

# Analysis of Passing Distances between Bicycles and Motorized Vehicles on Urban Arterials

by

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## **AUTHOR'S DECLARATION**

This thesis consists of material all of which I authored or co-authored: see Statement of Contributions included in the thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

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## Statement of Contributions

Some of the material in this thesis has already been published and/or presented at conferences. These publications are listed below:

1. “An Analysis of the Lateral Distance between Motorized Vehicles and Bicyclists During Overtaking Maneuvers”. CITE/OTC Annual Meeting 2014, Transportationfest – A Celebration of Innovation. Waterloo, ON, Canada (June 2014).

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Chapter 5 – Sections 5.1, 5.2, 5.3, 5.4

## Abstract

The absence of dedicated cycling infrastructure such as on-street bike lanes or physically separated bike routes forces cyclists to travel more frequently on urban arterials while sharing the road with motorized vehicles, and in turn, increasing the potential for vehicle-cyclist collisions. It is expected that the modal share of cycling will increase if cycling safety is improved; however, critical understanding is required about the relationship between vehicle-bicycle interactions, traffic conditions and their impact on cyclists' safety.

Several US states and Canadian Provinces have introduced, or (as is the case in Ontario) are considering, legislation requiring that motorists provide a minimum of one meter of lateral clearance when overtaking and passing a cyclist. These laws are often referred to as "safe passing" laws. However, there is currently very little evidence quantifying the proportion of overtaking maneuvers that are "unsafe" (i.e. a lateral clearance less than 1m). Furthermore, there is little evidence quantifying the influence that various factors (e.g. geometry, traffic, etc.) have on lateral clearances. And finally, though current design guidelines for selecting recommended geometric treatments for cyclists (e.g. shared lane; on-street bike lane; physically separated bike paths; etc.) are sensitive to roadway type, traffic volume, and posted speed limit, there is little consistency between guidelines from different jurisdictions and these guidelines do not appear to be based on objective measures of risk.

The research described in this thesis seeks to improve the current understanding of vehicle-cyclist interactions; specifically the lateral clearances between motorized vehicle and cyclists during overtaking maneuvers on urban arterial roadways and to be able to quantify the influence that geometric and traffic-flow parameters have on these lateral clearances.

A portable data acquisition system, capable of measuring and recording location, bike speed, and the lateral distance to vehicles overtaking the cyclist, was designed and built. This system was used to collect data for more than five thousand over taking maneuvers on two-lane and four-lane urban roads with and without on-street bike lanes within the Kitchener-Waterloo area in southern Ontario.

These data revealed that 12% of passing maneuvers on two-lane arterials without bike lane were unsafe. For two lane arterials with a bike lane, only 0.2% of passing maneuvers were unsafe. For four lane arterials, 5.9% of passing maneuvers were unsafe when no bike lane was present and only 0.5% were unsafe when a bike lane was present. These results suggest that a significant proportion of passing maneuvers on arterials without bike lanes are unsafe. Further analysis showed that for four lane roadways without bike lanes, drivers may attempt to provide increased lateral passing distance by changing lanes or encroaching partially in the adjacent lane, however their opportunity to do may be restricted when vehicles are in the adjacent lane. A model was developed to estimate the probability of unsafe passing on 4-lane roads without bike lanes for specific traffic conditions. The model shows that the proportion of passing maneuvers that are unsafe increases as traffic demand increases, the distance between consecutive traffic signals becomes shorter, and traffic signal cycle lengths become longer. The model is able to estimate both the proportion of unsafe passings as well as the expected number of unsafe passings per bike trip per hour for a given arterial roadway. We compare these quantitative estimates to

conventional cycling infrastructure design guidelines, including the Ontario Traffic Manual Book 18.

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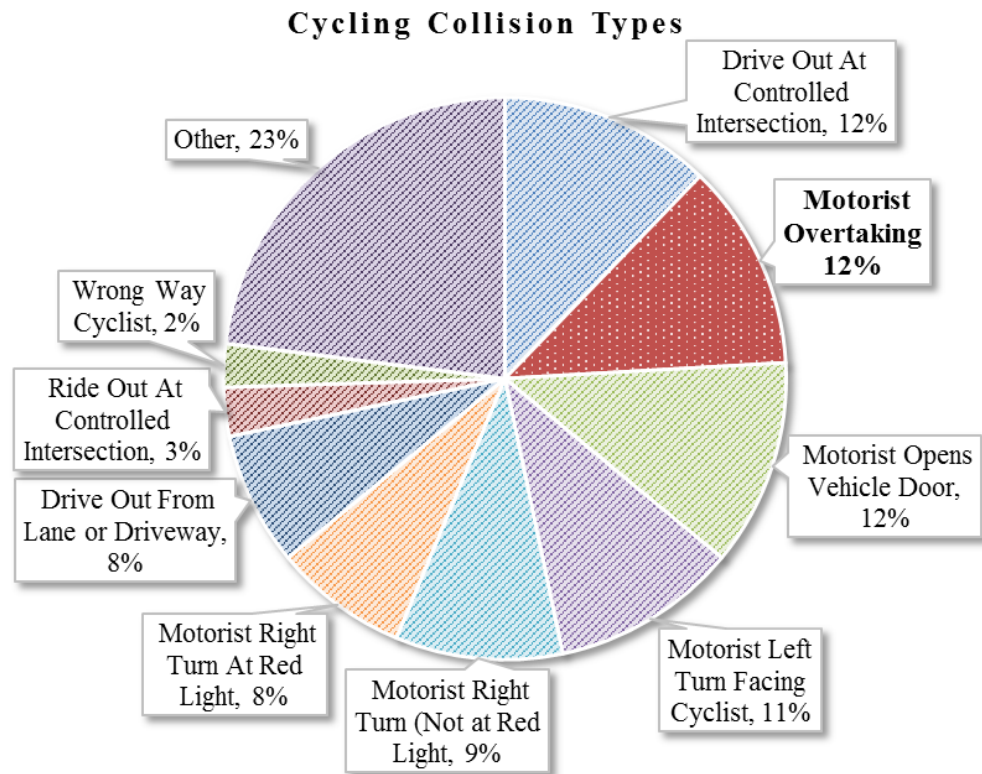
# Chapter 1

## Introduction

### 1.1 Background

Active transportation modes such as cycling are receiving increased consideration because of their potential for reducing the demand of motorized traffic, for their environmental and health benefits, and for the user and system cost savings. Despite a desire to increase the modal share of cycling, the use of motorized transportation modes is dominant in most North American urban and sub-urban centers. The absence of dedicated cycling infrastructure such as on-street bike lanes or physically separated bike routes forces cyclists to travel more frequently on urban arterials while sharing the road with motorized vehicles, and in turn, increasing the potential for vehicle-cyclist collisions. It is expected that the modal share of cycling will increase if cycling safety is improved. Hence, understanding the relationship between vehicle-bicycle interactions, traffic conditions and cyclists' safety is critical.

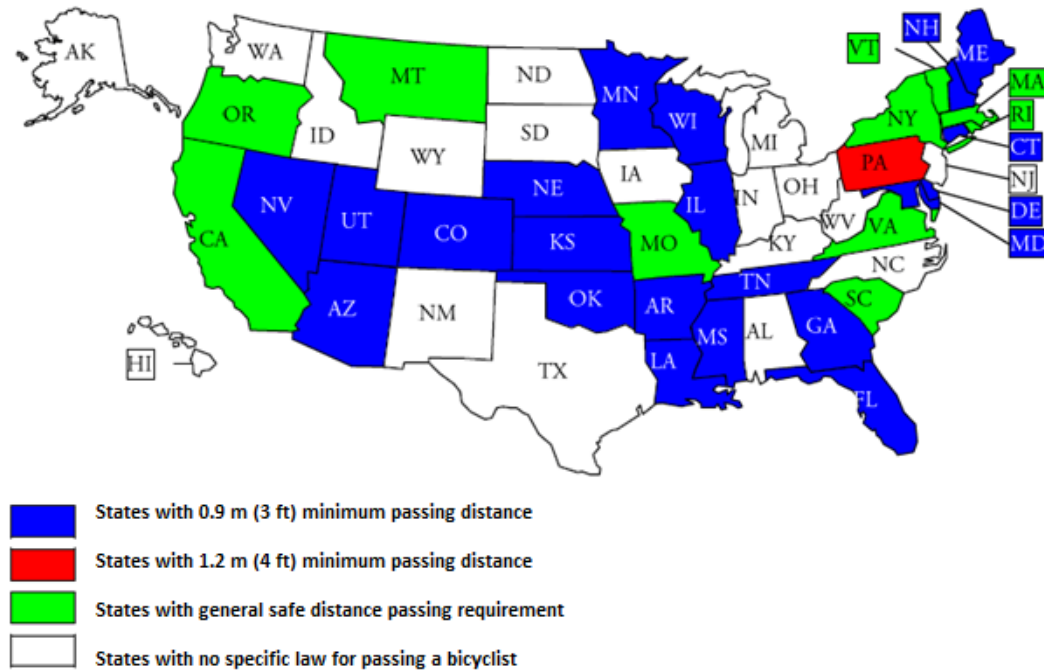
A primary concern for cyclists when sharing the road with motorized traffic is to avoid conflicts with motorized vehicles. A study conducted in the City of Toronto (City of Toronto, 2003)) found that 12% of all collisions occurred when the motorized vehicle was overtaking the cyclist (Figure 1) and that this was one of most frequent types of collisions. Detailed statistics obtained from this study are presented in Appendix A.



**Figure 1: Cycling Collision Types (City of Toronto, 2003)**

As a preventive measure, the province of Nova Scotia in Canada and many jurisdictions in the USA (Figure 2) have implemented legislation to require a driver to provide a minimum lateral

clearance (passing distance) when overtaking a cyclist. This clearance distance ranges between 0.9 meter and 1.2 meter across different jurisdictions. In the province of Nova Scotia, the minimum passing distance required is 1 meter and the law is also known as the *1-meter rule*. Other jurisdictions are also considering similar legislation (Legislative Assembly of Ontario, 2010).



**Figure 2: Enforcement of Safe Passing Distance Laws in the USA (NCSL, 2013)**

Another alternative widely used globally is to provide on-street dedicated bike lanes. Figure 3 and Figure 4 show facilities with a shared lane and an on-street dedicated bike lane respectively. As the name implies, while on the shared lanes, cyclists and motorized vehicles share the same lane. Cyclists are permitted to ride in the middle of the lane, forcing overtaking vehicles to leave the lane to pass, but more frequently, cyclists ride close to the right-hand side of the lane and vehicles may attempt to pass while remaining in the same lane. On-street bike lanes provide cyclists with a dedicated lane, most frequently on the right-hand side of a road, which is separated from the regular travel lane via pavement markings only (not physical barrier).



**Figure 3: Road without Bike Lane (Source: [www.transitmiami.com](http://www.transitmiami.com))**



**Figure 4: Road with Dedicated On-Road Bike Lane (Source: [www.blogs.calgaryherald.com](http://www.blogs.calgaryherald.com))**

## **1.2 Motivation**

There appears to be consensus of the importance of improving safety for cyclists. However, there is no consensus of how best to do this and there appears to be little objective data available on which to base decisions. As a result, public opinions are often highly polarized and frequently based on emotion or perceptions rather than objective data. The lack of empirical data undermines efforts to establish the effectiveness of statutes such as the “1-meter rule” or the actual benefits associated with providing dedicated cycling infrastructure. It also hinders efforts to establish and defend standards and guidelines for conditions under which dedicated cycling infrastructure is justified.

One of the main advantages of the dedicated bike lanes is that the lane marking between a bike lane and a motor-vehicle lane visually separates the bicycle traffic from the other traffic. In addition, the lane marking eliminates the guesswork associated with the minimum lateral clearance for the motor-vehicle drivers. A study conducted by Ipsos in the City of Toronto (Ipsos, 2009) concluded that only 31% of all cyclists were comfortable with sharing roads with the motorized traffic where dedicated on-road bike lanes are not available. In contrast, 72.5% of the cyclists were comfortable with sharing the roads with motorized vehicles where on-road bike lanes are provided. More information regarding this study is presented in Appendix A. Currently, the decision to provide (or not to provide) an on-street bike lane on a specific road is based on the expected vehicle volumes (Average Annual Daily Traffic - AADT) and vehicle speeds on that road (King, 2002). Thresholds for these volumes and speeds are decided based on 'engineering judgment' and to-date no scientific evidence exists to prove their validity.

