A SWEPT PATH ANALYSIS OF INTERSECTION DESIGNS FOR LONG COMBINATION VEHICLES

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Abstract

The efficiency of a supply chain depends heavily on a region's ability to accommodate trucks of varying sizes. Intersections are potential bottleneck locations for first- and last-mile logistics, where complexities arise due to inadequate geometric properties. The superior productivity of Long Combination Vehicles (LCVs) has led to increasing adoption by large establishments. However, LCVs face significant impediments due to their extra lengths and subsequent impacts on turning envelopes.

This thesis focuses on the range and combination of geometric factors leading to successful LCV right-turn movements, such as curb radii and lane widths. Swept-path simulations are conducted for seven intersections in the Region of Peel using AutoTURN software to classify scenarios as pass or fail. Binomial logit models are estimated from these results. The correct prediction rates of the models range from 74% to 97%. A quick-response toolkit is developed to assist roadway authorities in the LCV route acceptance process.

Dedication

To my parents, for their unending support and love

Acknowledgments

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List of Acronyms and Abbreviations

AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
ArcGIS	Software used for geospatial analysis
AutoCAD	Software used for intersection layouts
AutoTURN	Software used for vehicle swept path analysis
CAD	Computer-aided design
CADD	Computer-aided design and drafting
CMA	Census Metropolitan Area
CT	Census Tract
ESAL	Equivalent single axle load
FHWA	Federal Highway Administration
GHG	Greenhouse gas emissions
GNSS	Global Navigation Satellite System
Google Earth Pro	Software used for visualizing geospatial data
Green Book	Policy on Geometric Design of Highways and Streets
GTHA	Greater Toronto and Hamilton Area
GVW	Gross vehicle weight
HSSO	High-speed steady-state off-tracking
IntelliPath	A tool in AutoTURN used to run the simulation
LCV	Long combination vehicle
LIMDEP	LIMited DEPendent variable models
LSSP	Low speed swept path
LTM	Left turn movement
MOU	Memorandum of Understanding
MS Excel	Software used for developing toolkit, running macro, and storing simulation results
MTO	Ministry of Transportation Ontario
NLOGIT	Software used for econometric and statistical analysis

OBF	Ontario Bridge Formula
PBS	Performance-based standards
PDO	Property damage only
Protractor	An extension of the Google Chrome browser
RMD	Rocky Mountain double, WB-92D (AASHTO, 2018)
RTM	Right-turn movement
RWA	Rearward amplification
SAS	Statistical software suite developed by SAS Institute
SRT	Steady-state rollover threshold
Stata	Statistical software package developed by StataCorp
TAC	Transportation Association of Canada
TASP	Tracking ability on the straight path
TM	Through movement
TPD	Turnpike double, WB-109D (AASHTO, 2018)
Triple	Triple trailer combination, WB-100T (AASHTO, 2018)

Chapter 1. Introduction

Modern society relies on an efficient freight transport sector for successful economic growth (Nilsson, 2017). For a sizeable geographic country like Canada, industries and consumers rely on truck and rail carriers to provide efficient service. Without this access, markets will shrink and result in job losses and rising costs for consumer goods (Woodrooffe & Ash, 2001). Larger trucks, known as long combination vehicles, allow for more goods to be shipped at one time and therefore improve overall economic benefits.

1.1. Long Combination Vehicles

The Canadian definition of long combination vehicles (LCVs) is tractor-trailer combinations consisting of a tractor with two or three trailers and a total length exceeding 25 meters (Woodrooffe et al., 2004). LCVs are prohibited in several jurisdictions in North America due to policy and infrastructure-related issues. However, some states and provinces have allowed their operation in restricted geographic areas and roadways (Grislis, 2010). There is some public concern with these vehicles due to their large size. Yet, LCVs have gained increased acceptance due to careful implementation of the programs by different road authorities and better safety performance from a collision rate perspective than other articulated trucks (Regehr et al., 2009). Examples of this cautious approach are seen in the permit requirements when road authorities like the Ministry of Transportation Ontario (MTO) limit the number of permits for a carrier during their first year of LCV operation but offer additional licenses after a certain period. Also, the Ministry of Transportation Ontario (MTO) has established some rules for Long Combination Vehicle (LCV) carriers. For example, LCVs cannot have a GVW exceeding a traditional tractor-trailer (MTO, 2021).

Excellent safety records are seen for LCVs in numerous jurisdictions. A study conducted in Alberta during a six-year analysis period showed that severe collision (fatal, injury) for LCVs (Rocky Mountain double, Turnpike double, Triple trailer) was lower than any other vehicle type (Montufar et al., 2007). Figure 1 shows the allowed LCV types in the Canadian Prairie region.

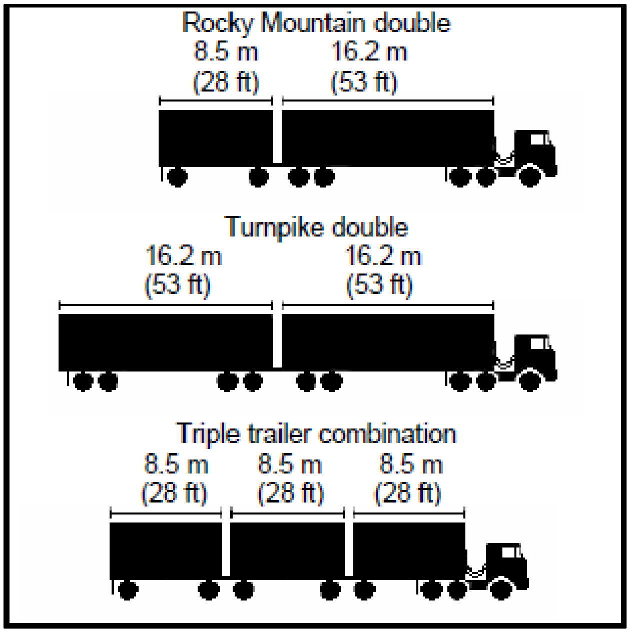


Figure 1 Permitted LCVs in the Canadian Prairie region
(Montufar et al., 2007)

LCVs provide environmental benefits when compared to the similar volume of two tractor-trailers. Greenhouse gas emissions (GHGs) caused by the freight transport sector could be lowered by one-third if a carrier decides to switch to LCVs from conventional tractor-trailers (MTO, 2013). Also, as LCVs operation requires cleaner fuels like methanol and liquid petroleum gas, this dramatically helps lower environmental pollution (Geuy, 1989). Also, LCVs can haul a larger amount of cargo with much better fuel efficiency than a single trailer truck, which helps reduce environmental pollution (RIG Logistics, 2017).

Economic benefits provided by LCVs have made them popular among various industries, especially retailers and manufacturers, as LCVs offer them a lower cost for transporting goods to market (MTO, 2013). Also, as LCVs use less fuel than normal tractor-trailers due to relying only upon the lead truck to carry the rest of the connected trailers, using them commercially is much more economical (Region of Peel, 2021).

Due to the economic, environmental, and road safety benefits provided by LCVs, MTO has been taking the initiative to increase their numbers on Ontario roads and build infrastructure that can adequately support them on major roadways. According to the MTO statute for the LCV program, each carrier is eligible for two (2) permits for their first-year operational period, subject to additional permits depending on successful freight operations (MTO, 2021). Recent changes to the LCV program have also eliminated the maximum capacity of permit numbers accessible to each carrier (Ontario Trucking Association, 2017).

This issuance can face some backlash from the public as a small pool of data was available to analyze the safety records used to showcase LCV's exceptional road safety performance. Others even have labeled LCVs as legalized weapons on the highways, and according to them, LCVs pose serious safety concerns when they share the roadway with other modes (Macmillan, 2019). However, the Canada Safety Council data shows that LCVs cause 40% fewer collisions than regular tractor-trailers (MTO, 2013). This issue further proves that carefully implementing policies and retaining adequate geometric designs of the roadways infrastructures can help maintain LCVs' excellent safety record.

Intersections are potential bottleneck locations where LCVs face issues while maneuvering because of their large turning envelope requirements. This is exacerbated for right-turn movements due to the risk of collision with vehicles in other lanes or the edge of the pavement. This issue can be identified by conducting a swept path analysis to track the trajectory of LCVs and their turning requirements in road design before construction. For example, the curb radii of an intersection may need adjustment due to the additional length of the vehicle creating a wider path as the vehicle makes a turn. Specialized software such as AutoTURN can be used to carry out this analysis. Figure 2 shows the swept path of an LCV while making a right-turn at the intersection.

Many jurisdictions within Ontario are now using LCVs to carry products. As noted by Torbic & Harwood (2006), it is logical to use LCVs such as turnpike doubles as the design vehicle for roadways if they are the largest and least maneuverable vehicle on the road. The Region of Peel, a regional municipality in Southern Ontario, has published an LCV usage study in 2019. Several action items have been prioritized in that report, including infrastructural improvements needed for LCVs to access major transportation centers (Parsons, 2019).

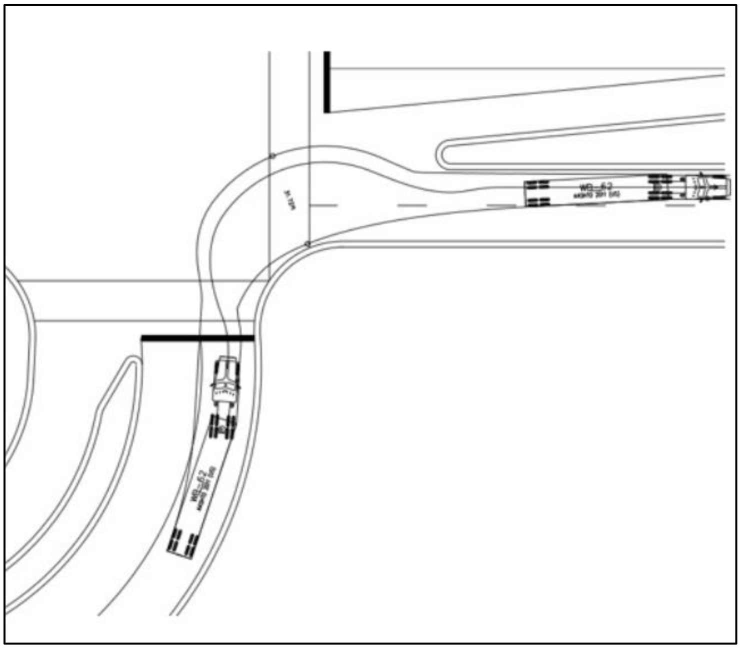


Figure 2 Truck swept path for a right-turn movement (Spack, 2017)

Depending upon the need for infrastructural improvements, different roadway authorities at both provincial and municipal levels will need to reassess their LCV route approval process. Identifying geometric attributes of the roadway intersections that require modifications or improvements can pave the way for making LCVs more mainstream modes for goods movement initiatives.

1.2. Research Goal

The number of LCV trips will likely increase in the future as more carriers are interested in adding LCVs to their fleets (Parsons, 2019). This also suggests that different roadway authorities will use LCVs as the design vehicles on roadways near the commercial and industrial areas where the LCVs network can be extended. Currently, MTO allows LCVs to maneuver only in the access-controlled and divided roads (primarily 400-series) (MTO, 2021). A study conducted for the Region of Peel (Parsons, 2019) suggests expanding approved LCV networks on more arterial roads for last-mile deliveries.

The primary goal of this thesis is to examine the right-turn movement of LCVs at seven major intersections in the Region of Peel and aid roadway authorities with the LCV route approval process. Six different types of at grade intersections have been selected, including 4-legged right-angled, 4-legged oblique, 4-legged offset, roundabout, 3-legged T, and 3-legged Y. Swept path simulations are conducted on these intersections by adjusting a range of values for geometric attributes collected from a sample of 93 intersections in Ontario. This approach ensures the appropriate transferability of several binomial logit models to a wide range of intersection design layouts. This research is made accessible by packaging results in a toolkit that packages the results in a user-friendly software application.

1.3. Research Objectives and Scope

The purpose of this thesis is to assess the conditions that impede the safe maneuvering of LCVs on roadways. The following objectives guide the research:

Objective 1. Perform data collection to identify a range of values for geometric attributes of different roadway intersection types in Ontario.

Objective 2. Use swept path analysis to determine the feasibility of intersections for safe LCV maneuvering using the range of values from Objective 1 and selected locations in the Region of Peel.

Objective 3. Estimate a set of binomial logit models to predict the likelihood of successful LCV maneuvering for different intersection layouts.

Objective 4. Create an LCV right-turn toolkit based on the results of the binomial logit models.

A literature review was conducted as part of the first objective to identify the different intersection categories in Ontario and the existing LCV categories. Later the range of values for the geometric attributes was collected from a sample of intersections in Ontario using software packages including ArcGIS Pro and Google Earth Pro.

The second objective is achieved using swept path simulations in AutoTURN software. The simulations are conducted on selected intersections in the case study area of the

Region of Peel. This region is known as a hub of freight activity in Canada.

The third objective is accomplished using NLOGIT to estimate a set of Binomial logit models where the two alternatives are pass or fail as assessed in the second objective. The results include sensitivity analysis of the variables used to analyze the geometric attributes based upon their effects on the safe turning movement.

For the fourth objective, a toolkit has been developed in MS Excel based on the results of the third objective to package the information in a user-friendly application.

Although the study depends heavily on the range of geometric attributes of the sampled intersections, the categorization scheme developed to take a sample of intersections from different parts of Ontario using dwelling types and population density to define development types (urban, suburban, and rural).

Based on the literature review, the geometric attributes prioritized in this study are curb radii and lane widths. This study also focuses mainly on the right-turn movements of LCVs. The rationale for analyzing right-turn movements instead of left-turn movements is due to the additional limitation of space available when LCVs make a right-turn. These vehicles face additional complexity when restricted to the right-most lane while conducting a turn. However, swept path simulations are run for some left-turn movements (roundabout) and through movements (roundabout and offset intersections) to see how LCVs behave while they perform these maneuvers.

1.4. Thesis Outline

Figure 3 shows the major methodological approach to this thesis. Color codes have been applied to differentiate among different framework components, including literature review, software works, and analysis.

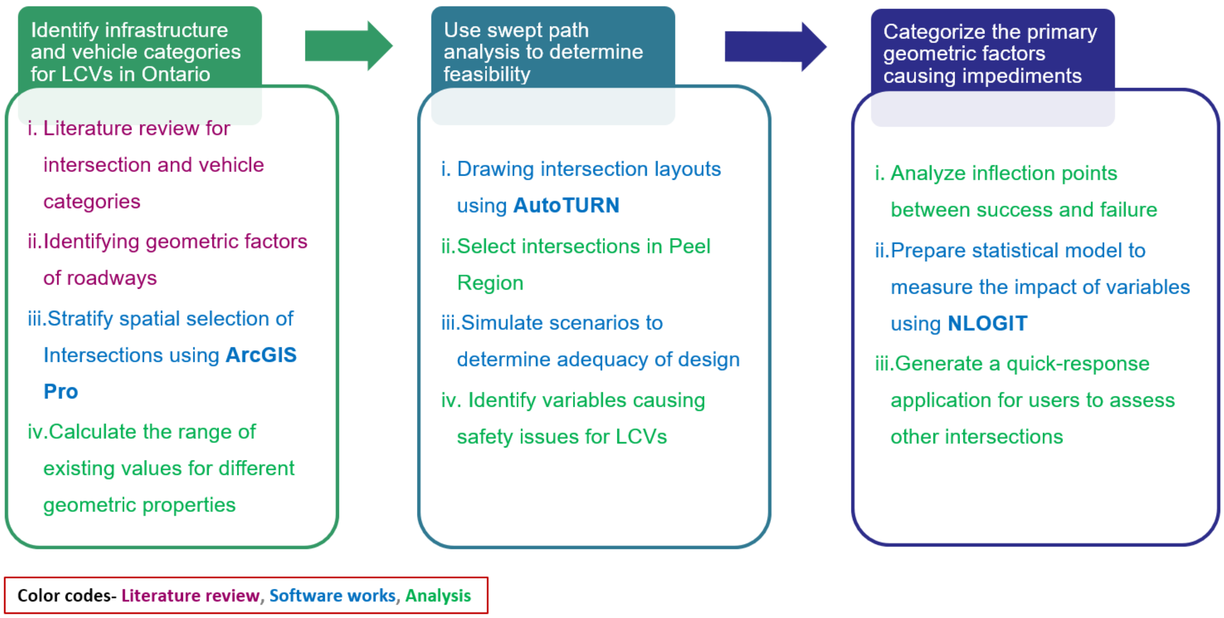


Figure 3 Methodological framework

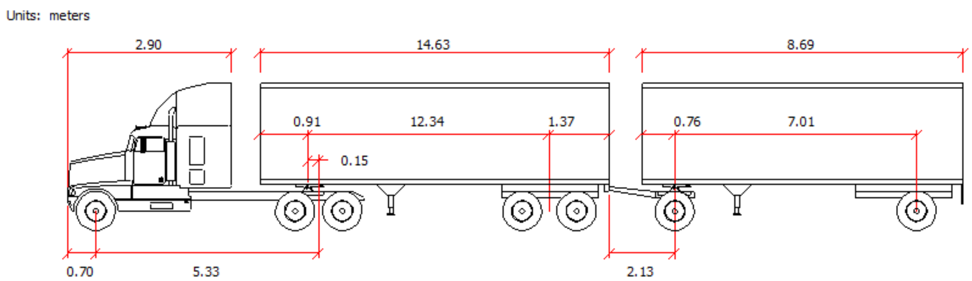
The remaining chapters of the thesis are as follows:

- Chapter 2 contains a literature review about LCV classification, its history, and road safety performance record in North America and Europe. Also, this chapter explores the impacts of geometric attributes on LCVs movement.
- Chapter 3 focuses on the data collection process from different intersections in Ontario. The details of the case study area and the selected intersections are discussed in this chapter.
- Chapter 4 outlines the analysis methods for the swept path simulations in AutoTURN. Developing the binomial logit model in NLOGIT is discussed later in this chapter.
- Chapter 5 provides the results of the swept path simulations in both tabular and graphical formats, followed by brief discussions. The results of the binomial logit model and its transferability have also been discussed in this chapter. Lastly, a brief description has been provided of the toolkit developed using MS Excel based on the results of this study.
- Chapter 6 summarizes the thesis along with its limitations and recommendations to overcome them. This chapter also lists the future scope of this study to pave the way for relevant works.

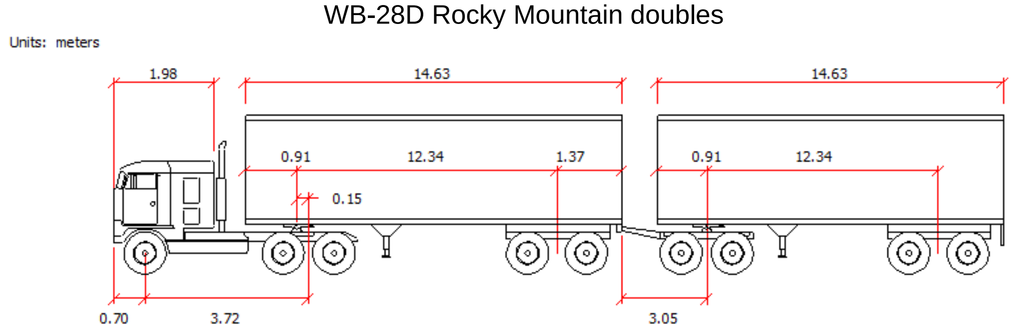
Chapter 2. Literature Review

2.1. LCV Classification

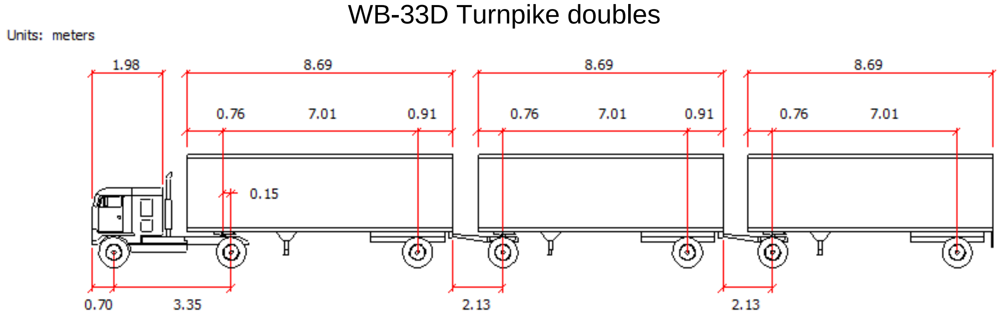
The longest LCVs exceed 30 meters in length, and road authorities generally restrict their movements depending on the roadway types and time of the day (Grislis, 2010). The Canadian standard defines LCVs as a combination of vehicles greater than 25 meters in length. There are three main types of LCVs: (1) Rocky Mountain doubles (RMDs); (2) Turnpike doubles (TPDs); and (3) triples or triple trailer combinations (Montufar et al., 2007). AASHTO (2018) standards represent these vehicle types as WB-92D, WB-33D, and WB-30T, respectively. These three categories in AutoTURN (2021) software are shown in Figure 4, with lengths of 29.66 m, 34.75 m, and 31.94 m.



WB-28D Rocky Mountain doubles



WB-33D Turnpike doubles



WB-30T Triple trailers

Figure 4 LCV types
(Adapted from Transoft, 2021)

Several other unique vehicles may fall into the definition of an LCV. One example in Figure 5 represents twin-stinger-steer auto carrier vehicles (MTO, 2021), which are used to transport multiple passenger vehicles and are essential for the automotive manufacturing industry.

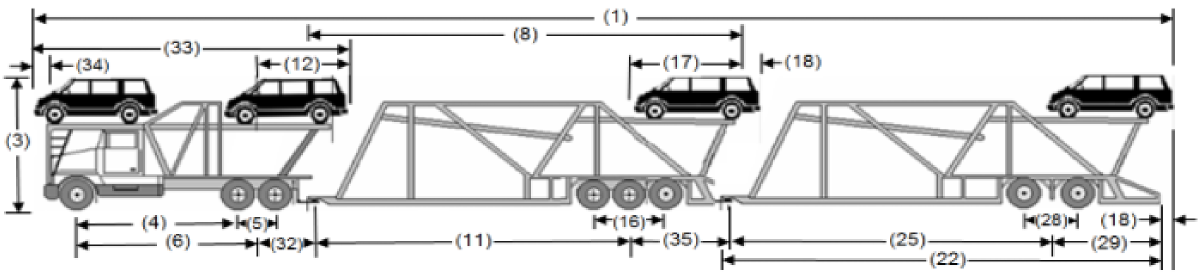


Figure 5 LCV Twin Stinger-Steer Auto Carrier
(MTO, 2021)

Figure 6 represents another distinct vehicle category known as the B-train Tanker. The general purpose of this truck is to haul flatbed, bulk, and liquid goods such as petroleum. In Canada, a tanker combination vehicle can have a length of a maximum of 26 meters for the linked trailers (Transcourt, 2017).

Figure 6 Crude Oil Tanker or B-train Tanker combination
(Transcourt, 2021)

For Ontario, MTO authorizes permits to qualified carriers to operate LCVs on permitted corridors and pre-approved off-network locations to connect to their origin and destination. Carriers interested in using LCVs must enter into a Memorandum of Understanding (MOU) with the MTO. They must also accept full responsibility outlined in the Ontario LCV Program Conditions (MTO, 2021).

Table 1 shows the permit requirements for LCV carriers in different provinces in Canada. The TPDs are the most commonly approved LCVs, while western provinces also allow RMD and triple trailer LCVs. The LCV permit duration for an approved carrier varies from province to province, with most of them requiring annual renewal. In addition, many jurisdictions require carriers and drivers to maintain a minimum safety rating.

Table 1 Permit requirements for LCV carriers in Canada (Adapted from Wood & Regehr, 2017)

Province or Territory	Permit Required	Permitted LCVs	Permit Duration	Safety Rating Maintenance
British Columbia	Yes	RMD, TPD	N/A	Yes
Alberta	Yes	RMD, TPD, Triple	12 months	No
Saskatchewan	Yes	RMD, TPD, Triple	12 months	No
Manitoba	Yes	RMD, TPD, Triple	12 months	No
Ontario	Yes	TPD	12 months	Yes
Québec	Yes	TPD	3 to 9 months	No
New Brunswick	Yes	TPD	12 months	Yes
Nova Scotia	Yes	TPD	12 months	Yes
Northwest Territories	Yes	RMD	12 months	Yes

Table 2 shows the dimensional limit for various features of different LCV types according to the MTO guidelines for the LCV program. This information reveals that LCVs can have a maximum length of 40 meters in Ontario. Also, depending on the connection types (A/B), the lead and second trailer's maximum lengths can vary slightly.

Table 2 Dimensional limit for LCV types in Ontario (Adapted from MTO, 2021)

Type	Feature	Dimensional Limit
LCV A-Train Double	Length of Combination and Load	Max. 40m
	Width of Vehicle and Load	Max. 2.6m
	Height of Vehicle and Load	Max. 4.15m
	Interaxle Spacing of Tractor	Min. 3.5m
	Semi-Trailer length (Lead and second)	12.2 to 16.2m
	Tandem Spread of Converter Dolly	1.2 to 1.85m
LCV B-Train Double	Length of Combination and Load	Max. 40m
	Width of Vehicle and Load	Max. 2.6m
	Height of Vehicle and Load	Max. 4.15m
	Interaxle Spacing of Tractor	Min. 3.5m
	Semi-Trailer length (Lead and second)	11.5 to 14.65m (lead),11.5 to 16.2m (second)
	Tandem Spread of Converter Dolly	1.2 to 1.85m
	Tridem Spread of Converter Dolly	2.4 to 3.7m
LCV Twin Stinger-Steer Auto Carrier	Length of Combination and Load	Max. 40m
	Width of Vehicle and Load	Max. 2.6m
	Height of Vehicle and Load	Max. 4.3m
	Interaxle Spacing of Tractor	Min. 3.5m
	Semi-Trailer length (Lead and second)	Max. 14.65m
	Tandem Spread of Converter Dolly	1.2 to 3.7m

Gross vehicle weight (GVW) limits are one of the most crucial variables that firms consider before adding a specific vehicle type to their freight fleets (Middendorf et al., 1994). This is because heavy vehicles can substantially impact highways and bridges by doing structural damage (Geuy, 1989). The concept of equivalent single axle load (ESAL), developed from the data collected by the American Association of State Highway and Transportation Officials (AASHTO), plays an essential role in designing roadway infrastructure. ESAL provides a standardized statistic of cumulative traffic load on pavements and establishes a damage relationship for axles bearing different loads (TxDOT, 2005). In the late 1960s, Ontario introduced weight regulations using the Ontario Bridge Formula (OBF) to control axle weights. The allowable single axle load was derived from different pavement considerations, and as a result, this formula provided a safe cumulative load threshold for bridges (Woodrooffe et al., 2010).

While larger vehicles increase transport efficiency, excessive weight can produce stress on both roads and bridges. A Memorandum of Understanding (MOU) was signed back in 1988 at the council of ministers' meeting, where weight limits and configurations for tractor-semitrailers were specified for each province within Canada. According to the MOU, the allowable axle load for the steer axle of a tractor is 5,500 kg (12,125 lb). Also, the MOU included the permissible load for different combinations of axles, including tandem and tridem. Quebec started a permit program in the mid-1980s to monitor the weights by allowing multi-axle semi tractor-trailers from Ontario to operate inside Quebec.

On the other hand, Ontario followed strict regulations in conformation to national standards and, in some cases, banned the use of specific axle types. Most of the highway systems of Alberta, Saskatchewan, and Manitoba did not have the pavement strength (due to thin and flexible pavement) mentioned in the MOU. As a result, they had to exclude those portions from the highway systems where MOU-defined configurations could operate (Woodrooffe et al., 2010).

2.2. Trucking History in Canada

The Ontario trucking industry in the 1950s pushed for increasing maximum vehicle weights to improve freight efficiency. While there was some initial hesitation from the public sector, the Ontario Department of Transport (currently the MTO) conducted a survey in 1967 that found short trucks with closely spaced axles did not cause distress to roads or bridges. The Ontario Department of Transport followed up with a series of studies on the load-carrying capacity of existing bridges. The Ontario Bridge Formula (OBF) was the outcome of these studies, which defined the safe operational load limit for bridges and became a guideline by which the axle weights are controlled in Ontario. This formula permitted a 10% increase in axle loads compared to previous regulations (Woodrooffe et al., 2010).

Based on the information provided by Woodrooffe et al. (2010), a timeline is shown in Figure 7 to represent the historical progression of long combination vehicles in Canada. The figure depicts the Ontario Bridge Formula's rolling effect back in 1970. After its introduction, the Canadian provinces developed a national standard for uniformity. In the

1980s, Québec and Ontario changed the size and weight limits for combination vehicles, which allowed some manufacturers to benefit from more permissible weights. Since the late 1990s, all provinces have agreed upon using common configurations, beneficial for inter-provincial goods movement and infrastructural solidity of roads and bridges regulations.

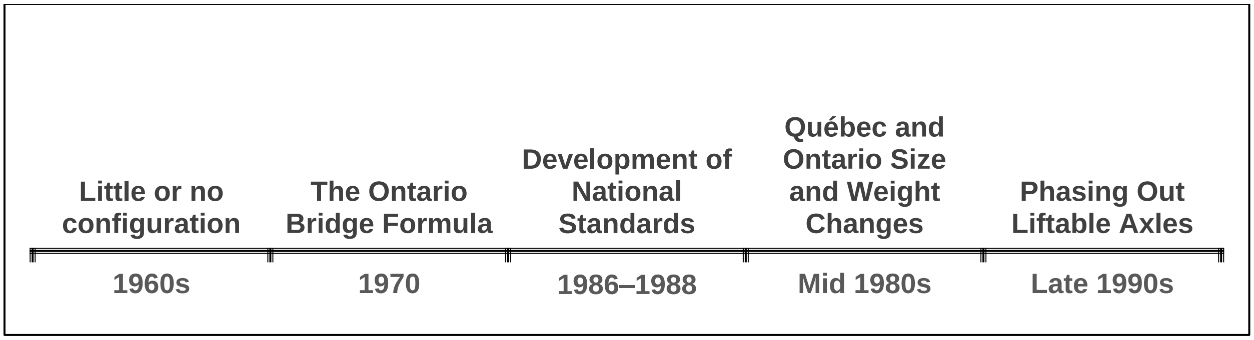


Figure 7 History of LCVs in Canada

In Ontario, a 2009 declaration from the province's Premier initiated a pilot program for LCVs. The intention of this program was primarily to improve inter-provincial trade with Québec. Ontario's LCV program requires minimum standards regarding carrier qualification and driver eligibility to maintain road safety (Billing & Madill, 2010). Moreover, LCVs in Ontario cause minor damage to bridge and road infrastructure relative to a standard truck since regulations do not permit increased maximum weights. These guidelines subsequently result in less weight per axle (MTO, 2021).

