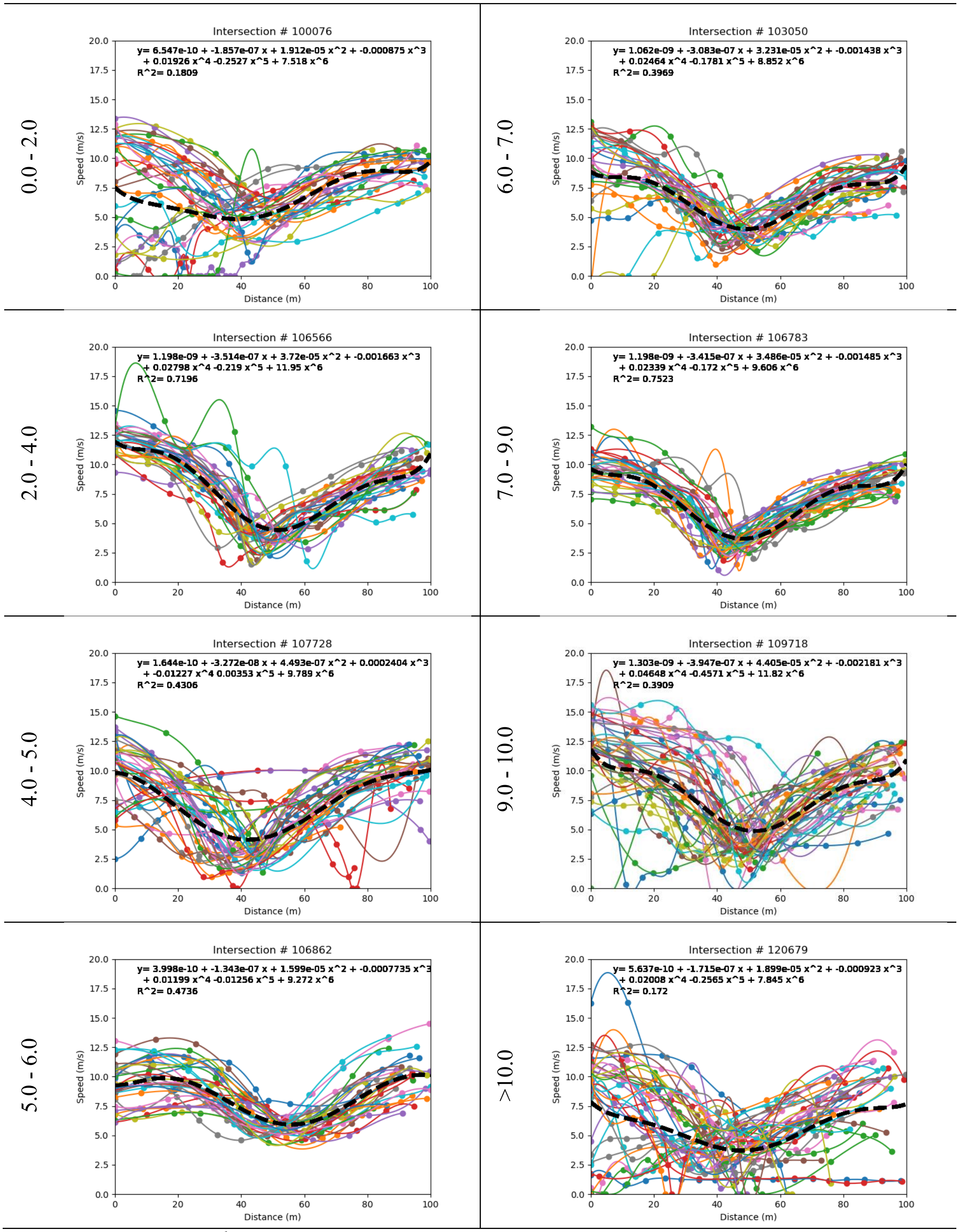

Figure 5-11 Trajectory and 6th degree polynomial functions for select intersections based on radius length categories

5.5 CONCLUSION

This chapter examines the direct relation between curb radius and the behavior and safety of turning vehicles using GPS data, thus, filling a literature gap on operating speed models for intersections using smartphone GPS data. With speed readings recorded every second or two, a GPS dataset collected using Mon Trajet application for Quebec City in Canada was used in this work. A total of 21,939 trips were obtained from the application.

The chapter follows a systematic methodology for data collection, processing, filtering, and analysis. Firstly, Quebec city's datasets were used to obtain all the intersections for the network, along with the road hierarchy database. From a total of 199,867 turning trips, 6,410 were used corresponding to 76 urban local intersections selected. The geometric characteristics including the number of lanes, crosswalk, and curb radii were measured and recorded. The data was later joint and filtered for the cross-sectional statistical analysis. Prior to the statistical analysis, the preliminary analysis exhibited a general trend of an increase of speed with respect to larger curb radii; hence, confirming the main hypothesis of reduced turning safety manifested by an increased curb radius.