The presented information suggests that the vehicle-bicycle interactions can be influenced by many factors such as driver and cyclist behavior, traffic conditions and road geometry and there is an obvious need to understand them in order to improve safety for the cyclists. However, to-date few studies have been conducted to analyze these vehicle-bicycle interactions largely due to data collection challenges. Overtaking maneuvers occur at random locations and times. As a result, the observation of overtaking maneuvers at a fixed location (e.g. using video cameras) is often impractical. An alternative is to use instrumented bicycles to collect the data.

### **1.3 Scope and Objectives**

This research seeks to better understand vehicle-cyclist interactions, specifically the lateral passing distances during overtaking maneuvers and to be able to quantify the influence that traffic volume and geometry have on these lateral clearances.

This research had the following four objectives:

1. Develop a portable sensor array suitable for collecting passing distances between bicycles and motorized vehicles.
2. Use the developed sensor array to collect an empirical data set of passing distances on various categories of urban arterials.
3. On the basis of the empirical data:
  - a. Quantify the passing distance distributions
  - b. Investigate the influence of driver behavior on passing distance
  - c. Explore the influence of traffic-flow parameters such as vehicle speed and time headway on the passing distance
  - d. Provide scientific evidence regarding the benefits of the dedicated on-street bike lanes.
4. Develop a model that can be used to estimate the relative safety benefits associated with providing on-street bike lanes for a give road facility.

## **1.4 Thesis Organization**

This thesis document has been organized in to seven chapters.

Chapter 2 reviews the previous investigations carried out in the area of cycling safety and summarizes the current design guidelines for selecting cycling facilities for different jurisdictions worldwide. Chapter 3 describes the sensor array developed for data collection and summarizes the criteria for site selection on which the data were collected. Chapter 4 describes the methodology developed to analyze the collected data. Chapter 5 describes the application of the methodology developed in the previous chapter and discusses the results. Chapter 6 describes the proposed model for evaluating the safety benefits of implementing on-street bike lanes. Chapter 7 summarizes the outcomes of this study and identifies potential future extensions.



## Chapter 2

### Literature Review

In this chapter, past research and current practices relevant to the safety of the cyclists on urban arterials are discussed. The literature discussed in this chapter provided the primary premises required for the development of the research procedure presented in the subsequent sections.

#### 2.1 Past Studies

Over the past decade researchers conducted several studies using different data collection techniques to evaluate the impact of road geometry, vehicle composition and driver/cyclist characteristics on the passing distance during overtaking maneuvers.

A study undertaken by Walker tries to explain the changes in motorists' behavior based upon the gender of the cyclists and their helmet usage (Walker, 2007). Walker used a bike instrumented with an ultrasonic sensor to study the relationship between cyclist's position and overtaking maneuvers. Walker found that for female riders, motorists provided more lateral clearance compared to male riders. Furthermore, riders wearing a bike helmet experienced more close passing encounters as compared to the riders not wearing a bike helmet. Walker also found that drivers driving large vehicles like bus or truck provided a smaller passing distance as compared to drivers with smaller vehicles (i.e. a passenger car). Walker also found that passing distances were smaller when the cyclists rode farther away from the curb. Overall, this study focused on the behavioral parameters of the motorists and cycling practice of the riders.

A follow up study undertaken by Olivier and Walter concluded that Walker's claim of the impact of helmet usage on passing distance was not correct (Olivier and Walter, 2013). They concluded that though helmet usage resulted in a small reduction in passing distance, it did not have any influence on the number of unsafe<sup>1</sup> passing distances. Olivier concluded that factors like vehicle size and curb distance were more influential in governing the passing distance compared to helmet usage.

A study conducted by Meyers and Parkin tried to assess the effectiveness of bicycle lanes on passing distance (Meyers and Parkin, 2008). They used a video camera to record passing events on facilities with and without a bicycle lane with varying speed limits. These videos were later used to measure the separation distances. The following factors were controlled: geometric features of the road, traffic volume and vehicle speed. During the analysis, they found that drivers generally provide a larger passing distance for cyclists on roads without bicycle lanes. They concluded that the bike lanes do not provide greater separation for the cyclists; however, they reduce the perception of risk for the motorists and the cyclists. They also found that the motorists and the cyclists are generally more confident during passing events when bike lanes are present.

Sando et al. carried out a study to ascertain the influence of different site characteristics such as geometric features and traffic volumes on the drivers' behavior when passing cyclists on wide curb lanes (Sando et al., 2011). This study mainly focused on four measures of effectiveness, namely separation between bicycle and motorized vehicle, usage of the curb lane, encroachment

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<sup>1</sup> "Unsafe" is defined as a passing distance of  $\leq 1\text{m}$

of the vehicle in the curb lane into the adjacent lane, and vehicle speeds before, during & after passing maneuvers. Data were collected in the form of video recordings, which were later visually inspected to extract relevant data. The study concluded that in general smaller vehicles (passenger cars) drive closer to the cyclists compared to other vehicle types. The lateral separation between bicycles and motorized vehicles increases as the width of the curb lane increases. The lateral separation decreases as the traffic volume increases. In addition, it was observed that the drivers reduced their speed to ensure safe passing maneuvers and then accelerated after passing the cyclists.

A study performed by Kay and Gates to examine the effectiveness of a bicycle warning signage with a “Share the Road” plaque (Kay and Gates, 2013). Video recordings were collected from two segments of a high-speed rural two-lane highway with similar geometric and traffic features. The only difference between the two segments was that one segment had rumble strips at the painted centerline while the other segment did not have the rumble strips. Data were collected before and after placing the sign along the segments to perform before/after analysis. The results showed that the sign was ineffective at shifting motorized vehicles away from the riders on both segment types, thus the separation distance between riders and motorized vehicles remained similar in the before and after periods. The number of unsafe passes (those with a lateral distance of less than 1,524 mm or 5 ft) also remained relatively the same in both periods. Furthermore, it was found that motor-vehicle drivers tended to encroach less on the segment with rumble strips at the centerline which, in turn, decreased the passing distance between vehicles and bicycles. The lateral position of the cyclist was also a significant factor in the passing separation. It was found that passing distances were greater when the riders were in the center of the shoulder lane compared to when they were on the right edge of the shoulder lane.

A study conducted by Chuang et al. using an instrumented bike in Taiwan investigated the behavior of motorists overtaking cyclists (Chuang et al, 2013). They found that passing distances were smaller when motorcycles passed the cyclists than when cars and small trucks passed. In addition, they concluded that the presence of the bike lanes resulted in greater lateral distances between the cyclists and the passing vehicles.

Nosal and Miranda-Moreno performed a study in the City of Montreal to analyze preliminary cyclist injury risk between streets with and without bicycle provisions (such as bicycle lanes and bicycle tracks) (Nosal and Miranda-Moreno, 2012). For the purpose of the study, nine control streets were selected. Average annual daily bicycle volumes (AADBV) were used to determine the cyclist exposure on these sites. The injury data were collected from Department of Public Health in Montreal and these injuries were plotted on bike segments using ArcMAP GIS software. It was concluded that the injury rate on routes with bicycle facilities was significantly lower than the facilities without bicycle provisions. The study warranted the need for further research, particularly in the area of finding the exact effect of factors associated with these bicycle facilities. These factors include type of the facility (unidirectional or bidirectional), visibility, physical separation, location of parking, and the volume of vehicular traffic.

Turner et al. carried out a study in Chirstchurch, New Zealand and Adelaide, Australia to determine the risks faced by cyclists on various parts of the road network and to recommend measures to mitigate those risks (Turner et al., 2011). The collected data included collision data, vehicle and bike volumes and geometric layouts of road links, signalized intersections and roundabouts. Furthermore, variables like motorized vehicle speed, visibility, presence and type of

bicycle-facility provision, lane and road width were also included in the model to gain the idea of their impact on different crash types. A total of 102 intersections and 383 approaches were selected for the study. The models were prepared using generalized linear modelling and before-after control impact methods. The primary goal of the models was to develop relationships between the mean number of accidents (as the dependent variable) and traffic volumes, cyclist volumes and variables indicating qualities of the cycling infrastructure (such as whether the bike lane is colored). The results showed that the overall effect of bike lanes is neutral. Bike lanes built to high standards (such as bicycle boxes, colored lanes, etc.) can improve cyclist's safety and those built to lesser standard can reduce cyclist safety. The results showed that the colored bike lanes reduced all crash types by 39% and resulted in better driver behavior towards cyclists. Wider bicycle lanes (1.60 meter) showed higher safety levels than standard (1 meter) lanes.

## **2.2 Existing Bicycle-facility Selection Guidelines**

As previously stated in section 1.2, currently the decision regarding which cycling facility to install is made using engineering judgments. Different jurisdictions have set different guidelines, which are based on expected volumes and vehicle speeds. In this section, the guidelines to select appropriate on-street cycling facilities for a specific roadway section are presented. The on-street cycling facilities can be classified into the following four categories (facility-types).

1. **Narrow Lane:** Narrow lanes are 2.75 meter to 3.65 meter wide. No special provisions are provided to the cyclists and they are allowed to either take the entire lane or operate in the margins (Figure 5).
2. **Wide Lane/Wide Curb Lane:** Wide lanes are 4 meter to 4.50 meter wide. Cyclists generally operate on the sides of the road but they are allowed to take over the lane (Figure 6).
3. **Bike Lane:** They are usually 1 to 2 meter wide lanes on the sides of the motorized vehicle travel lanes. The separation between the bike lane and the motorized vehicle lane is delineated using pavement markings (Figure 7).
4. **Separated Path:** They include on-road bike lanes that are wider than 2 meter, bike lanes separated with medians or curbs, raised bike lanes, bike lanes on the sidewalks and physically separated bike tracks (Figure 8).



**Figure 5: Narrow Lane Cycling Facility**  
(Source: [www.letstrythat.com](http://www.letstrythat.com))



**Figure 7: On-street Bike Lane Facility**  
(Source: [www.richmond.ca](http://www.richmond.ca))



**Figure 6: Wide Lane Cycling Facility**  
(Source: FHWA)



**Figure 8: Separated Path**  
(Source: Bicycle Quarterly)

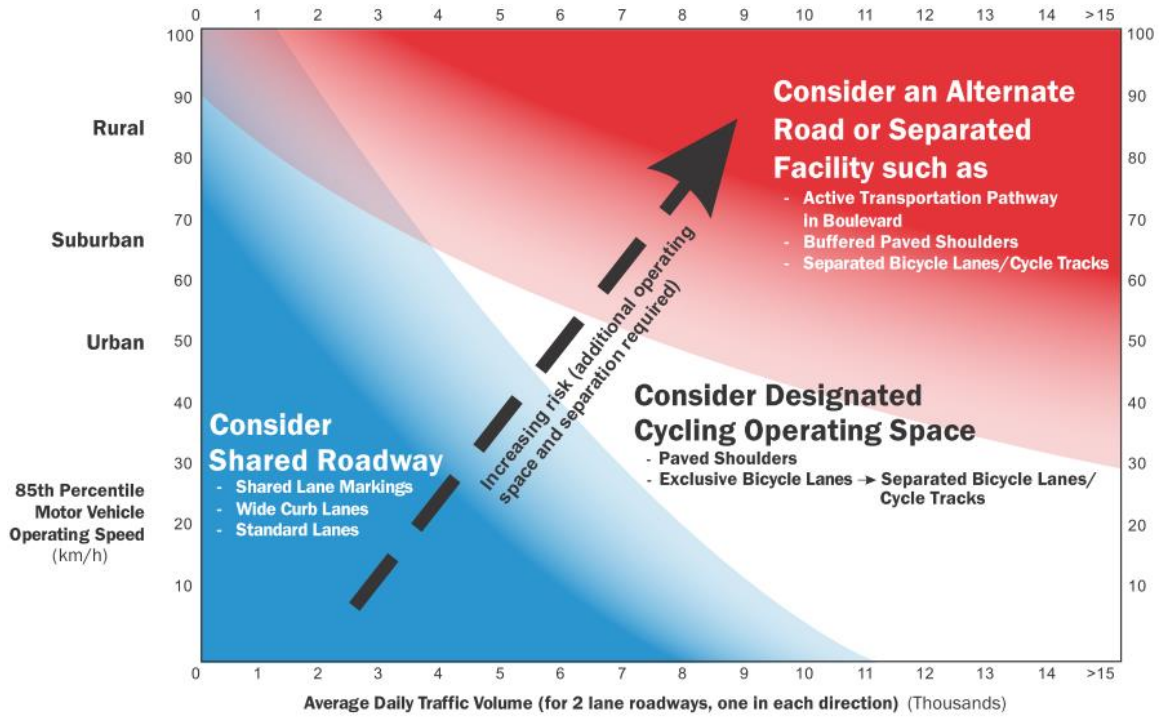
On ‘narrow lane’ and ‘wide lane’ facility-types the cyclists and motorists use the same lane(s) for travel, hence, they are often combined under the same category named ‘shared lane’. A study conducted in Copenhagen in which several cyclists were interviewed found that the cyclists feel most secure on roads with separated cycle paths and least secure on roadways with shared lanes (Jensen et al.).