Canada's current bridge live load models may need modifications in the future as LCV's extra configuration length can challenge the different limit states of the bridges they maneuver through (Pushka, 2021). However, governmental entities are generally conservative with LCV policies due to the public's negative perception of LCVs.

LCVs have several possible linkages that connect each container, labeled as A-Train, B-Train, and C-Train, as shown in Figure 8. MTO initially planned to allow only A-train TPDs in the LCV pilot program but later included the B-train configuration. It offers more significant benefits such as better load transfer ratio, payload weights, and heights for all vehicle configurations (Billing & Madill, 2010).

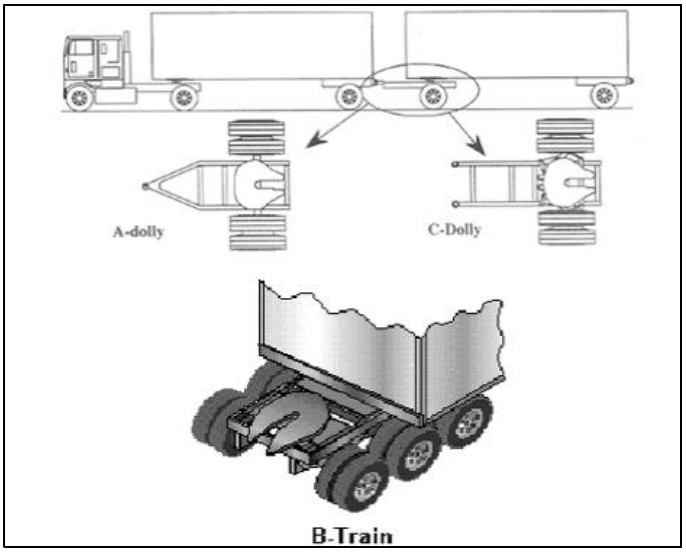


Figure 8 Connection types in LCVs
(USDOT, 2004)

Figure 9 shows an increasing trend line for the total number of commercial vehicle sales in Canada from 2008 to 2019. The increasing trend, excluding the pandemic in 2020, can be used as a reference point to prepare the current roadways for a future increase in freight vehicles. This rising trend is expected to include LCVs due to the removal of Ontario permit and carrier limits in 2017 (MTO, 2021).

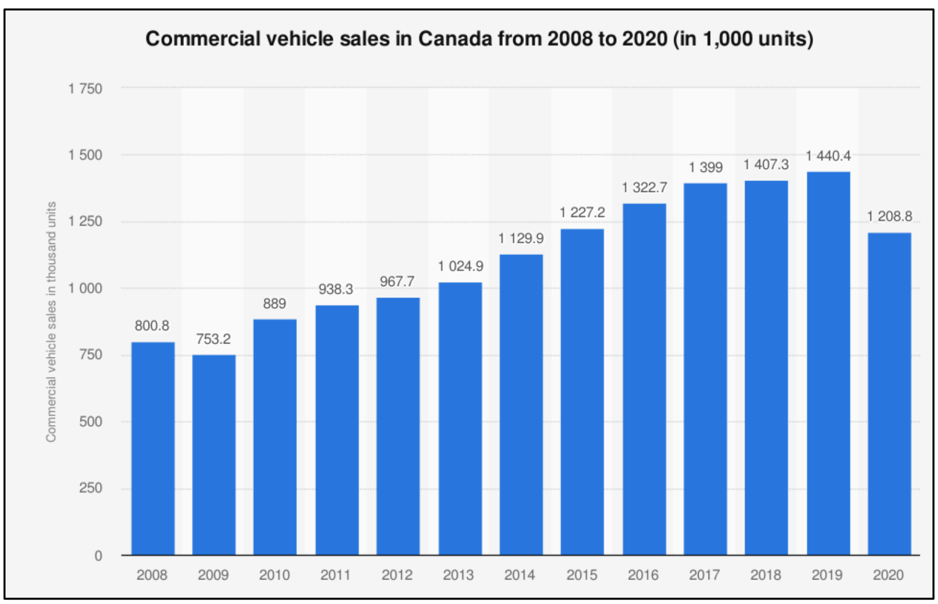


Figure 9 Commercial vehicle sales in Canada (2008-2020)
(OICA, 2021)

2.3. LCV Safety

Previous studies concluded that two approaches could define the safety performance of LCVs: (1) the analysis of safety performance using collision rates; and (2) the assessment of vehicle handling characteristics (Montufar et al., 2007).

Studies that assessed the safety performance of LCVs have shown different results due to a small sample of data compared to traditional vehicles. Some studies conclude that LCVs are relatively safer than other truck configurations in terms of collision rates (Woodrooffe, 2001). Careful implementation of policies and regulations on LCV programs attribute to this sense of safety. For example, the LCV program in Ontario requires extensive driver training and education, route restriction, and a careful route acceptance process.

On the other hand, some safety experts have concluded that LCVs threaten overall road safety. These negative feedbacks are based upon (1) the behavioral impacts LCVs have on other drivers in the traffic stream (Barnett, 1995 via Regehr et al., 2009), and (2) poor fatal crash performance under particular weather, traffic, and infrastructural conditions including gloomy weather, adverse road conditions, higher volumes of traffic, and higher maneuvering speeds (Forkenbrock & Hanley, 2003).

A study conducted in the Alberta LCV network from 1999 to 2005 showed that LCVs are responsible for about two percent of all articulated trucks in each of fatal, injury, and property damage only (PDO) collisions. LCVs had approximately the same collision rate (ratio between the number of collisions by vehicle type and the total exposure of the same vehicle type) as other articulated trucks in fatal collisions. Road surface condition, driver engagement, and weather condition are three contributing factors that were most often reported causes for these collisions (Regehr et al., 2009).

Forkenbrock and Hanley (2003) investigated the reasons behind fatal collisions between single-trailer trucks and two or three trailer trucks. The authors used multiple classification analysis and automatic interaction detector techniques in this study and determined that multiple trailer trucks are more likely to be involved in fatal collisions if one or more of the following conditions are present: darkness; snow, slush, or ice on the road surface; three or more vehicles, and roadways with higher speed limits between 65 to 75 mph.

A study conducted by the United States Federal Highway Administration (FHWA) in 1996 involved 75 commercial motor carriers who operate both LCVs and non-LCVs. FHWA developed the survey to get an idea about crash and exposure data from 1989 to 1994. Findings from the study were: (1) LCV crashes were more severe than non-LCV crashes; (2) LCV operators mainly preferred rural areas to operate in addition to higher-quality roads; and (3) LCVs tended to have highly qualified drivers to operate their vehicles (Montufar et al., 2007). In summary, the required driver standards of LCVs, along with training obligations, act positively to the overall safety performance (Woodro0ffe, 2001).

Several studies suggested that further investigations are required to connect LCVs safety issues with the data on crash rate. The separation of LCVs crash data from the other large trucks data can play a vital role in improving the dataset quality to investigate crashes (Scopatz, 2001). Also, until better data on comparative crash rates becomes available, strictly maintained safety regulations in areas where LCVs usage is high can preserve safety (Forkenbrock and Hanley, 2003).

When an LCV is impeding or passing another vehicle, it can cause safety concerns for other drivers on two-lane roads and undivided roads. The extra length of LCVs requires more time and distance to complete passing maneuvers safely (Barton & Morrall, 1998). Some studies also suggest that the speed variation of heavy vehicles remains negligible when the vehicles make lane changes from one lane to another (Nilsson et al., 2018). Nilsson et al. (2014) developed a driver model that used optical variables to determine safe and conservative situations when long vehicle combinations can make lane changes in a two-lane road. Parameters in this model included lane width, the width of the lead vehicle, distances to the near and far points. The model combined both longitudinal and lateral control with optical heuristics and provided a reliable deacceleration and steering profile for the lane change scenario developed in the study.

Trailer sway and rearward amplification of the LCVs are two critical factors that may cause additional hesitancy to the surrounding drivers to perform passing maneuvers (Harkey et al., 1996). Most importantly, the decisions of the heavy vehicle drivers are affected by the cooperation of the surrounding vehicles. As a result, if LCVs threaten the surrounding drivers and the surrounding cars start to behave erratically, it can lead to a potential safety issue.

Esmaili (2020) developed a controller (the critical component of an electric vehicle, which helps balance speed, acceleration, driving range) to reduce rearward amplification and lateral instability, common for autonomously driven long combination vehicles. A linear single-track model of an A-train was the controller's base. Later, the author validated the model against real-world data. The model sets the controller in such a way that it chooses the steering angle, which will give the lowest rearward amplification (RWA) value. The result showed that the controller successfully reduced RWA for every maneuver of the simulation model.

Daniels (2006 via Grislis, 2010) conducted a study using field measurement results. The results showed that an intermediate LCV with a total length exceeding 26.0 meters and less than 30 meters has better curvature area stability than a traditional 5-axle tractor-semitrailer combination vehicle. The result implicated that the additional length of the LCVs can offer more safety on turning movement. The author further found that double and triple combinations are less off-tracking than a standard tractor and semitrailer combination in the roadway. Off-tracking represents the distance between the path of the inside of the front wheel and the rear inside wheel of the vehicle.

2.4. Geometric Design Impacts

Compared to shorter trucks, triple-trailer combinations have a poorer handling characteristic (March, 2001 via Regehr et al., 2009). Vehicle handling characteristics are alternative measures to determine safety performances for LCVs. Different vehicle handling aspects, including off-tracking, rearward amplification, trailer sway, static roll stability, load transfer ratio, and lateral stability, help see how the roadway's geometric properties impact LCV's safety performance. Geometric attributes such as (1) lane and shoulder width at horizontal curves, (2) intersections and access and (or) egress points, (3) shoulder and pavement integrity, (4) stopping and intersection sight distance, and (5) vertical grade can affect the safe movement of combination vehicles (Regehr et al., 2009).

Elefteriadou et al. (1997 via Donnell et al., 2001) evaluated the performance of combination vehicles based on how they can handle off-tracking and the widths of their swept paths. The result showed that horizontal curves on roadways and curb radii for intersection right-turns might require modifications before those roadways can accommodate LCVs.

Wood & Regehr (2017) studied the dynamic performance measures that influence the Canadian regulations regarding LCV operation. Table 3 presents their findings which show the different regulatory items and their relationship with dynamic performance measures and geometric design elements.

Table 3 Regulated items for LCV operation in Canada (Adapted from Wood and Regehr, 2017)

Regulated item	Dynamic performance measure	Geometric design elements
Trailer sway	Trailer sway	Lane width; pavement widening on horizontal curves
Coupling device	Turning radius, off tracking and swept path width	Lane width; horizontal curve radius; pavement widening on horizontal curves; intersection and channelization geometrics
Maximum speeds	Off tracking and swept path width	Lane width
Cargo restrictions	Rollover threshold	Horizontal curve radius
Restricted weather conditions	Trailer sway	Lane width

Table 3 shows that lane width and curve radius are two of the most common geometric design elements that contribute to the regulations of LCVs operation.

Off-tracking (low-speed and high-speed) is typical for combination vehicles when they try to turn in an intersection. High-speed off-tracking occurs when the vehicle travels at a higher speed on a curve with a large radius. In the case of low-speed off-tracking, the rear wheels trail inside the path of the front wheels. AASHTO recommends a minimum lane width value of 3.7 meters to high-speed facilities where off-tracking can cause problems. However, if the widths of the lanes are lower than 3.4 meters, there are chances of LCVs encroaching into the adjacent lane and creating serious safety hazards. In the case of low-speed off-tracking, TPDs show the greatest off-tracking, and they also need more lane width than the AASHTO recommendation (4.9 meters) in case their lengths are longer than usual. It is advisable to widen the pavement width to prevent encroachment into the nearby lane or roadway edge for low off-speed facilities with moderate to severe curvature (Harkey et al., 1996a).

A survey revealed that law enforcement officers, who deal with commercial vehicle accidents, are worried that rollover can happen anytime with LCVs as a sharp turn in the roadways can suddenly shift the load in the trailers and can make the behavior of the LCVs unpredictable. The authors used a Static rollover threshold to measure the roll stability, which revealed that at a higher turning radius, the LCVs perform better as increased lateral acceleration helps to keep the vehicles from rolling over (Eastham et al., 2013).

TPDs are generally a more popular type among LCVs because of the trailer flexibility issue, which allows using a 16.2-meter trailer as a trailer in both TPDs and single tractor-trailer combinations. However, a report provided by AASHTO states that TPDs with 16.2-meter trailers cannot make a 90° right-turn at intersections with a 22.9-meter turning radius while TPDs with 14.6-meter trailers successfully navigate them. This suggests that the lengths of LCVs impact travel on local or arterial road systems where roads are narrower (Torbic & Harwood, 2006).

AASHTO recommends using three-centered compound curves or simple curves with tapers at intersections where turns are sharp. Also, increasing pavement widths at curves can prevent LCVs from encroaching into the adjacent lanes. One study found that RMDs and TPDs need to infringe on opposing lanes much more than regular tractor semitrailers to make right-turns at intersections to avoid conflicts with the curbs or other roadside signs and features (Harkey et al., 1996). Bareket & Fancher (1993) ran different simulations to assess the extent of modifications necessary for turning radii in an intersection to accommodate LCVs movement. The results showed that, if needed, LCVs can end the turn in the lane closest to the center of the road when turning to a four-lane road.

Kharrazi et al. (2017) developed an open assessment tool for calculating Performance-Based Standards (PBS) measures for combination vehicles. The author identified low speed swept path (LSSP), high-speed steady state off tracking (HSSO), tracking ability on the straight path (TASP), steady-state rollover threshold (SRT), as well as few other items as distinct PBS in this tool. Some motivations of the calculated PBS are- LCVs can not make sharp turns without having conflict with obstacles nearby (LSSP), LCVs have high lateral deviation when maneuvering on curves (HSSO), LCVs can deviate laterally when traveling on straight roads (TASP), and rollover can occur on long curves (SRT). The main benefit of this tool is that it can unambiguously define various maneuvers, which is essential to measure the impacts of geometric attributes on the LCV's movement. Similarly, the Canadian PBS for LCVs takes friction demand on the driven axles into account only when making a narrow turn (Kashampur, 2017).

2.5. Modelling Techniques and Software

2.5.1. Binomial Logit Model

In statistics, discrete choice models are used to measure the probabilities for a set of choices facing a decision-maker. These models include a deterministic component arising from known factors influencing the decision and an error component capturing uncertainty. The model is identified as a logit model if the error component is assumed to be an extreme-value Gumbel distribution, also known as a logistic distribution (Train, 2009). Many studies have used the binomial logit models to predict the outcome of two alternatives, which is a fairly common design for experiments and observational studies (Johnson & Albert, 1999).

In a study conducted by Ramli et al. (2010), a binomial logit model was developed to analyze the variables that affect the traveler’s choice between two different transport modes (minibus and private car). The study's findings revealed that trip frequency and travel time affect the mode choice significantly. A sensitivity analysis was also carried out to determine how to increase the minibus trip rate compared to the privately-owned vehicles.

Mattson (2012) developed a binary logit model to determine whether a person made a trip during a given week or not. The study used the National Household Travel Survey (NHTS) data to identify the trends in the travel behavior with variables including driving, trip frequency, staying in the same place all day or week, miles driven per year, mode choice, use of public transportation, trip purpose, trip distance, and concerns regarding transportation.

Several software packages can be used to estimate logit models, including SAS (Mattson, 2012), Stata (Gaskin et al., 2021), and NLOGIT (Regmi & Hanaoka, 2014). NLOGIT is an extension of the econometric and statistical software package LIMDEP. It offers the users flexibility to estimate the choice models, including discrete choices, choice sets, alternatives defined by attributes, repeated measures, and respondent characteristics. Using this software package, users can generate probabilities and calculate elasticities from the estimated models (Lancsar et al., 2017).

2.5.2. Swept-Path Analysis

The turning envelopes and swept paths of design vehicles influence the layout of roadway corridors and intersections (Carrasco, 1995). The accurate prediction of vehicle movements ensures that conflicts such as tire collisions with curbs can be avoided (Gkoutzini et al., 2020).

Hwang et al. (2017) proposed a method combining swept path analysis and multi-body dynamic simulation to facilitate transportation projects. Multi-body dynamic simulation offers to examine the vehicle's stability when making a turn. Curve angle, width, and slope affect the vehicle’s swept path when moving in a corridor. The integrated method proved efficient as it reduced the overall simulation running time. Figure 10 shows the concept of a vehicle’s swept path.

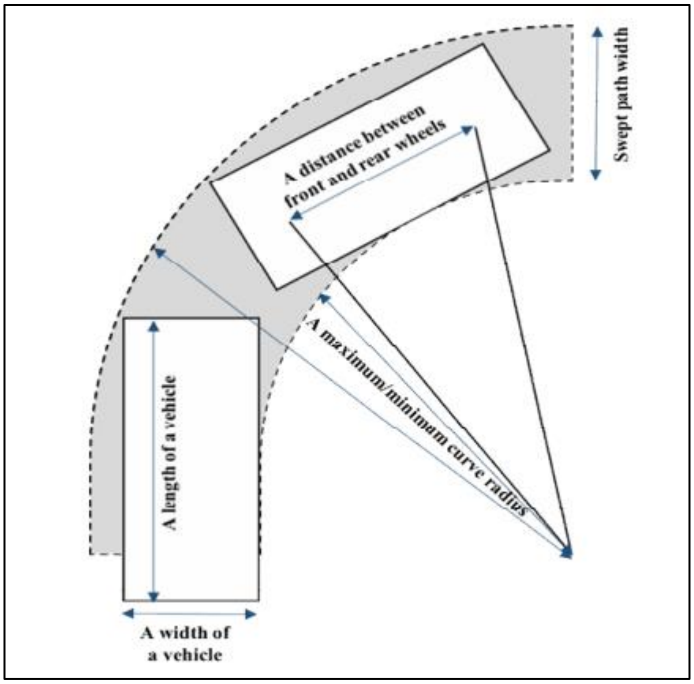


Figure 10 Swept path of a vehicle
(Hwang et al., 2017)

Džambas et al. (2021) suggested that swept path analysis should be conducted in the early stages of a transportation project. This will help identify the design elements that can cause issues to the movement of a design vehicle. One approach for this analysis is to conduct empirical testing of vehicles with Global Navigation Satellite System (GNSS) devices to determine the movement trajectory of the test vehicle. However, similar results were found with simulation testing using the software at a presumably lower cost.

AutoTURN is a third-party Computer-aided design (CAD) software released for AutoCAD. It can track the swept paths of vehicles with the help of its algorithm. Its ease of use has made it popular among transportation professionals. This software can trace specific points' paths and automate the entire design process. Using this software, the user can check a vehicle's turn requirements which is a prerequisite to designing a roadway facility (Carrasco, 1995).

2.6. Literature Review Summary

In summary, it is expected that LCV volumes will increase on roadways in Canada for the foreseeable future. Therefore, a need exists to help assess the capability of existing infrastructure to accommodate the movements of these large vehicles. Previous studies suggest that specific geometric attributes of the roadways have significant impacts on LCV movements. The two most prominent attributes include curb radii and lane widths. The research in this thesis focuses on these attributes, as seen later in Chapter 5.

Binomial logit models are frequently used in the analysis of transportation phenomena, yet this is the first study to apply this modelling type to the results of swept path analysis for LCVs. The model results are incorporated into a quick-response toolkit that provides the likelihood of LCV collision for right-turns based on the layout specified by a user.

Chapter 3. Study Area and Data

Approximately 14.7 million people live in the Province of Ontario, the most populous area of Canada (Statistics Canada, 2018). The population depends heavily on multimodal goods movement for its economic development, with almost 40% of the economy in Ontario consisting of industries pertaining to goods movement (Casey, 2019). The LCV program, which began in 2009 in Ontario, ensures that a larger population can be served more efficiently by the extra capacity provided by an additional trailer without the need to add a second driver (MTO, 2013).

Section 3.1. to Section 3.4. provide discussions on the sampling process to obtain a range of feasible values for geometric attributes at intersections in Ontario. The sampling is conducted on 93 intersections from various locations and population densities. Seven individual intersections in the Region of Peel are then discussed in Section 3.5. Simulations are later conducted on these seven intersections to analyze the existing performance of intersections for LCV swept path movements using AutoTURN software. While the simulations are conducted exclusively for the seven Region of Peel intersections, the modelling results are expected to be transferable to other intersections in Ontario because of the range of values taken from the 93 sampled intersections.

3.1. Regions of Ontario

A stratified sample was used in the collection of a range of geometric attributes from intersections in Ontario. The strata for this sample are based on location and population type. Three regions of Ontario are used for the sampling to account for differences in roadway design that may differ to suit different requirements by location. These regions include the Greater Toronto and Hamilton Area (GTHA), Northern Ontario, and Southern Ontario. The regions have been selected based on the initial observation of the land use context and population density. For example, GTHA has a higher population density and predominantly urban area; Northern Ontario has a lower population density and mostly rural area, and Southern Ontario has a mix of urban and rural features.

Figure 11 shows the categories developed in ArcGIS Pro software. The boundaries for each region were delineated using census divisions files obtained from the 2016 Census published by Statistics Canada.

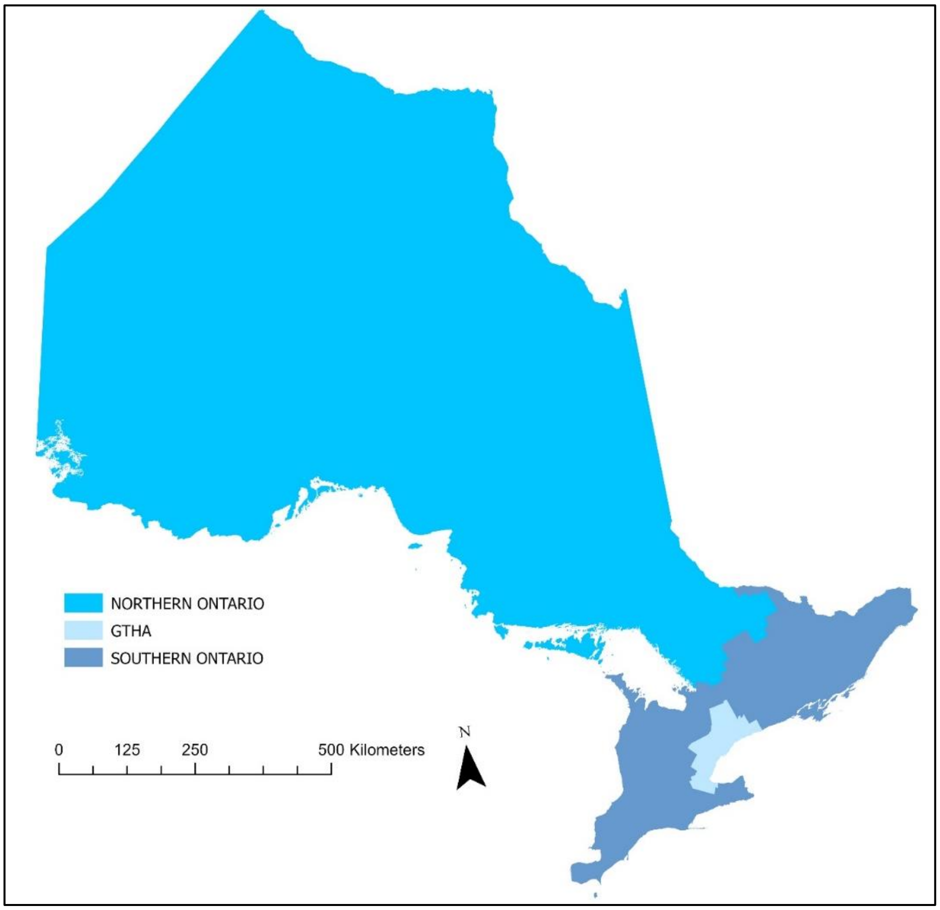


Figure 11 Sampling Regions in Ontario

3.2. Development Types in Ontario

Development type functioned as the second category for intersection sampling. Three strata were defined for development type, including urban, suburban, and rural. Each census tract in Ontario was allocated to one of these three categories using population density and dwelling type percentage. Figure 12 shows the population density for Ontario census tracts. Figure 13 shows the map of single and semidetached housing proportions in the Greater Toronto and Hamilton Area. The CHASS database of the University of Toronto (U of T, 2021) provided the 2016 Canadian census population data and a mix of housing types. The shapefile for the 2016 census tracts (CTs) created by Statistics Canada was acquired from Scholars GeoPortal.

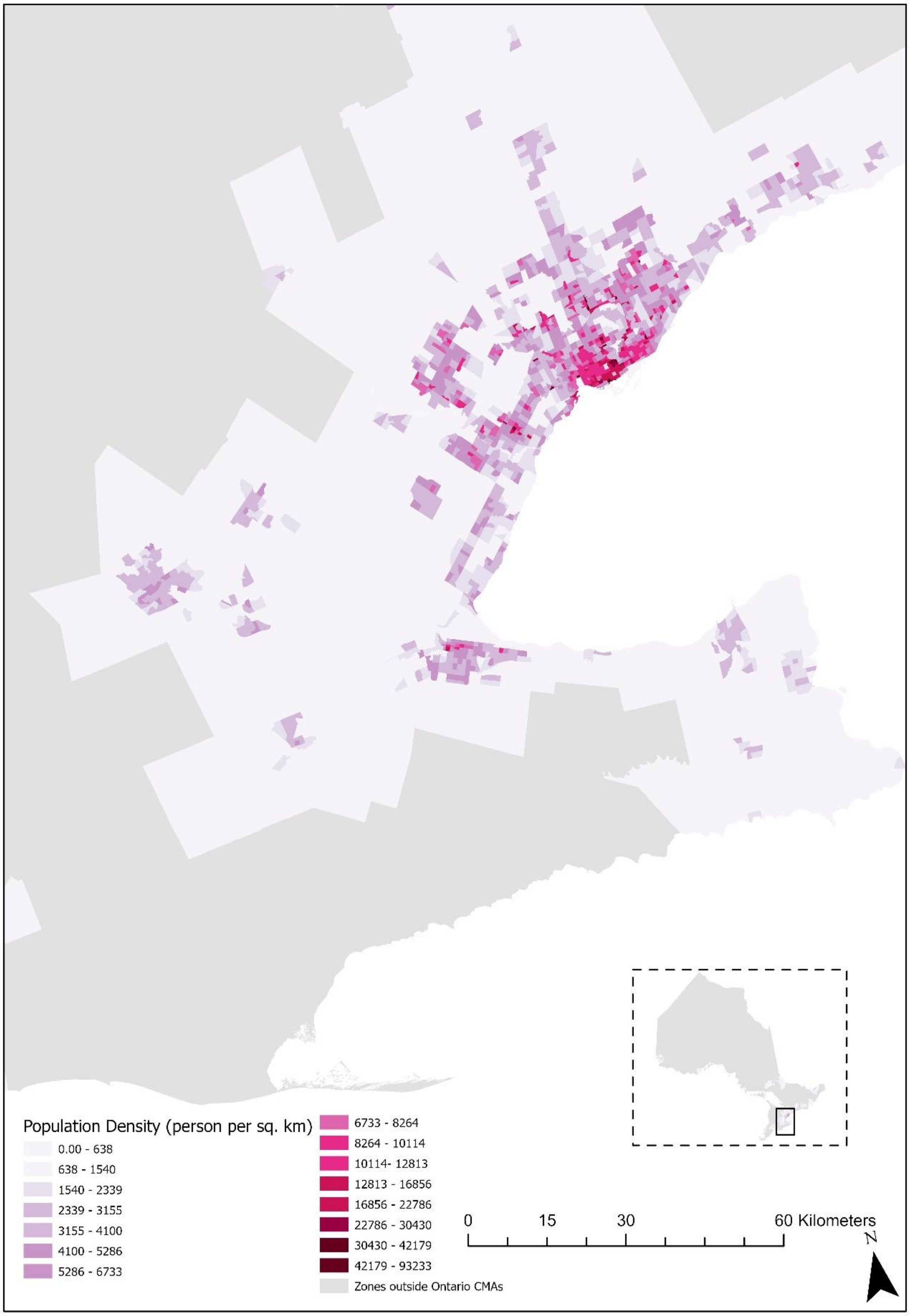


Figure 12 Population density in the Greater Toronto and Hamilton Area

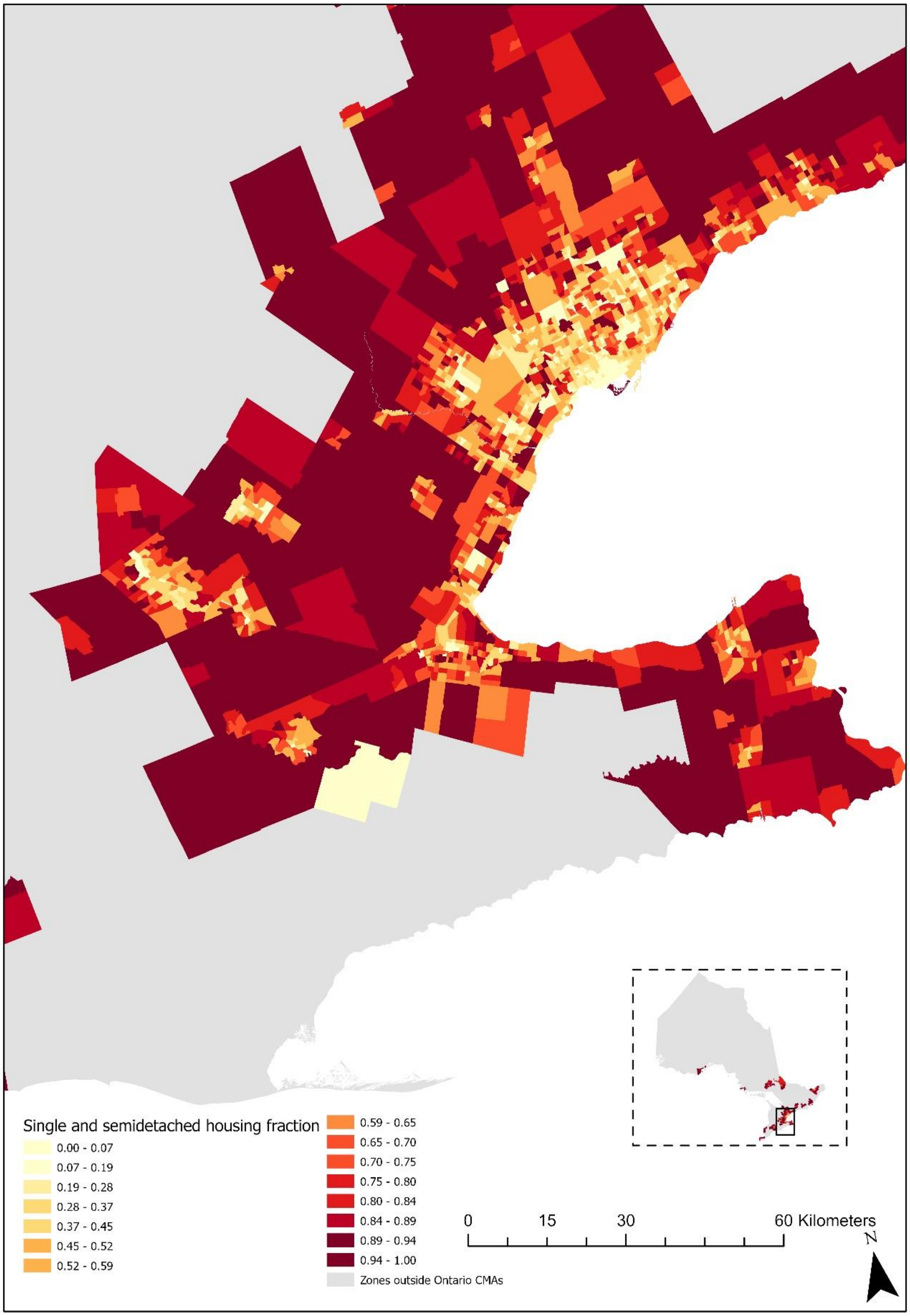


Figure 13 Housing proportions in the Greater Toronto and Hamilton Area

A rural census tract was defined using the definition given by Statistics Canada (2001) for a rural community with a population density of fewer than 150 persons per square kilometer. This definition for density identifies rural communities inside and outside of larger urban centers (du Plessis et al., 2001).