The cross-sectional statistical analysis included the use of linear regression models, Maximum Likelihood (ML) random mixed-effect regression estimator, and polynomial models. For all models, the curb radius was statistically significant and had contributed to an increase in the turning speed and the deceleration rate. This increase translates to decreased safety and increased conflict severity. The linear regression model of the median speed had an R^2 value of 0.13, the highest of all three models computed. Other trip attributes, road characteristics, and intersection geometry variables were used to capture the effect of other influencing factors. For instance, the presence of a median, crosswalk on the exit of the turn, higher signalization control, and night time had increased the speeds, as expected. The random mixed-effects models were used with an error factor on the intersection level to account for unidentifiable influencers. With the use of these models, intersection specific variables (road hierarchy, signalization, and intersection type) are of no statistical significance. However, the turn types became statistically significant, with left turns increasing the speeds. This could be due to the increased distance travelled, leaving room for speeding, as compared to a right turn. From these models, the deceleration model would be the model of choice with the minimum AIC value.

The polynomial models were computed to capture the movement and behavior of turning vehicles. A generic polynomial was used for all 44,604 trip points for the 6,410 trips. With an R^2 value of 0.064, a 6th degree polynomial was used to correlate the values of the cumulative distance from the entry point into the 45-meter buffer until its exit in relation to the measured GPS speed. This model was later broken down to the categorical level, for each intersection selected at random, a polynomial was fitted along with its R^2 value. The highest R^2 was reported for the turning radius category of 7-9 meters with a value of 0.75. These R^2 values, however, are subject to change for an increased data filtering process. The models show that very few vehicles reach full stops in the intersection which brings into light the question of the effectiveness of signalization.

Based on the results, GPS data has been more advantageous in this context compared to video footage because of the ease of processing. The higher coverage allowed for a greater sample to be studied which included a wider variation in signalization as compared to the previous chapters. However, the elimination of the variability of the signalization could aid in isolating the effect of the curb radius. Despite assuming no car following effects, this study established operating speed models which can be used to study intersection design outcomes which has been rarely studied in urban local environments. These proposed polynomial models could be used for modelling turning behavior. Using smartphone GPS data, which is easily attainable, and the automated code used for this study, more accurate microsimulations can be produced as needed. Thus, going forward with this study would include running these microsimulations and comparing them to existing models. Future work would also include more elaborate filtering techniques and relating the effective turning radius of the vehicle to the measured curb radius.

CHAPTER 6 CONCLUSION

6.1 SUMMARY OF RESULTS AND STUDY CONTRIBUTION

This thesis investigates the link between curb radius and speeds using vehicle trajectory data extracted from video cameras and Global Positioning System (GPS) smartphone data. The work provides empirical evidence about the role of the curb radius as a contributing factor in the safety of urban local intersections (with usually radii less than 10 m) within a Canadian urban context. Through the use of the aforementioned automated data collection techniques, this research proposes a methodology to investigate the speed-radius relationship. The data was filtered and SSMs were obtained in three urban settings. These mainly include median, 85^{th} percentile speeds and PET from video trajectories and speeds and deceleration from GPS trajectories. Speed trajectories and profiles were also examined to understand the turning vehicle behavior. To control for observed and unobserved factors, statistical models were calibrated using standard linear and random-effects linear regression modeling techniques. Furthermore, using operating speeds, deceleration, and PET outcomes, statistical models were developed based on the empirical data.

Among the main outcomes of this research, the following points can be highlighted:

- A methodology based on observed vehicle trajectories data was proposed and implemented using video and GPS collected data. Each of these methods carry a handful of advantages and disadvantages which are highlighted in this research. While video data represents an easy mean to set up for obtaining continuous measures, the camera placement is a limiting factor. The view of the camera limits the measurements only to the conflict area of the intersection. Not only this, but it also varies between intersections. Thus, the smartphone

GPS data obtained helped address this problem. The buffers created from the center point of each intersection has aided in maintaining consistency throughout the intersections examined. Also, GPS data covered a larger part of the network; however, a smaller sample of vehicles was studied because it is dependent on the willingness of drivers to share their information. Lastly, the GPS data required less advanced processing techniques, hence, we were able to map the speed profiles.

- This research helped establish a relation between the measured curb radius and surrogate safety measures (speed, deceleration, and PET) for local urban intersections. The case studies in Montreal and Quebec City investigate this relationship using a cross-sectional approach using video and GPS trajectory data, respectively. The case study of the curb radius reduction treatment uses a before-after observational approach.
- Empirical evidence from the three case studies confirm the statistically significant relationship between the curb radius and the corresponding speed outcomes. Based on the AIC values for the models obtained, median speed has shown to be superior to that of 85th percentile speeds. However, 85th percentile speed models have exhibited higher increases from the change in the curb radius. In the first study, an increase of 1-meter of the radius represents an increase of 0.8 kph in the 85th percentile speed. For instance, with respect to GPS data, the radius-speed relationship is also confirmed with a statistically significant impact of 0.4 kph increase in the 85th percentile speed for every 1-meter increase in the radius. In other words, a 5-meter increase in the radius results in a 5.6% increase in the speed observed. A similar pattern was observed for the median speed models.
- The naïve before-after study of the curb radius reduction treatment has resulted in an overall decrease in speed. The results have shown that a more subtle change (10 m decrease