### 2.2.1 Ontario Traffic Manual (OTM Book 18)

The Ontario Traffic Manual Book 18 – Cycling Facilities has been developed by the Ministry of Transportation Ontario (MTO) and Ontario Traffic Council (OTC) and provides assistance with planning and design of cycling facilities in the Province of Ontario (MTO, 2013). The process of selecting an appropriate cycling facility is separated into three steps as described below:

1. **Facility Pre-Selection:** In this step, using the expected demand and speed on the roadway section, a facility-type is selected. This is undertaken using the nomograph presented in Figure 9. The x-axis represents the Average Annual Daily Traffic (AADT) for 2-lane roads and the y-axis represents the 85<sup>th</sup> percentile motor-vehicle speed (km/h). The blue area on the nomograph represents a shared roadway (‘narrow lane’ and ‘wide lane’ facility-types); the white area represents a paved shoulder or bike lane; and the red area represents a physically separated path. The nomograph was designed for 2-lane roadways, however it is also applicable to roadways with more than 2-lanes. For such roadways, only the traffic volume and the vehicle speed

of the vehicles travelling in the lane immediately adjacent to the cycling facility should be considered.



**Figure 9: Desired Bicycle-facility Pre-selection Nomograph (MTO, 2013)**

2. Review of Site-Specific Characteristics: The facility-type selected in Step 1 may not be the optimum solution for all roadway sections. Variations in traffic-flow parameters and administrative and demographic characteristics can be observed between similar roadway sections. For this reason, it becomes necessary to evaluate these factors for each site individually. In Step 2, 13 site-specific criteria are evaluated for the given roadway section to aid the selection of facility-type for a specific roadway section. These criteria are built on knowledge-based rules (application heuristics) and they are listed in Table 1.

**Table 1: Site-specific Criteria (MTO, 2013)**

<b>Primary Determining Criteria</b>	<b>Secondary Determining Criteria</b>
85 <sup>th</sup> percentile motor-vehicle operating speeds	Costs
Motor-vehicle volumes	Anticipated users in terms of skill and trip purpose
Function of street, road or highway	Level of bicycle use
Vehicle Distribution (e.g. vehicle types)	Function of route within bicycle-facility network
Collision history	Type of roadway improvement project
Available space	On-street parking
	Frequency of Intersections

The guideline recommends different facility-types based on different categories of these criteria. The planner is required to assess the site for all criteria and document the most compatible facility-type in Step 2. The selection of the facility in Step 2 is independent of the decision made in Step 1. The categories for ‘85th percentile speed’ and ‘motor-vehicle volumes’ criteria are presented in Table 2. Detailed information about these criteria is presented in Appendix B.

**Table 2: Categories of Vehicle Volumes and Speeds (Site-Specific Characteristics) (MTO, 2013)**

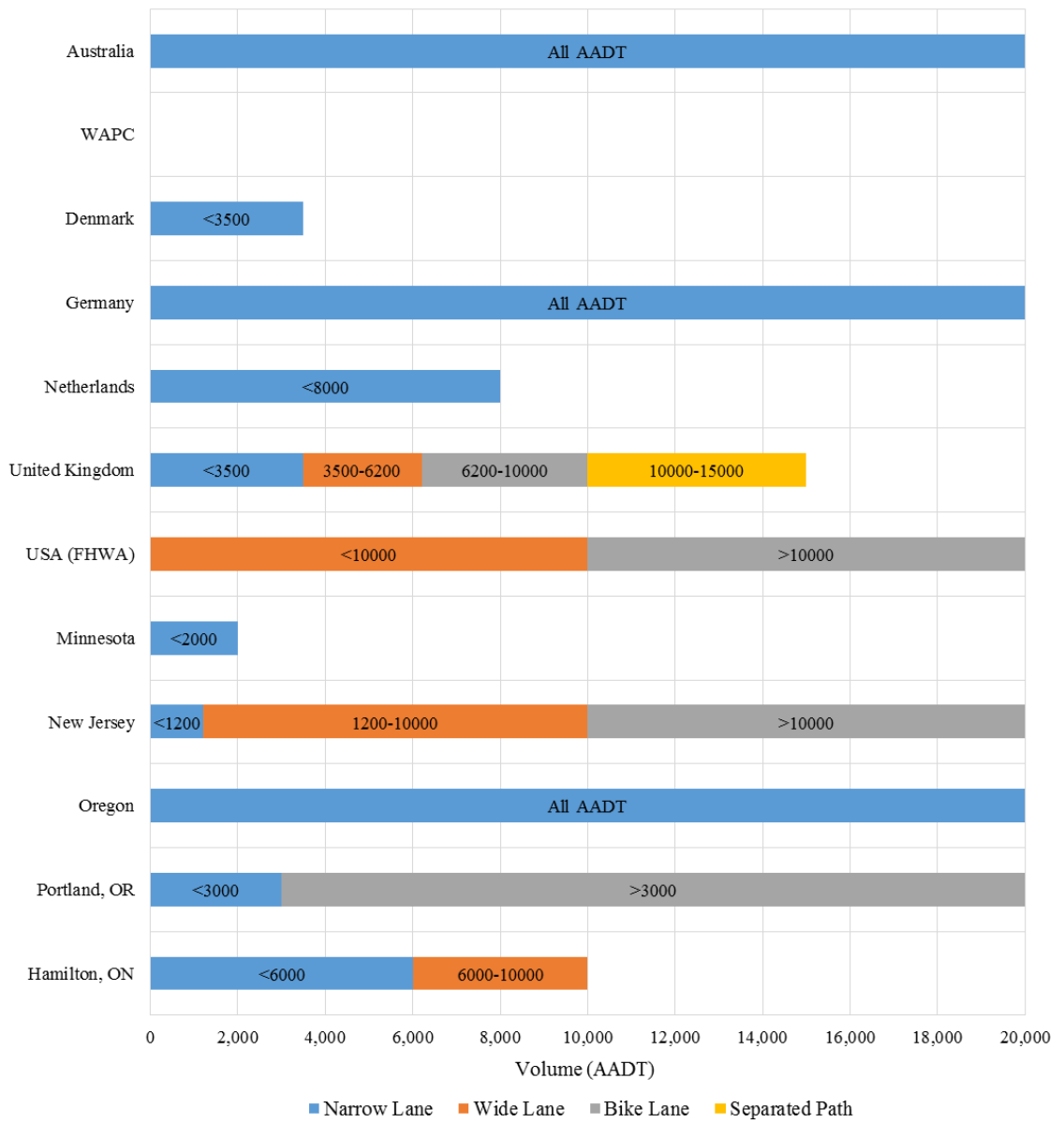
<b>Criteria</b>	<b>Categories</b>	<b>Recommended Facility-Type</b>
<b>Motor-vehicle volumes</b>	Very low (< 500 vpd on a 2-lane road)	Narrow Lane
	Low (500-2,000 vpd on a 2-lane road)	Narrow Lane or Wide Lane
	Moderate (2000-10,000 vpd on a 2-lane road)	Bike Lane
	High (>10,000 vpd on a 2-lane road)	Separated Path
	Hourly one-way volume in the curb lane > 250 vph	Bike Lane
<b>85th percentile motor-vehicle operating speeds</b>	Low (30-49 km/h)	Narrow Lane or Wide Lane
	Moderate (50-69 km/h)	Bike Lane
	High (70-89 km/h)	Separated Path
	Very high (90 km/h and greater)	Separated Path

3. Finalizing Facility Selection: Using the decisions made regarding the selection of cycling facility in the previous steps, the final facility is chosen in this step. To do this, the compatibility of the facility-type in Step 1 is checked with the recommended facility-type obtained from Step 2. If the site-specific conditions documented in step 2 do not support the result of Step 1, alternative facility-types are considered. Once all the factors are considered, the final decision is made regarding the appropriateness of a facility-type for a specific roadway section. Finally, the entire facility selection process and rational behind it is also documented in Step 3.

### 2.2.2 Other Guidelines

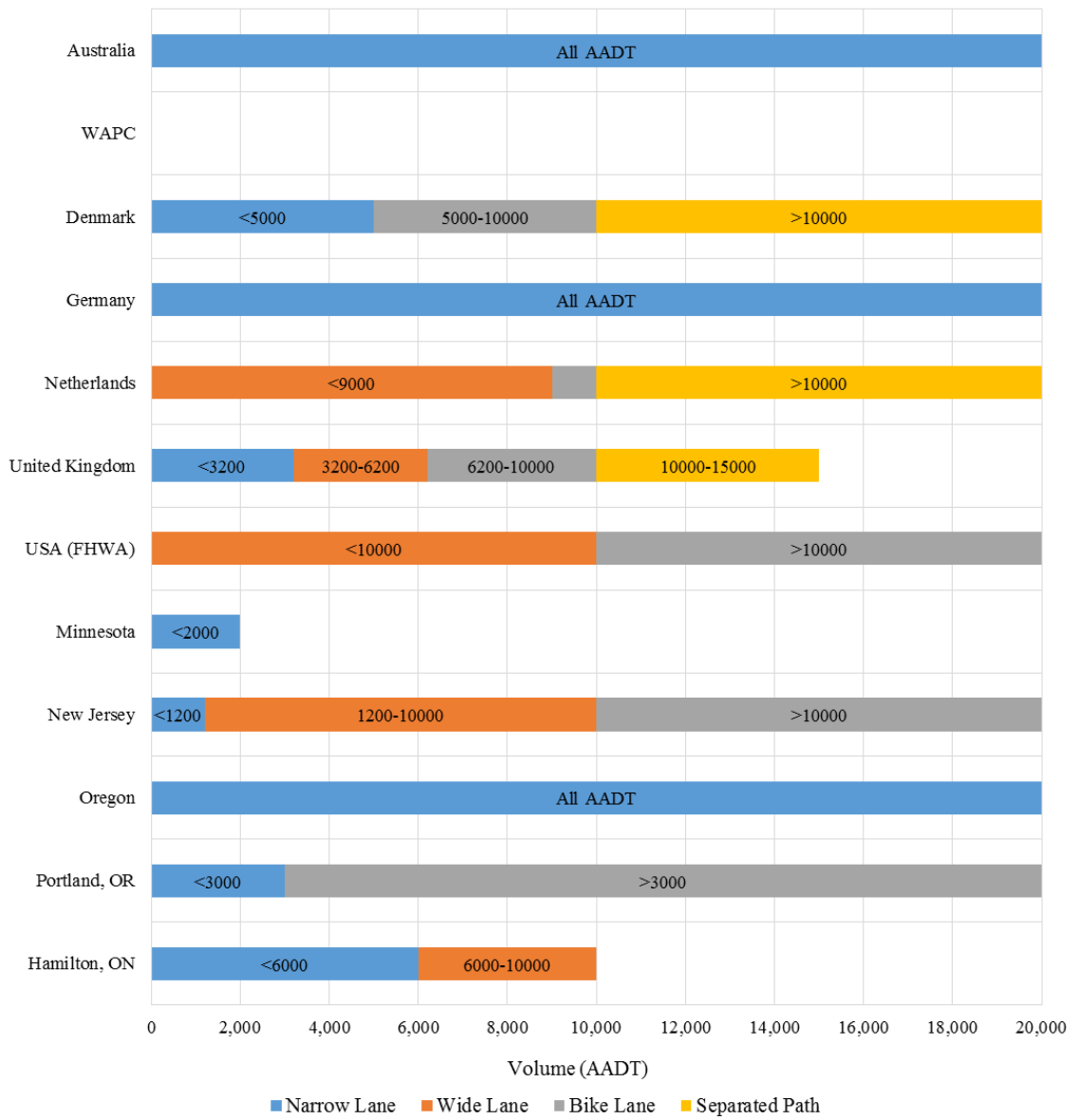
In this section, Bicycle-facility Selection Guidelines from other jurisdictions or agencies are presented. These guidelines are summarized in Figure 10 through Figure 15. There are significant variations between guidelines from different jurisdictions. The facility-type selection is made using the volume-speed matrices as shown in the figures. Detailed information regarding some of these guidelines is presented in Appendix B.