The underrepresentation of suburban areas made using population density alone inadequate to separate suburban and urban zones. For example, one approach to defining these categories used four criteria: political boundaries, zones outside the inner city, distance from the city center, and neighborhood density. The method developed by Turcotte (2008 via Gordon & Janzen, 2013) solved the inadequacy issue. The author used the fraction of single and semidetached dwellings to determine urban and suburban neighborhoods. This fraction was a proxy for population density as the measurement using only population density can significantly influence the boundaries between urban and suburban neighborhoods when commercial areas are present.

A detailed set of criteria is beyond the scope of this thesis; therefore, a simpler method was adopted from Gordon & Janzen (2013) to separate urban and suburban locations by comparing the percentage share of housing type for each census tract with Census Metropolitan Areas (CMAs) percentage and national percentage. A census tract is identified as suburban if the percentage of single and semidetached dwellings is higher than the CMA and national average. The census tract is otherwise identified as an urban zone. Table 4 shows the summary of the conditions that helped to identify different development types in Ontario. Figure 14 shows the results of the development type categorization in the Greater Toronto and Hamilton Area. This map has been developed using ArcGIS Pro.

Table 4 Summary of development type conditions

Development type	Condition 1: Population density	Condition 2: Percentage of single and semidetached dwellings
Rural	$\leq 150/km^2$	Not applicable
Suburban	$>150/km^2$	Higher than the highest value between national percentage and CMA percentage for single and semidetached dwellings
Urban	$>150/km^2$	Lower than the highest value between national percentage and CMA percentage for single and semidetached dwellings

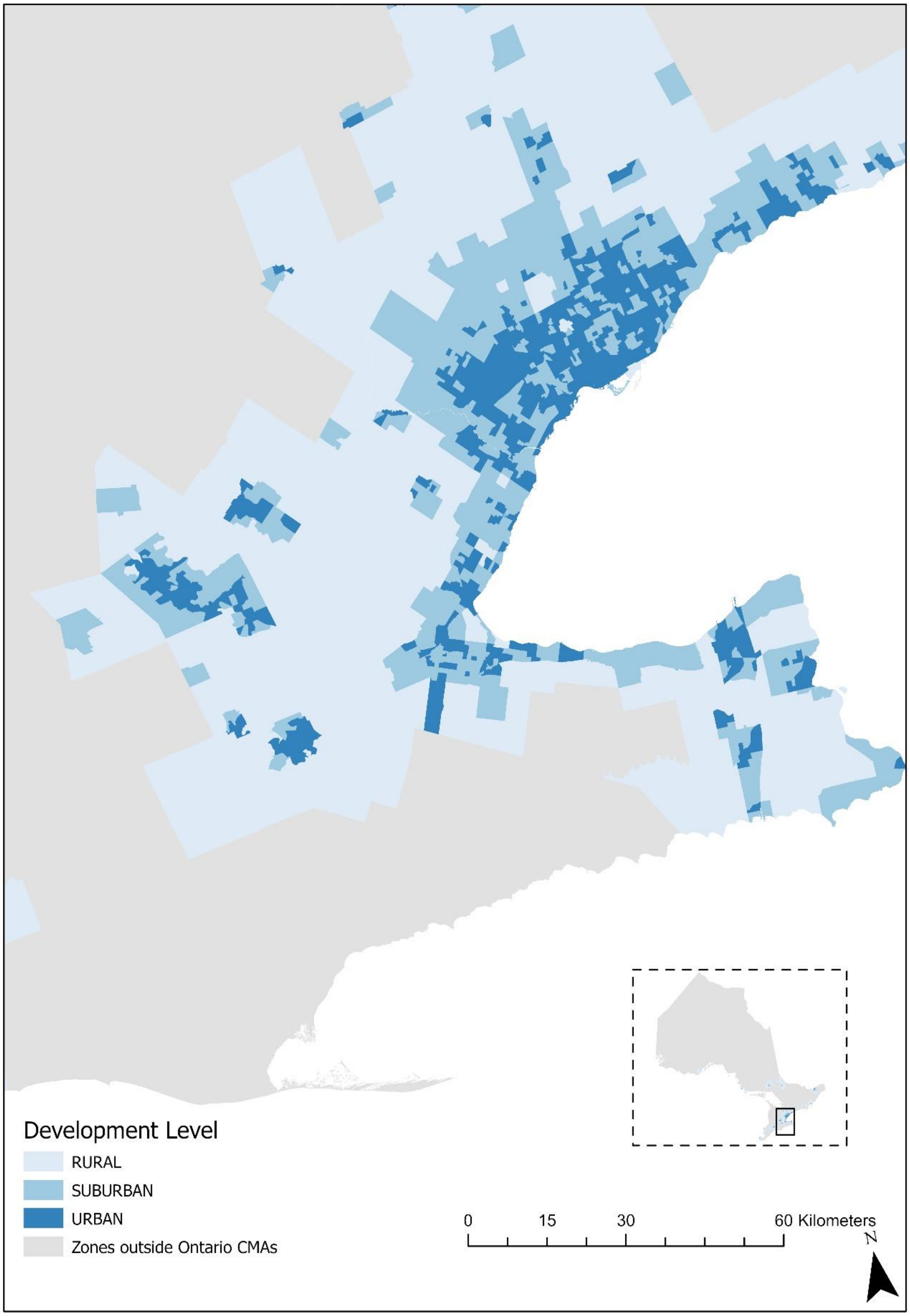


Figure 14 Development Types in the Greater Toronto and Hamilton Area

3.3. Stratified Sampling of Intersections

After categorizing Ontario based upon location and development type, the next task was to collect sample data on intersection geometric attributes from different locations. The categorization helped this process as there were already nine unique locations in Ontario, depending on the location and development type. The individual locations were Southern-Urban, Southern-Suburban, Southern-Rural, GTHA-Urban, GTHA-Suburban, GTHA-Rural, Northern-Urban, Northern-Suburban, and Northern-Rural.

The process began with selecting six different types of intersections present in Canada. The Transportation Association of Canada Geometric Design Guide for Canadian Roads (TAC, 2017) helped to identify intersection categories. The selected intersection types were: (1) four-legged right-angled, (2) oblique, (3) offset, (4) T- intersection, (5) Y-intersection, and (6) roundabout. The guideline in TAC listed out the basic attributes (intersection angle range, number of legs) that a certain intersection should have, which acted as a reference during sampling intersections from different parts of Ontario to create the sample database. Figure 15 shows the configurations of these six types of intersections.

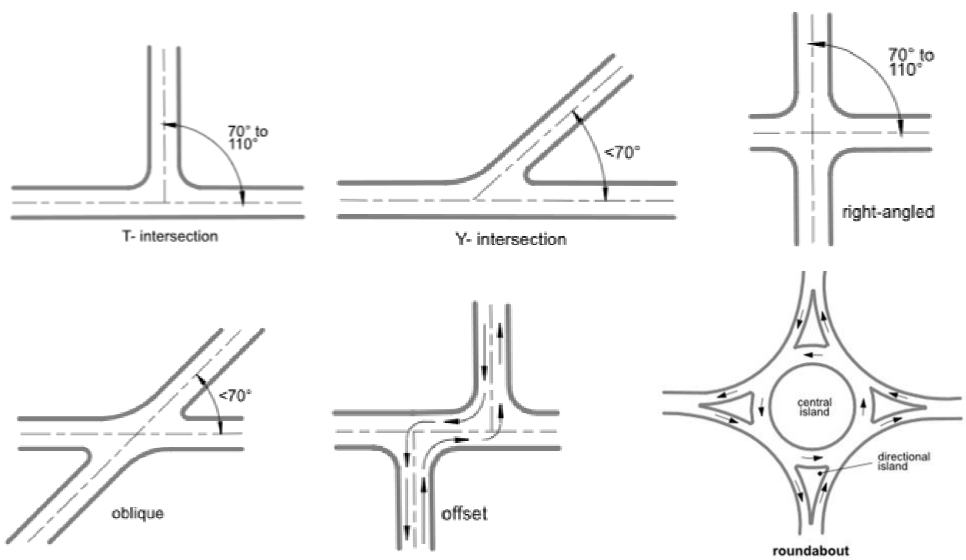


Figure 15 Selected intersection types (Adapted from TAC, 2017)

TAC guideline mentions another type of intersection configuration called multi-legged intersection; however, this study avoided this intersection category for vagueness arising from having no clear definition on the maximum number of allowed approaches. Figure 16 shows the configuration of this intersection category.

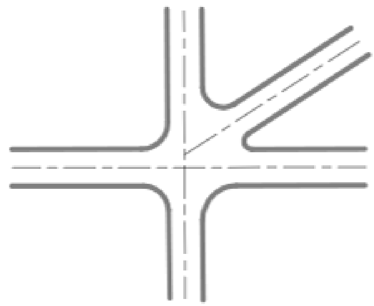


Figure 16 Multi-legged intersection (TAC, 2017)

After selecting the intersection categories, two samples from each category of intersections were identified and listed from the previously mentioned nine unique locations within Ontario. For an easy understanding of the sampling table, a 4-digit ID system was introduced. Table 5 provides the details of the 4-digit ID system.

Table 5 Details of the 4-digit IDs

4-digit ID details		
1st digit	Location in Ontario	1=Southern, 2= GTHA, 3= Northern
2nd digit	Development type	1= Urban, 2= Suburban, 3= Rural
3rd digit	Intersection type	1= 4-legged right angled, 2= oblique, 3= offset, 4= roundabout, 5= T, 6= Y
4th digit	Sample number	1= 1st sample, 2= 2nd sample

The goal of the stratified sampling of the intersections was to list the properties of eighteen different intersections from the identified nine unique locations for each of the six intersection types. However, due to the lack of numbers for some intersection categories (offset, roundabout) in different parts of Ontario, the list had a total number of 93 intersections instead of 108 intersections. Google Earth Pro helped list the coordinates (latitudes and longitudes) of each intersection. Matching the locations of the intersections with the categorization maps developed earlier in ArcGIS Pro ensured that the selection of locations was consistent. Appendix A includes the table containing all the values of the geometric attributes of the sampled intersections.

3.4. Geometric Properties

A thorough literature review helped to see which of the geometric attributes have the most impacts on the safe movement of LCVs. The sample table had the data for the following geometric attributes for each intersection: shoulder and lane widths, the number of lanes, turning radii, intersection angles, inner circle radius (roundabout), intersection size. The geometric attributes were measured using the ‘Ruler’ tool of the Google Earth Pro software.

An extension of the Google Chrome browser named ‘Protractor’ made it possible to calculate the obtuse and acute angles between intersection approaches. Figure 17 shows the workaround for this tool.

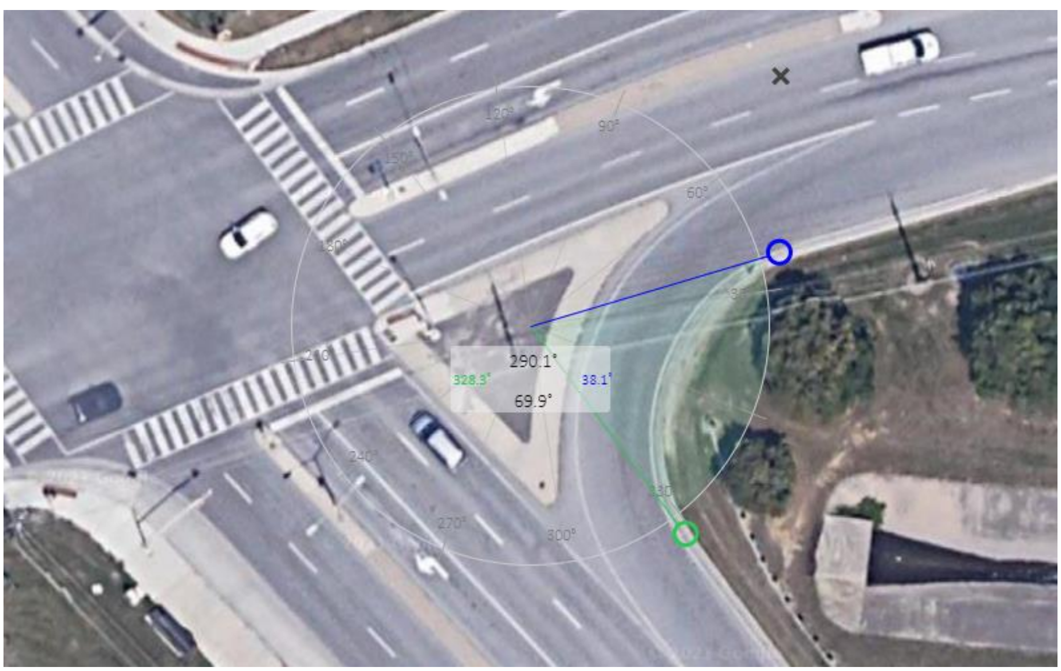


Figure 17 Protractor extension in Google Chrome

Table 6 shows the range of geometric attributes for sampled intersections. Appendix A includes the entire table containing the data collected from all 93 sampled intersections.

Table 6 Range of attribute values for sampled intersections

Intersection Type	**Observations**	**Curb Radius**		**Lane and shoulder width**	
		Min	Max	Min	Max
T	18	5.86	18.94	0.05	6.44
Y	18	1.87	364.73	1.23	5.79
Roundabout	14	4.1	113.63	1.42	5.67
4-legged right-angled	18	4.6	38.59	0.97	7.22
Oblique	18	5.25	88.78	0.62	9.74
Offset	7	5.11	17.89	1.53	4.92

The range of values for geometric attributes was later used in the seven intersections of the case study area, where simulations were run to study the LCVs swept paths. A set of seven unique intersections used for the simulations that are not part of the 93 sampled intersections is discussed next in Section 3.5.

3.5. Case Studies – the Region of Peel

Seven intersections within the Region of Peel were selected to run the swept-path simulations for different geometric attributes. These seven intersections represent the intersection categories that were selected for this study. The Region of Peel comprises the City of Mississauga, Brampton, and the Town of Caledon and is the origin and destination for a vast amount of goods movement by road. According to 2017 data, an estimated $1.8 billion worth of goods has their footprint daily in Peel. As a result, there is a significant amount of growth of industries related to goods movement within the region (Lightstone & Duggal, 2017)

The main reason behind choosing the Region of Peel as the area for case studies is that this region accounts for 26% of all LCV trips within Ontario. Origin or destination of a high percentage of the LCV trips (21%) within Ontario is connected to the City of Mississauga, making it one of the most important trade zones (Parsons, 2019). Table 7 shows the intersections within the Region of Peel selected for running the simulations in AutoTURN.

Table 7 Selected intersections in the Region of Peel

No.	Intersection type	Location	Existing condition*
1	4-legged right-angled with channelization	Dixie Rd and Britannia Rd	
2	4-legged right-angled without channelization	Atlantic Dr and Britannia Rd E	
3	T	Derry Rd and Torbram Rd	
4	Roundabout	Horseshoe Hill Rd and Olde Base Line Rd	

No.	Intersection type	Location	Existing condition*
5	Oblique	Orenda Rd and West Dr	
6	Offset	Kennedy Rd N and Olde Base Line Rd	
7	Y	Lakeshore Rd W and Lorne Park Rd	

**Images have been obtained from Google Map*

The Region of Peel has published a map in 2019 showing areas with high potential for future LCV route expansion. Based on the map, Figure 18 has been adapted to indicate the locations of the selected seven intersections with reference to the expansion areas chosen by the Region of Peel.

The image shows that except for the roundabout and offset intersections, all other intersections for the case studies are in good vicinity of the potential LCV route expansion areas designated by the Region of Peel.

The initial setups for the simulations in AutoTURN began after examples of each selected intersection category had been identified in the Region of the Peel. The seven intersections were first used as a base scenario to see if sufficient spaces are present for LCVs movements. The steps of the analysis methods to develop the simulations for the case study area are described in a detailed manner in the next chapter.

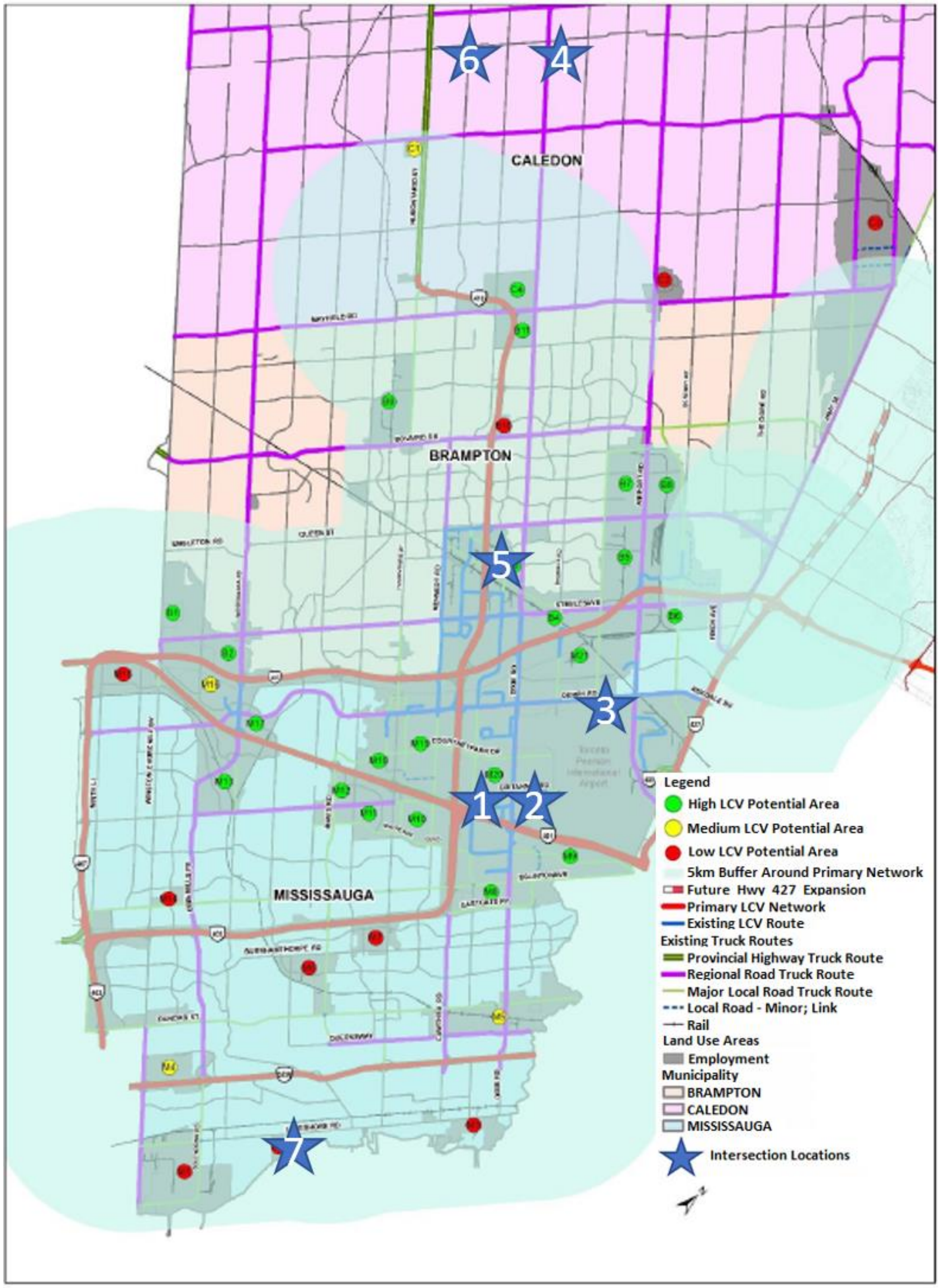


Figure 18 Locations of the case study intersections (Adapted from Parsons, 2019)

Chapter 4. Methods of Analysis

Chapter four includes details on the adopted approaches followed to run swept-path simulations. These simulations are developed using AutoTURN software as a third-party extension for AutoCAD. Section 4.1. describes the creation of intersection layouts in AutoCAD. Section 4.2. outlines the swept path properties used for the simulations in AutoTURN. Section 4.3. includes a detailed description of the simulation scenarios. Lastly, Section 4.4. describes the development of binomial models in NLOGIT software.

4.1. Intersection Layouts

The first step in the methodological approach was to identify the locations of the intersections and draw their layouts to scale in AutoCAD. At first, 'Meter' was set as the distance unit in AutoCAD. The latitude and longitude coordinates of the intersections helped to geolocate them within the software, as seen in Figure 19.

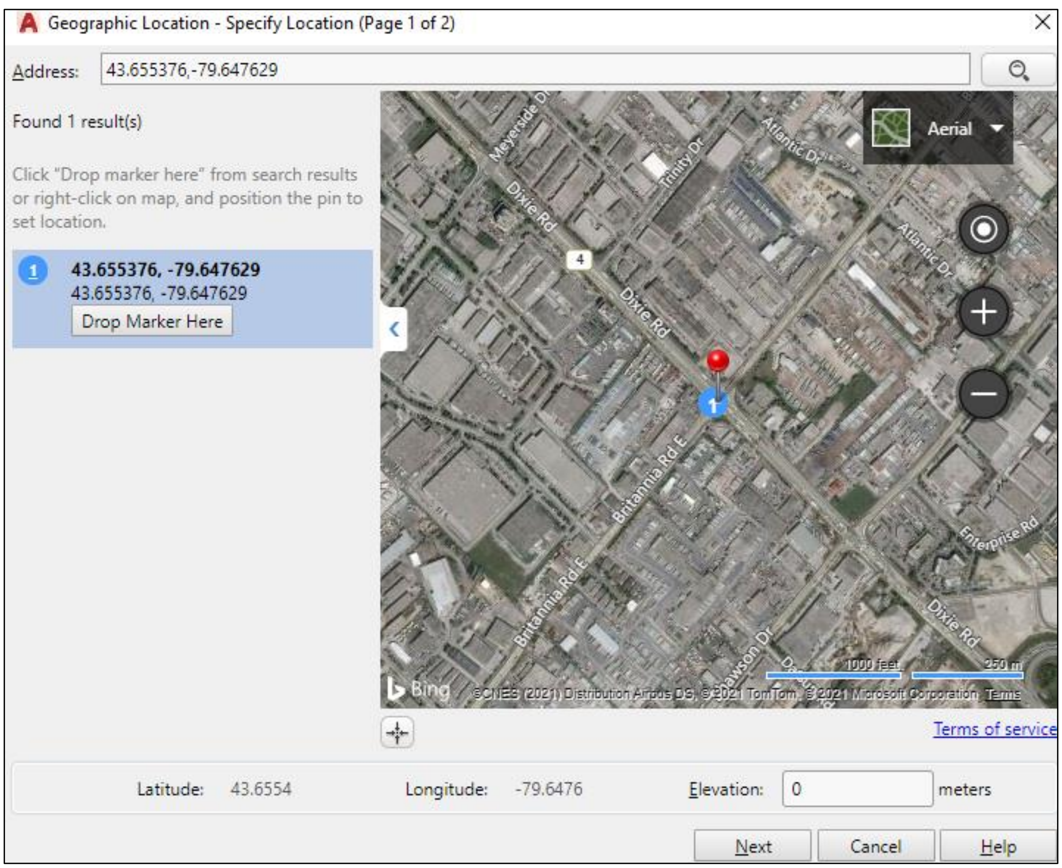


Figure 19 Geographic Location tool in AutoCAD

Different layers created in AutoCAD helped to draw the intersection layouts systematically. These layers include lane markings, curve radius, pedestrian crossings, stop lines, bus lanes, curb medians, and channelization islands. The boundary of the route analysis area on the side of the right most lane consists of the outermost line of the right-most back approach lane (in some cases right shoulder), the turning radius of that section of the intersection, and the outermost line of the right-most forward approach lane (in some cases right shoulder). Figure 20 shows the layout for a four-legged intersection with channelization for the right-turns.

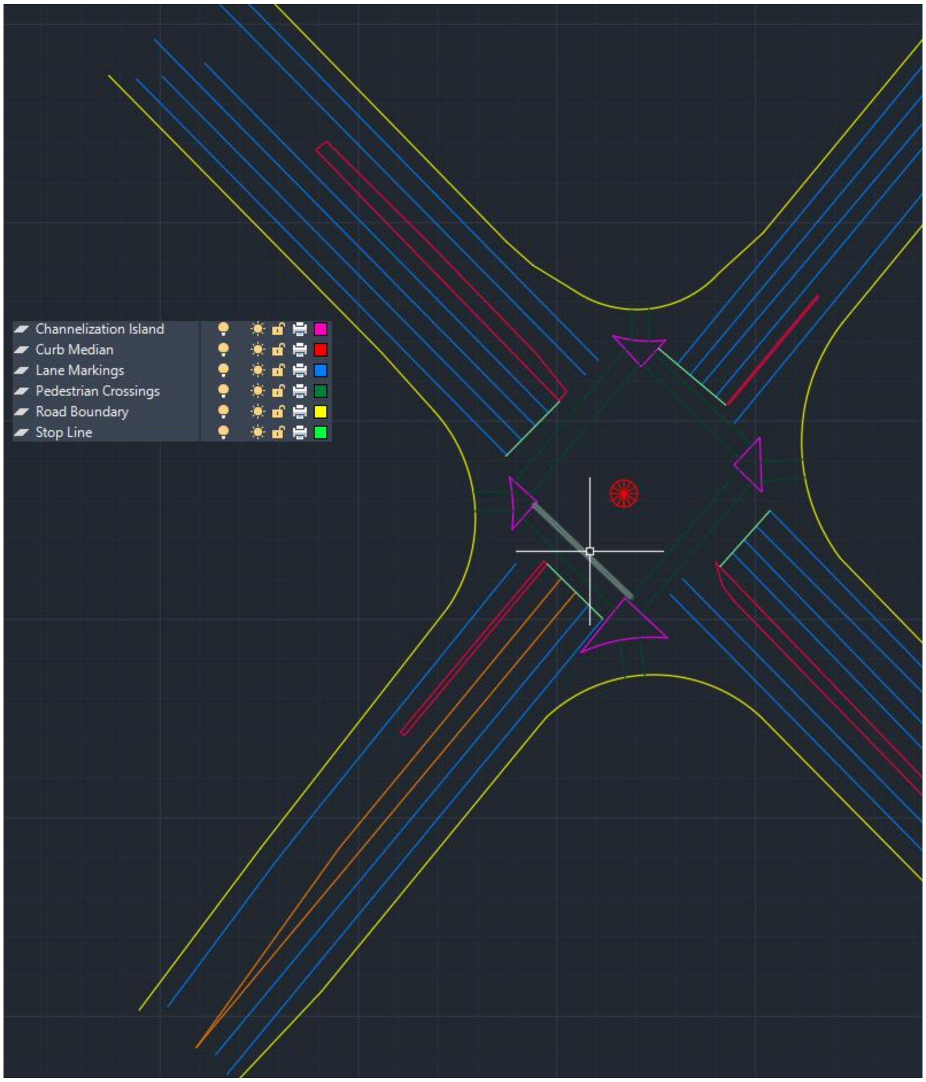


Figure 20 Base intersection design in AutoCAD

As discussed in the previous chapter, seven intersections were selected from the Region of Peel to simulate the range of the selected variables for each category of intersections in AutoTURN.

4.2. Swept-Path Properties

The selection of appropriate vehicle categories for LCV from a pre-defined library in AutoTURN began the process of the swept path simulations on the intersection layouts. The WB-33D vehicle type from the AASHTO 2018 (US) library inside AutoTURN was chosen as the default vehicle for this study. Figure 21 shows the process of selecting vehicle type in AutoTURN software.