instead of 20 m) in the curb radius have resulted in a greater decrease in the speed. For a 10-meter decrease in the radius, the 85th percentile speed decreased by 3 kph for conflict and non-conflict involved vehicles. While the probability of a conflict increased (presented by PET), the overall risk after treatment decreased showing a negative coefficient, however, not statistically significant. Contrarily, the intersection with 20 m radius reduction showed an increase in the conflict speed by 2.6 kph and an overall increased risk. However, this has been explained by the change of the dynamics of the turn as the camera now captures a longer portion of the through-movement prior to turning. A decrease of 8 kph was expected using the video-based models (chapter 3) or 4 kph based on the GPS models (chapter 5) (as compared to the 3 kph witnessed), hence, the GPS models present more accurate results.

- In addition to the radius, other geometric variables such as the intersection type (3-legged or 4-legged), number of lanes, presence of crosswalk in exit or approach, presence of bike lanes in exit or approach, and presence of road median had impacted the SSMs examined. The road hierarchy (local, national, regional) and level of signalization (non-signalized, stop-controlled, signalized) had the most sizable statistically significant effects (largest coefficients) for all models computed.

6.2 LIMITATIONS AND FUTURE WORK

This thesis presents many opportunities for future work to continue this research to address several limitations faced. The focus on speed profiles instead of point speed measurements from video footage could be an interesting extension of this work in order to look at the variations of the speed with respect to the distance (from the intersection's approach or the midpoint of the curb radius).

These speed profiles and models can be further tested through the use of microsimulations. Moreover, the empirical results obtained for speeds can be used for retrofitting the design of the curb radius with the average speeds found to obtain the percentage of deviation of existing radius to the newly designed ones.

Furthermore, some sources of error related to camera installation and calibration could affect the quality of the data. A validation process could also be stablished to evaluate the data quality and improve it. This can be done through collecting both data tyo for each intersection and cross calibrating the results. For instance, video data collection can be done for the intersections from Quebec City which have been studied using GPS data (chapter 5) or obtaining GPS data for the Montreal intersections (chapter 3). While statistical models provide a powerful tool to assess large datasets, it does not fully isolate the effect of the curb radius. Thus, this opens the door for further studies of intersections which are similar in hierarchy and signalization. Additionally, crash and injury data could be obtained for the studied intersections to further confirm the results.

Moreover, smartphone GPS data accuracy is limited due to the urban canyon effect. In other words, the urban environment contributed to blocked signals therefore affecting the data. While this is usually treated through the use of map matching, it could not be utilized given that the data is transformed into a 2D grid. Such filtering technique would have not made this research possible. Thus, more research can be done to compare the filtering techniques specific to the intersections rather than the rich literature presented for road segments.

REFERENCE

AASHTO, 2011. A Policy on Geometric Design of Highways and Streets, 6th Edition, 2011 - Table of Contents.

Ai, C., Tsai, Y., 2015. Automatic horizontal curve identification and measurement method using GPS data. J. Transp. Eng. 141, 04014078. https://doi.org/10.1061/(ASCE)TE.1943-5436.0000740

Ale, G.B., Varma, A., Gage, B., Gyawali, S., 2014. Erratum for “Safety-Based Volume Warrants for Right-Turn Lanes at Unsignalized Intersections and Driveways on Two-Lane Roadways” by Gom Bahadur Ale, Amiy Varma, Brian Gage, and Sunil Gyawali [J. Transp. Eng. 140, 12, 2014] 10.1061/(ASCE)TE.1943-5436.00007. J. Transp. Eng. 140, 04014064. https://doi.org/10.1061/(ASCE)TE.1943-5436.0000723

Alhajyaseen, W.K.M., Asano, M., Nakamura, H., 2013a. Left-turn gap acceptance models considering pedestrian movement characteristics. Accid. Anal. Prev. 50, 175–185. https://doi.org/10.1016/j.aap.2012.04.006

Alhajyaseen, W.K.M., Asano, M., Nakamura, H., 2012. Estimation of left-turning vehicle maneuvers for the assessment of pedestrian safety at intersections. IATSS Res. 36, 66–74. https://doi.org/10.1016/j.iatssr.2012.03.002

Alhajyaseen, W.K.M., Asano, M., Nakamura, H., Tan, D.M., 2013b. Stochastic approach for modeling the effects of intersection geometry on turning vehicle paths. Transp. Res. Part C Emerg. Technol. 32, 179–192. https://doi.org/10.1016/j.trc.2012.09.006

Archer, J., 2004. Methods for the assessment and prediction of traffic safety at urban intersections and their application in micro-simulation modelling. Acad. thesis, R. Inst. Technol.

Asano, M., Alhajyaseen, W.K.M., Suzuki, K., Nakamura, H., 2010. Modeling the Variation in the Trajectory of Left Turning Vehicles Considering Intersection Geometry. 90th Annu. Meet. Transp. Res. Board.