The figures presented below are classified by the vehicles speeds. The vehicle speed is represented by either the 85<sup>th</sup> percentile speed of traffic or the design speed. However, where the data regarding the speeds were unavailable, 15 km/h was added to the posted speed limit as a surrogate measure for the 85<sup>th</sup> percentile speed, as described in The Bicycle Compatibility Index (BCI) (Harkey et al., 1998). The volumes are represented as AADT (average annual daily traffic). For each jurisdiction, the recommended facilities for a specific design speed are indicated using horizontal bars. If no indication is present, it means that jurisdiction does not recommend any facility-type for any volume for the current design speed. The guideline for Minnesota (Minnesota Department of Transportation, 2007) is specific to 4-lane roadways. The guidelines by FHWA (Wilkinson, 1994) and Oregon (Oregon Department of Transportation, 2011) are applicable to both 2-lane and 4-lane roadways. The remaining guidelines do not specify the number of lanes and it was assumed that they are applicable to only 2-lane roadways (King, 2002). From these figures, it is apparent that design guidelines prepared outside of North America are relatively more conservative for roadways with higher speeds and volumes. Most of the guidelines outside of North America recommend provision of separated paths on roadways with higher speeds and volumes. Comparatively, within North America shared lanes or bike lanes are recommended for roadways comprising similar traffic-flow characteristics.