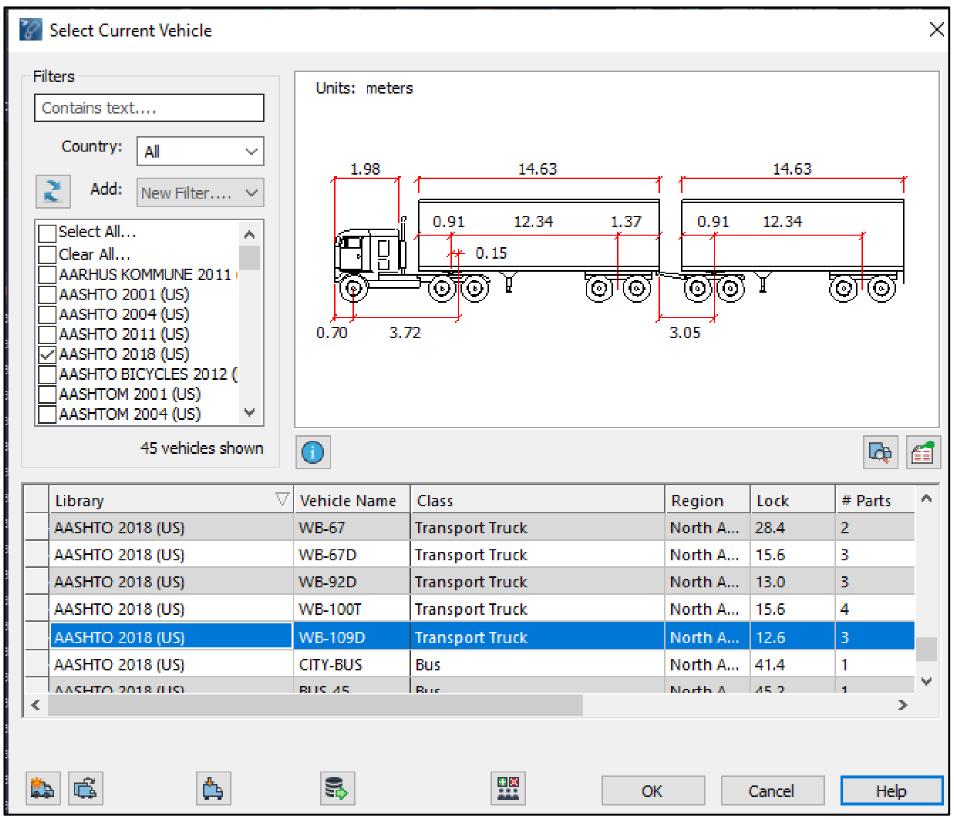


Figure 21 Vehicle selection in AutoTURN

One crucial point to be added here is that the vehicle dimensions for TPDs that have been labeled in the LCV program by the MTO are slightly different from the vehicle dimension in the AutoTURN library. The difference is mainly because the AutoTURN library uses a cab-over tractor for the TPDs, while the MTO LCV program uses a conventional tractor. The use of the cab-over tractor aligns with the AASHTO Green Book (Policy on Geometric

Design of Highways and Streets) standard. Studies found that using a cabover tractor instead of a conventional tractor has little to no effect on the vehicle off-tracking. Also, changing any dimensions for the WB-33D design vehicle is not recommended (Harwood et al., 2003). As a result, modifying the vehicle dimensions was beyond the scope of the study. Figure 22 shows the typical dimensions of both cabover and conventional tractors.

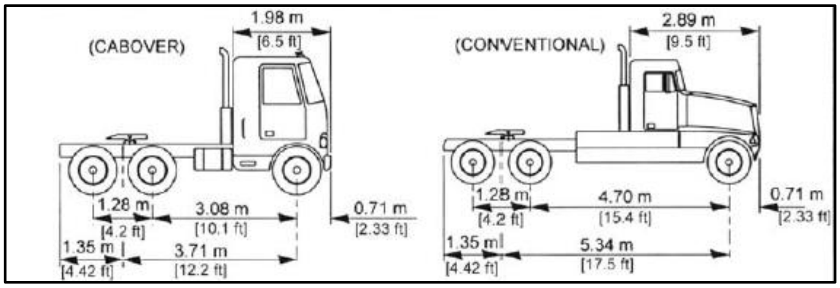


Figure 22 Dimensions of allowed truck tractors for TPDs (Harwood et al., 2003)

Two simulations were conducted in AutoTURN to see the difference between swept paths of a cabover tractor and a conventional tractor. For the simulations, a custom vehicle was created where the tractor of the WB-28D was used to carry the trailers of the WB-33D. The results showed similarity as the cabover, and the conventional trailer both showed similar swept paths and simulation status for a right-turn movement, as shown in Figure 23. The paths have a maximum divergence of 1.2 meters at the end of the turn. This divergence is not expected to be an issue affecting the swept paths produced later in the thesis since the result is caused by the final position of the vehicle. However, the paths are indistinguishable at the mid-point of the turn, indicating there will be no impact on the binomial logit models shown later in the thesis.

Figure 23 Overlayed swept paths (in green) for conventional and cabover tractors

Figure 23 Overlayed swept paths (in green) for conventional and cabover tractors

Figure 24 shows the swept path envelope for LCVs (WB-33D) used in this study. The maximum achievable steering angle is 12.6 degrees.

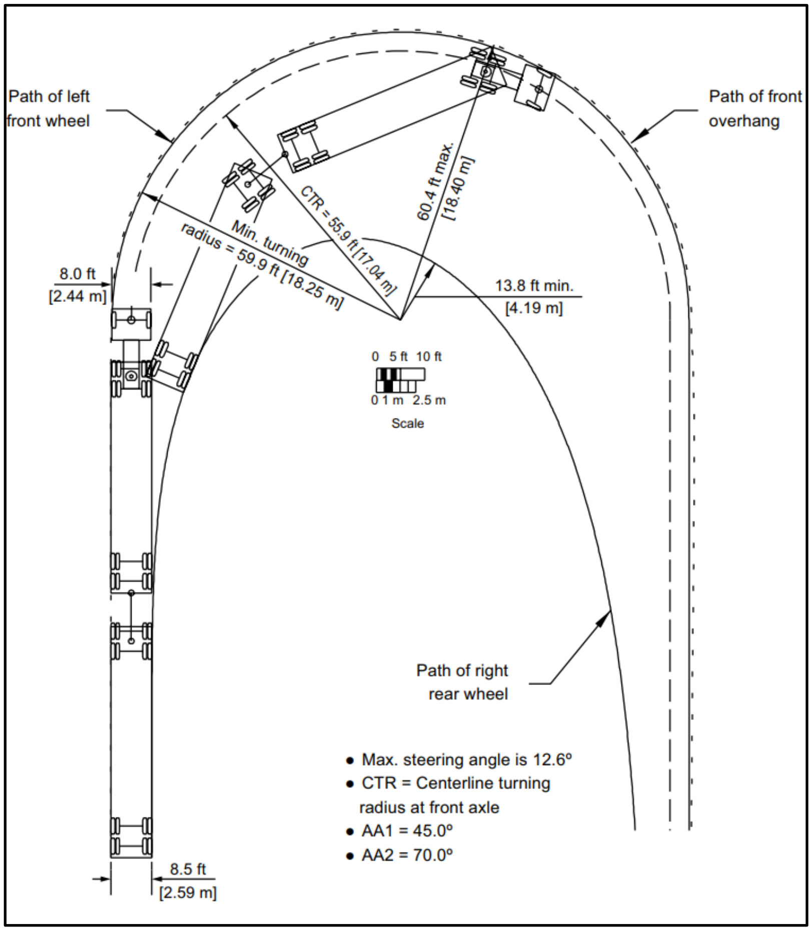


Figure 24 Turning template for the WB-33D (AASHTO, 2018)

A tool in AutoTURN known as IntelliPath was used to run the simulation models. The IntelliPath tool simulates optimal vehicle paths within a predefined corridor of analysis. Figure 25 highlights the corridor with the blue polygon for a right-turn movement from the northeast to the southeast. The software will inform the user if there is no feasible path for the vehicle to move without conflict defined with additional boundaries shown by the green lines. This output is used in the simulation analysis to determine the success or failure of a specified geometry to accommodate the LCV.

The speed of an approaching vehicle can also be adjusted and may impact the results as a higher speed can reduce the steering angle and lead to wider turns. As shown in Figure 25, the maximum speed is 36 km/hr for a particular scenario where an additional lane was allowed before making the turn. The initial simulation for a turning movement in this thesis is set to 5 km/hr. This speed was carefully chosen based on the assumption that the LCV will slow down while approaching the intersection. This aligns with the TAC Geometric Design Guide for Canadian Roads (2017), where design vehicles have turn speeds between 5 to 10 km/hr and control vehicles have 5 km/hr or fewer turn speeds.

For conflicts check, the front and rear tires envelope was selected as the preferred envelope type before running the simulation in IntelliPath. Vehicle body envelope is the other type of envelope type available in IntelliPath. However, the LCV program of the MTO requires that for any turning template of the design drawings, the vehicle wheels need to have at least a buffer of 0.5 meters from any curbs or pavements. The selection of front and rear tires as envelope type helped keep this study consistent with the MTO guideline.

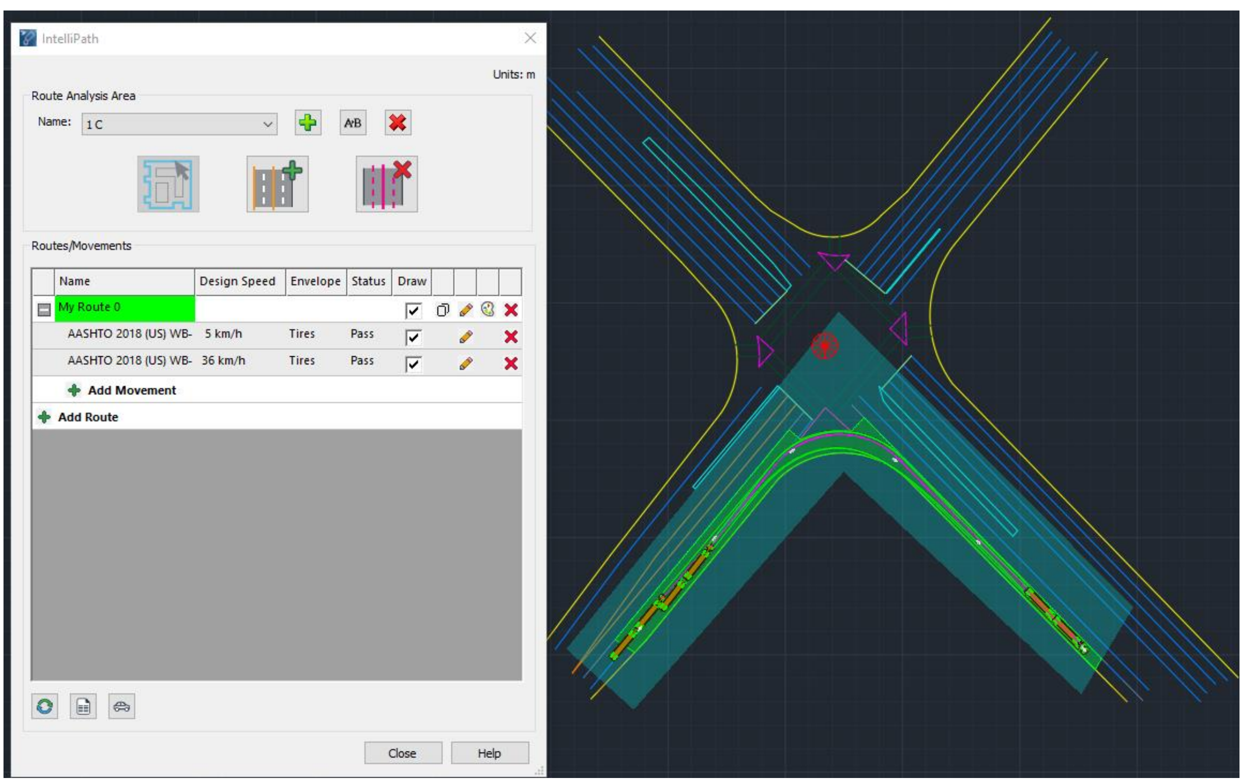


Figure 25 Right-turn movement simulation in IntelliPath

In summary, the simulations are initiated as follows: (1) set the conflict type for the simulation; (2) a route analysis area is defined using the IntelliPath tool; (3) exclusion lines are drawn, which represent boundaries that a vehicle cannot cross; (4) the direction of traffic in the route is defined; (5) the vehicle type and speed for the simulation are selected; (6) the starting location and orientation of the vehicle are placed at the intersection; and (7) the simulation is performed. The software will show the simulation status as “Pass” if the vehicle can successfully turn and reach the destination point from the origin point. Otherwise, the status will be shown as “Fail” if any conflict happens with the exclusion lines that the vehicle cannot maneuver through.

If the simulation passes at the initial speed of 5 km/hr, then the simulation is rerun with AutoTURN allowed to adjust the speed as high as possible. This has a negative relationship with the success of the turning movement, where a lower speed can be used as a proxy to indicate how close the simulation is to failure.

4.3. Simulation Scenarios

Table 8 shows the four major scenarios that helped categorize the study's simulations. Scenario 1 is the base scenario, with turning movements tested for the existing conditions.

Table 8 Simulation scenario categories

Scenario ID	Name	4-legged right angled without channelization	4-legged right angled intersection	T intersection	Roundabout	Oblique intersection	Offset intersection	Y intersection
1	Base	RTM	RTM	RTM	RTM, LTM, TM	RTM	RTM, TM	RTM
2	Curb Radius	RTM	RTM	RTM	RTM, LTM, TM	RTM	RTM, TM	RTM
3	Lane Width	RTM	RTM	RTM	RTM, LTM, TM	RTM	RTM, TM	RTM
4	Channelization	-	RTM	RTM	-	RTM	-	RTM

Note: ‘RTM’ = right-turn movement; ‘LTM’= left-turn movement; ‘TM’= through movement; ‘-’= no movement analyzed

Scenario 2 tests the impact of changing the curb radius. Shifting the start and end points of the curves helped the adjustments of the curb radius. The layouts have been drawn in a way that changes in the start and end points of the curves from the existing layout would not affect lane widths. As a result, the lane widths remained the same. If the output for Scenario 1 was a failure, then the curb radius is increased in 5-meter increments until the simulation status shows a fail. If the output for Scenario 1 was a success, then the curb radius is incrementally decreased by 5 meters until the simulation status shows a pass. This sensitivity analysis identifies an inflection point between success and failure to better understand what value of curb radius is sufficient for a given intersection.

Scenario 3 tests the impact of changing the lane width using a similar approach to Scenario 2. In this case, the lane width is changed in 0.5-meter increments. While drawing the new widths of the lanes, the starting and ending points of the curves were adjusted so that the base turning radii were unchanged. The change in width can represent either a change in the demarcated lane or a change in the width of an available shoulder. However, this distinction is not necessary for the simulation.

Scenario 4 tests the impact of channelization on a given scenario if the base scenario had channelized island. The scenario, therefore, removes the channelization island to provide more space for the turning movement. This is useful in the cases where the base scenario failed. However, as channelization improves the safety of the roadway, conducting a thorough investigation is necessary before removing it. This is a significant concern as this might affect other modes that share the road.

Each scenario was further categorized into four conditions identifying which lanes are available for the vehicle to utilize. These conditions acknowledge the differences between design vehicles and control vehicles for many municipalities and the varying accommodation levels. Design vehicles are more likely to be restricted to their lane when performing a turning maneuver, whereas a control vehicle may be given more flexibility to utilize additional lanes. The details of these conditions are as follows: Condition A restricts movements of LCVs to remain in the right lane in the approach and exit of the turn; Condition B restricts movement for the approach to the turn but enables the vehicle to utilize a second lane when exiting the turn; Condition C enables the LCV to use two lanes on the approach to the turn but restricts the vehicle to the right lane on exit. Condition D enables the LCV to use two lanes for both the approach and exit. These conditions are visualized below in Figure 26.

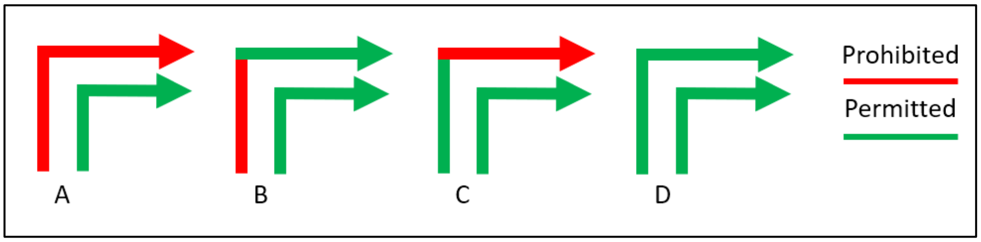


Figure 26 Conditions developed for the study

All four conditions are tested for each scenario. Only the right lane has geometric attributes adjusted when required for a given scenario, such as the lane width for Scenario 2.

Primarily the simulations were run with a focus to find the passing and failing points. However, creating more in-between simulation scenarios afterward helped to narrow down the location of the inflection point. The LCVs turning status switch from fail to pass or vice versa at the inflection point. Narrowing down the locations gave more accuracy to the results.

4.4. Modelling Approach

After getting all the results of the swept path simulations from AutoTURN, multiple binomial logit models were created to measure the elasticities among the identified variables. For this purpose, the dependent and independent variables were first identified. The dependent variables for all the models were whether the simulation scenarios passed or failed. The independent variables of the models were curb radius and lane widths. The models included several dummy variables depending on their statistics on the simulation scenarios' overall passing or failing status. Chapter 5 has a comprehensive discussion on the dummy variables.

After selecting the dependent, independent, and dummy variables, simulation scenarios results were exported into NLOGIT software, where the model development took place. The final models excluded channelization as a binary variable because of not being significant enough to affect the outcome of the models. The results of the models had elasticities and marginal effects for different variables, predicted probabilities for different scenarios, degree of confidence, goodness-of-fit (log-likelihood, ρ^2, adj-ρ^2, AIC), t-statistics, p-value. Later, probability results from the simulation scenarios helped create confusion matrices to check the transferability of the models. A new intersection in the case study area helped carry out the task to test the model's predictive power regarding pass alternatives.

The following equations of measuring the probabilities of binomial logistic regression assisted in calculating the likelihood of fail and pass alternatives:

$$P_{f,s} = \frac{e^{U_{f,s}}}{e^{U_{f,s}} + e^{U_{p,s}}} \qquad (1)$$

$$P_{p,s} = \frac{e^{U_{p,s}}}{e^{U_{f,s}} + e^{U_{p,s}}} \qquad (2)$$

Where:

- $P_{f,s}$= Probability of fail for scenario *s*
- $P_{p,s}$= Probability of pass for scenario *s*
- $U_{f,s}$ = Utility of fail for scenario *s*
- $U_{p,s}$ = Utility of pass for scenario *s*

Later, a comparison between the simulation status of right-turn movement at the new intersection and the probability value given by the model helped to estimate the model's transferability.

Chapter 5. Swept Path Simulation Results

The results of the simulation scenarios for selected intersections are presented in this chapter. This includes discussions of patterns with emphasis on curb radius and lane width. Each simulation is tested to determine the feasibility of an LCV safely performing a right-turn movement or through movement. The results are denoted with a binary pass or fail condition, which is later used to estimate a set of binomial logit models to provide further analysis and predictive capabilities.

The chapter's arrangement is as follows: Section 5.1. discusses the general results obtained for each intersection. Next, Section 5.2. focuses on the patterns arising from a sensitivity analysis of the curb radius for each intersection. Section 5.3. performs a similar analysis but emphasizes the lane width available for the LCV turning maneuver. Section 5.4. presents the results of a binomial model for quantitative analysis of the results. Section 5.5. demonstrates the predictive capability of the model using a new intersection as a holdout observation and Section 5.6. describes the development of a quick-response toolkit.

5.1. General Trends of the Geometric Attributes

The simulation results for each intersection are presented below. The tabular results from Table 9 to Table 15 include data on the following variables: direction, scenario, default attributes (if the simulation scenario layout is the same as the existing layout of the intersection), curb radius, lane width, channelization, intersection angle, simulation status (simulation scenario passing status from AutoTURN) and maximum achievable speed (highest achievable speed for LCVs for a scenario in case the simulation status is 'Pass'). The pass and fail statuses were previously defined in Section 4.2.

The existing geometric attributes were tested for each intersection as Scenario 1 with additional conditions A, B, C, and D to represent the number of permitted lanes for the approach and receiving ends of the turn. Adjusting a selected variable helped test the additional scenarios, such as the changing curb radius until there is a change in pass or fail outcome. In the absence of an available second lane approaching the curve, at the end of the curve, or both, the associated conditions of B, C, D, respectively, could not be included. For example, the 4-legged right-angled intersection without channelization did not have a second lane on the forward end of the maneuver at the end of the curve. Therefore, conditions B and D are absent from the results.

The range of values tested for the simulation sometimes differs from previously observed values from the sampled intersections across Ontario. The reason behind that is for some intersections in the Region of Peel, the existing values for both turning radii and lane widths are significantly off from the range of observed values of the sampled intersection data. For example, the turning radius for sampled T intersections in Ontario ranged from 5.9 meters to 18.9 meters. In comparison, the existing turning radius was 30.8 meters for that intersection category in the case study area. As the intersection was failing at 18.9 meters curb radius and passing at 30.8 meters curb radius, the simulated range varied between 18.9 meters to 30.8 meters to find the location of the inflection point.

Although the Roundabout had the left-turn movement (LTM) simulation scenario, the results were always negative, which means LCVs could not make the turn for the simulated values tested in the AutoTURN. So, the following sections and subsections of Chapter 5 do not include any results containing the left-turn movement simulations.

5.1.1. 4-Legged Right-Angled with Channelization Intersection

Table 9 shows the results of the simulation scenarios for the 4-legged right-angled with channelization intersection.

Table 9 Simulation results for 4-legged right-angled with channelization intersection

Direction	Scenario	Default attributes	Curb radius (m)	Avg. lane width (m)	Channel	Int. angle (degree)	Status	Max. speed (km/h)
Major Road to Minor Road (Britannia Rd East to Dixie Rd South)	1 A	Y	39.53	5.1	Y	96	Fail	0
	1 B	Y	39.53	5.1	Y	96	Pass	36
	1 C	Y	39.53	5.1	Y	96	Pass	36
	1 D	Y	39.53	5.1	Y	96	Pass	39
	2 A	N	38.59	5.1	Y	96	Fail	0
	2 A	N	41.56	5.1	Y	96	Fail	0
	2 A	N	43.59	5.1	Y	96	Pass	1
	2 B	N	38.59	5.1	Y	96	Fail	0
	2 B	N	43.59	5.1	Y	96	Pass	37
	2 C	N	38.59	5.1	Y	96	Fail	0
	2 C	N	46.09	5.1	Y	96	Pass	36
	2 C	N	43.59	5.1	Y	96	Pass	38
	2 C	N	48.59	5.1	Y	96	Pass	36
	2 D	N	38.59	5.1	Y	96	Pass	39
	2 D	N	36.09	5.1	Y	96	Pass	36
	2 D	N	33.59	5.1	Y	96	Fail	0
	3 A	N	39.53	8.2	Y	96	Pass	38
	3 A	N	39.53	6.6	Y	96	Pass	37
	3 A	N	39.53	2.6	Y	96	Fail	0
	3 B	N	39.53	7.4	Y	96	Pass	42
	3 B	N	39.53	4.2	Y	96	Pass	12
	3 B	N	39.53	3.2	Y	96	Fail	0
	3 C	N	39.53	7.4	Y	96	Pass	41
	3 C	N	39.53	4.3	Y	96	Fail	0
	3 C	N	39.53	3.3	Y	96	Fail	0
	3 D	N	39.53	6.6	Y	96	Pass	44
	3 D	N	39.53	4.4	Y	96	Pass	40
	3 D	N	39.53	3.8	Y	96	Fail	0
	4 A	N	39.53	5.1	N	96	Pass	41
Minor Road to Major Road (Dixie Rd South to Britannia Rd West)	1 A	Y	40.20	5.3	Y	80	Pass	18
	1 B	Y	40.20	5.0	Y	80	Pass	37
	1 C	Y	40.20	5.1	Y	80	Pass	14
	1 D	Y	40.20	4.9	Y	80	Pass	41
	2 A	N	38.59	5.3	Y	80	Fail	0
	2 A	N	43.59	5.3	Y	80	Pass	18
	2 B	N	33.59	5.0	Y	80	Pass	9
	2 B	N	43.59	5.0	Y	80	Pass	40
	2 B	N	38.59	5.0	Y	80	Pass	40
	2 B	N	28.59	5.0	Y	80	Fail	0
	2 B	N	31.09	5.0	Y	80	Fail	0
	2 C	N	28.59	5.1	Y	80	Fail	0
	2 C	N	33.59	5.1	Y	80	Fail	0
	2 C	N	38.59	5.1	Y	80	Pass	16
	2 C	N	36.09	5.1	Y	80	Fail	0
	2 D	N	38.59	4.9	Y	80	Pass	41

Direction	Scenario	Default attributes	Curb radius (m)	Avg. lane width (m)	Channel	Int. angle (degree)	Status	Max. speed (km/h)
	2 D	N	33.59	4.9	Y	80	Pass	40
	2 D	N	28.59	4.9	Y	80	Fail	0
	2 D	N	36.09	4.9	Y	80	Pass	41
	3 A	N	40.20	8.3	Y	80	Pass	44
	3 A	N	40.20	2.6	Y	80	Fail	0
	3 A	N	40.20	3.9	Y	80	Fail	0
	3 B	N	40.20	3.0	Y	80	Fail	0
	3 B	N	40.20	7.3	Y	80	Pass	43
	3 B	N	40.20	4.1	Y	80	Pass	43
	3 C	N	40.20	3.1	Y	80	Fail	0
	3 C	N	40.20	7.4	Y	80	Pass	46
	3 C	N	40.20	4.3	Y	80	Fail	0
	3 D	N	40.20	6.5	Y	80	Pass	47
	3 D	N	40.20	3.7	Y	80	Fail	11
	3 D	N	40.20	4.3	Y	80	Pass	47
	4 A	N	40.20	5.3	N	80	Pass	37

This intersection category includes a total of 61 simulations. The simulations show that the curb radii and average lane width vary between 28.59 meters to 48.59 meters and 2.6 meters to 8.3 meters. The intersection angle is 96 degrees for the major road to minor road (Britannia Rd East to Dixie Rd South) direction, and 80 degrees for the minor road to major road (Dixie Rd South to Britannia Rd West) direction. The maximum achievable speed for right-turn movements is 47 km/h. In total, this intersection category has a passing rate of 60.7% for right-turn movements. Lastly, the removal of channelization islands facilitates the turning movement of LCVs.

5.1.2. 4-Legged Right-Angled Intersection

Table 10 shows the results of the simulation scenarios for the 4-legged right-angled intersection.

Table 10 Simulation results for 4-legged right-angled intersection

Direction	Scenario	Default attributes	Curb radius (m)	Avg. lane width (m)	Channel	Int. angle (degree)	Status	Max. speed (km/h)
Major Road to Minor Road (Britannia Rd East to Atlantic Dr South)	1 A	Y	24.40	7.2	N	95	Pass	37
	1 C	Y	24.40	5.5	N	95	Pass	39
	2 A	N	19.40	7.2	N	95	Fail	0
	2 A	N	21.90	7.2	N	95	Fail	0
	2 A	N	23.15	7.2	N	95	Fail	0
	2 A	N	23.78	7.2	N	95	Pass	36
	2 C	N	19.40	5.5	N	95	Pass	1

Direction	Scenario	Default attributes	Curb radius (m)	Avg. lane width (m)	Channel	Int. angle (degree)	Status	Max. speed (km/h)
	2 C	N	14.40	5.5	N	95	Fail	0
	2 C	N	16.90	5.5	N	95	Pass	39
	3 A	N	24.40	2.6	N	95	Fail	0
	3 A	N	24.40	6.5	N	95	Fail	0
	3 A	N	24.40	7.1	N	95	Pass	37
	3 C	N	24.40	3.1	N	95	Fail	0
	3 C	N	24.40	4.6	N	95	Fail	0
	3 C	N	24.40	5.0	N	95	Pass	36
Minor Road to Major Road (Atlantic Dr South to Britannia Rd West)	1 A	Y	25.95	5.9	N	83	Fail	0
	1 B	Y	25.95	5.6	N	83	Pass	72
	1 C	Y	25.95	5.8	N	83	Fail	0
	1 D	Y	25.95	5.5	N	83	Pass	72
	2 A	N	36.09	5.9	N	83	Pass	39
	2 A	N	38.59	5.9	N	83	Pass	45
	2 A	N	33.59	5.9	N	83	Fail	0
	2 B	N	20.95	5.6	N	83	Pass	46
	2 B	N	15.95	5.6	N	83	Fail	0
	2 B	N	18.45	5.6	N	83	Fail	0
	2 C	N	36.09	5.8	N	83	Pass	41
	2 C	N	38.59	5.8	N	83	Pass	48
	2 C	N	33.59	5.8	N	83	Fail	0
	2 D	N	20.95	5.5	N	83	Pass	72
	2 D	N	15.95	5.5	N	83	Pass	53
	2 D	N	8.45	5.5	N	83	Pass	38
	2 D	N	10.95	5.5	N	83	Pass	72
	2 D	N	5.95	5.5	N	83	Fail	0
	3 A	N	25.95	2.6	N	83	Fail	0
	3 A	N	25.95	8.9	N	83	Pass	42
	3 B	N	25.95	3.1	N	83	Fail	0
	3 B	N	25.95	7.9	N	83	Pass	48
	3 C	N	25.95	8.1	N	83	Pass	45
	3 C	N	25.95	3.4	N	83	Fail	0
	3 D	N	25.95	7.1	N	83	Pass	72
	3 D	N	25.95	3.9	N	83	Pass	37
	3 D	N	25.95	3.6	N	83	Fail	0

This intersection category includes a total of 42 simulations. The simulations show that the curb radii and average lane width vary between 5.95 meters to 38.59 meters and 2.6 meters to 8.9 meters, respectively. The intersection angle is 95 degrees for the major road to minor road (Britannia Rd East to Atlantic Dr South) direction, and 83 degrees for the minor road to major road (Atlantic Dr South to Britannia Rd West) direction. The maximum achievable speed for right-turn movements is 72 km/h. In total, this intersection category has a passing rate of 55% for right-turn movements.

5.1.3. T Intersection

Table 11 shows the results of the simulation scenarios for the T intersection.