Autey, J., Sayed, T., Zaki, M.H., 2012. Safety evaluation of right-turn smart channels using automated traffic conflict analysis. Accid. Anal. Prev. 45, 120–130. https://doi.org/10.1016/j.aap.2011.11.015

Bauer, K., Harwood, D., 2000. Statistical models of at-grade intersection accidents. Rep. No. FHWA-RD-99-094, Fed. Highw. Adm. 1996.

Bella, F., Calvi, A., D’Amico, F., 2013. Operating Speed Prediction for Italian Two-Lane Rural Roads Using Speed Profiles from GPS Data. International Conference Road Safety and Simulation RSS2013 23-25 October 2013 Rome, Italy Road Safety and Simulation International Conference RSS2013, Rome, Italy.

Bella, F., Silvestri, M., 2015. Effects of safety measures on driver's speed behavior at pedestrian crossings. Accid. Anal. Prev. 83, 111–124. https://doi.org/10.1016/j.aap.2015.07.016

Boonsiripant, S., 2009. Speed profile variation as a surrogate measure of road safety based on GPS-equipped vehicle data, ProQuest Dissertations and Theses.

Brisk Synergies, 2017. BriskLUMINA - On Demand Safety Analysis [WWW Document]. URL https://brisksynergies.com/brisklumina/ (accessed 7.31.19).

Cafiso, S., Cerni, G., 2012. New approach to defining continuous speed profile models for two-lane rural roads. Transp. Res. Rec. 157–167. https://doi.org/10.3141/2309-16

City of London, 2015. Dictionary of musicians. Notes Queries s1-IV, 444–444. https://doi.org/10.1093/nq/s1-iv.110.444c

City of Montreal, 2019. Vision Zero: Des assises solides pour mieux travailler ensemble 15.

City of Newmarket, 2020. Traffic Mitigation Strategy [WWW Document]. URL https://www.newmarket.ca/LivingHere/Pages/Roads and Traffic/Traffic Management/Speed Management/Traffic-Mitigation-Strategy.aspx (accessed 3.30.20).

City of Toronto, 2018. 2018 City of Toronto Road Classification of Streets List.

City of Toronto, 2017. Road Engineering Design Guidelines 18.

City of Toronto, 2016. Transportation Association of Canada Submission for Road Safety Engineering Award CITY OF TORONTO Curb Radii Design Guidelines.

De Ceunynck, T., 2017. Defining and applying surrogate safety measures and behavioural indicators through site-based observations, Bulletin / Lund University, Lund Institute of Technology. Hasselt University.

Dimensions Guide, 2020. Passenger Turning Path - 90° Dimensions & Drawings | Dimensions.Guide [WWW Document]. URL https://www.dimensions.guide/element/passenger-vehicle-90-degree-turning-path-radius (accessed 5.29.20).

Dinh, D.D., Kubota, H., 2013. Profile-speed data-based models to estimate operating speeds for urban residential streets with a 30km/h speed limit. IATSS Res. 36, 115–122. https://doi.org/10.1016/j.iatssr.2012.06.001

Distefano, N., Leonardi, S., 2019. Evaluation of the benefits of traffic calming on vehicle speed reduction, Civil Engineering and Architecture. https://doi.org/10.13189/cea.2019.070403

Données Québec, 2019a. Adresses Québec [WWW Document]. URL https://www.donneesquebec.ca/recherche/fr/dataset/adresses-quebec (accessed 5.24.20).

Données Québec, 2019b. Intersection de voie publique [WWW Document]. URL https://www.donneesquebec.ca/recherche/fr/dataset/vque_53 (accessed 5.24.20).

Emmerson, J., 1970. A note on speed-road curvature relationships. Traffic Eng. Control.

Esri Inc., 2019. ArcGIS Pro.

Fitzpatrick, K., Schneider H, W., 2005. Turn Speeds and Crashes within Right-Turn Lanes. static.tti.tamu.edu 7, 88p.

Fitzpatrick, K., Schneider IV, W.H., Park, E.S., 2006. Predicting speeds in an urban right-turn lane. J. Transp. Eng. 132, 199–204. https://doi.org/10.1061/(ASCE)0733-947X(2006)132:3(199)

Fitzpatrick, K., Shamburger, C.B., Krammes, R.A., Fambro, D.B., 1997. Operating Speed on Suburban Arterial Curves. Transp. Res. Rec. J. Transp. Res. Board 1579, 89–96. https://doi.org/10.3141/1579-11

Fu, T., Hu, W., Miranda-Moreno, L., Saunier, N., 2019. Investigating secondary pedestrian-vehicle interactions at non-signalized intersections using vision-based trajectory data. Transp. Res. Part C Emerg. Technol. 105, 222–240. https://doi.org/10.1016/j.trc.2019.06.001

Fu, T., Miranda-Moreno, L., Saunier, N., 2016. Pedestrian Crosswalk Safety at Nonsignalized Crossings During Nighttime: Use of Thermal Video Data and Surrogate Safety Measures. Transp. Res. Rec. J. Transp. Res. Board 2586, 90–99. https://doi.org/10.3141/2586-10

Google Inc., 2019. Google Earth Pro. Geospatial Solut.