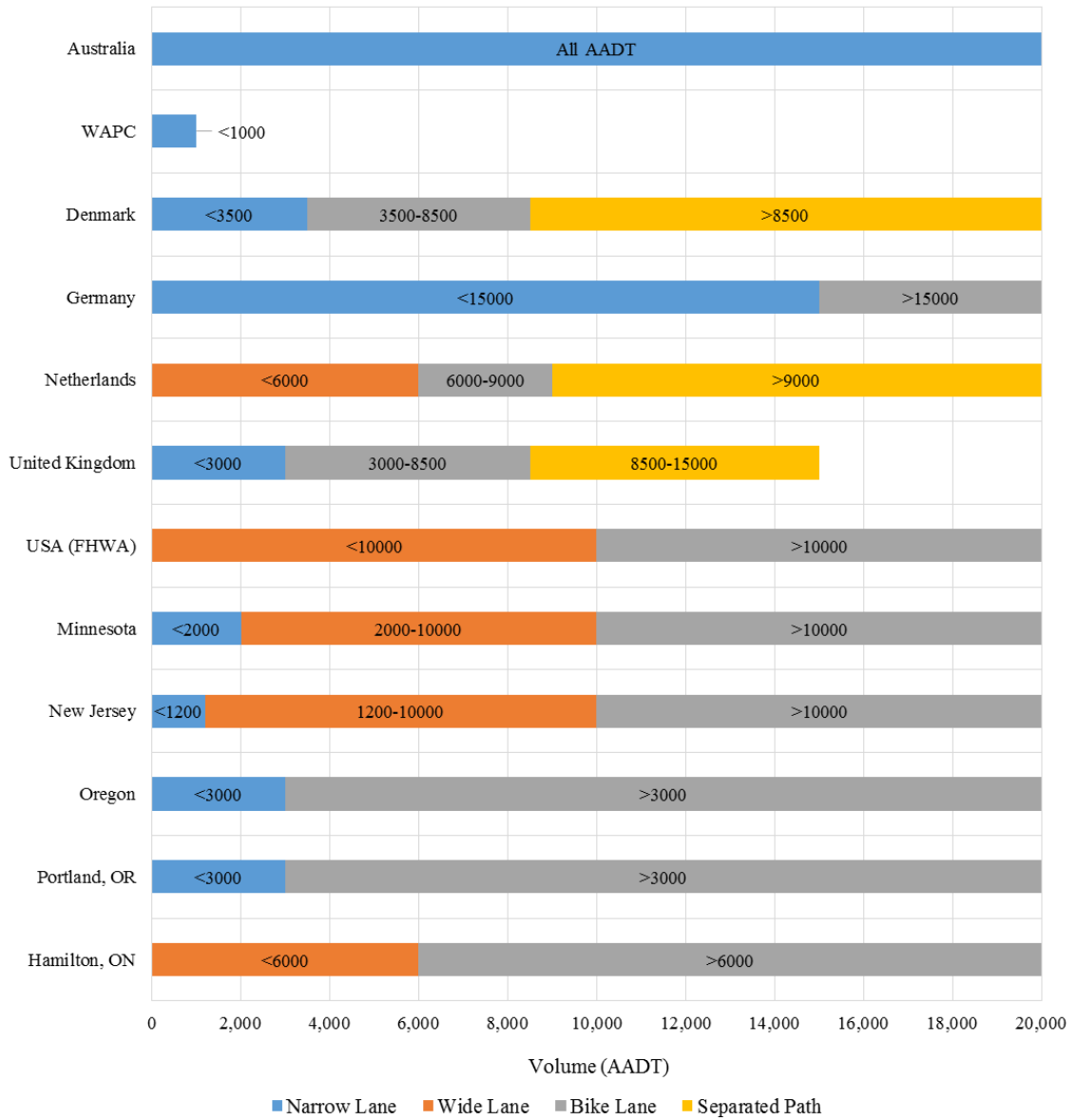


**Figure 10: Bicycle-facility Selection Guidelines for Design Speed of 25 km/h**

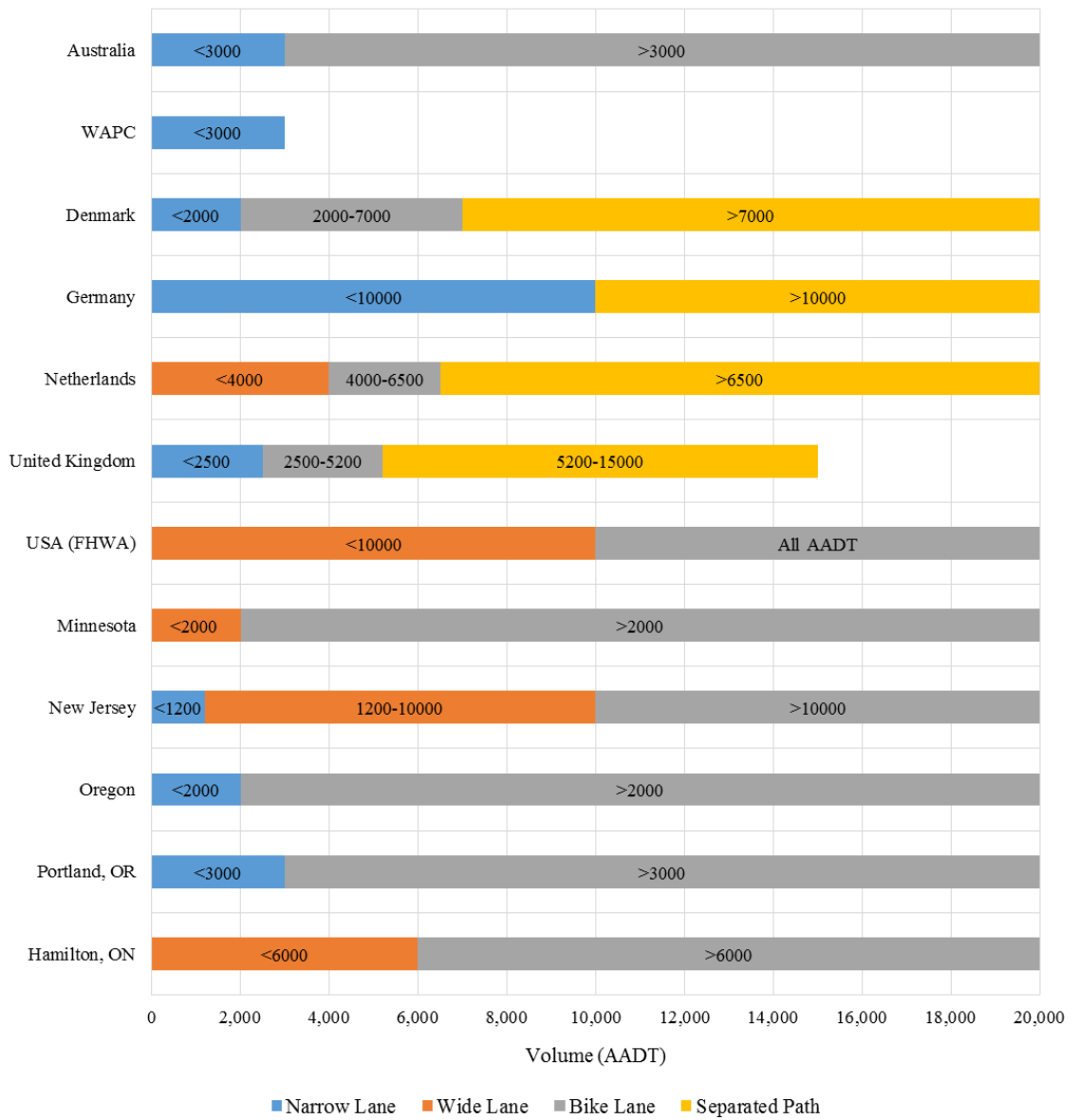




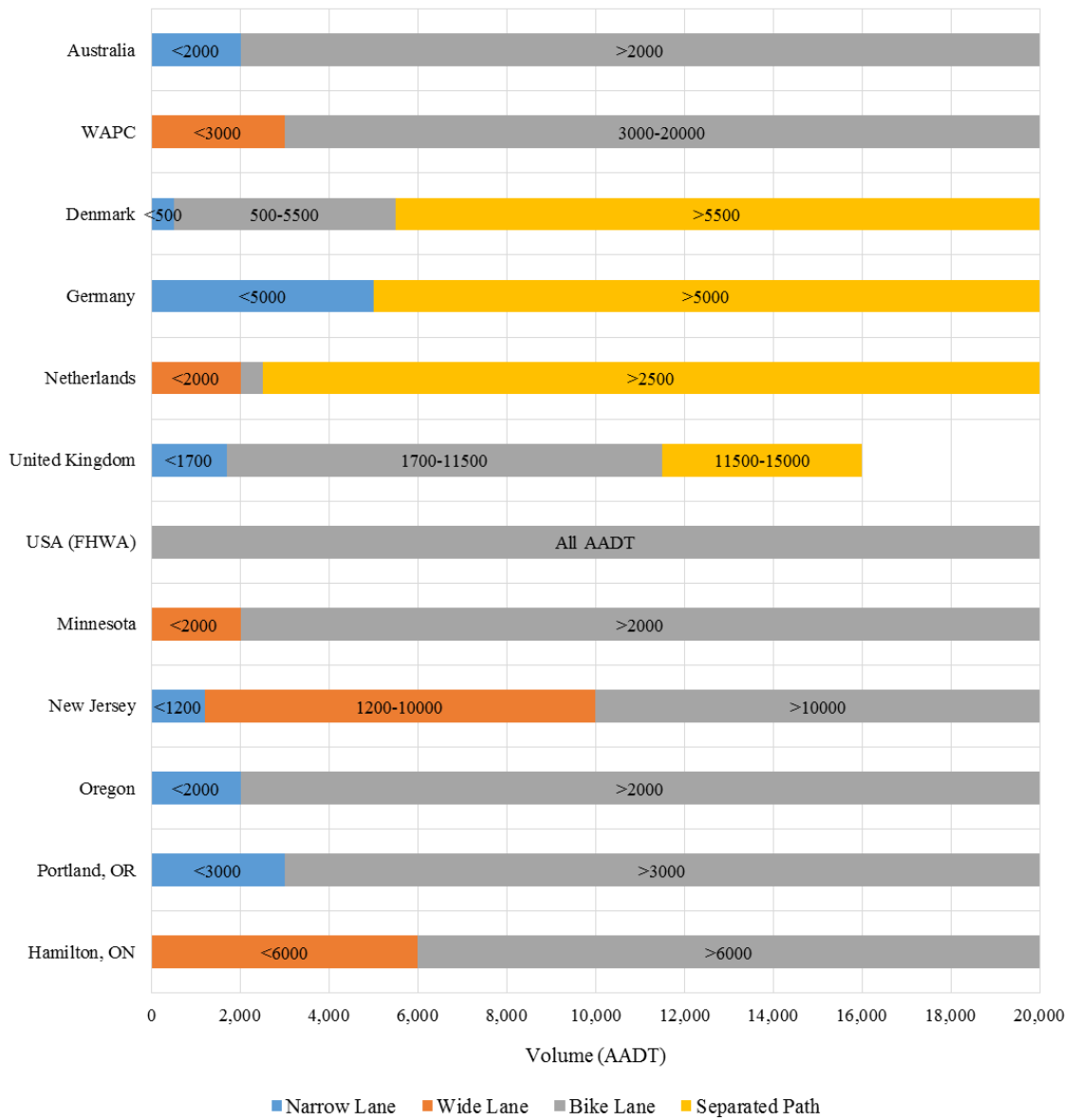
**Figure 11: Bicycle-facility Selection Guidelines for Design Speed of 30 km/h**



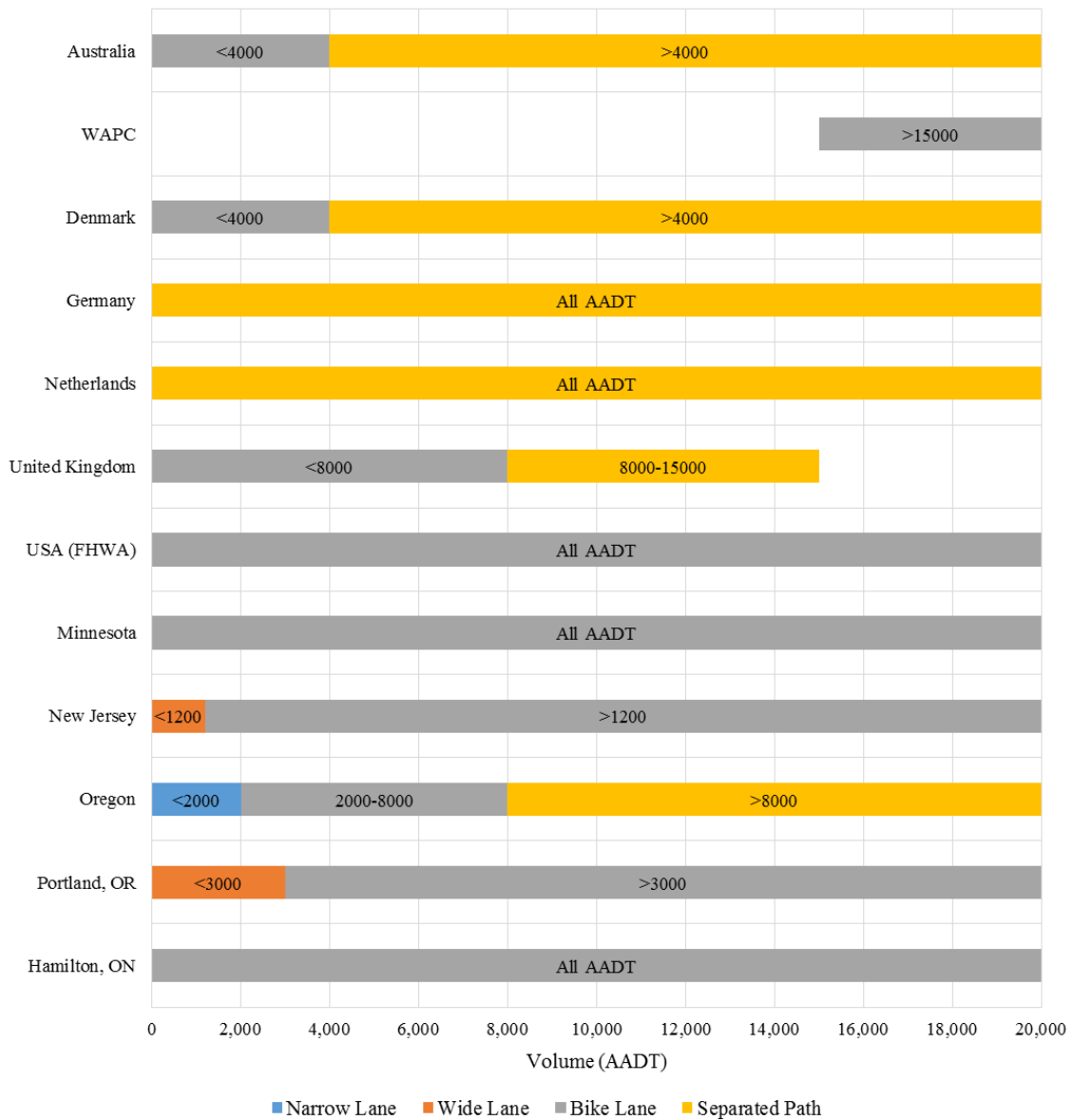
**Figure 12: Bicycle-facility Selection Guidelines for Design Speed of 40 km/h**



**Figure 13: Bicycle-facility Selection Guidelines for Design Speed of 50 km/h**



**Figure 14: Bicycle-facility Selection Guidelines for Design Speed of 55 km/h**



**Figure 15: Bicycle-facility Selection Guidelines for Design Speed of 65 km/h**

From the review of the past research and the current design guidelines, it appears that:

1. There is lack of consensus regarding the impact of on-street bike lanes on passing distances.
2. There is yet not a comprehensive understanding of the factors influencing passing behavior.
3. There is a need to establish best practices with respect to collecting data that can address items 1 and 2. This research tries to address all of these concerns.

## **Chapter 3**

### **Data Collection**

This chapter discusses the procedure leading to the development of the sensor array used for data acquisition for this study. The later part of this chapter discusses the criteria for site selection and the procedure of data collection. Locations of the sites where the data were collected are also shown on a map.

Two types of data acquisition methods are commonly used; fixed data collection method and portable data collection method. The fixed data collection method makes use of video cameras installed on the roadside to record videos of passing events. The advantage of this method is that once the cameras are installed, no additional physical effort is required for the acquisition of data. The video recordings can be processed later either manually or with the help of computers and algorithms specifically designed for video processing. Manual inspection of each passing event in every video can be extremely resource intensive and may prove to be infeasible in most cases. Furthermore, overtaking of bicycles can occur at random locations. Therefore, several cameras have to be installed to capture all passing occurrence in the area of interest.

An alternative is to use a portable data collection method where a bicycle can be instrumented with one or more sensors capable of measuring the passing distance. The measured data can be stored on a storage media for post processing. This type of data acquisition system can be powered by a portable power source. Currently there are several low cost and low power portable data acquisition systems available for a range of jobs. Therefore, it is important to choose the right combination of components (e.g. sensors, data logger and power source) that is suitable for the job.

#### **3.1 Sensor Array Design and Bicycle Instrumentation**

A custom sensor array was designed and built for this research. The sensor array consisted of an ultrasonic sensor, a GPS receiver, a microcontroller, and a data logger. There are mainly two types of range finding sensors that can be used to measure the passing distances: namely, optical (e.g. infrared and laser sensors) and sonic (e.g. ultrasonic sensor). The selection of the range finding sensor should be based on accuracy, cost, maximum range, measuring speed and communication protocols. For this study, the infrared sensors were tested and later rejected due to low accuracy in passing distance measurements. Laser sensors are the most accurate but they are expensive, hence they were not considered. Finally, ultrasonic sensors were considered because of their high fidelity measurements, lower cost and faster measuring speed. The ultrasonic sensor selected for the study (HRLV-MAXSONAR-EZ4 from MaxBotix) is capable of taking measurements at every 100 ms (frequency = 10 Hz), is relatively low cost, low power (20 mA) and has a maximum range of 5 meter for measurements. Furthermore, it also facilitates multiple communication protocols to choose from, such as analog, pulse width modulation and I2C. This sensor also has onboard temperature and humidity sensors, which allow automatic correction of measured data for different environmental conditions.

To analyze the passing maneuvers on various roadway types in various traffic conditions, it was necessary to obtain the information about bicycle location and speed at the time of passing. Therefore, a GPS component (EM-406A) was also used while collecting data. This GPS was

selected based on its low power requirement, relatively low cost and higher accuracy. The location information was captured by longitude and latitude. In addition, the GPS unit also facilitated the measurement of bicycle travel speed. The collected data using the ultrasonic sensor and GPS were stored in a flash memory (SD card) using a data logger. An Arduino protocol based microcontroller (UNO R3) was selected to serve as a host, power and drive the other sensors. The information regarding the components used to develop the sensor array is presented in Table 3. A program was written in C++ language to enable communication of the microcontroller with the other components, to collect and filter appropriate data and to store the data in the right sequence and format on the memory card. This program is presented in Appendix E of this document. The system was powered by a portable Li-Ion battery (12 V, 10,000 mAh). These components were packaged together in a plastic (ABS) enclosure as shown in Figure 16 to enable mounting of the sensor array on the back of the bicycle. Its higher machinability and low cost properties made ABS plastic a suitable material for enclosure.