Table 11 Simulation results for T intersection

Direction	Scenario	Default attributes	Curb radius (m)	Avg. lane width (m)	Channel	Int. angle (degree)	Status	Max. speed (km/h)
Major Road to Minor Road (Derry Road West to Torbram Rd)	1 A	Y	30.76	4.7	Y	95	Fail	0
	1 B	Y	30.76	5.0	Y	95	Pass	35
	1 C	Y	30.76	4.7	Y	95	Fail	0
	1 D	Y	30.76	5.0	Y	95	Pass	39
	2 A	N	18.94	4.7	Y	95	Fail	0
	2 A	N	35.76	4.7	Y	95	Fail	0
	2 A	N	48.26	4.7	Y	95	Pass	36
	2 A	N	40.76	4.7	Y	95	Fail	0
	2 A	N	45.76	4.7	Y	95	Fail	0
	2 A	N	50.76	4.7	Y	95	pass	1
	2 B	N	18.94	5.0	Y	95	Fail	0
	2 B	N	25.76	5.0	Y	95	Fail	0
	2 B	N	23.94	5.0	Y	95	Fail	0
	2 B	N	28.94	5.0	Y	95	Fail	0
	2 B	N	29.94	5.0	Y	95	Pass	35
	2 C	N	33.26	4.7	Y	95	Pass	37
	2 C	N	18.94	4.7	Y	95	Fail	0
	2 C	N	23.94	4.7	Y	95	Fail	0
	2 C	N	28.94	4.7	Y	95	Fail	0
	2 C	N	35.76	4.7	Y	95	Pass	36
	2 D	N	18.94	5.0	Y	95	Fail	0
	2 D	N	23.94	5.0	Y	95	Pass	36
	2 D	N	21.44	5.0	Y	95	Pass	39
	3 A	N	30.76	2.5	Y	95	Fail	0
	3 A	N	30.76	9.9	Y	95	Pass	41
	3 A	N	30.76	7.3	Y	95	Pass	38
	3 B	N	30.76	8.9	Y	95	Pass	44
	3 B	N	30.76	4.2	Y	95	Fail	0
	3 B	N	30.76	3.4	Y	95	Fail	0
	3 C	N	30.76	6.4	Y	95	Pass	37
	3 C	N	30.76	8.7	Y	95	Pass	44
	3 C	N	30.76	3.1	Y	95	Fail	0
	3 D	N	30.76	7.6	Y	95	Pass	45
	3 D	N	30.76	3.9	Y	95	Pass	4
	3 D	N	30.76	3.7	Y	95	Fail	0
	4 A	N	30.76	4.7	N	95	Fail	0
	4 B	N	30.76	5.0	N	95	Pass	35
	4 C	N	30.76	4.7	N	95	Pass	40
	4 D	N	30.76	5.0	N	95	Pass	38
Minor Road to Major Road (Torbram Rd to Derry Rd West)	1 A	Y	29.99	5.6	Y	82	Fail	0
	1 B	Y	29.99	5.3	Y	82	Pass	38
	1 C	Y	29.99	5.4	Y	82	Fail	0
	1 D	Y	29.99	5.1	Y	82	Pass	42
	2 A	N	37.49	5.6	Y	82	Pass	43
	2 A	N	18.94	5.6	Y	82	Fail	0
	2 A	N	34.99	5.6	Y	82	Fail	0

Direction	Scenario	Default attributes	Curb radius (m)	Avg. lane width (m)	Channel	Int. angle (degree)	Status	Max. speed (km/h)
	2 A	N	39.99	5.6	Y	82	Pass	37
	2 B	N	18.94	5.3	Y	82	Fail	0
	2 B	N	29.44	5.3	Y	82	Pass	38
	2 B	N	23.94	5.3	Y	82	Fail	0
	2 B	N	28.94	5.3	Y	82	Fail	0
	2 C	N	18.94	5.4	Y	82	Fail	0
	2 C	N	34.99	5.4	Y	82	Pass	38
	2 C	N	32.49	5.4	Y	82	Pass	39
	2 D	N	21.44	5.1	Y	82	Pass	38
	2 D	N	18.94	5.1	Y	82	Fail	0
	2 D	N	23.94	5.1	Y	82	Pass	18
	3 A	N	29.99	10.9	Y	82	Pass	51
	3 A	N	29.99	2.5	Y	82	Fail	0
	3 A	N	29.99	8.2	Y	82	Pass	39
	3 B	N	29.99	4.2	Y	82	Fail	0
	3 B	N	29.99	9.2	Y	82	Pass	45
	3 B	N	29.99	2.9	Y	82	Fail	0
	3 C	N	29.99	7.2	Y	82	Pass	40
	3 C	N	29.99	9.4	Y	82	Pass	41
	3 C	N	29.99	3.1	Y	82	Fail	0
	3 D	N	29.99	4.3	Y	82	Pass	36
	3 D	N	29.99	7.7	Y	82	Pass	46
	3 D	N	29.99	3.5	Y	82	Fail	0
	4 A	N	29.99	5.6	N	82	Pass	9

This intersection category includes a total of 70 simulations. The simulations show that the curb radii and average lane width vary between 18.94 meters to 50.76 meters and 2.5 meters to 10.9 meters. The intersection angle is 95 degrees for the major road to the minor road (Derry Road West to Torbram Rd) direction, and 83 degrees for the minor road to major road (Torbram Rd to Derry Rd West) direction. The maximum achievable speed for right-turn movements is 51 km/h. In total, this intersection category has a passing rate of 51.4% for right-turn movements. The removal of channelization islands facilitates the turning movement of LCVs in this intersection category, especially in the major road to the minor road direction.

5.1.4. Roundabout

Table 12 shows the results of the simulation scenarios for the Roundabout.

Table 12 Simulation results for Roundabout

Direction	Scenario	Default attributes	Curb radius (m)	Avg. lane width (m)	Channel	Int. angle (degree)	Status	Max. speed (km/h)
Right-turn (Olde Base Line Rd East to Dixie Rd South)	1 A	Y	35.73	6.8	Y	93	Pass	35
	2 A	N	38.23	6.8	Y	93	Pass	37
	2 A	N	40.73	6.8	Y	93	Pass	40
	2 A	N	36.98	6.8	Y	93	Pass	35
	2 A	N	36.35	6.8	Y	93	Pass	35
	2 A	N	30.73	6.8	Y	93	Fail	0
	2 A	N	33.23	6.8	Y	93	Fail	0
	3 A	N	35.73	10.2	Y	93	Pass	43
	3 A	N	35.73	3.0	Y	93	Fail	0
	3 A	N	35.73	4.8	Y	93	Fail	0
Through movement (Olde Base Line Rd)	1 A	Y	35.01	6.8	Y	180	Fail	0
	2 A	N	40.01	6.8	Y	180	Pass	37
	2 A	N	37.5	6.8	Y	180	Fail	0
	2 A	N	38.75	6.8	Y	180	Fail	0
	3 A	N	35.01	10.2	Y	180	Pass	40
	3 A	N	35.01	3.1	Y	180	Fail	0
	3 A	N	35.01	8.5	Y	180	Pass	35

This intersection category includes a total of 17 simulations. The right-turning simulations show that the curb radii and average lane width vary between 30.73 meters to 40.73 meters and 3.0 meters to 10.2 meters. The intersection angle for right-turning is 93 degrees. The maximum achievable speed for right-turn movements is 43 km/h. In total, this intersection category has a passing rate of 60% for the right-turning simulation scenarios. Unlike other intersection types, roundabout did not have any major road to minor road or minor road to major road movement direction for right-turn movements.

The through movement simulations show that the curb radii and average lane width vary between 35.01 meters to 40.01 meters and 3.1 meters to 10.2 meters. The maximum achievable speed for through movements is 40 km/h. In total, this intersection category has a passing rate of 42.85% for the through movement simulation scenarios.

5.1.5. Oblique Intersection

Table 13 shows the results of the simulation scenarios for the Oblique intersection.

Table 13 Simulation results for Oblique intersection

Direction	Scenario	Default attributes	Curb radius (m)	Avg. lane width (m)	Channel	Int. angle (degree)	Status	Max. speed (km/h)
Major Road to Minor Road (West Dr South to Orenda Rd West)	1 A	Y	20.40	8.1	Y	100	Fail	0
	1 B	Y	20.40	7.0	Y	100	Fail	0
	1 C	Y	20.40	7.1	Y	100	Fail	0
	1 D	Y	20.40	6.0	Y	100	Fail	0
	2 A	N	30.40	8.1	Y	100	Pass	36
	2 A	N	27.9	8.1	Y	100	Pass	38
	2 A	N	25.40	8.1	Y	100	Fail	0
	2 B	N	25.40	7.0	Y	100	Pass	36
	2 B	N	30.40	7.0	Y	100	Pass	42
	2 B	N	22.90	7.0	Y	100	Fail	0
	2 C	N	30.40	7.1	Y	100	Pass	44
	2 C	N	25.40	7.1	Y	100	Pass	42
	2 C	N	22.90	7.1	Y	100	Fail	0
	2 D	N	30.40	6.0	Y	100	Pass	40
	2 D	N	25.40	6.0	Y	100	Pass	43
	2 D	N	22.90	6.0	Y	100	Fail	0
	3 A	N	20.40	11.2	Y	100	Pass	38
	3 A	N	20.40	2.2	Y	100	Fail	0
	3 A	N	20.40	9.6	Y	100	Fail	0
	3 B	N	20.40	8.1	Y	100	Pass	36
	3 B	N	20.40	9.4	Y	100	Pass	40
	3 B	N	20.40	2.6	Y	100	Fail	0
	3 C	N	20.40	8.2	Y	100	Pass	38
	3 C	N	20.40	9.5	Y	100	Pass	40
	3 C	N	20.40	2.8	Y	100	Fail	0
	3 D	N	20.40	6.8	Y	100	Pass	41
	3 D	N	20.40	7.6	Y	100	Pass	48
	3 D	N	20.40	3.6	Y	100	Fail	0
	4 A	N	20.40	8.1	N	100	Fail	0
	4 B	N	20.40	7.0	N	100	Pass	39
	4 C	N	20.40	7.1	N	100	Pass	41
	4 D	N	20.40	6.0	N	100	Pass	44
Minor Road to Major Road (West Dr South to Orenda Rd West)	1 A	Y	23.76	6.6	N	68	Fail	0
	1 B	Y	23.76	6.1	N	68	Fail	0
	1 C	Y	23.76	6.1	N	68	Pass	37
	1 D	Y	23.76	5.7	N	68	Pass	38
	2 A	N	36.26	6.6	N	68	Fail	0
	2 A	N	28.76	6.6	N	68	Fail	0
	2 A	N	33.76	6.6	N	68	Fail	0
	2 A	N	38.76	6.6	N	68	Pass	39
	2 B	N	38.76	6.1	N	68	Pass	39
	2 B	N	28.76	6.1	N	68	Fail	0
	2 B	N	31.26	6.1	N	68	Pass	43
	2 B	N	33.76	6.1	N	68	Pass	38
	2 C	N	21.26	6.1	N	68	Fail	0

Direction	Scenario	Default attributes	Curb radius (m)	Avg. lane width (m)	Channel	Int. angle (degree)	Status	Max. speed (km/h)
	2 C	N	18.76	6.1	N	68	Fail	0
	2 C	N	28.76	6.1	N	68	Pass	40
	2 D	N	18.76	5.7	N	68	Pass	37
	2 D	N	13.76	5.7	N	68	Fail	0
	2 D	N	16.26	5.7	N	68	Pass	39
	3 A	N	23.76	2.2	N	68	Fail	0
	3 A	N	23.76	9.7	N	68	Pass	39
	3 A	N	23.76	8.1	N	68	Fail	0
	3 B	N	23.76	7.1	N	68	Pass	36
	3 B	N	23.76	8.4	N	68	Pass	39
	3 B	N	23.76	2.8	N	68	Fail	0
	3 C	N	23.76	2.9	N	68	Fail	0
	3 C	N	23.76	4.6	N	68	Pass	38
	3 C	N	23.76	8.5	N	68	Pass	45
	3 D	N	23.76	4.5	N	68	Pass	41
	3 D	N	23.76	7.2	N	68	Pass	50
	3 D	N	23.76	3.4	N	68	Fail	0

This intersection category includes a total of 62 simulations. The simulations show that the curb radii and average lane width vary between 13.76 meters to 38.76 meters and 2.2 meters to 11.2 meters. The intersection angle is 100 degrees for the major road to minor road (West Dr South to Orenda Rd West) direction, and 68 degrees for the minor road to major road (West Dr South to Orenda Rd West) direction. The maximum achievable speed for right-turn movements is 50 km/h. In total, this intersection category has a passing rate of 54.8% for right-turn movements. The removal of channelization islands facilitates the turning movement of LCVs in this intersection category, especially in the major road to the minor road direction.

5.1.6. Offset Intersection

Table 14 shows the results of the simulation scenarios for the Offset intersection.

Table 14 Simulation results for Offset intersection

Direction	Scenario	Default attributes	Curb radius (m)	Avg. lane width (m)	Channel	Int. angle (degree)	Status	Max. speed (km/h)
Major Road to Minor Road (Olde Base Line Rd East to Kennedy Rd South)	1 A	Y	19.05	7.0	N	97	Fail	0
	2 A	N	24.05	7.0	N	97	Fail	0
	2 A	N	29.05	7.0	N	97	Pass	36
	2 A	N	26.55	7.0	N	97	Fail	0
	3 A	N	19.05	8.9	N	97	Fail	0
	3 A	N	19.05	9.4	N	97	Fail	0
	3 A	N	17.56	9.9	N	97	Pass	35
Minor Road to Major Road (Kennedy Rd South to Olde Base Line Rd West)	1 A	Y	21.67	5.7	N	83	Fail	0
	2 A	N	26.67	5.7	N	83	Fail	0
	2 A	N	31.67	5.7	N	83	Pass	35
	2 A	N	29.17	5.7	N	83	Pass	37
	3 A	N	21.67	2.7	N	83	Fail	0
	3 A	N	21.67	7.2	N	83	Fail	0
	3 A	N	21.67	8.7	N	83	Pass	35
Through movement (Olde Base Line Rd)	1 A	Y	20.36	5.6	N	180	Fail	0
	2 A	N	25.36	5.6	N	180	Fail	0
	2 A	N	30.36	5.6	N	180	Pass	35
	2 A	N	22.86	5.6	N	180	Fail	0
	3 A	N	20.36	7.6	N	180	Fail	0
	3 A	N	20.36	8.6	N	180	Pass	39
	3 A	N	20.36	8.1	N	180	Pass	37

This intersection category includes a total of 21 simulations. The right-turning simulations show that the curb radii and average lane width vary between 17.56 meters to 31.67 meters and 2.7 meters to 9.9 meters. The intersection angle is 97 degrees for the major road to minor road (Olde Base Line Rd East to Kennedy Rd South) direction and 83 degrees for the minor road to major road (Kennedy Rd South to Olde Base Line Rd West) direction. The maximum achievable speed for right-turn movements is 37 km/h. In total, this intersection category has a passing rate of 36% for right-turn movements.

The through movement simulations show that the curb radii and average lane width vary between 20.36 meters to 30.36 meters and 5.6 meters to 8.6 meters. The maximum achievable speed for through movements is 39 km/h. In total, this intersection category has a passing rate of 42.85% for the through movement simulation scenarios.

5.1.7. Y Intersection

Table 15 shows the results of the simulation scenarios for the Y intersection.

Table 15 Simulation results for Y intersection

Direction	Scenario	Default attributes	Curb radius (m)	Avg. lane width (m)	Channel	Int. angle (degree)	Status	Max. speed (km/h)
Major Road to Minor Road (Lakeshore Rd West to Lorne Park Rd)	1 A	Y	17.91	5.5	N	47	Pass	8
	1 C	Y	17.91	5.4	N	47	Pass	44
	2 A	N	12.91	5.5	N	47	Fail	0
	2 A	N	15.41	5.5	N	47	Fail	0
	2 C	N	12.91	5.4	N	47	Pass	0
	2 C	N	10.41	5.4	N	47	Pass	44
	2 C	N	7.91	5.4	N	47	Fail	0
	3 A	N	17.91	2.5	N	47	Fail	0
	3 A	N	17.91	4.0	N	47	Fail	0
	3 A	N	17.91	10.6	N	47	Pass	43
	3 C	N	17.56	3.2	N	47	Fail	0
	3 C	N	17.91	4.4	N	47	Pass	37
Minor Road to Major Road (Lorne Park Rd to Lakeshore Rd West)	1 A	Y	17.25	6.1	Y	133	Fail	0
	1 B	Y	17.25	5.7	Y	133	Fail	0
	2 A	N	22.25	6.1	Y	133	Fail	0
	2 A	N	24.75	6.1	Y	133	Fail	0
	2 A	N	27.25	6.1	Y	133	Pass	36
	2 B	N	27.25	5.7	Y	133	Pass	40
	2 B	N	24.75	5.7	Y	133	Pass	36
	2 B	N	22.25	5.7	Y	133	Fail	0
	3 A	N	17.25	8.7	Y	133	Fail	0
	3 A	N	17.25	11.3	Y	133	Pass	36
	3 B	N	17.25	7.6	Y	133	Fail	0
	3 B	N	17.25	9.6	Y	133	Pass	38
	4 A	N	17.25	6.1	N	133	Fail	0

This intersection category includes a total of 25 simulations. The simulations show that the curb radii and average lane width vary between 7.91 meters to 27.25 meters and 2.5 meters to 11.3 meters. The intersection angle is 47 degrees for the major road to minor road (Lakeshore Rd West to Lorne Park Rd) direction and 33 degrees for the minor road to major road (Lorne Park Rd to Lakeshore Rd West) direction. The maximum achievable speed for right-turn movements is 44 km/h. In total, this intersection category has a passing rate of 44% for right-turn movements. Lastly, this intersection category does not benefit from removing channelization islands.

5.2. Curb Radii

Visualization of simulation results for curb radii is represented together in Appendix B to show successful LCV right-turn maneuvering based on Scenario 1 and Scenario 2. However, the individual results by intersection are represented in Figures 27 to 34. Two columns represent a turn's movement from either a major road to a minor road or a minor road to a major road. The figure presents each simulation's pass or fail status as the curve radius is changed. A smaller radius decreased the chances of successful maneuvering; therefore, the failure result is shown on the left side of each bar. With increasing radius, the result of the simulations switches to indicate a successful maneuver identified as ‘passing.’ Therefore, the right side of each bar shows a pass result. Someplace in the middle of each bar is an inflection point representing the shift from fail to pass. A lower radius for this inflection point is typically preferred since this allows an intersection to be designed using less space and has additional positive safety implications.

Each bar in Figures 27 to 34 represents one of the four conditions pertaining to lane restrictions discussed in Section 4.3. The red region of a bar represents the inability of an LCV to make a right-turn without conflict successfully. Conversely, the green region of a bar represents a range of values that the LCV can successfully make the turn. Points or triangles on each bar represent the curb radii for individual simulations. The triangle indicates the curb radius of the existing intersection layout. Circular points represent other simulation runs.

5.2.1. Curb Radii Results by Intersection Type

Figure 27 shows the simulation results of curb radii for the 4-legged right-angled with channelization intersection. The existing curb radii for the major road to minor and minor road to major road are 39.5 meters and 40.2 meters, respectively. For both directions, the existing curb radii pass in all the conditions. In both directions, Condition D performs better than Condition A. However, for the minor road to major road direction, Condition B performs better than all the other conditions. This unexpected result is unique among all other intersections since Condition D is expected to produce the best outcome.

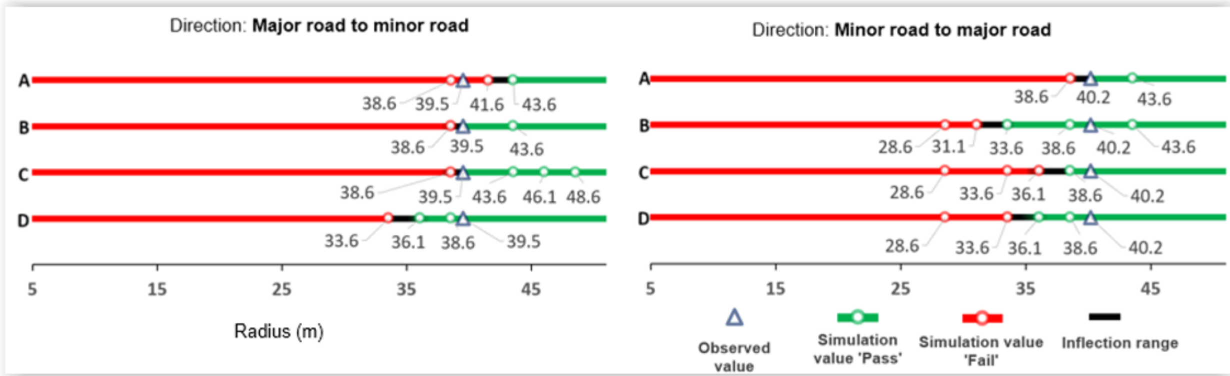


Figure 27 Curb radii (m) for 4-legged right-angled with channelization intersection

Figure 28 shows the simulation results of curb radii for the 4-legged right-angled intersection. The existing curb radii for the major road to minor and minor road to major road are 24.4 meters and 26 meters, respectively. For the minor road to major road direction, Condition D performs better than Condition A. Condition C performs better than Condition A for the major road to minor road direction. Condition D and Condition B are absent for this direction as the receiving lane only has a single lane.

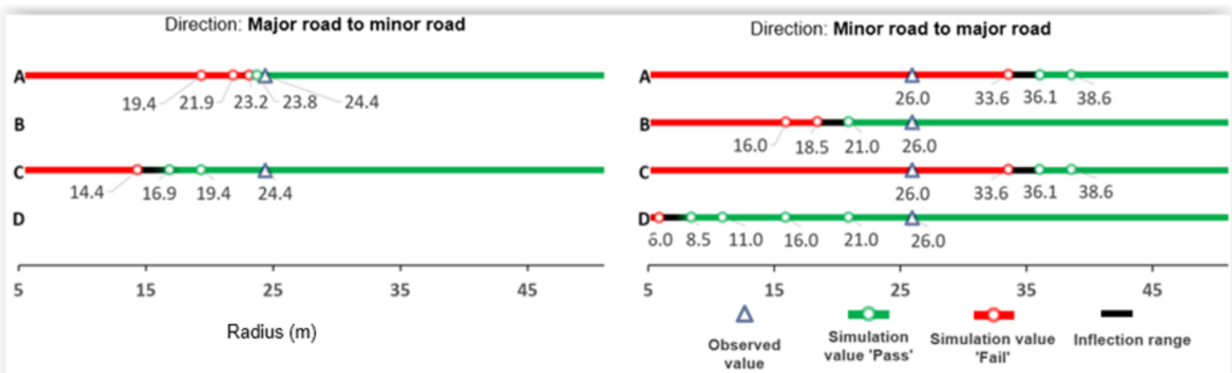


Figure 28 Curb radii (m) for 4-legged right-angled intersection

Figure 29 shows the simulation results of curb radii for the T intersection. The existing curb radii for the major road to minor and minor road to major road are 30.8 meters and 30 meters, respectively. In both directions, Condition D performs better than Condition A.

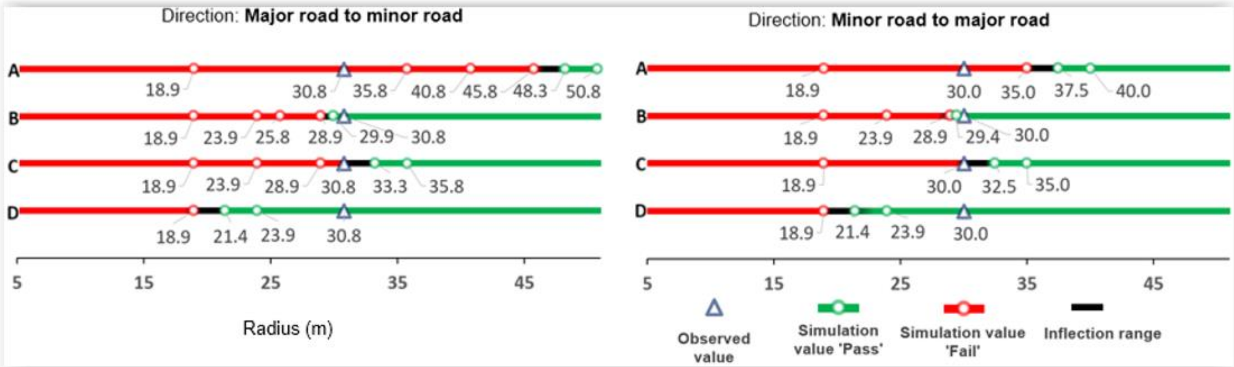


Figure 29 Curb radii (m) for T intersection

Figure 30 shows the simulation results of curb radii for the Oblique intersection. The existing curb radii for the major road to minor and minor road to major road are 20.4 meters and 23.8 meters, respectively. In both directions, Condition D performs better than Condition A.

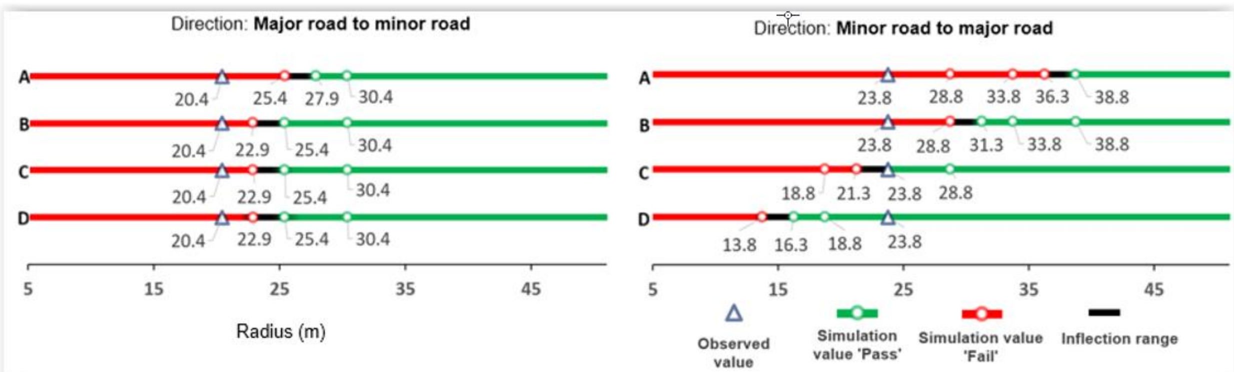


Figure 30 Curb radii (m) for Oblique intersection

Figure 31 shows the simulation results of curb radii for the Offset intersection. The existing curb radii for the major road to minor and minor road to major road are 19.1 meters and 21.7 meters, respectively. This intersection only has a single lane in both directions.

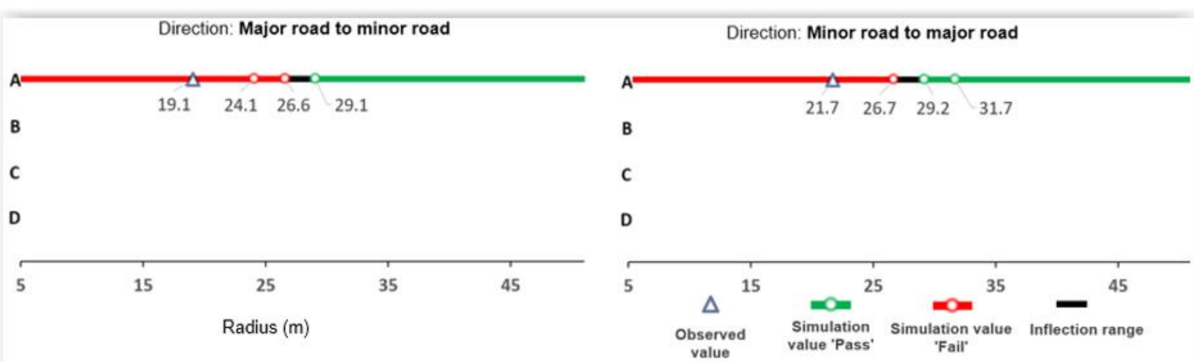


Figure 31 Curb radii (m) for Offset intersection

Figure 32 shows the simulation results of curb radii for the Y intersection. The existing curb radii for the major road to minor and minor road to major road are 17.9 meters and 17.3 meters, respectively. This intersection has two approaching lanes and one receiving lane in the major road to the minor road direction and two receiving lanes and one approaching lane in the minor road to the major road direction. The existing curb radii pass for the major to the minor road direction, but they fail for the minor road to the major road direction.

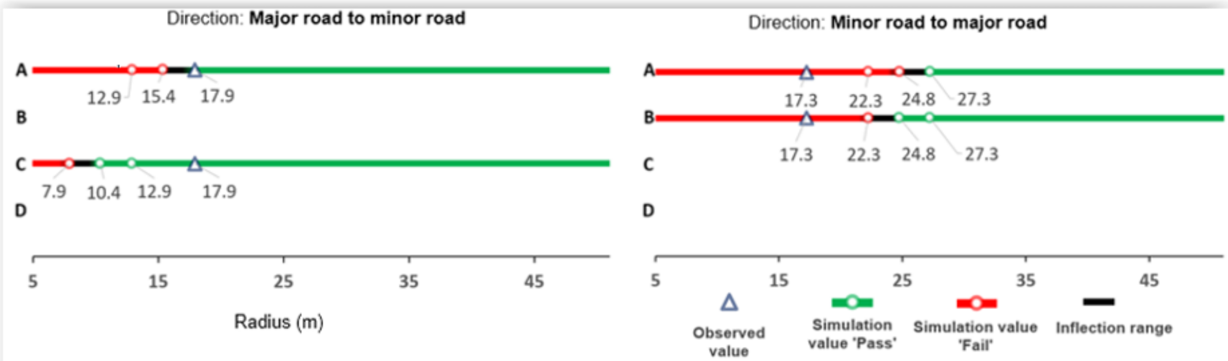


Figure 32 Curb radii (m) for Y intersection

Figure 33 shows the simulation results of curb radii for the Roundabout. The existing curb radius for the major road to minor is 35.7 meters. Only Condition A was tested for the roundabout's major road to minor road direction. Availability of only one lane prevented the inclusion of other conditions. In addition, the intersection had an almost symmetric layout, which made it redundant to test a direction for the minor road to the major road. The existing curb radius was passing for Condition A in the roundabout.