Haleem, K., Abdel-Aty, M., 2010. Examining traffic crash injury severity at unsignalized intersections. J. Safety Res. 41, 347–357. https://doi.org/10.1016/j.jsr.2010.04.006

Hassan, Y., Sayed, T., Tabernero, V., 2001. Establishing Practical Approach for Design Consistency Evaluation. J. Transp. Eng. 127, 295–302. https://doi.org/10.1061/(ASCE)0733-947X(2001)127:4(295)

Highway Traffic Safety Administration, 2018. Critical Reasons for Crashes Investigated in the National Motor Vehicle Crash Causation Survey.

Highway Traffic Safety Administration, N., 2008. National Motor Vehicle Crash Causation Survey: Report to Congress.

Huang, J., Deng, M., Zhang, Y., Liu, H., 2017. Complex road intersection modelling based on low-frequency GPS track data. Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci. - ISPRS Arch. 42, 23–28. https://doi.org/10.5194/isprs-archives-XLII-2-W7-23-2017

Hydén, C., 1987. The development of a method for traffic safety evaluation: The Swedish Traffic

Conflicts Technique. trid.trb.org.

Hydén, C., 1977. A traffic conflicts technique for examining urban intersection problems, in: First Workshop on Traffic Conflicts. Oslo, Norway.

Jiang, B., 2009. Street hierarchies: A minority of streets account for a majority of traffic flow. Int. J. Geogr. Inf. Sci. 23, 1033–1048. https://doi.org/10.1080/13658810802004648

Johnson, R., 2005. Pedestrian Safety Impacts of Curb Extensions: A Case Study.

Käfer, E., Hermes, C., Wöhler, C., Ritter, H., Kummert, F., 2010a. Recognition of situation classes at road intersections. Proc. - IEEE Int. Conf. Robot. Autom. 3960–3965. https://doi.org/10.1109/ROBOT.2010.5509919

Käfer, E., Hermes, C., Wöhler, C., Ritter, H., Kummert, F., 2010b. Recognition of situation classes at road intersections, in: Proceedings - IEEE International Conference on Robotics and Automation. pp. 3960–3965. https://doi.org/10.1109/ROBOT.2010.5509919

Karlaftis, M.G., Golias, I., 2002. Effects of road geometry and traffic volumes on rural roadway accident rates. Accid. Anal. Prev. 34, 357–365. https://doi.org/10.1016/S0001-4575(01)00033-1

Kawasaki, A., Tasaki, T., 2018. Trajectory Prediction of Turning Vehicles based on Intersection Geometry and Observed Velocities, in: IEEE Intelligent Vehicles Symposium, Proceedings. IEEE, pp. 511–516. https://doi.org/10.1109/IVS.2018.8500472

Kieć, M., Ambros, J., Bąk, R., Gogolín, O., 2019. Evaluation of safety effect of turbo-roundabout lane dividers using floating car data and video observation. Accid. Anal. Prev. 125, 302–310. https://doi.org/10.1016/j.aap.2018.05.009

Korpilo, S., Virtanen, T., Lehvävirta, S., 2017. Smartphone GPS tracking—Inexpensive and efficient data collection on recreational movement. Landsc. Urban Plan. 157, 608–617. https://doi.org/10.1016/j.landurbplan.2016.08.005

Krammes, R.A., Rao, K.S., Oh, H., 1995. Highway geometric design consistency evaluation software. Transp. Res. Rec. 19–24.

Langford, B.C., Chen, J., Cherry, C.R., 2015. Risky riding: Naturalistic methods comparing safety behavior from conventional bicycle riders and electric bike riders. Accid. Anal. Prev. 82, 220–226. https://doi.org/10.1016/j.aap.2015.05.016

Laureshyn, A., 2010. Application of automated video analysis to road user behaviour. Bulletin.

Leisch, J.P., Eng, P., Consultant, T., Carrasco, M., Eng, P., Solutions, T., 2014. Design Vehicles : From Turning Templates to Smart Systems Paper prepared for presentation at the 2014 Transportation Association of Canada Conference Montreal , Quebec Abstract – “ Design

Vehicles : From Turning Templates to Smart Systems ” 1–20.

Levine, K., 2012. Curb Radius and Injury Severity at Intersections.

Maze, T.H., Henderson, J.L., 1994. Impacts on safety of left-turn treatment at high speed signalized intersections.

Morency, P., Archambault, J., Cloutier, M.S., Tremblay, M., Plante, C., 2015. Major urban road characteristics and injured pedestrians: A representative survey of intersections in Montréal, Quebec. Can. J. Public Heal. 106, e388–e394. https://doi.org/10.17269/CJPH.106.4821

Moreno, A.T., García, A., 2013. Use of speed profile as surrogate measure: Effect of traffic calming devices on crosstown road safety performance. Accid. Anal. Prev. 61, 23–32. https://doi.org/10.1016/j.aap.2012.10.013

Mussone, L., Matteucci, M., Bassani, M., Rizzi, D., 2011. Traffic analysis in roundabout intersections by image processing, in: IFAC Proceedings Volumes (IFAC-PapersOnline). IFAC Secretariat, pp. 14922–14927. https://doi.org/10.3182/20110828-6-IT-1002.02626

NACTO, 2012. NACTO Urban street design guide, National Association of City Transportation Officials.