**Table 3: Components Used in Sensor Array**

<b>Component</b>	<b>Model Name</b>	<b>Function</b>	<b>Frequency</b>
<b>Microcontroller</b>	Arduino UNO R3	Main driver and host to other components	N/A
<b>Global Positioning System</b>	EM-406A	Obtains coordinates, bike speed, time stamps	1 Hz
<b>Ultrasonic Sensor</b>	HRLV-Maxsonar-EZ4	Measures lateral distance between bicycle and passing vehicles	10 Hz
<b>Data Logger</b>	generic	Records data obtained from GPS and Ultrasonic Sensor on SD Card	N/A

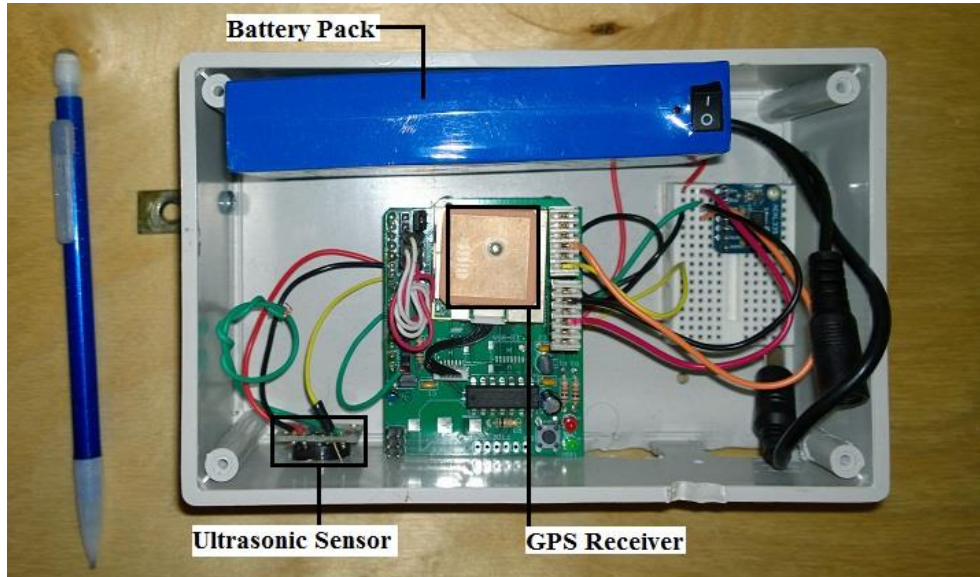


Figure 16: Sensor Array

The sensor array was programmed to write data to the memory card in a specific sequence as show in Figure 17. The data from the GPS (begins with ‘GPRMC’) was collected at each one-second interval. The data from the GPS unit contained information about current date and time, longitude, latitude, heading, speed (knots) and checksum. The GPS data was followed by 10 consecutive records of distance measurement (in mm) at every 100 ms intervals from the ultrasonic sensor. The cycle was repeated until the duration of the data collection. The explanation of each string in the GPS data is explained in Table 4.

```
GPRMC,164909.000,A,4327.9048,N,08032.4669,W,8.20,196.75,180613,,A*77
992
992
992
993
993
992
992
993
993
992
GPRMC,164910.000,A,4327.9025,N,08032.4679,W,8.85,199.46,180613,,A*75
```

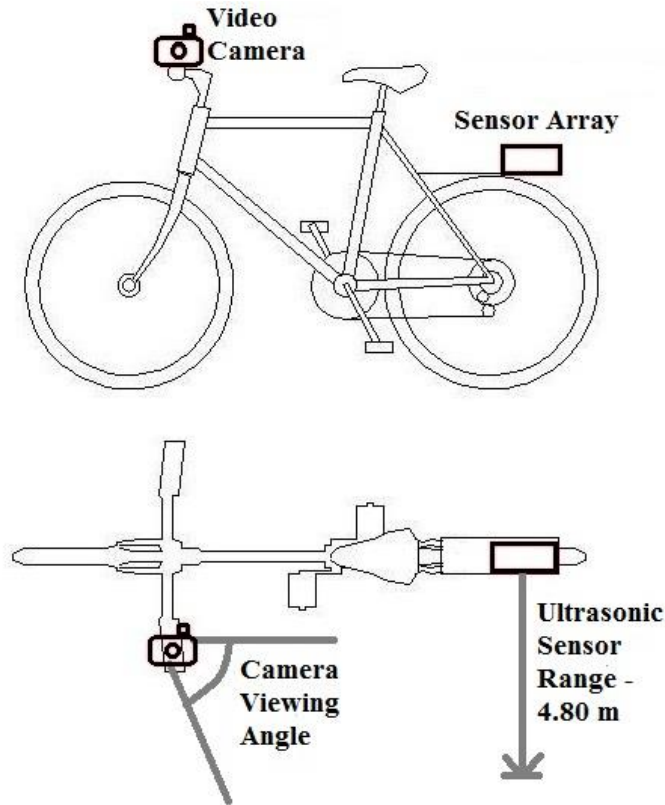
Figure 17: The Format of Collected Data



**Table 4: Explanation of the GPS Data strings**

<b>String</b>	<b>Explanation</b>
<b>GPRMC</b>	GPS protocol – Recommended minimum data
<b>164909.000</b>	Current time (4:49:09 PM)
<b>A</b>	GPS status (A – Active, N – Inactive)
<b>4327.9048</b>	Latitude
<b>N</b>	Longitude hemisphere (N – North, S – South)
<b>08032.4669</b>	Longitude
<b>W</b>	Latitude hemisphere (E – East, W – West)
<b>8.20</b>	Current speed (in knots)
<b>196.75</b>	Current heading with true north
<b>180613</b>	Date (18 June 2013)
<b>A*77</b>	Checksum for data validation

Additionally, a video camera was installed on the handlebar of the bicycle to record the videos of the passing observations. These videos were used to calibrate the sensor array and later to identify, if necessary, individual passing observations captured by the sensor. The video camera included an onboard GPS receiver for overlaying the real-time locations, bike speeds and time stamps on the videos, which facilitated synchronization of the videos with the data collected by the sensor array. Figure 18 shows the instrumentation of the bicycle.



**Figure 18: Bicycle Instrumentation**

### **3.2 Site Selection and Data Collection**

The data were collected on urban roads within the Kitchener-Waterloo area in southern Ontario. The urban arterials can be categorized by various geometric features such as lane widths, numbers of lanes, bicycle facility-types, sight distances, speed limits, etc. To narrow down the focus of the study on the most common combinations of these features the selection of the data collection sites was made based on the following criteria:

1. Roads with an on-road bike lane
2. Roads without an on-road bike lane where bicycles share a lane with other vehicles

The following road-related features were controlled when selecting the sites for data collection:

3. Number of Lanes: Only 2-lane or 4-lane urban arterials were selected.
4. Speed Limit: This research is focused on urban cycling and most urban local and collector roadways have a maximum speed limit of 50km/h. Routes with posted speed between 40 km/h or 50 km/h were selected for 2-lane roads and routes with 50 km/h posted speed limit were selected for 4-lane roads.
5. Lane Width: Routes with standard lane width of 3.65 meter were selected. Lanes with width up to 3.65 meter are defined as ‘Narrow Lanes’ in bicycle-facility selection guidelines presented in section 2.2. In case of a route with an on-road bike lane, the width of the bike lane was to be between 1 meter and 1.2 meter. The lane widths were measured using spot measurements on roads and/or Google Earth software.

6. Grade: Data was only collected on roadways without significant vertical grade. The following bicycle-related and ambient factors were also controlled while collecting the data:

- 7. Visibility: Data was only collected during the day time under bright sunny conditions to ensure optimum visibility.
- 8. Bike Location: For the routes with bike lanes, the bicycle was ridden in the middle 0.5 meter portion of the bike lane. For the routes without a bike lane, the bike was ridden within 0.5 meter of the curb.

Consequently, data were collected on the following four route types:

- (i) 2-lane road with no bike lane (2LNB)
- (ii) 2-lane road with bike lane (2LWB)
- (iii) 4-lane road with no bike lane (4LNB)
- (iv) 4-lane road with bike lane (4LWB)

The data were collected on these four types of facilities between June 18, 2013 and September 3, 2013. The duration of each data collection session was between 12 to 86 minutes. The data was collected during different times of the day to include a range of traffic conditions. The total duration of data collection sessions over all facilities was 27 hours and 19 minutes during which 5,227 passing maneuvers were recorded. For each passing vehicle, the time and location were obtained using the GPS, and the passing distances were collected using the ultrasonic sensor. Following is the breakdown of data collection durations and number of passing observations by route types.

**Table 5: Summary of Data Collection Durations and Number of Passing Observations**

<b>Facility-Type</b>	<b>Total Duration of Data Collection (HH:MM)</b>	<b>Total Number of Passing Events</b>
<b>2LNB</b>	05:29	680
<b>2LWB</b>	03:32	515
<b>4LNB</b>	08:56	1,895
<b>4LWB</b>	09:22	2,137
<b>Total</b>	<b>27:19</b>	<b>5,227</b>

Locations of the sites where the data were collected are shown on a map in Figure 19. The sites are color coded by facility-types.

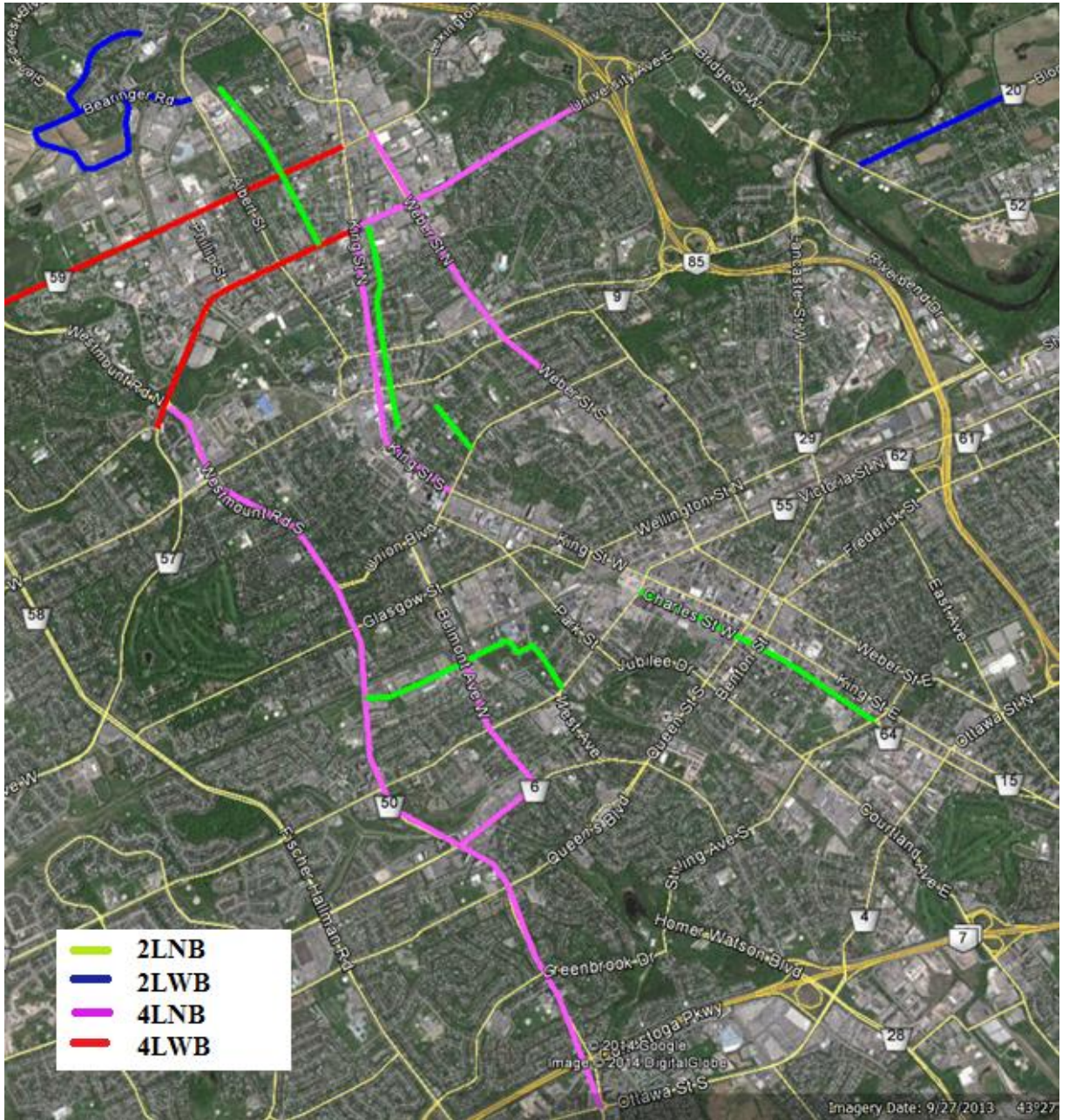


Figure 19: Data Collection Sites

## **Chapter 4**

### **Methodology for Data Analysis**

This chapter proposes the methodology to analyze the collected passing data and addresses the following problems:

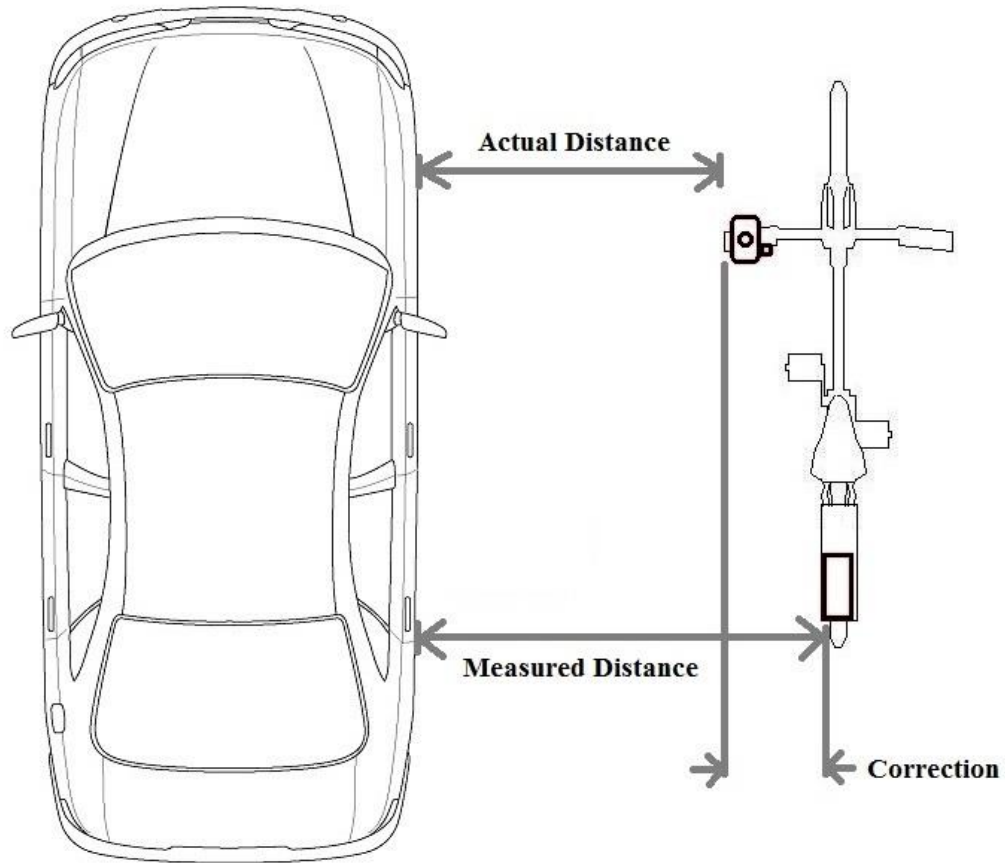
1. Define the passing distance and identify the correction required in the passing data before performing further analyses (section 4.1).
2. Identify the threshold to categorize the passing observations in to safe and unsafe passing (section 4.1.1).
3. Define the passing types based on the drivers' behavior during the passing maneuvers (section 4.3).
4. Propose the methodology to investigate the relationship of passing distances with traffic-flow parameters such as vehicle speed and time headway (section 4.4).

Before performing the analyses explained in this chapter, the collected data were processed using MATLAB software. The MATLAB code to parse the collected data is presented in Appendix F. The passing distance observations were extracted using the data from the ultrasonic sensor. The extracted passing distances were measured in millimeters from the sensor. Due to the higher frequency of 10 Hz (data collection rate) of the ultrasonic sensor, each passing observation was captured multiple times. An arithmetic average of these multiple distance measurements was used for a single passing event. The number of times the distance was measured for each passing event (sensor occupancy) was also recorded. The information regarding the locations of these passing events, the times of passing and the bike speeds at the time of passing was extracted from the GPS data strings. The location information (longitude and latitude) were converted to the decimal degree format. Using the decimal degree format for longitude and latitude, the straight-line distance between any two passing events can be calculated. The speed was converted from knots to km/h and m/s units. The equations for carrying out these conversions are provided in Appendix C.

#### **4.1 Definition of Passing Distance**

The passing distance was defined as the perpendicular distance between the right edge (passenger side) of a motorized vehicle and the left extremity of the bicycle (Figure 9). The left extremity of the bicycle was located on the left side of the handle bar. Since the ultrasonic sensor was positioned near the center of the bicycle, the measured distance using the ultrasonic sensor had an offset equal to the distance between ultrasonic sensor and the left extremity of the bike, which was found to be 200 mm and was deducted from all measured passing distances.





**Figure 20: Passing Distance Correction**

#### **4.1.1 Safe and Unsafe Passing**

Bill 74 of Highway Traffic Amendment Act filed under The Legislative Assembly of Ontario requires at least 1,000 mm separation (so called “1m rule”) between bicycles and motorized vehicles at the time of passing (Legislative Assembly of Ontario, 2010). Furthermore, several states in the USA have enforced a similar distance of 0.90 m (3 ft) as the minimum required separation distance (Figure 2, section 1.1). In this thesis, we do not attempt to determine the collision risk as a function of the passing distance nor do we attempt to establish collision risk for passing distances less than the minimum relative to passing distances greater than the minimum. Instead, we determine the complete distribution of passing distances for different roadway types and then we summarize the relative frequency of passing distances into two categories, namely those which are less than 1,000mm and those which are greater than or equal to 1,000mm. The implication of the proposed “1m rule” for Ontario and similar laws in other provinces in Canada and in various states in the USA imply that passing distances less than the legislated minimum are unsafe. Consequently, we refer in the remainder of the thesis to passing events with less than 1,000 mm of lateral clearance as “unsafe” and those with 1,000mm or more of lateral clearance as “safe”. These terms are meant to reflect the legislated minimum passing distance and should not be interpreted to mean that all passing events in which the passing distance is greater than or equal to 1,000mm have no collision risk.

## 4.2 Average Vehicle Width and Length

The distance from the bike to the right edge of the passing vehicle was measured. However, classification of the passing maneuver also required an estimate of the vehicle width to be able to estimate the position of the left edge of the vehicle relative to the lane markings. In addition, as discussed in the following section, vehicle lengths must be known to estimate the speed of the vehicle during the passing maneuvers. However, the sensor array developed for this research could not identify the type of the passing vehicles (i.e. sedan, SUV, etc.), and therefore the dimensions of the vehicles were unknown. Manual identification of the type (and size) of each passing vehicle was possible through visual inspection of the video recordings; however it was extremely resource intensive. Alternatively, an analysis was conducted to estimate an average vehicle width and length that can be used for all passing vehicles. For this purpose, a random sample of video data was selected for each of the four facility-types. In the end, 474 passing observations were identified and each was manually categorized into one of seven vehicle classes (Table 6). Typical vehicle widths and lengths were assigned to each vehicle class using publically available vehicle manufacturer data. Based on this analysis the average width and length of the vehicles were found to be 1.78 meter and 5.16 meter, respectively. It is expected that vehicle fleet compositions vary depending on the urban region and therefore the distribution observed in Kitchener-Waterloo region may not be applicable to other locations.

**Table 6: Distribution of Vehicle Types (Kitchener-Waterloo Region)**

<b>Vehicle Class</b>	<b>Number of Vehicles</b>	<b>Average Width (m)</b>	<b>Average Length (m)</b>
<b>Compact</b>	4	1.60	3.55
<b>Mid-Sized Sedan</b>	88	1.60	4.30
<b>Sedan</b>	69	1.70	4.75
<b>SUV/Van</b>	188	1.80	5.15
<b>Pickup Truck</b>	114	1.90	5.40
<b>Bus</b>	7	2.35	11.00
<b>Tractor-Trailer</b>	4	2.50	16.30
<b>All Combined</b>	<b>474</b>	<b>1.78</b>	<b>5.16</b>

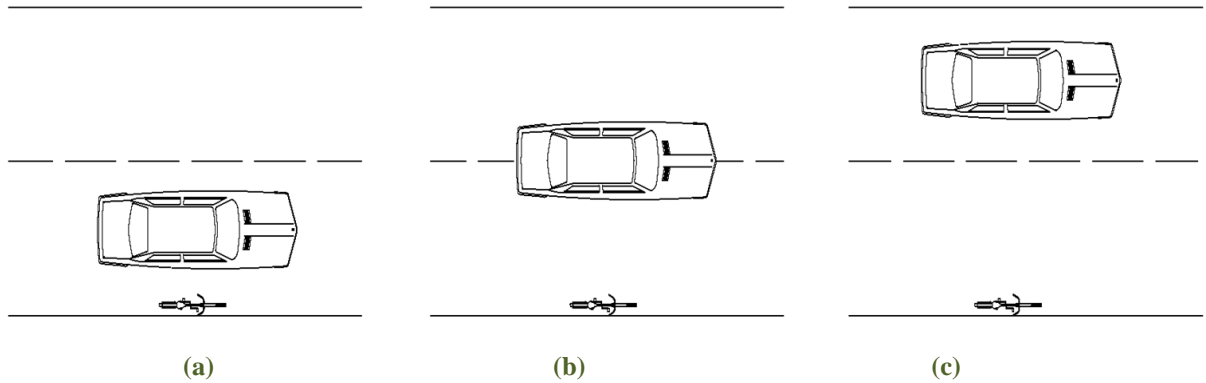
## 4.3 Passing Behaviors

Drivers' behaviors during all of the observed passing maneuvers were classified in three categories, namely:

1. Near Lane Passing – where a passing vehicle stays entirely within the curbside travel lane (near lane) during the passing maneuver (Figure 21 a)
2. Encroachment Passing – where the vehicle partially travels on the near lane and the far lane simultaneously (Figure 21 b)

3. Far Lane Passing – where the passing vehicle stays entirely within the central travel lane (far lane) during the passing maneuver on 4-lane roads, or the vehicle stays in the lane accommodating the traffic in the opposite direction on 2-lane roads (Figure 21 c)

On 2-lane roadways, the propensity of Encroachment Passings and Far Lane Passings depends on the vehicular flow rate of the traffic in the opposite direction.



**Figure 21: Types of Passing Behavior**

These passing behaviors were identified using the average vehicle width of 1.78 meter. For example, on a road without a bike lane, the width of the curbside lane is 3.65 meter. Using the average vehicle width of 1.78 meter, a vehicle can only be entirely within the curbside lane if its right edge is located no more than  $(3.65 - 1.78 =) 1.87$  meter away from the curb. Since the left extremity of the bike was controlled at approximately 500 mm from the curb, passing observations with less than  $(1.87 - 0.5 =) 1.37$  meter clearance were classified as near lane passes. Similarly, passing observations with greater than  $(3.65 - 0.5 =) 3.15$  meter clearance were classified as far lane passes. Passing observations with lateral clearances between 1.37 meter and 3.15 meter were classified as encroachment passes. The thresholds to determine the passing behaviors for the roads with bike lanes were estimated in a similar manner. These thresholds are presented in Table 7.

**Table 7: Threshold for Passing Behavior Types**

Road Type	Threshold for Near Lane Passing	Threshold for Far Lane Passing	Thresholds for Encroachment Passing
Roads Without Bike Lanes	Passing Distance < 1.37 m	Passing Distance > 3.15 m	1.37 m < Passing Distance < 3.15 m
Roads With Bike Lanes	Passing Distance < 2.12 m	Passing Distance > 3.90 m	2.12 m < Passing Distance < 3.90 m



## 4.4 Estimation of Traffic-flow Parameters

Apart from road geometric features, and driver and cyclist behavior, traffic-flow parameters such as speed and flow may also influence vehicle-bike interactions. One of the objectives of this research was to evaluate and quantify these relationships. However, since the sensor array developed for this research was not capable of measuring traffic-flow parameters from the field, an alternative methodology was developed to estimate the speed of the passing vehicles and the time headway of the passing traffic from the collected data.