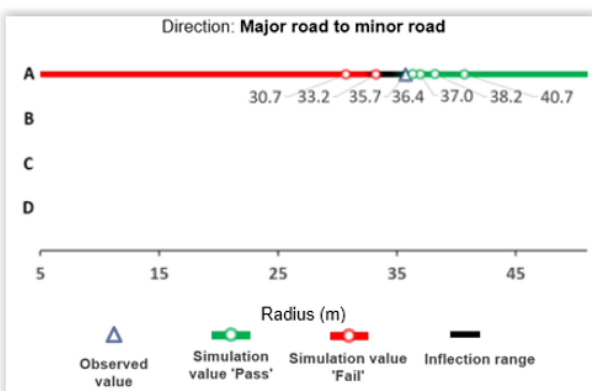


Figure 33 Curb radii (m) for Roundabout

Through movements are tested for the roundabout and offset intersections to examine how they differ from right-turn movements. Only Condition A is applicable for both intersections since they only have one lane available in each direction. Figure 34 shows that LCVs cannot make the through movement at both the roundabout and offset intersections for the existing turning radius. For the roundabout intersection, the existence of a curbed inner circle radius forces the LCVs to deviate from their original trajectory and creates difficulties for the completion of through movements. A truck apron, or gently raised curb, can provide additional space for the LCV to complete the maneuver while still maintaining a restricted turn for smaller vehicles. For the cases of offset intersections, the alignment of the back and forward lanes cause the LCVs to deviate from a straight line.

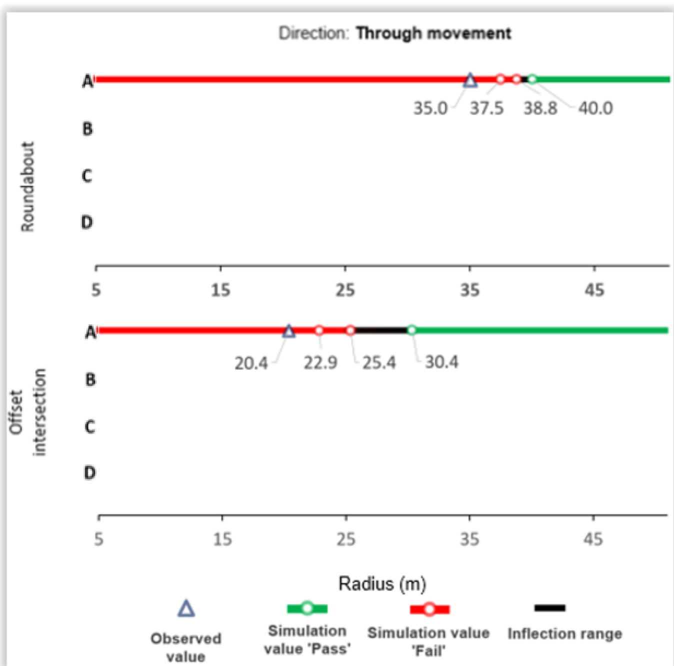


Figure 34 Simulation results based on curb radii (m) for through movements

5.2.2. Curb Radii Summary

For turning radii, in approximately 50% of cases (18 out of 35 cases), the existing layout of the intersection accommodates LCV turning movements. A critical finding from this result is that Condition D has an 85% passing success rate (6 out of 7 cases) for the existing intersection layouts. This implies that allowing extra lanes for LCV movements can be beneficial. Utilizing the added space from existing lanes will consequently reduce the need to reconstruct an intersection to accommodate LCVs. The oblique intersection is the only case where Condition D fails for the current layout. The T-intersection requires the most substantial adjustment to the turning radius of the existing layout. In Condition A, an extra 17.5 meters of turning radius is needed to obtain a passing status for the major to minor direction.

In 9 out of 10 cases, simulations with Condition A perform worse than all other conditions. This matches expectations since Condition A limits the vehicle to only use the right-most lane for the entire maneuver, while the other conditions provide additional space. In 4 out of 7 cases where Conditions B and C are possible, Condition B performs better than Condition C with a lower radius required for a passing result. Conversely, Condition C outperforms Condition B in only 1 out of 7 observed cases, occurring for the minor to the major direction in the oblique intersection. The intersection angle of the oblique intersection at 68 degrees is noted as a likely cause of this issue.

Condition D, where two lanes are permitted for the entire turn, performs best in 5 out of 7 cases as expected. However, exceptions are present in two cases. First, the 4-legged right-angled intersection shows Condition B performing better than Condition D in the minor to major direction. Secondly, Conditions B, C, and D perform equally for the oblique intersection major road to minor road direction.

The minimum radius required for a passing result varied by intersection from 10.4 meters at the Y intersection (Condition C) to 48.3 meters at the T intersection (Condition A). The range of values required for successful maneuvering is likely due to a unique combination of variables at each intersection. The next variable discussed for this analysis is lane width.

5.3. Lane Widths

The lane widths in this section are calculated as follows. The width per lane is calculated separately for the approach (back) and the receiving (forward) lanes in any given condition. This value is then averaged to obtain a single value. For example, Condition D has two lanes for both the approach and the receiving lanes. If the total width of the approach lanes is measured as 8 meters, and the total width of the receiving lanes is measured as 10 meters, then the average width per lane is calculated as 4.5 meters (average of 8 meters / 2 lanes + 10 meters / 2 lanes). This provides a suitable comparison across all four conditions.

Visualization of simulation results for lane widths is represented together in Appendix C to show successful LCV right-turn maneuvering based on Scenario 1 and Scenario 3. However, the individual results by intersection are represented in Figures 35 to 42. Two columns represent a turn's movement from either a major road to a minor road or a minor road to a major road. The figure presents each simulation's pass or fail status as the lane width is changed. A smaller width decreased the chances of successful maneuvering; therefore, the failure result is shown on the left side of each bar. With increasing width, the result of the simulations switches to indicate a successful maneuver identified as 'passing.' Therefore, the right side of each bar shows a pass result. Someplace in the middle of each bar is an inflection point representing the shift from fail to pass. A lower width for this inflection point is typically preferred since this allows an intersection to be designed using less space and has additional positive safety implications.

Each bar in Figures 35 to 42 represents one of the four conditions pertaining to lane restrictions discussed in Section 4.3. The red region of a bar represents the inability of an LCV to make a right-turn without conflict successfully. Conversely, the green region of a bar represents a range of values that the LCV can successfully make the turn. Points or triangles on each bar represent the lane widths for individual simulations. The triangle indicates the lane width of the existing intersection layout. Circular points represent other simulation runs.

5.3.1. Lane Width Results by Intersection Type

Figure 35 shows the average lane widths simulation results for the 4-legged right-angled with channelization intersection for the major road to minor and minor road to major road directions. In both directions, Condition D performs better than Condition A. However, Condition B performs best in both directions. As with the curb radii analysis, this unexpected result is unique among all other intersections since Condition D is expected to produce the best outcome.

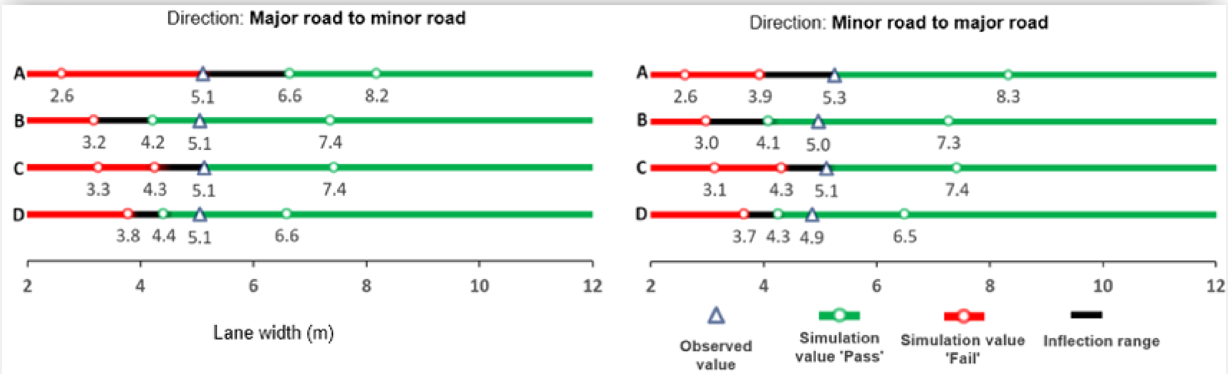


Figure 35 Average lane widths (m) for 4-legged right-angled with channelization intersection

Figure 36 shows the simulation results of average lane widths for the 4-legged right-angled intersection for the major road to minor and minor road to major road directions. In both directions, Condition D performs better than Condition A. Condition C performs better than Condition A for the major road to minor road direction. Condition D and Condition B are absent for this direction as the receiving lane only had a single lane.

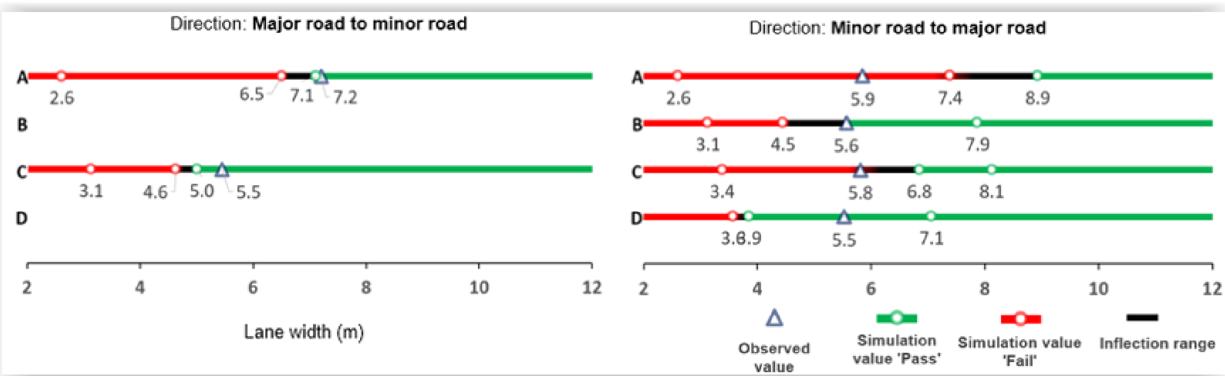


Figure 36 Average lane widths (m) for 4-legged right-angled intersection

Figure 37 shows the simulation results of average lane widths for the T intersection for the major road to minor and minor road to major road directions. In both directions, Condition D performs better than Condition A. However, for the minor road to major road direction, Condition B performs better than all the other conditions.

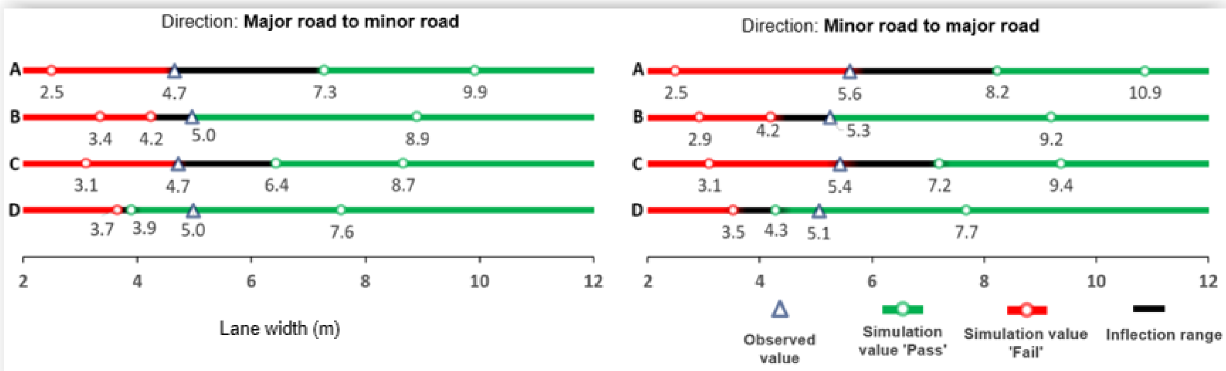


Figure 37 Average lane widths (m) for T intersection

Figure 38 shows the simulation results of average lane widths for the Oblique intersection for the major road to minor and minor road to major road directions. In both directions, Condition D performs better than Condition A.

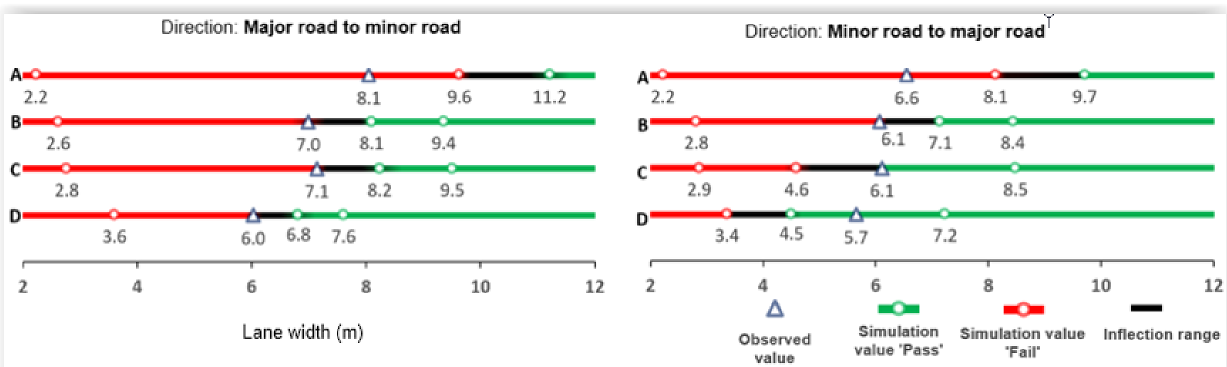


Figure 38 Average lane widths (m) for Oblique intersection

Figure 39 shows the simulation results of lane widths for the Offset intersection. This intersection only has a single lane in both directions. Existing average lane widths are failing at both directions for Condition A.

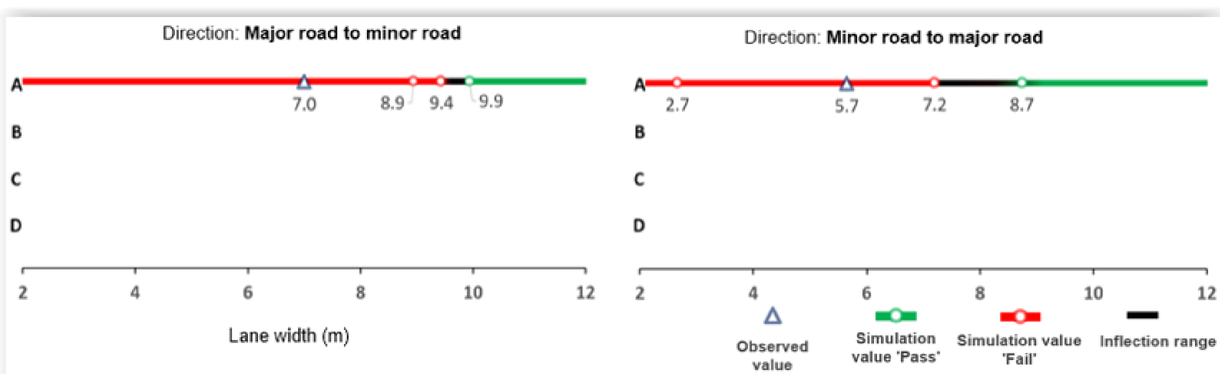


Figure 39 Average lane widths (m) for Offset intersection

Figure 40 shows the simulation results of average lane widths for the Y intersection. Due to the available number of lanes, Condition C is possible for the major road to minor road direction, but Condition B is possible for the minor road to major road direction. The existing layout for the major road to minor road direction results in a passing simulation status, but it fails for the minor road to major road direction.

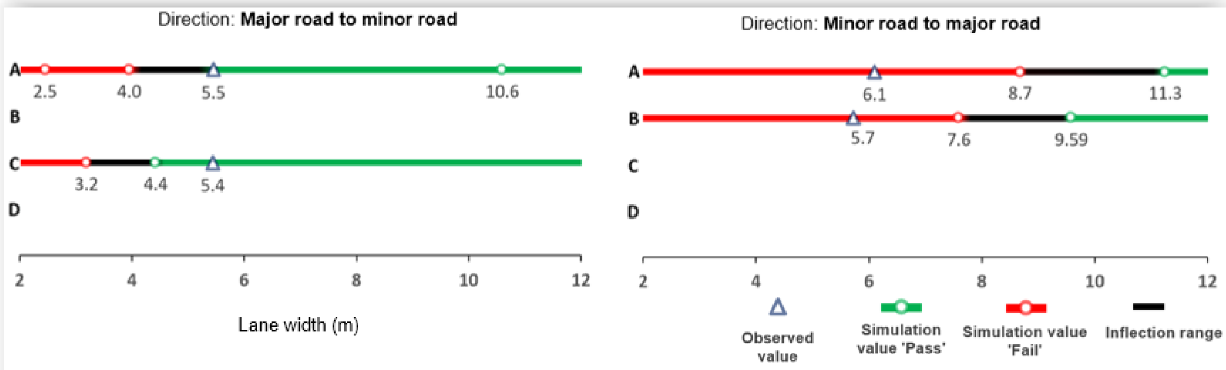


Figure 40 Average lane widths (m) for Y intersection

Figure 41 shows the simulation results of average lane widths for the Roundabout intersection. Only Condition A was tested for the major road to minor road direction. Availability of only one lane prevented the inclusion of other conditions. In addition, the intersection has a nearly symmetric layout, which made it redundant to test the minor road to major road direction. The existing average lane width received a passing status for Condition A in the roundabout.

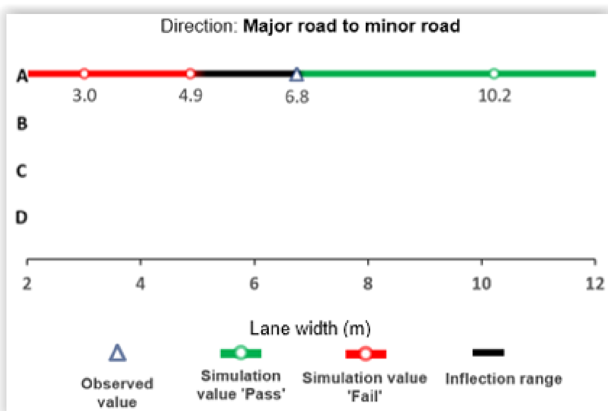


Figure 41 Average lane widths (m) for Roundabout

For two intersections, including roundabout and offset, the through movements are tested in AutoTURN to observe the impact of average lane widths on these maneuvers. These two intersections only included Condition A, with Figure 42 showing that LCVs cannot make the through movements for existing average lane widths.

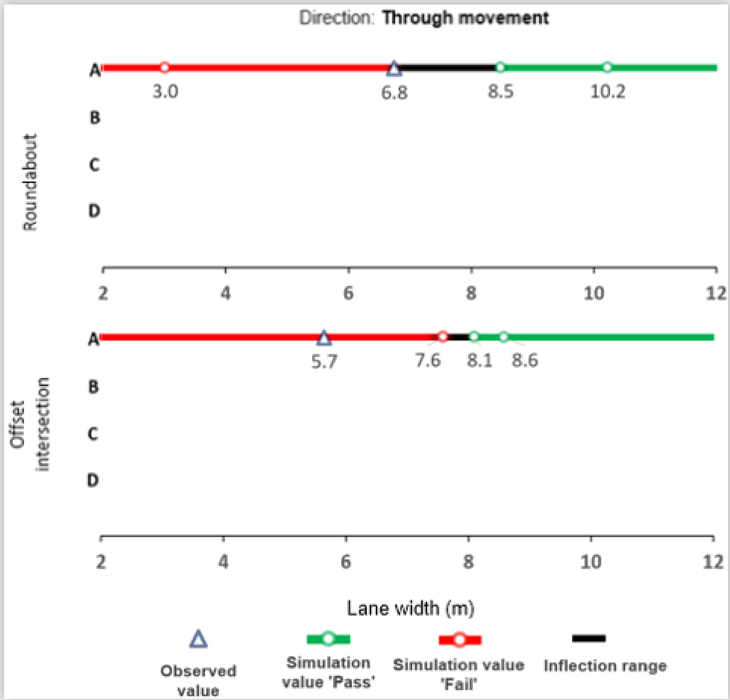


Figure 42 Simulation results based on average lane widths (m) for through movements

5.3.2. Lane Width Summary

For average lane widths, in more than 50% of cases (19 out of 35 cases), the existing layout of the intersection accommodates LCV turning movements. A critical finding from this result is that Condition D has an 85% success rate (6 out of 7 cases) for the existing layout, which implies that adding extra lanes in both back and forward lanes will be beneficial for LCVs. The oblique intersection is the only case where Condition D fails for the existing layout. The Y intersection requires the most substantial adjustment to the existing layout to obtain a passing result when the average lane width is considered. An additional 5.2 meters of average lane width is needed for the minor to major direction.

Condition A performs the worst in all cases (10 out of 10 cases). The roundabout and offset intersections are excluded because only Condition A is viable. The implication is that only one lane for LCV movements is always sub-optimal compared to the other conditions.

Another trend observed for the average lane widths is that Condition B performs better than Condition C in most cases (6 out 7 cases). This means that adding an extra lane to the forward segment is generally better than adding an extra lane to the back segment. One exception is observed for the Oblique intersection, where Condition C performs better than Condition B for the minor to major direction. The intersection angle of the oblique intersection is suspected as the cause of this result.

One of the major trends found from the simulation results is that Condition D performs better than all other conditions in most cases (5 out 7 cases). The two exceptions are observed in both directions for the 4-legged right-angled channelization intersection, where Condition B performs better than Condition D.

The general pattern for the observed values of the existing conditions is similar for both turning radii and average lane widths. The main finding from this analysis is that Condition A is always performing worse than Condition D, which means LCV turning movements with only one lane are problematic for many of the case study intersections in this research.

5.4. Binomial Logit Model Results

This study includes a total of five binomial models for right-turning movements: all intersections (Model 1), 4-legged with channel (Model 2), 4-legged (Model 3), T intersection (Model 4), and Oblique intersection (Model 5). Continuous independent variables that are added to the models include *Radius* (curb radii), *Width* (average lane widths), and *Intersection angle*. In addition, nine dummy variables with values of zero (false) or one (true) are considered, including *Width 2m to 4m, Condition A, Condition D, Intersection: 4-legged, Intersection: 4-legged with channel, Intersection: Roundabout, Intersection: Oblique, Intersection: Offset, and Intersection: Y*.

Table 16 shows the results for these models using NLOGIT software with all variables applied to the pass alternative. As a result, the utility of the other alternative (fail) is zero. The *Radius, Width, Intersection angle, Condition A*, and *Condition D* variables are common for all five models. The intersection dummy variables in Model 1 help capture the heterogeneity across intersection types. Due to smaller sample sizes, the Offset and Y intersections did not have individual models.

Elasticities for the continuous variables are included in the results. Elasticities measured using NLOGIT show the percentage change in the pass alternative when changing the independent variable by one percent. Marginal effects are measured for each dummy variable using NLOGIT as the percentage change in the pass alternative when changing the independent variable by one unit. Appendix D contains the codes used in NLOGIT to develop the models.

Table 16 Binomial logit model results

Variable	Model 1: All intersections	Model 2: 4-legged with channel	Model 3: 4-legged	Model 4: T intersection	Model 5: Oblique intersection
Constant	-13.49 (-6.04***)	-37.87 (-2.94***)	-27.25 (-2.21**)	-118.15 (-2.24**)	-17.81 (-3.16***)
Radius	0.35 (6.63***)	0.76 (3.03***)	0.24 (2.31**)	1.27 (2.49**)	0.37 (3.12***)
Elasticity	4.49	11.51	2.46	17.92	3.98
Width	1.60 (5.85***)	4.05 (2.94***)	1.99 (2.31**)	12.44 (2.3**)	2.14 (3.05***)
Elasticity	3.86	7.13	4.60	28.51	5.64
Width 2m to 4m	-3.31 (-3.11***)				
Marginal effect	-0.39				
Condition A	-3.44 (-5.49***)	-3.87 (-2.43**)	-4.04 (-2.17**)	-15.29 (-2.41**)	-5.21 (-3.21***)
Marginal effect	-0.40	-0.32	-0.58	-0.75	-0.60
Condition D	3.50 (5.11***)	2.43 (1.96*)	4.17 (2.31**)	13.42 (2.37**)	3.57 (2.55**)
Marginal effect	0.41	0.20	0.60	0.67	0.41
Intersection angle	-0.06 (-4.26***)	-0.12 (-1.8*)	0.13 (1.34)	0.19 (1.28)	-0.059 (-1.73*)
Elasticity	-2.43	-4.23	5.01	8.61	-2.30
Intersection: 4-legged	2.49 (3.38***)				
Marginal effect	0.30				
Intersection: 4-legged with channel	-2.33 (-3.38***)				
Marginal effect	-0.27				
Intersection: Roundabout	-0.26 (-0.25)				
Marginal effect	-0.03				
Intersection: Oblique	-0.80 (-1.18)				
Marginal effect	-0.09				
Intersection: Offset	1.43 (1.52)				
Marginal effect	0.17				
Intersection: Y	4.20 (4.29***)				
Marginal effect	0.49				
Observations (N)	272	52	42	65	58
Log-likelihood	-98.04	-15.25	-18.07	-9.98	-20.63
ρ^2	0.48	0.62	0.38	0.78	0.49
adj-ρ^2	0.45	0.57	0.27	0.76	0.43
AIC/N	0.82	0.72	1.14	0.50	0.92

Note 1: All variables are applied to the pass alternatives

Note 2: Results are given in following format-β(t-stat) – parameter coefficient (t statistic)

*Note 3: *, **, *** indicate the parameter is statistically significant with 90%, 95% and 99% confidence respectively*

The results of all the models showed that curb radii, average lane widths, and intersection angles highly affect the passing status of LCV right-turn movements at the intersections. For Model 1, all three parameters of the continuous variables (*Radius*, *Width*, and *Intersection angle*) are statistically significant with more than 99% confidence. The other four models show the same results, where curb radii and average lane widths are statistically significant with at least 95% confidence. Positive coefficients for curb radius and lane width indicate a positive relationship with the pass alternative. Therefore, a higher value for curb radius at a given intersection will have a higher chance of LCVs completing the right-turn movements. The intersection angle variable shows a negative sign, indicating that a higher value will decrease the probability of an LCV successfully making a right-turn movement.

The results of the elasticities in Table 16 suggest that curb radius has a higher impact on the LCVs passing status than average lane width for Model 1 and Model 2. However, the results of the other three models showed the opposite results, where lane widths have a higher impact on the pass alternatives. Model 4, which is for the T intersection, shows the highest elasticity values for both turning radius and lane width among all the models.

The models also provided results pertaining to the dummy variables. A negative coefficient with a statistically significant parameter for *Width 2m to 4m* reflects that the LCVs are more likely to fail to make a right-turn movement for intersections with average lane widths between 2 meters to 4 meters. The model results also indicate that LCVs have a higher chance of completing right-turn movements with *Condition D* and a lower chance with *Condition A*, which further supports earlier discussion on the impact of additional lanes. Lastly, the goodness-of-fit results (ρ^2 values) ranging from 0.38 to 0.78 are suitable for this model type and geometric swept-path context.

5.5. Model Transferability

The model results in Section 5.4 predict the probability of successful LCV right-turn movements for each simulation scenario, leading to the confusion matrices shown in Table 17 when compared with the observed outcomes. The probabilities from the model are converted into a pass or fail outcome based on the alternative exceeding a 50%

threshold.

Table 17 Confusion matrices

	Predicted fail	Predicted pass	Total
Model 1: All intersections			
Observed fail	108 (84%)	21 (16%)	129 (100%)
Observed pass	19 (13%)	124 (87%)	143 (100%)
Model 2: 4 legged with channel			
Observed fail	19 (79%)	5 (21%)	24 (100%)
Observed pass	3 (9%)	32 (91%)	35 (100%)
Model 3: 4 legged			
Observed fail	14 (74%)	5 (26%)	19 (100%)
Observed pass	3 (13%)	20 (87%)	23 (100%)
Model 4: T intersection			
Observed fail	30 (91%)	3 (9%)	33 (100%)
Observed pass	1 (3%)	31 (97%)	32 (100%)
Model 5: Oblique intersection			
Observed fail	23 (85%)	4 (15%)	27 (100%)
Observed pass	5 (16%)	26 (84%)	31 (100%)

The results of the confusion matrices show that all the models are correctly predicting the outcomes of the observed values in the majority of cases. Model 1 for all intersections can successfully predict 84% of the observed fails and 87% of the observed passes. Model 5 for the T intersection has the highest prediction rate with up to 97% accuracy.

Two-tailed t-tests were conducted to check the observed and predicted values differences. Null hypotheses for t-tests assume no differences between observed and predicted values. At a 95% confidence interval, the results of the t-tests show that the null hypotheses are valid. This is a positive result indicating that the model predictions are statistically similar to the observed statuses as an outcome of the binomial logit models. Table 18 shows the results of the t-tests.

Table 18 Two-tailed t-test for prediction results

Group	t-Stat	t-Critical two-tail*
Observed Pass and Predicted Pass	1.91	2.78
Observed Fail and Predicted Fail	2.25	2.78

**95% confidence interval*

The simulation of an additional 4-legged intersection from the Region of Peel is used to test the model's predictive capabilities in real life. The new intersection at Bramalea Road and Drew Road has the following properties while turning right from Bramalea Road to Drew Road: 24.33-meter curb radius, 7.5-meter average lane width, 81 degrees intersection angle, and no channelization islands. In addition, Condition A is assumed with only one lane used for the turn. The intersection location is in one of the corridors identified as a potential LCV expansion area by the Region of Peel.

Model 1 developed for all intersection types is used to calculate the pass alternative utility. The coefficients are presented in the pass utility equation below.

$$U_{f,s} = 0 \tag{3}$$

$$U_{p,s} = -13.49 + 0.35 * Radius + 1.60 * Width - 3.44 \ - 0.06 * Intersection\ angle + 2.49 \tag{4}$$

Where:

- $U_{f,s}$ = Utility of fail for scenario *s*
- $U_{p,s}$ = Utility of pass for scenario *s*

The above utilities are used with Equation 2 to calculate the probability of a successful (passing status) LCV right-turn movement. The probability of the pass alternative is calculated as 77.12%, indicating a 77.12% chance that LCVs will successfully make the right-turn movement using one lane (Condition A).

The 77.12% prediction is compared with the observed status for the turn using IntelliPath in AutoTURN shown in Figure 43. The observed simulation resulted in successful LCV turn completion with a speed value of 5 km/h. The observed success is in alignment with the 77.12% model prediction. Therefore, the binomial logit models show promise as a tool for a quick assessment of intersections for LCV right-turn movements.