O’cinneide, D., 1998. The relationship between geometric design standards and safety.

Othman, S., Thomson, R., Lannér, G., 2009. Identifying critical road geometry parameters affecting crash rate and crash type. Ann. Adv. Automot. Med. - 53rd Annu. Sci. Conf. 53, 155–165.

Pei, X., Wong, S.C., Sze, N.N., 2012. The roles of exposure and speed in road safety analysis. Accid. Anal. Prev. 48, 464–471. https://doi.org/10.1016/j.aap.2012.03.005

Phondeenana, P., Noomwong, N., Chantranuwathana, S., 2013. Driving Maneuver Detection System based on GPS Data. Int. Symp. Futur. Act. Saf. Technol. Towar. zero-traffic-accident 1–7. https://doi.org/10.13140/2.1.1734.3685

Roefaro, S.A., 2011. Channelized right-turning lanest at signalized intersections: A review of practice and an imperical study. Montana State University - Bozeman, College of Engineering.

Roudsari, B., Kaufman, R., Koepsell, T., 2006. Turning at intersections and pedestrian injuries. Traffic Inj. Prev. 7, 283–289. https://doi.org/10.1080/15389580600660153

Sacchi, E., Sayed, T., Deleur, P., 2013. A comparison of collision-based and conflict-based safety evaluations: The case of right-turn smart channels. Accid. Anal. Prev. 59, 260–266. https://doi.org/10.1016/j.aap.2013.06.002

Shekhar Babu, S., Vedagiri, P., 2018. Proactive safety evaluation of a multilane unsignalized intersection using surrogate measures. Transp. Lett. 10, 104–112. https://doi.org/10.1080/19427867.2016.1230172

Shirazi, M.S., Morris, B.T., 2017. Looking at Intersections: A Survey of Intersection Monitoring, Behavior and Safety Analysis of Recent Studies. IEEE Trans. Intell. Transp. Syst. https://doi.org/10.1109/TITS.2016.2568920

St-Aubin, Paul and Ledezma-Navarro, Bismarck and Labbe, Aurélie and Fu, Ting and Saunier, Nicolas and Miranda-Moreno, L.F., 2018. Speed at partially and fully stop-controlled intersections. Transp. Res. Board 97th Annu. Meet.

St-Aubin, P., Miranda-Moreno, L., Saunier, N., 2013. An automated surrogate safety analysis at protected highway ramps using cross-sectional and before-after video data. Transp. Res. Part C Emerg. Technol. 36, 284–295. https://doi.org/10.1016/j.trc.2013.08.015

St-Aubin, P.G., 2011. Traffic Safety Analysis for Urban Highway Ramps and Lane-Change Bans Using Accident Data and Video-Based Surrogate Safety Measures Prepared by.

StataCorp, 2013. Stata Statistical Software: Release 13. College Station, TX, USA.

Stipancic, J., Miranda-Moreno, L., Saunier, N., 2018. Vehicle manoeuvers as surrogate safety measures: Extracting data from the gps-enabled smartphones of regular drivers. Accid. Anal. Prev. 115, 160–169. https://doi.org/10.1016/j.aap.2018.03.005

Stipancic, J., Miranda-Moreno, L., Saunier, N., 2016. The Who and Where of Road Safety: Extracting Surrogate Indicators from Smartphone-Collected GPS Data in Urban Environments, TRB 2016 Annual Meeting.

Stipancic, J., Miranda-Moreno, L., Strauss, J., Labbe, A., 2020. Pedestrian safety at signalized intersections: Modelling spatial effects of exposure, geometry and signalization on a large urban network. Accid. Anal. Prev. 134, 105265. https://doi.org/10.1016/j.aap.2019.105265

Stover, V.G., 2008. Issues Relating to the Geometric Design of Intersections. Proc. 8th Int. Conf. ACCESS Manag.

Strauss, J., Miranda-Moreno, L.F., 2017. Speed, travel time and delay for intersections and road segments in the Montreal network using cyclist Smartphone GPS data. Transp. Res. Part D Transp. Environ. 57, 155–171. https://doi.org/10.1016/j.trd.2017.09.001

TAC, 1999. Geometric Design Guide for Canadian Roads.

Transoft Solutions Inc., 2019. Swept Path [WWW Document].

Transport Canada, 2018. Canadian motor vehicle traffic collision statistics. Transport Canada.

Transport Canada, 2011. Road safety in Canada.

Troutbeck, R.J., Brilon, W., 2001. Unsignalized Intersection Theory, in: Gartner, N.H., Messer, C.J., Rathi, A. (Ed.), Traffic-Flow Theory. Transportation Research Board Special Report., pp. 8-1-8–47.

Turner, S., Fitzpatrick, K., Brewer, M., Park, E.S., 2006. Motorist Yielding to Pedestrians at Unsignalized Intersections. Transp. Res. Rec. J. Transp. Res. Board 1982, 1–12. https://doi.org/10.1177/0361198106198200102

Ville de Montreal, 2018. Geobase - road network - Datasets - Open data portal [WWW Document]. URL http://donnees.ville.montreal.qc.ca/dataset/geobase (accessed 6.7.20).

Ville de Quebec, 2015. Mon Trajet [WWW Document]. 2015.

Wang, J., Dixon, K.K., Li, H., Hunter, M., 2006. Operating-Speed Model for Low-Speed Urban Tangent Streets Based on In-Vehicle Global Positioning System Data. Transp. Res. Rec. J. Transp. Res. Board 1961, 24–33. https://doi.org/10.1177/0361198106196100104

Wang, J., Dixon, K.K., Li, H., Ogle, J., 2004. Normal Acceleration Behavior of Passenger Vehicles Starting from Rest at All-Way Stop-Controlled Intersections. Transp. Res. Rec. J. Transp. Res. Board 1883, 158–166. https://doi.org/10.3141/1883-18

Wang, Jun, Dixon, K.K., Li, H., Ogle, J., Wang, J, 2005. Normal Deceleration Behavior of Passenger Vehicles at Stop Sign-Controlled Intersections Evaluated with In-Vehicle Global Positioning System Data, Transportation Research Record: Journal of the Transportation Research Board.

Wang, T., Gan, A., Alluri, P., 2013. Estimating Annual Average Daily Traffic for Local Roads for Highway Safety Analysis. Transp. Res. Rec. J. Transp. Res. Board 2398, 60–66. https://doi.org/10.3141/2398-07

Xie, K., Wang, X., Huang, H., Chen, X., 2013. Corridor-level signalized intersection safety analysis in Shanghai, China using Bayesian hierarchical models. Accid. Anal. Prev. 50, 25–33. https://doi.org/10.1016/j.aap.2012.10.003

Xu, C., Wang, X., Yang, H., Xie, K., Chen, X., 2019. Exploring the impacts of speed variances on safety performance of urban elevated expressways using GPS data. Accid. Anal. Prev. 123, 29–38. https://doi.org/10.1016/j.aap.2018.11.012

Yan, X.;, Radwan, E.;, Guo, Dahai, 2007. Effect of a Pavement Marking Countermeasure on Improving Signalized Intersection Safety, Institute of Transportation Engineers. ITE Journal.

Yu, B., Chen, Y., Wang, R., Dong, Y., 2016. Safety reliability evaluation when vehicles turn right from urban major roads onto minor ones based on driver's visual perception. Accid. Anal. Prev. 95, 487–494. https://doi.org/10.1016/j.aap.2015.08.014

Zageer, C.V., Seiderman, C., Lagerwey, P., Cynecki, M., Ronkin, M., Schneider, R., 2002. Pedestrian facilities users guide – providing safety and mobility. Fed. Highw. Adm. Rep. No. FHWA- RD-01-102.

Zahabi, S.A.H., Chang, A., Miranda-Moreno, L.F., Patterson, Z., 2016. Exploring the link between the neighborhood typologies, bicycle infrastructure and commuting cycling over time and the potential impact on commuter GHG emissions. Transp. Res. Part D Transp. Environ. 47, 89–103. https://doi.org/10.1016/j.trd.2016.05.008

Zangenehpour, S., 2017. Impact of Curb Radius Reduction on Pedestrian Safety : A Before-After Surrogate Safety Study in Toronto 18–21.

Zangenehpour, S., Miranda-Moreno, L.F., Saunier, N., 2015. Automated classification based on video data at intersections with heavy pedestrian and bicycle traffic: Methodology and application. Transp. Res. Part C Emerg. Technol. 56, 161–176. https://doi.org/10.1016/j.trc.2015.04.003

Zangenehpour, S., Miranda-Moreno, L.F., Saunier, N., 2013. Impact of Bicycle Boxes on Safety of Cyclists:A Case Study in Montreal.

Zheng, L., Sayed, T., Tageldin, A., 2018. Before-after safety analysis using extreme value theory: A case of left-turn bay extension. Accid. Anal. Prev. 121, 258–267. https://doi.org/10.1016/j.aap.2018.09.023

APPENDIX

This appendix is a supplement to the study presented in **chapter 5**. **Table 0-1** presents the angles measured and used for a sample data set and highlighted in yellow are the used selection boundaries.

Table 0-1 Sensitivity analysis for angle selected

	Low limit	High limit	tolerance	# of turns
<180	65	145	80	
>180	215	295	80	14
<180	60	150	90	
>180	210	300	90	16
<180	55	155	100	
>180	205	305	100	17
<180	50	160	110	
>180	200	310	110	19
<180	45	165	120	
>180	195	315	120	19
<180	70	140	70	
>180	220	290	70	14
<180	75	135	60	
>180	225	285	60	14
<180	80	130	50	
>180	230	280	50	12
<180	85	125	40	
>180	235	275	40	5
<180	65	150	85	
>180	210	295	85	16

Using ArcTan2 discussed in the chapter, the results are from |0-180| measures anticlockwise for each vector. Thus, the results are positive for I and II, and negative for III and IV. Using that information, the algorithm used added 360 for negative angles to have two positive angels when measure the angle of turn of the vehicle (see below).