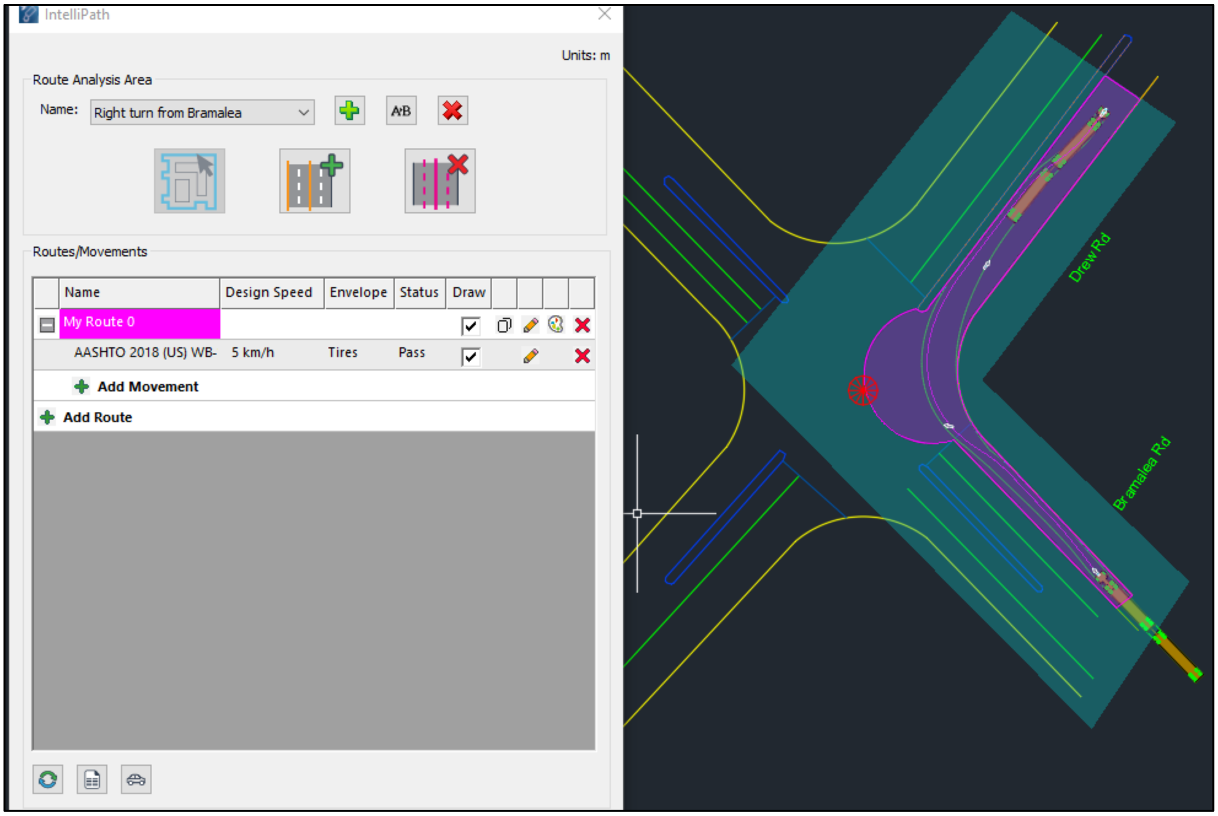


Figure 43 Right-turn movement at Bramalea Rd West to Drew Rd North

5.6. Model Application

A quick-response toolkit has been developed based on the model results. The toolkit has been developed in MS Excel using a macro programming language called Visual Basic. The toolkit's macro capability allows users to navigate different pages according to their choices. Users input their intersection attributes, including the type of intersection, average lane width, curb radius, intersection angle, and condition. The toolkit gives the user the probability of a TPD LCV successfully making a right-turn at an intersection. This probability is derived from the models in Table 16. Figure 44 shows the first page of the toolkit in development.

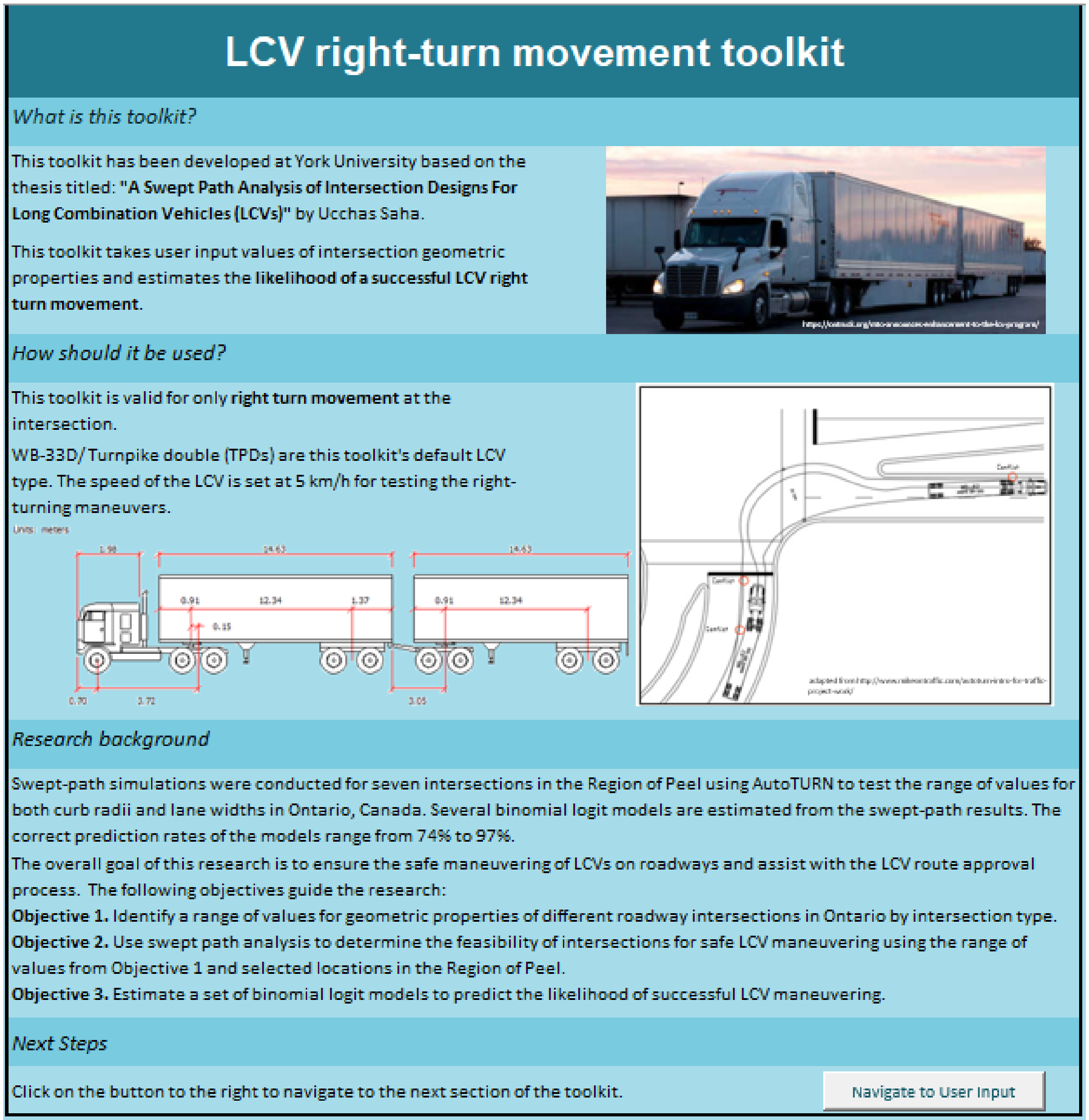


Figure 44 LCV right-turn movement toolkit

Figure 45 shows the second page of the toolkit, which requires user input. For example, the user puts in the following criteria – intersection: *T intersection*, lane width: *5 meters*, curb radius: *35 meters*, intersection angle: *90 degrees,* and condition: *A*. Messages are included with the input options so that the users understand their meaning and the appropriate range of each variable as tested in the models.

After inputting these criteria, the user can navigate to the model probability page, as shown in Figure 46. In the above example, the toolkit gives a probability of 11.11% for successfully completing the right-turn for all these values for Model 1 and a 0.01% chance of success for Model 4. The latter model will change depending on the intersection selected on the previous input page. The toolkit is also sensitive to the user input. If the user changes one or more criteria values, the model will adjust the probabilities accordingly. For example, changing the condition from *A* to *D* in the current example will change the probability of completing a right-turn movement from 11.11% to 99.23% for Model 1.

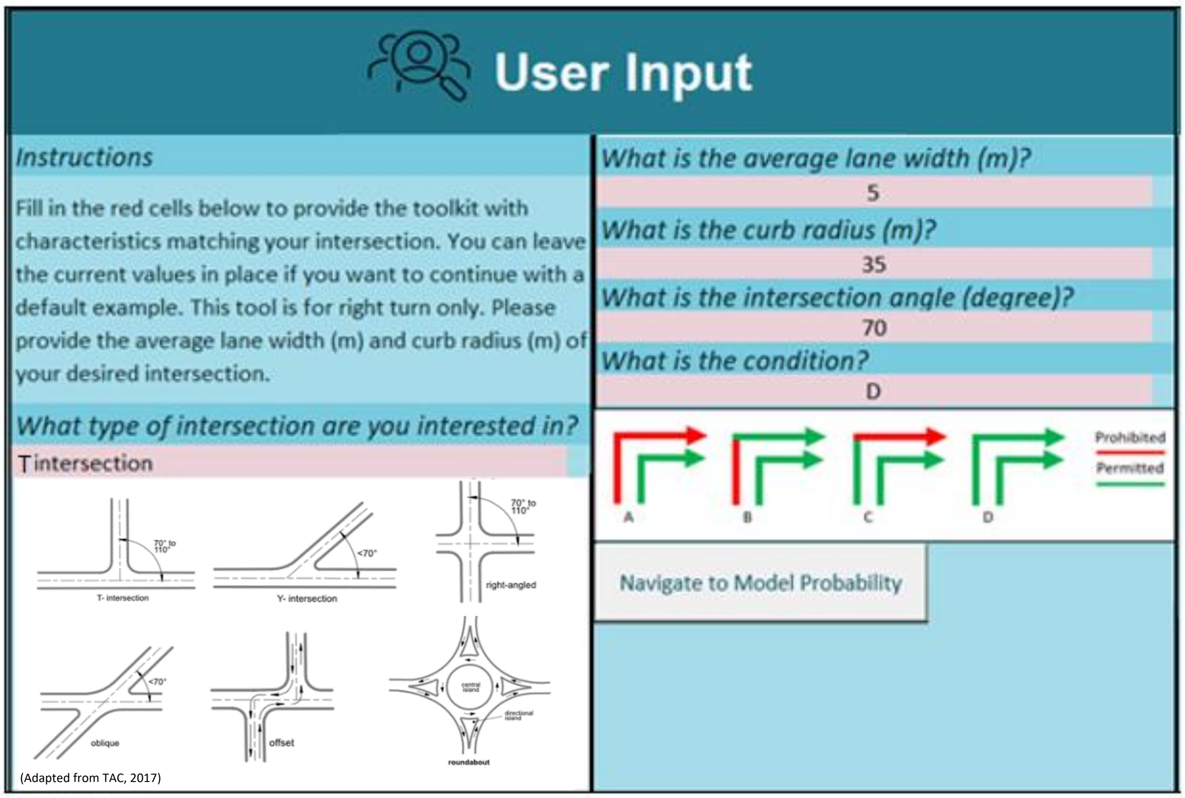
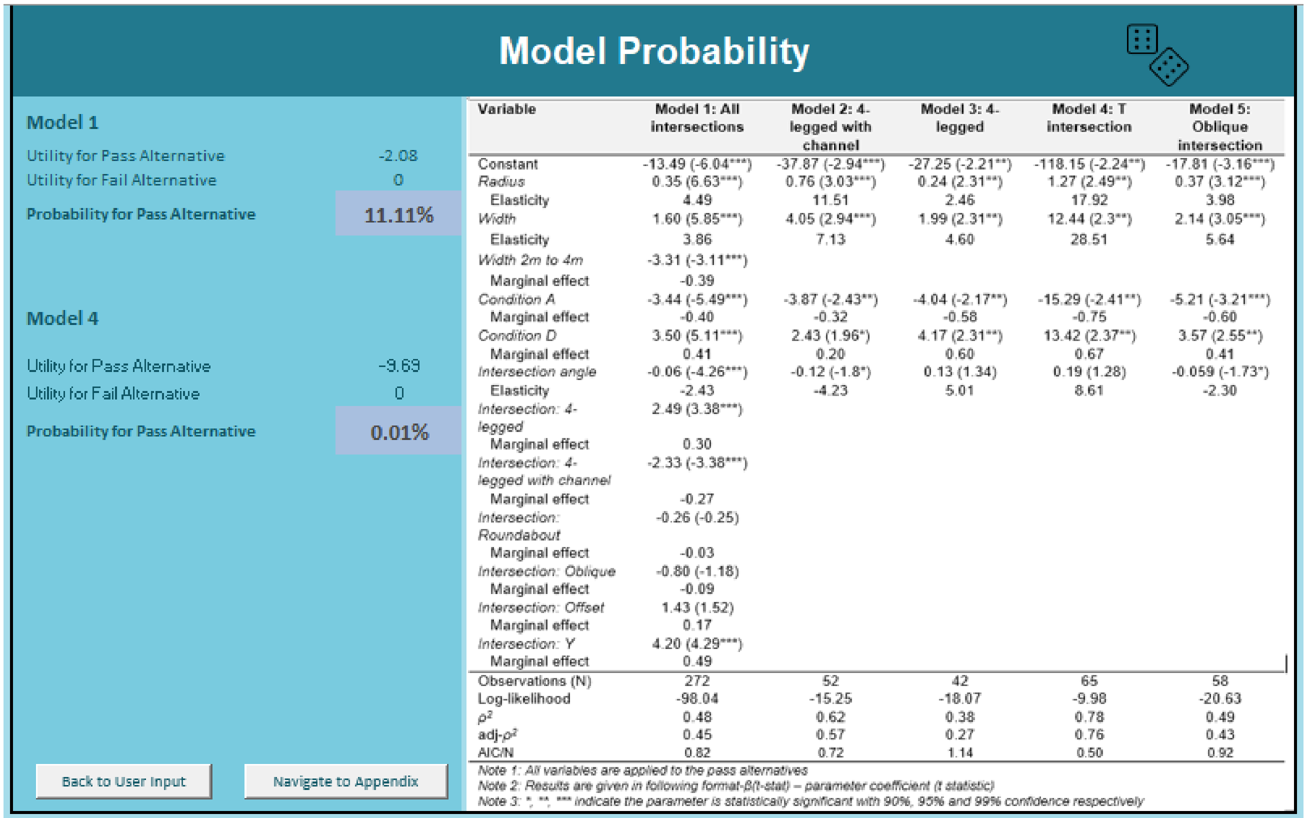


Figure 45 User input page of the toolkit



Variable	Model 1: All intersections	Model 2: 4-legged with channel	Model 3: 4-legged	Model 4: T intersection	Model 5: Oblique intersection
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Radius	0.35 (6.63***)	0.76 (3.03***)	0.24 (2.31**)	1.27 (2.49**)	0.37 (3.12***)
Elasticity	4.49	11.51	2.46	17.92	3.98
Width	1.60 (5.85***)	4.05 (2.94***)	1.99 (2.31**)	12.44 (2.3**)	2.14 (3.05***)
Elasticity	3.86	7.13	4.60	28.51	5.64
Width 2m to 4m	-3.31 (-3.11***)				
Marginal effect	-0.39				
Condition A	-3.44 (-5.49***)	-3.87 (-2.43**)	-4.04 (-2.17**)	-15.29 (-2.41**)	-5.21 (-3.21***)
Marginal effect	-0.40	-0.32	-0.58	-0.75	-0.60
Condition D	3.50 (5.11***)	2.43 (1.96*)	4.17 (2.31**)	13.42 (2.37**)	3.57 (2.55**)
Marginal effect	0.41	0.20	0.60	0.67	0.41
Intersection angle	-0.06 (-4.26***)	-0.12 (-1.8*)	0.13 (1.34)	0.19 (1.28)	-0.059 (-1.73*)
Elasticity	-2.43	-4.23	5.01	8.61	-2.30
Intersection: 4-legged	2.49 (3.38***)				
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Marginal effect	-0.03				
Intersection: Oblique	-0.80 (-1.18)				
Marginal effect	-0.09				
Intersection: Offset	1.43 (1.52)				
Marginal effect	0.17				
Intersection: Y	4.20 (4.29***)				
Marginal effect	0.49				
Observations (N)	272	52	42	65	58
Log-likelihood	-98.04	-15.25	-18.07	-9.98	-20.63
ρ^2	0.48	0.62	0.38	0.78	0.49
adj-ρ^2	0.45	0.57	0.27	0.76	0.43
AIC/N	0.82	0.72	1.14	0.50	0.92

Note 1: All variables are applied to the pass alternatives
Note 2: Results are given in following format-β(t-stat) – parameter coefficient (t statistic)
*Note 3: *, **, *** indicate the parameter is statistically significant with 90%, 95% and 99% confidence respectively*

Figure 46 Model probability page of the toolkit

Chapter 6. Conclusion

6.1. Thesis Summary

This thesis provides an insight into the existing geometric attributes (curb radii, lane widths) of the intersections in Ontario and how their values can be adjusted so that LCVs can become a more mainstream mode for goods movement by maintaining roadway safety.

The benefits of adding LCVs to their existing fleets, such as less driver cost and more capacity, have made the carriers and shippers interested in looking more into these types of vehicles. However, the MTO’s LCV program conditions make this a challenge. Various requirements, including driver training, route approval, vehicle weights, and dimensions, must be fulfilled before LCVs maneuver in the roadways. These conditions, particularly the route approval process, are critical for arterial roadways. They are usually the routes that the LCVs take when they need to reach their origin/destination locations. So, a study conducted to see how the arterials and other lower-tier roadways are suitable to accommodate LCVs movement can help to achieve more efficient movement of goods and, as a result, help shape the province's economy.

As part of the study, at first, a literature review was conducted to understand better the existing conditions of the roadway infrastructure in Ontario. As intersections have been the focus of this research, a thorough investigation helped identify the impactful geometric variables when LCVs turn at the intersections. Evaluating LCV's safety performances helped relate to the safety issue that the LCVs pose for values of geometric attributes while making the turns. Lastly, the literature review section also included different LCV types and their history in Canada.

For data collection, Ontario was categorized based upon location and development types. The maps for this purpose were created in ArcGIS Pro using the data published by Statistics Canada. Creating nine unique zones helped draw sample data in an unbiased way. The sample data collected for this study contained data on different geometric attributes of major intersection types in Ontario. In total, 93 intersections were part of the sampled data collection procedure.

After collecting all the data, simulations were run in the selected intersections of the Region of Peel. Using the IntelliPath tool in AutoTURN software, the user can test turning movements in a selected corridor. Four different scenarios, which had four more sub-scenario conditions, helped run the simulations systematically. The following scenarios helped to develop this study: base scenario, change in the curb radii scenario, change in the lane widths scenario, and removal of channelization scenario. The four conditions associated with each scenario are the following:

- Condition A = turn from the right-most lane to the right-most lane
- Condition B = turn from the right-most lane to the right-most lane + extra additional lane
- Condition C = turn from the right-most lane + extra additional lane to the right-most lane
- Condition D = turn from the right-most lane + extra additional lane to the right-most lane + extra additional lane

After importing the simulation results into MS Excel, customized scatter plot charts helped create visual narratives from the simulation results. The results show some interesting facts about the existing geometric attributes of the selected intersection types. When right-turning from the right-most lane to the right-most lane is not possible, providing additional lanes can help the LCVs complete the turns. The conditions developed for this study show that condition A is the worst and D is the best, suggesting that LCVs can benefit from having access to additional lanes if the traditional rightmost lane to rightmost lane right-turning is not possible. Condition B is generally better than C but not always, which indicates that having access to additional lanes after turning is beneficial for LCVs right-turn movements. Among intersection categories, the T-intersection and Y-intersection perform the worst to accommodate right-turning maneuvers for the LCVs.

The simulation results helped estimate multiple binomial logit models. Identifying independent and dependent variables was the first step to estimating these models. The introduction of several dummy variables assisted in identifying the unique cases that can significantly impact LCV's safe movement. Results of the models showed which of the geometric attributes have the highest effects on LCVs swept paths. The sensitivity analysis revealed that curb radii affect the LCV right-turn movements the most and positively affect LCV passing status. The binomial logit model developed for this study also found that lane widths and intersection angles can impact the safe right-turn maneuvers at the intersections.

In later parts of the thesis, confusion matrices helped test the model's transferability issue. For this purpose, a comparison between the model's predictive capability and the simulation status in AutoTURN showed that the model developed for all intersections (Model 1) can predict the LCV's passing status at an intersection.

6.2. Limits and Recommendations

Few limitations related to this research presented below will assist the individuals who might take this study as a reference to develop their own.

The thesis used housing and population data to categorize Ontario based on development type to take sample data of intersections. However, one of the drawbacks of this method is that it can underrepresent the total number of urban cores in a region. The inclusion of employment data can help mitigate this issue as the identification of commercial zones is better through this data. Therefore, using some method to combine all three data types can make the categorization process more precise.

The vehicle dimension used to run the simulations in AutoTURN uses WB-33D as the design vehicle, which is slightly different from the dimension mentioned in the MTO's LCV program guidelines. Although different studies suggested that this difference has minimal effect on LCVs swept path, modifying the vehicle according to the guideline can improve the overall results for the context of Ontario.

The IntelliPath tool in AutoTURN uses the route boundary feature to identify the analysis area. This is a prerequisite to simulate the movements of the vehicles. However, this feature has some accuracy concerns that can alter the passing status. This issue can significantly impact the research outcomes if there is a lack of caution during the simulation development stage.

6.3. Future Scope

This study focuses on one of the classical problems in transportation engineering- whether the current roadways are fit to maintain proper safety. The addition of LCVs introduces the context of freight transportation in this research and helps to relate how roadway geometric attributes can impact turning movements for freight vehicles.

As intersections are potential bottleneck locations for last-mile deliveries due to large turning envelopes required by LCVs, the study results can help significantly to identify the range and combination of geometric attributes needed for successful LCV right-turn movements. This is a unique approach and, in the future, can help other relevant studies to find desirable routes for LCVs while maintaining both mobility and accessibility.

The exciting prospect of this study is the transferability of the models, which can have significant practical applications for different roadway authorities. It would be useful in the future to test more intersection types and curb designs (smart channel, compound curve) to check how the models can accurately predict the outcomes. The intersections tested in this thesis for the right-turn curb typically exhibit a simple curve. A quick response toolkit developed from the modelling results can assist provincial authorities such as the MTO or municipalities like the Region of Peel, the Regional Municipality of York, and the City of Toronto to decide on the LCVs route approval process. This toolkit will complement the existing methods used by different organizations or authorities for the LCV route acceptance process.

From the point of view of the policymaking process, the research results can help decision-makers accommodate necessary budgets for roadway development. Depending upon the result from the toolkit, they can decide the level of adjustments (curb radii or lane widths, or both) they need to their existing layout to accommodate LCVs and allocate their budgets accordingly.

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Appendices

Appendix A: Collected Data of the Sampled Intersections

The table below shows the raw results collected for 93 intersections. The ID value for each row corresponds to the information listed in Table 5. Each color represents a different intersection type.

ID	Latitude	Longitude	Curb median	Ontario Region	Development type	Intersection type	Sample Number
1111	43.4258	-80.4459	0	1	1	1	1
1112	42.3156	-83.0325	0	1	1	1	2
1211	42.2805	-82.9804	1	1	2	1	1
1212	42.9757	-81.3204	1	1	2	1	2
1311	42.8863	-81.2392	0	1	3	1	1
1312	45.4712	-76.2150	0	1	3	1	2
2111	43.5858	-79.6329	0	2	1	1	1
2112	43.6952	-79.7013	1	2	1	1	2
2211	43.6270	-79.6302	1	2	2	1	1
2212	43.6617	-79.7990	1	2	2	1	2
2311	43.5101	-79.6752	0	2	3	1	1
2312	44.0455	-79.1473	0	2	3	1	2
3111	46.5218	-84.3074	0	3	1	1	1
3112	46.5341	-84.3075	0	3	1	1	2
3211	48.4000	-89.2582	0	3	2	1	1
3212	46.5278	-84.3264	0	3	2	1	2
3311	48.3171	-89.3600	0	3	3	1	1
3312	46.4238	-81.0977	0	3	3	1	2
1121	42.3236	-83.0081	1	1	1	2	1
1122	43.4456	-80.5056	0	1	1	2	2
1221	44.3287	-79.7147	1	1	2	2	1
1222	42.2608	-82.9823	1	1	2	2	2
1321	42.9151	-81.5118	1	1	3	2	1
1322	42.2040	-82.8758	0	1	3	2	2
2121	43.7397	-79.5803	1	2	1	2	1
2122	43.7442	-79.6076	1	2	1	2	2
2221	43.8189	-79.1155	1	2	2	2	1
2222	43.7818	-79.1729	0	2	2	2	2
2321	44.0140	-79.2382	0	2	3	2	1
2322	44.2212	-79.3370	1	2	3	2	2
3121	46.4932	-80.9906	1	3	1	2	1
3122	46.4858	-81.0054	0	3	1	2	2
3221	46.5023	-84.2953	0	3	2	2	1
3222	46.4984	-84.2833	0	3	2	2	2
3321	46.5814	-84.3226	0	3	3	2	1
3322	46.4849	-84.0700	0	3	3	2	2
1131	42.3179	-83.0045	0	1	1	3	1
1132	42.9865	-81.2711	0	1	1	3	2
2131	43.9036	-78.8663	0	2	1	3	1
2132	43.6483	-79.4857	1	2	1	3	2
3131	46.5203	-84.3417	0	3	1	3	1
3132	46.5194	-84.3384	0	3	1	3	2
3231	46.5229	-84.3391	0	3	2	3	1

ID	Latitude	Longitude	Curb median	Ontario Region	Development type	Intersection type	Sample Number
1141	42.3136	-83.0205	1	1	1	4	1
1142	42.3069	-83.0730	1	1	1	4	2
1241	42.2960	-82.9654	1	1	2	4	1
1242	43.3870	-80.4903	1	1	2	4	2
1341	43.4799	-80.5499	1	1	3	4	1
1342	43.4765	-80.5625	1	1	3	4	2
2141	43.6891	-79.4250	1	2	1	4	1
2142	43.5533	-79.7176	1	2	1	4	2
2241	43.7591	-79.8354	1	2	2	4	1
2242	43.9100	-79.4681	1	2	2	4	2
2341	43.4669	-79.8567	1	2	3	4	1
2342	43.5065	-79.9107	1	2	3	4	2
3141	48.4315	-89.2196	1	3	1	4	1
3341	46.3340	-79.4871	1	3	3	4	1
1151	42.9284	-81.1894	0	1	1	5	1
1152	42.3040	-82.9326	1	1	1	5	2
1251	43.1834	-80.2974	0	1	2	5	1
1252	43.0163	-81.3178	1	1	2	5	2
1351	42.2766	-82.8929	0	1	3	5	1
1352	42.8910	-79.3359	0	1	3	5	2
2151	43.7102	-79.4718	1	2	1	5	1
2152	43.6680	-79.3973	0	2	1	5	2
2251	43.6320	-79.6394	0	2	2	5	1
2252	43.6582	-79.8176	1	2	2	5	2
2351	43.5188	-79.6787	0	2	3	5	1
2352	44.4873	-79.8188	0	2	3	5	2
3151	46.2951	-79.4547	0	3	1	5	1
3152	46.4710	-80.9702	1	3	1	5	2
3251	46.3612	-79.4169	0	3	2	5	1
3252	46.4865	-80.9118	0	3	2	5	2
3351	46.5862	-81.3420	0	3	3	5	1
3352	46.0821	-79.3590	0	3	3	5	2
1161	42.9893	-81.2634	0	1	1	6	1
1162	43.1519	-80.2606	1	1	1	6	2
1261	42.9820	-81.1590	0	1	2	6	1
1262	43.0166	-82.3426	0	1	2	6	2
1361	43.1426	-80.6686	1	1	3	6	1
1362	42.2192	-82.8700	0	1	3	6	2
2161	43.6710	-79.4623	0	2	1	6	1
2162	43.6850	-79.4857	0	2	1	6	2
2261	43.2447	-79.9499	0	2	2	6	1
2262	43.2370	-79.9662	0	2	2	6	2
2361	43.4306	-80.0824	0	2	3	6	1
2362	43.4464	-80.0604	0	2	3	6	2
3161	46.3160	-79.4660	1	3	1	6	1
3162	46.5093	-84.3252	0	3	1	6	2
3261	46.4857	-80.9259	0	3	2	6	1
3262	46.3494	-79.4326	0	3	2	6	2
3361	46.4916	-84.0382	0	3	3	6	1
3362	46.4871	-80.7808	0	3	3	6	2

ID	EB/WB right shoulder width (m)	Shoulder Comment 1	EB/WB left shoulder width (m)	Shoulder Comment 2
1111	0	0	0	0
1112	0	0	0	0
1211	0	0	0	0
1212	1.44	2	0	0
1311	0	0	0	0
1312	0	0	0	0
2111	0	0	0	0
2112	0	0	0	0
2211	0	0	0	0
2212	0	0	0	0
2311	0	0	0	0
2312	0	0	0	0
3111	0	0	0	0
3112	0	0	0	0
3211	0	0	0	0
3212	0	0	0	0
3311	0.97	0	0	0
3312	2.47	0	0	0
1121	1.69	2	0	0
1122	0	0	0	0
1221	0	0	0	0
1222	1.41	2	0	0
1321	0.76	0	0	0
1322	0	0	0	0
2121	2.79	0	0	0
2122	2.09	0	0	0
2221	2	2	0	0
2222	0	0	0	0
2321	1.26	0	0	0
2322	3.13	0	0	0
3121	0	0	0	0
3122	0	0	0	0
3221	1.41	2	0	0
3222	1.39	2	0	0
3321	0.62	0	0	0
3322	0	0	0	0
1131	0	0	0	0
1132	0	0	0	0
2131	0	0	0	0
2132	0	0	0	0
3131	1.53	1	0	0
3132	0	0	0	0
3231	1.77	1	0	0
1141	0	0	0	0
1142	0	0	0	0
1241	0	0	0	0
1242	0	0	0	0
1341	2.03	2	0	0
1342	1.53	0	0	0
2141	0	1	0	0
2142	3.48	1	0	0
2241	3.2	1	0	0
2242	0	0	0	0