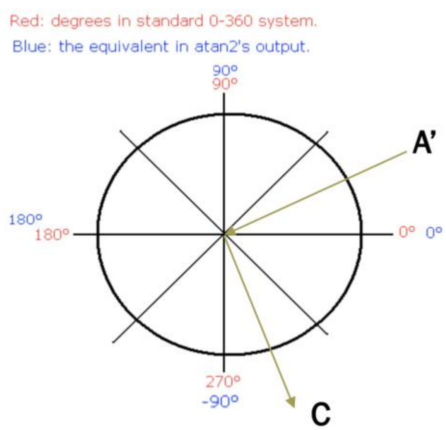

Figure 0-1 Atan2 vs standard angle system

“

```
Atan2C= math.degrees(math.atan2(c[1]-b[1], c[0]-b[0]))
    if Atan2C<0:
            Atan2C=360+Atan2C
    else:
            continue

Atan2A=math.degrees(math.atan2(a[1]-b[1], a[0]-b[0]))
    if Atan2A<0:
            Atan2A=360+Atan2A
    else:
            continue
ang = Atan2C - Atan2A
```

”

Based on the angles and the vectors which the angles are based on, the bounds and the angles were decided. Angles of right turns were less than 180º if positive and greater than 180º if negative. The opposite was true for the left turns. Table 0-2 shows the sign assessment of vectors for the bounds of the movements in Quebec City intersections. Note that this isn't the case in all cities where the north of the streets is aligned with the true north.

*Table 0-2 Using vectors to assess the bounds of the movement according the north of Quebec (true northwest)**

Left Turn							
	A'			**C**			
	x	**y**		**x**	**y**		
1	+	+	E	-	+	N	EN
2	+	-	S	+	+	E	SE
3	-	+	N	-	-	W	NW
4	-	-	W	+	-	S	WS

Right Turn							
	A'			**C**			
	x	**y**		**x**	**y**		
4	+	-	S	-	-	W	SW
3	-	-	W	-	+	N	WN
2	+	+	E	+	-	S	ES
1	-	+	N	+	+	E	NE

** where **A'** is b-a instead of a-b*

Table 0-3 presents the turn specific models for the GPS data discussed in chapter 5.

Table 0-3 Turn specific models

	Right Turn Models			**Left Turn Models**		
	X85th	**Median**	**Decel**	**X85th**	**Median**	**Decel**
Curb Radius	0.060***	0.066***	-0.004	0.068***	0.076***	-0.009
	(0.013)	(0.013)	(0.005)	(0.017)	(0.017)	(0.007)
Lanes_Approach	-0.561**	-0.069	0.141*	-0.348	0.044	0.175**
	(0.266)	(0.247)	(0.082)	(0.264)	(0.264)	(0.089)
Lanes_Exit	-1.259***	-0.826***	0.167**	-0.989***	-0.734***	0.267***
	(0.281)	(0.261)	(0.085)	(0.256)	(0.254)	(0.090)
Crosswalk_Approach	0.274	-0.037	-0.032	0.005	0.161	-0.093
	(0.215)	(0.200)	(0.072)	(0.243)	(0.239)	(0.085)
Crosswalk_Exit	0.577***	0.193	-0.206***	0.157	0.181	0.035
	(0.211)	(0.197)	(0.070)	(0.265)	(0.260)	(0.091)
Peak Hour	-0.498***	-0.491***	0.148***	-0.751***	-0.591***	0.198***
	(0.105)	(0.098)	(0.041)	(0.104)	(0.105)	(0.046)
Night Time	0.705***	0.638***	-0.148**	0.181	0.316*	0.008
	(0.195)	(0.182)	(0.075)	(0.166)	(0.167)	(0.073)
Constant	8.871***	6.469***	-1.652***	9.457***	6.420***	-1.861***
	(0.302)	(0.283)	(0.080)	(0.298)	(0.286)	(0.086)
u_i	2.019***	1.889***	0.435***	1.768***	1.653***	0.381***
Constant	(0.179)	(0.167)	(0.042)	(0.171)	(0.160)	(0.044)
ϵ_{ij}	2.495***	2.333***	0.967***	2.118***	2.131***	0.943***
Constant	(0.029)	(0.027)	(0.011)	(0.030)	(0.030)	(0.013)
Observations	3753	3753	3753	2657	2657	2657

Note: The table presents the coefficients of the mixed-effect linear regression models, using trip (road user) level random effect and an independent covariant structure and linear regression models. Statistical significance is indicated as follows * p<0.10 ** p<0.05 *** p<0.01. Standard errors of regression coefficients are reported in parentheses.