ID	EB/WB right shoulder width (m)	Shoulder Comment 1	EB/WB left shoulder width (m)	Shoulder Comment 2
2341	1.88	2	0	0
2342	2.08	2	0	0
3141	0	0	0	0
3341	0	0	0	0
1151	3.85	0	0	0
1152	0	0	0	0
1251	2.89	0	0	0
1252	2.1	2	0	0
1351	2.3	0	0	0
1352	0.32	0	0	0
2151	0.05	0	0	0
2152	2.66	1	0	0
2251	0	0	0	0
2252	0	0	0	0
2351	0	0	0	0
2352	0	0	0	0
3151	0	0	0	0
3152	1.26	0	0	0
3251	0	0	0	0
3252	2.01	2	0	0
3351	5.27	0	0	0
3352	0	0	0	0
1161	0	0	0	0
1162	0	0	0	0
1261	0	0	0	0
1262	0	0	0	0
1361	3.53	0	0	0
1362	3.46	0	0	0
2161	1.83	2	0	0
2162	0	0	0	0
2261	0	0	0	0
2262	0	0	0	0
2361	0	0	0	0
2362	0	0	0	0
3161	1.23	1	0	0
3162	0	0	0	0
3261	0	0	0	0
3262	4.06	0	0	0
3361	2.39	0	0	0
3362	2	0	0	0

ID	NB/SB right shoulder width (m)	Shoulder Comment 3	NB/SB left shoulder width (m)	Shoulder Comment 4
1111	0	0	0	0
1112	0	0	0	0
1211	0	0	0	0
1212	0	0	0	0
1311	0	0	0	0
1312	0	0	0	0
2111	0	0	0	0
2112	0	0	0	0
2211	0	0	0	0
2212	0	0	0	0
2311	0	0	0	0
2312	0	0	0	0
3111	0	0	0	0
3112	0	0	0	0
3211	0	0	0	0
3212	0	0	0	0
3311	3.08	0	0	0
3312	0	0	0	0
1121	0	0	0	0
1122	0	0	0	0
1221	0	0	0	0
1222	1.45	2	0	0
1321	0	0	0	0
1322	1.52	0	0	0
2121	0	0	0	0
2122	3.16	3	0	0
2221	0	0	0	0
2222	1.78	3	0	0
2321	1.34	0	0	0
2322	1.3	0	0	0
3121	0	0	0.21	0
3122	0	0	0	0
3221	0	0	0	0
3222	0	0	0	0
3321	0.99	0	0	0
3322	0.78	0	0	0
1131	0	0	0	0
1132	1.94	1	0	0
2131	0	0	0	0
2132	0	0	0	0
3131	0	0	0	0
3132	0	0	0	0
3231	0	0	0	0
1141	0	0	0	0
1142	0	0	0	0
1241	0	0	0	0
1242	0	0	0	0
1341	1.42	2	0	0
1342	1.57	2	0	0
2141	0	1	0	0
2142	3.36	1	0	0
2241	0	0	0	0
2242	0	0	0	0

ID	NB/SB right shoulder width (m)	Shoulder Comment 3	NB/SB left shoulder width (m)	Shoulder Comment 4
2341	1.91	2	0	0
2342	2.86	0	0	0
3141	0	0	0	0
3341	2.63	0	0	0
1151	3.22	0	0	0
1152	0	0	0	0
1251	0.57	0	0	0
1252	0	0	0	0
1351	0.21	0	0	0
1352	0.32	0	0	0
2151	0	0	0	0
2152	3.03	1	0	0
2251	0	0	0	0
2252	0	0	0	0
2351	0	0	0	0
2352	0.62	0	0	0
3151	0	0	0	0
3152	0	0	0	0
3251	0	0	0	0
3252	0	0	0	0
3351	0	0	0	0
3352	0	0	0	0
1161	0	0	0	0
1162	0	0	0	0
1261	0	0	0	0
1262	2.86	0	0	0
1361	0	0	0	0
1362	0	0	1.56	0
2161	0	0	0	0
2162	0	0	0	0
2261	2.49	0	0	0
2262	0	0	0	0
2361	0	0	0	0
2362	0	0	0	0
3161	2.05	1	0	0
3162	0	0	0	0
3261	0	0	0	0
3262	2.84	0	0	0
3361	0	0	0	0
3362	0	0	0	0

ID	EBT/WBT number of lane	EBT/WBT left-most lane width (m)	EBT/WBT Left lane protective?
1111	1	0	1
1112	2	3.09	0
1211	1	0	0
1212	4	3.22	1
1311	1	0	0
1312	1	0	0
2111	1	0	0
2112	5	2.79	1
2211	4	3.41	1
2212	1	0	0
2311	1	0	0
2312	2	3.66	0
3111	4	2.84	1
3112	2	2.97	0
3211	2	3.35	1
3212	1	0	0
3311	1	0	0
3312	3	3.25	0
1121	3	3.47	1
1122	3	2.85	1
1221	4	3.06	1
1222	3	4.2	1
1321	1	0	0
1322	2	3.47	0
2121	4	3.1	1
2122	4	3.64	1
2221	5	3.1	1
2222	2	3.59	0
2321	3	3.8	1
2322	2	3.67	0
3121	4	3.18	1
3122	3	3.18	1
3221	2	3.37	0
3222	2	3.24	0
3321	1	0	0
3322	1	0	0
1131	2	2.66	0
1132	1	0	0
2131	4	2.9	1
2132	2	3.63	1
3131	1	0	0
3132	1	0	0
3231	1	0	0
1141	1	0	0
1142	1	0	0
1241	1	0	0
1242	1	0	0
1341	1	0	0
1342	2	4.28	0
2141	1	4.17	0
2142	1	0	0
2241	1	0	0
2242	1	0	0

ID	EBT/WBT number of lane	EBT/WBT left-most lane width (m)	EBT/WBT Left lane protective?
2341	2	3.89	0
2342	2	3.7	0
3141	1	0	0
3341	2	3.11	0
1151	1	0	0
1152	2	3.6	1
1251	1	0	0
1252	3	3.1	0
1351	2	3	0
1352	2	3.25	0
2151	3	3.6	1
2152	2	3.42	1
2251	2	3.35	0
2252	3	3.68	0
2351	1	0	0
2352	1	0	0
3151	1	0	0
3152	2	3.13	0
3251	2	2.91	0
3252	1	0	0
3351	2	3.64	0
3352	0	0	0
1161	1	0	0
1162	2	4.2	0
1261	2	2.88	0
1262	2	3.82	0
1361	2	3.08	0
1362	1	0	0
2161	2	2.88	1
2162	1	0	0
2261	1	0	0
2262	1	0	0
2361	1	0	0
2362	1	0	0
3161	1	0	0
3162	2	3.42	0
3261	1	0	0
3262	2	3.9	0
3361	1	0	0
3362	2	3.35	0

ID	EBT/WBT right-most lane width (m)	EBT/WBT Right lane channelized?	EBT-D/WBT-D lane width (m)
1111	4.04	0	4.4
1112	3.72	0	3.84
1211	4.05	0	3.61
1212	3.45	0	3.38
1311	3.19	0	3.1
1312	4.05	0	5.15
2111	3.65	0	3.55
2112	2.93	1	2.61
2211	3.71	0	3.78
2212	3.74	0	3.54
2311	6.94	0	6.73
2312	3.9	0	2.98
3111	3.38	0	3.73
3112	3.49	0	5.81
3211	3.43	0	6.15
3212	4.4	0	4.6
3311	6.82	0	4.29
3312	3.62	0	7.22
1121	3.62	0	3.88
1122	3.71	0	3.25
1221	3.37	1	3.9
1222	4.37	0	3.55
1321	3.58	0	3.39
1322	3.68	0	3.04
2121	3.52	0	3.4
2122	4.27	1	3.26
2221	3.58	1	3.09
2222	6.09	1	4.45
2321	2.42	0	4.76
2322	4.27	0	4.93
3121	3.48	0	3
3122	3.38	0	3.43
3221	3.12	0	3.05
3222	3.34	0	3.27
3321	3.03	0	3.38
3322	4.71	0	3.25
1131	3.29	0	3.21
1132	3.21	0	3.12
2131	4.33	1	3.16
2132	4.05	0	3.82
3131	4.41	0	4.45
3132	3.78	0	4.64
3231	4.07	0	3.76
1141	3.45	0	3.7
1142	3.01	0	3.98
1241	5.61	0	5.45
1242	4.26	0	4.51
1341	3.39	0	3.18
1342	4.14	0	4.87
2141	3.88	0	0
2142	4.87	0	4.44
2241	3.55	0	4.44
2242	4.7	0	4.69

ID	EBT/WBT right-most lane width (m)	EBT/WBT Right lane channelized?	EBT-D/WBT-D lane width (m)
2341	4.51	0	3.85
2342	3.8	0	3.63
3141	5.57	0	4.62
3341	3.48	0	3.45
1151	3.56	0	3.4
1152	3.59	0	0
1251	3.48	0	3.56
1252	3.35	0	3.35
1351	3.2	0	2.81
1352	3.29	0	6.44
2151	3.6	0	4.98
2152	3.57	0	3.46
2251	3.36	0	3.36
2252	3.74	0	3.82
2351	4.13	0	4.39
2352	3.06	0	3.03
3151	3.16	0	0
3152	3.54	0	3.49
3251	3.29	0	0
3252	3.76	0	3.85
3351	3.75	0	3.66
3352	4.04	0	3.86
1161	3.2	0	0
1162	5.15	0	0
1261	3.3	0	3
1262	2.5	0	0
1361	3.98	1	2.86
1362	3.08	0	3.02
2161	4.22	0	0
2162	3.84	0	0
2261	4.99	0	0
2262	3.34	0	0
2361	3.64	0	0
2362	3.19	0	3.09
3161	4.58	0	0
3162	3.26	0	3.84
3261	3.85	0	0
3262	3.77	0	0
3361	2.95	0	3.35
3362	3.67	0	3.68

ID	NBT/SBT number of lane	NBT/SBT left-most lane width (m)	NBT/SBT Left lane protective?
1111	1	0	0
1112	3	3.24	0
1211	3	2.7	1
1212	3	2.92	0
1311	1	0	0
1312	1	0	0
2111	3	3	0
2112	5	3.21	1
2211	6	3.35	1
2212	2	3.32	0
2311	1	0	0
2312	2	3.67	0
3111	3	2.99	1
3112	2	3.21	0
3211	3	3.42	1
3212	1	0	0
3311	3	3.31	0
3312	2	3.24	0
1121	2	2.88	1
1122	2	4.24	0
1221	3	3.81	1
1222	3	3.35	1
1321	1	0	0
1322	1	0	0
2121	3	3.4	1
2122	4	3.62	1
2221	5	3.2	1
2222	1	0	0
2321	2	4.28	0
2322	4	3.17	0
3121	4	3.68	1
3122	4	3.37	1
3221	1	0	0
3222	1	0	0
3321	3	2.71	0
3322	3	3.95	0
1131	2	3.13	0
1132	1	0	0
2131	4	3.35	1
2132	4	2.96	1
3131	3	3.76	0
3132	2	3.75	0
3231	2	3.28	0
1141	1	0	0
1142	1	0	0
1241	1	0	0
1242	1	0	0
1341	1	0	0
1342	2	3.76	0
2141	1	3.45	0
2142	1	0	0
2241	1	0	0
2242	1	0	0

ID	NBT/SBT number of lane	NBT/SBT left-most lane width (m)	NBT/SBT Left lane protective?
2341	2	4.12	0
2342	2	3.49	0
3141	1	0	0
3341	2	3.49	0
1151	2	2.5	0
1152	4	3.24	1
1251	1	0	0
1252	1	0	0
1351	1	0	0
1352	1	0	0
2151	2	2.84	0
2152	1	0	0
2251	1	0	0
2252	2	3.62	0
2351	1	0	0
2352	1	0	0
3151	2	3.08	0
3152	2	3.45	0
3251	2	3.47	0
3252	1	0	0
3351	1	0	0
3352	1	0	0
1161	2	3.39	0
1162	2	3.2	0
1261	1	0	0
1262	1	0	0
1361	1	0	0
1362	1	0	0
2161	2	2.87	1
2162	2	3.3	0
2261	2	2.84	0
2262	1	0	0
2361	1	0	0
2362	1	0	0
3161	2	3.64	1
3162	2	3.63	0
3261	1	0	0
3262	2	3.22	0
3361	1	0	0
3362	1	0	0

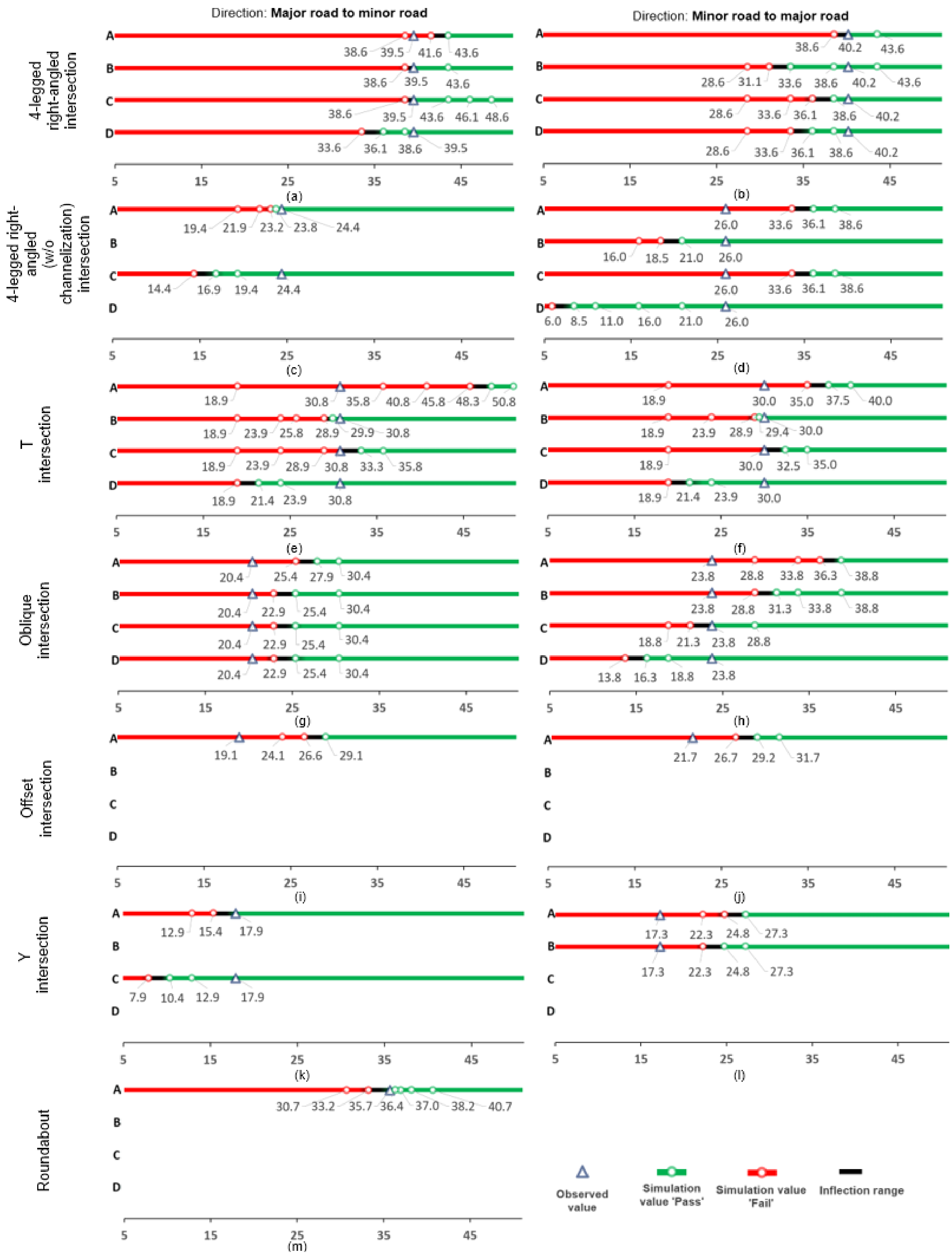
ID	NBT/SBT right-most lane width (m)	NBT/SBT Right lane channelized/unchannelized?	NBT-D/SBT-D lane width (m)
1111	4.29	0	4.47
1112	4.04	0	4.06
1211	3.94	0	3.22
1212	2.84	0	3.69
1311	3.89	0	3.42
1312	3.73	0	3.75
2111	3.65	0	3.2
2112	3.38	1	3.47
2211	3.37	1	3.34
2212	3.66	0	5.07
2311	4.83	0	6.91
2312	3.7	1	3.72
3111	3.42	0	3.81
3112	4.41	0	4.28
3211	3.54	0	3.45
3212	4.08	0	4.45
3311	3.27	0	3.46
3312	3.86	1	3.3
1121	3.64	1	6.1
1122	4.39	0	4.55
1221	3.04	0	4.15
1222	3.39	1	3.47
1321	3.55	0	2.22
1322	2.91	0	5.51
2121	4.28	1	3.52
2122	3.27	1	3.59
2221	3.82	0	3.59
2222	5.09	0	3.97
2321	4.14	1	4.26
2322	3.69	0	4.16
3121	3.89	1	3.94
3122	3.41	0	3.5
3221	3.2	0	6.52
3222	3.97	0	9.74
3321	2.58	0	3.73
3322	3.43	0	3.66
1131	3.27	0	3.85
1132	4.92	0	3.21
2131	3.25	0	3.52
2132	2.95	0	3.63
3131	3.59	1	4.45
3132	3.8	0	3.75
3231	3.99	0	3.76
1141	4.53	0	4.45
1142	4.68	0	4.26
1241	5.36	0	0
1242	5.67	0	6.75
1341	3.62	0	3.6
1342	3.86	0	3.93
2141	3.18	0	0
2142	4.79	0	4.49
2241	3.79	0	0

ID	NBT/SBT right-most lane width (m)	NBT/SBT Right lane channelized/unchannelized?	NBT-D/SBT-D lane width (m)
2242	4.62	0	4.5
2341	3.76	0	3.41
2342	3.23	0	4.06
3141	5.09	0	0
3341	3.33	0	4.79
1151	3.07	0	0
1152	3.68	0	3.67
1251	3.74	0	0
1252	6.86	0	0
1351	3.2	0	0
1352	3.4	0	0
2151	3	0	0
2152	3.53	0	0
2251	3.29	0	0
2252	3.9	0	0
2351	3.93	0	0
2352	3.12	0	0
3151	3.29	0	3.25
3152	3.77	0	0
3251	3.63	0	4.16
3252	5.64	0	0
3351	7.42	0	0
3352	3.12	0	0
1161	3.46	0	3.4
1162	3.19	0	3.1
1261	3.19	0	0
1262	3.12	0	3.09
1361	5.57	0	0
1362	4.69	0	0
2161	2.94	0	3.62
2162	3.36	0	3.53
2261	3.53	0	4.08
2262	2.69	0	2.85
2361	3.35	0	3.43
2362	2.77	0	0
3161	3.58	0	3.49
3162	3.81	0	3.43
3261	3.29	0	3.5
3262	3.82	1	3.32
3361	2.45	0	0
3362	5.79	0	0

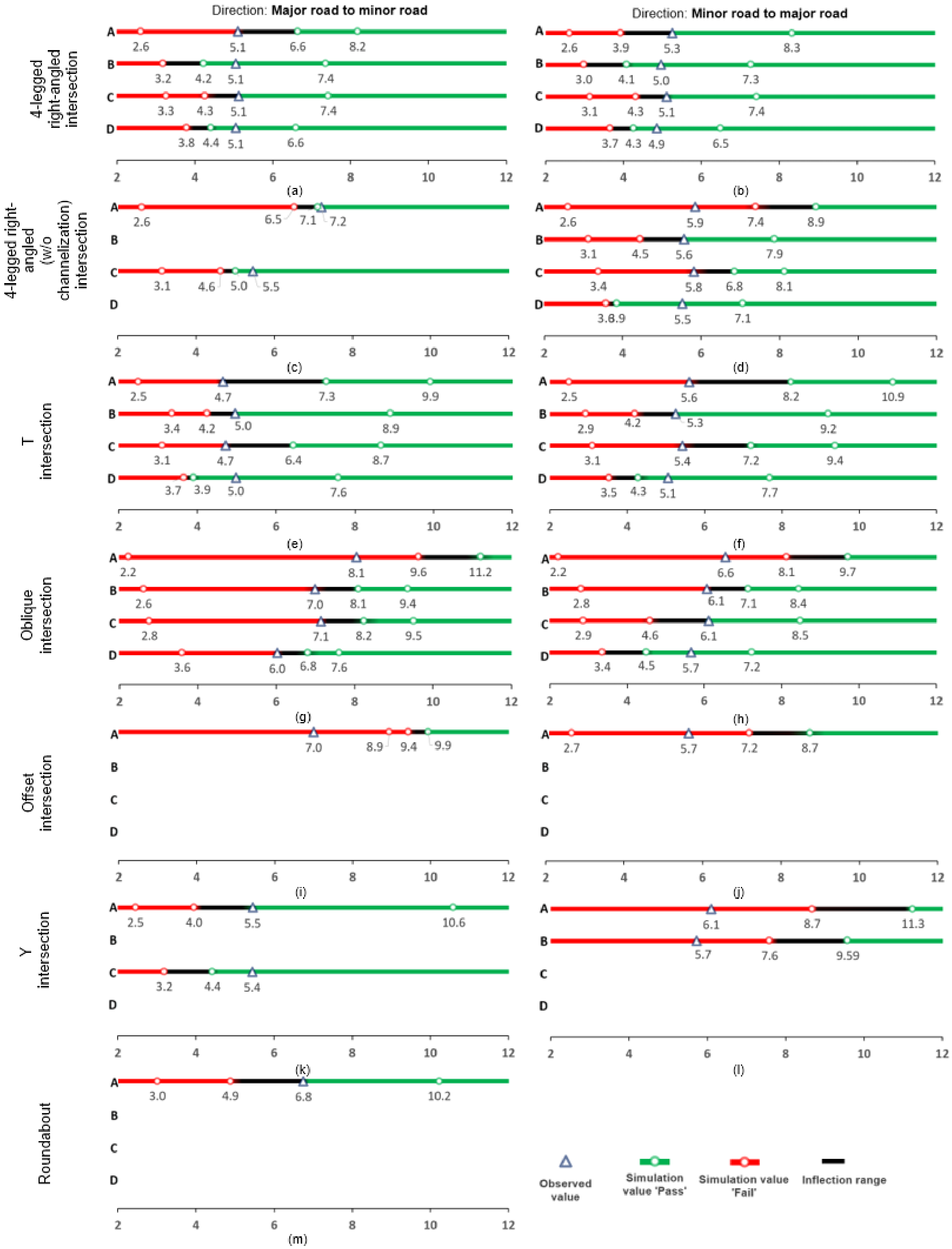
ID	S-E curve radius (m)	W-S curve radius (m)	N-W curve radius (m)	E-N curve radius (m)	Inner circle radius (Roundabout) (m)	Intersection area (m^2)
1111	9.6	8.95	8.28	9.39	0	443.3
1112	4.18	4.6	4.8	5.27	0	647.53
1211	15.45	11.13	11.02	14.29	0	1063.74
1212	15.55	14.08	13.53	13.77	0	1944.57
1311	13.8	10.77	13.05	10.18	0	642.92
1312	5.11	5.74	6.16	5.17	0	339.93
2111	9.91	10.46	10.78	10.26	0	747.52
2112	29.83	36.63	35.35	38.59	0	7385.34
2211	25.79	25.25	24.76	25.25	0	4423.83
2212	11.27	12.09	11.9	11.24	0	629.78
2311	10.87	10.75	9.01	10.6	0	805.6
2312	33.51	18.18	16.64	9.49	0	1937.57
3111	9.34	9.79	9.94	9.79	0	969.44
3112	12.68	12.96	13.22	12.85	0	938.38
3211	14.63	15.21	15.47	15.31	0	1451.77
3212	9.23	9.27	10.11	9.06	0	500.44
3311	17.61	16.63	9.25	10.41	0	1477.36
3312	34.2	12.3	34.37	15.31	0	3277.46
1121	10.96	14.4	12.25	7.81	0	3332.01
1122	26.88	9.66	29.65	9.47	0	2039.07
1221	43.35	13.05	35.39	14.17	0	3914.68
1222	15.86	30.18	15.5	28.7	0	5338.25
1321	20.76	10.42	19.45	14.4	0	1329.12
1322	13.17	17.25	10.1	20.71	0	1169.78
2121	16.06	22.49	16.06	27.43	0	4198.87
2122	23.91	56.34	14.32	88.78	0	8227.36
2221	16.67	9.58	17.69	11.07	0	5960.92
2222	20.25	15.26	18.6	15.44	0	20.31.65
2321	53.71	17.45	31.67	17.42	0	4368.48
2322	20.8	17.92	19.82	17.9	0	3379.36
3121	10.25	17.02	15.93	18.32	0	3284.17
3122	17.11	9.11	8.8	9.47	0	1556.15
3221	9.2	14.23	5.25	11.75	0	915.6
3222	7.41	12.44	8.63	12.74	0	983.06
3321	23.72	16.34	21.11	11.63	0	2663.28
3322	12.73	26	11.95	23.17	0	1748.96
1131	6.24	7.16	12.23	7.08	0	1245.05
1132	9.47	13.13	7.97	7.9	0	667.05
2131	9.54	8.22	13.5	8.52	0	3445.95
2132	11.72	8.93	9.09	11.98	0	2348.2
3131	9.45	17.89	7.73	10.54	0	1140.83
3132	9.76	5.65	5.11	8.37	0	448.14
3231	9.26	8.61	9.38	7.8	0	693.14
1141	12.54	15.11	18.25	16.35	7.96	1243.44
1142	13.95	113.63	0	4.1	11.01	1390.16
1241	50.27	47.41	0	0	15.34	3285.41
1242	38.52	34.73	28.56	30.47	15.06	3698.91
1341	62.95	67.31	65.6	62.95	27.28	8063.46
1342	40.04	30.64	32.28	14.98	18.87	5772.65
2141	8.26	0	7.7	7.77	15.77	1860.17
2142	22.81	23.42	23.33	22.33	12.34	4128.64

ID	S-E curve radius (m)	W-S curve radius (m)	N-W curve radius (m)	E-N curve radius (m)	Inner circle radius (Roundabout) (m)	Intersection area (m^2)
2241	0	0	20.12	20.9	9.87	1568.09
2242	24.05	19.33	18.6	15.98	9.5	1590.39
2341	31.59	46.41	59.06	34.9	20.48	6384.14
2342	32.87	42.56	37.01	35.36	20.29	5696.4
3141	0	0	34.45	23.62	13.57	1973.51
3341	31.46	23.07	27	27.59	16.59	4359.86
1151	0	0	18.94	18.94	0	858.97
1152	0	14.77	15	0	0	1546.99
1251	11.88	12.67	0	0	0	500.8
1252	0	0	14.81	15.1	0	1349.53
1351	0	0	14.9	14.95	0	612.35
1352	14.31	13.93	0	0	0	813.02
2151	11.75	10.75	0	0	0	1092.72
2152	0	0	8.61	7.13	0	555.52
2251	0	0	16.03	16.6	0	918.31
2252	0	0	17.92	18.11	0	1897.62
2351	13.61	14.59	0	0	0	606.42
2352	10.28	13.04	0	0	0	334.53
3151	0	0	9.18	5.86	0	511.06
3152	7.82	8.14	0	0	0	662.51
3251	16.9	0	0	7.87	0	984.85
3252	0	0	8.47	8.47	0	491.99
3351	0	0	12.64	13.26	0	609.3
3352	0	0	7.66	7.66	0	303.13
1161	2.82	0	0	8.72	0	344.6
1162	1.87	0	0	35.63	0	762.57
1261	4.85	40.67	0	0	0	581.15
1262	0	9.33	22.4	0	0	614.72
1361	11.02	364.73	0	0	0	8306.64
1362	226	3.2	0	0	0	716.33
2161	3.51	0	0	17.11	0	571.99
2162	12.7	2.68	0	0	0	380.74
2261	0	6.48	40.52	0	0	671.65
2262	49.38	0	0	5.84	0	408.45
2361	24.9	0	6.56	0	0	430.81
2362	23.48	7.34	0	0	0	419.65
3161	6.82	0	0	10.03	0	593.58
3162	24.48	0	0	33.73	0	886.46
3261	0	17.29	5.5	0	0	335.45
3262	311.44	0	0	4.93	0	6675.9
3361	0	0	3.21	108.26	0	499.83
3362	14.07	12.55	0	0	0	1733.6

Appendix B: Simulation results based on curb radii (m) for right-turns



Appendix C: Simulation results based on lane widths (m) for right-turns



Appendix D: NLOGIT Codes

Code for Model 2, Model 3, Model 4, and Model 5:

```
NLOGIT

;Lhs = DV

;Choices = F,P

;Model:

U(F) = 0/

U(P)=
P_Const+RADIUS*RADIUS+WIDTH*WIDTH+COND_A*COND_A+COND_D*COND_D
+INT_ANG*INT_ANG

;Prob=PROB

;effects:RADIUS(P)/WIDTH(P)/INT_ANG(P)/W2_4[P]/COND_A[P]/COND_D[P]$
```

Code for Model 1:

```
NLOGIT

;Lhs = DV

;Choices = F,P

;Model:

U(F) = 0/

U(P)=
P_Const+RADIUS*RADIUS+WIDTH*WIDTH+W2_4*W2_4+COND_A*COND_A+COND
_D*COND_D+I_4L*I_4L+I_4LWC*I_4LWC+I_R*I_R+I_OB*I_OB+I_OF*I_OF+I_Y*I_Y

+INT_ANG*INT_ANG

;Prob=PROB

;effects:RADIUS(P)/WIDTH(P)/INT_ANG(P)/W2_4[P]/COND_A[P]/COND_D[P]/I_4L[P]/I
_4LWC[P]/I_R[P]/I_OB[P]/I_OF[P]/I_Y[P]$
```