### 4.4.1 Estimation of the Speed of the Passing Vehicles

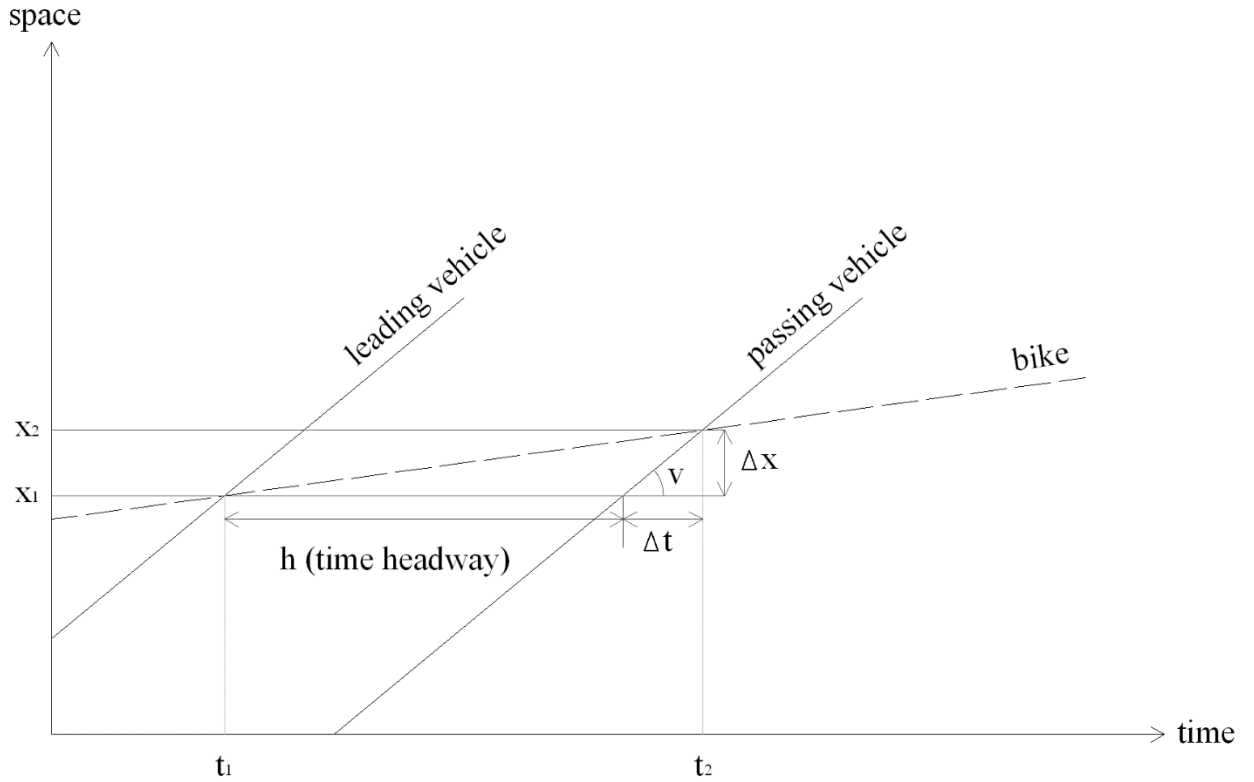
The speed of each passing vehicle was estimated using the average vehicle length of 5.16 meter (Table 6) and the occupancy time of the ultrasonic sensor for that particular passing maneuver. The ultrasonic sensor used in the data collection unit polls a distance measurement every 0.1 second. Therefore, for each passing vehicle the distance is polled multiple times between the beginning and the end of the passing maneuver. Hence, the time required an individual vehicle to complete a passing maneuver (sensor occupancy time) can be estimated given the number of times the distance was polled. Using this information, the speed of a passing vehicle ( $v$ ) in m/s can be estimated using equation (1).

$$v = \frac{\bar{l}}{n_p \times t_p} + v_b \quad (1)$$

Where,  $\bar{l}$  is the average vehicle length (5.16 meter),  $n_p$  is the number of distance measurements recorded for that passing maneuver,  $t_p$  is the polling interval (0.1 second), and  $v_b$  is the bicycle speed reported by the GPS unit (m/s).

### 4.4.2 Estimation of the Time Headway

It is equally important to evaluate the relationship between the passing distance and the traffic-flow rate. However, the sensory array is not capable of directly measuring the flow rate and typically available measures of flow rate, such as AADT, are too aggregate to be of significant value in explaining passing behavior. Alternatively, a methodology was developed to estimate the instantaneous time headway of each passing vehicle as a surrogate for traffic-flow rate at the time of the passing. The time headway on urban arterials varies substantially depending on the average flow rate, the effect of upstream traffic signal in creating platoons, and the dispersion of these vehicle platoons as they travel downstream of the signal. Figure 22 shows a time-space diagram for a hypothetical vehicle-bike passing maneuver. The times (e.g.  $t_1$  and  $t_2$ ) and locations (e.g.  $x_1$  and  $x_2$ ) of all passing maneuvers were recorded and are known.



**Figure 22: Time-Space Diagram for Vehicle-Bike Passing Maneuver**

Figure 22 illustrates two vehicles that pass the cyclist. The passing maneuver of interest occurs when the *passing vehicle* overtakes the cyclist at time  $t_2$  and location  $x_2$ . The speed of this vehicle can be estimated using equation (2).

$$v = \frac{\Delta x}{\Delta t} \quad (2)$$

Equation (3) can be derived from equation (2) considering the time headway ( $h$ ).

$$v = \frac{x_2 - x_1}{t_2 - t_1 - h} \quad (3)$$

Since the speed of the passing vehicle ( $v$ ) is known from equation (1), equation (3) can be solved for the time headway:

$$h = (t_2 - t_1) - \frac{x_2 - x_1}{v} \quad (4)$$

For simplicity, it is assumed that the speed of the passing vehicle remains constant between consecutive passing maneuvers.

## Chapter 5

### Analyses Results

The proposed methodology in the previous chapter was applied to the collected data and the results are discussed in this chapter. The summary and distributions of passing distances are presented in sections 5.1 and 5.2. The relationship of passing distances with the vehicle speeds and time headways are discussed in sections 5.3 and 5.4 respectively.

#### 5.1 Data Collection Summary

Table 8 presents a summary of all observed passing maneuvers. Numbers of total passing and unsafe passing (passing distance less than 1,000 mm) are classified by facility-types. A total of 5,227 passing events were observed, out of which 204 (3.9%) were found to be unsafe.

**Table 8: Summary of Field Observations**

Facility-Type	Total number of Passing Events	Number of Unsafe Passing Events	% Unsafe Passing Events	Passing Distance (mm)		
				Min	Max	Avg.
<b>2LNB - (2-lane road with no bike lane)</b>	680	82	12.0 %	894	1,808	1,339
<b>2LWB - (2-lane road with bike lane)</b>	515	1	0.2 %	984	1,907	1,533
<b>4LNB - (4-lane road with no bike lane)</b>	1,895	111	5.9 %	601	4,561	2,911
<b>4LWB - (4-lane road with bike lane)</b>	2,137	11	0.5 %	530	4,595	2,826
<b>Total</b>	5,227	204	3.9 %	-	-	-

For 2-lane facilities without bike lanes, 12% of all passing maneuvers were unsafe compared to only 0.2% unsafe passing maneuvers for 2-lane facilities with bike lanes. Similarly, for 4-lane facilities, approximately 6% of the passing maneuvers were unsafe for facilities without bike lanes compared to only 0.5% for facilities with bike lanes. In general, the passing distances were found to be larger on facilities with bike lanes compared to facilities without bikes lanes. These findings contradict the conclusions from Meyers and Parkin that drivers generally provide larger passing distances for cyclists on roads without bike lanes (Meyers and Parkin, 2008). The results show that the presence of on-street bike lanes significantly reduces unsafe passing maneuvers and provides larger separation between bikes and motorized vehicles, therefore improving cyclist's safety.

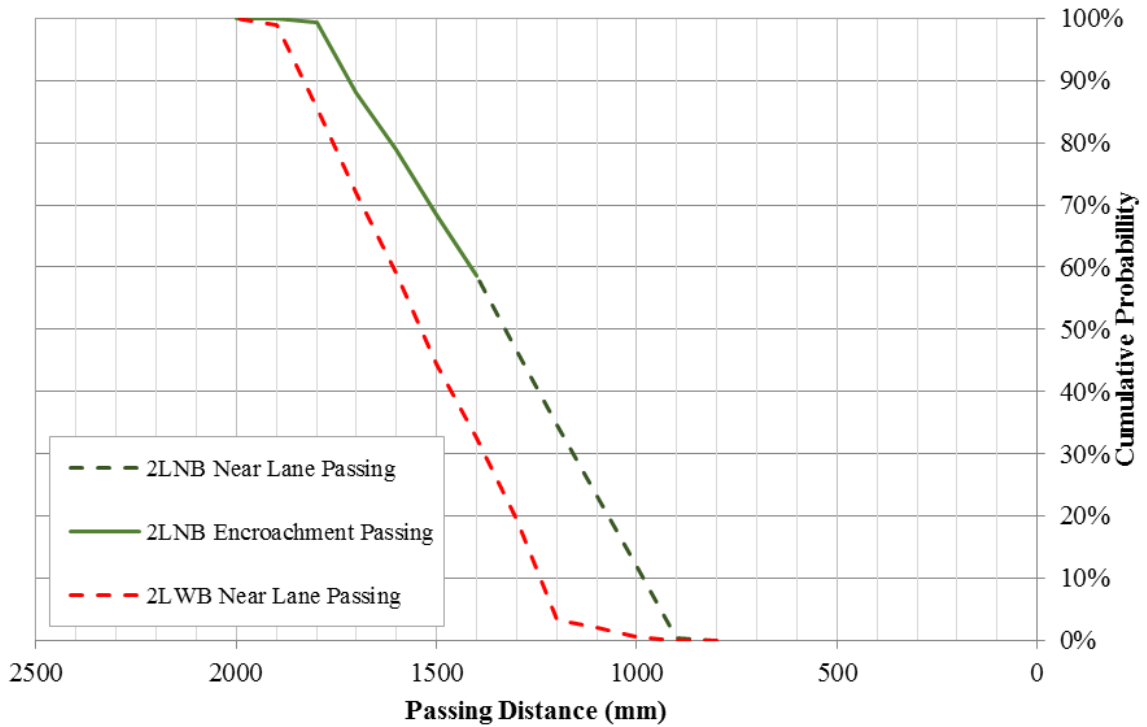
## 5.2 Passing Distance Distributions

Table 8 also shows the average passing distance observed on each facility-type. For 2-lane roads, the average passing distance on roads with bike lanes is 194 mm larger than on roads without bike lanes, representing a 14% increase in the average passing distance. For 4-lane roads, the average passing distance on roads without bike lanes is larger than for roads with bike lanes, which appears to contradict the results obtained for 2-lane roads. However, it is hypothesized that on 4-lane roads, drivers have increased opportunities to encroach or change lanes when passing cyclists and they elect to do so on 4-lane facilities without bike lanes, but do not do so on 4-lane roads with bike lanes. If this hypothesis is correct, a smaller fraction of near lane passing maneuvers should occur on 4-lane roads without bike lanes as compared to 4-lane roads with bike lanes. Table 9 summarizes the percentage of passing maneuvers by behavior across different facilities. From these results, it is observed that on 4-lane facilities with bike lanes, approximately 52% of passing vehicles were in the near lane and the observed encroachment passing maneuvers were relatively negligible (4%). However, for 4-lane facilities without bike lanes, only 15% of passing vehicles were in the near lane and 34% of all passing vehicles encroached between the near lane and the far lane at the time of passing. These results support the above hypothesis and suggest that drivers have a preference to encroach or change lanes when passing a cyclist on 4-lane facilities without bike lanes. Drivers on 4-lane facilities with bike lanes do not share a similar preference suggesting that they perceive the separation provided by the on-street bike lanes as sufficient. Similar driver behavior is also apparent on 2-lane roads. For 2-lane roads with bike lanes, all (100%) vehicles passed from the near lane and no encroachment was observed. In contrast, on 2-lane roads without bikes lanes, 59% of vehicles passed from the near lane and 41% vehicles encroached between the near lane and the lane for opposing traffic. These results suggest that introducing dedicated bike lanes not only improves the safety for cyclists but also reduces the number of potential conflicts between motorized vehicles that arise from the lane changes or the encroaching vehicles while passing cyclists. Reduction in these conflicts may also reduce the likelihood of head-on (on 2-lane roads) or sideswipe (on 4-lane roads) type collisions.

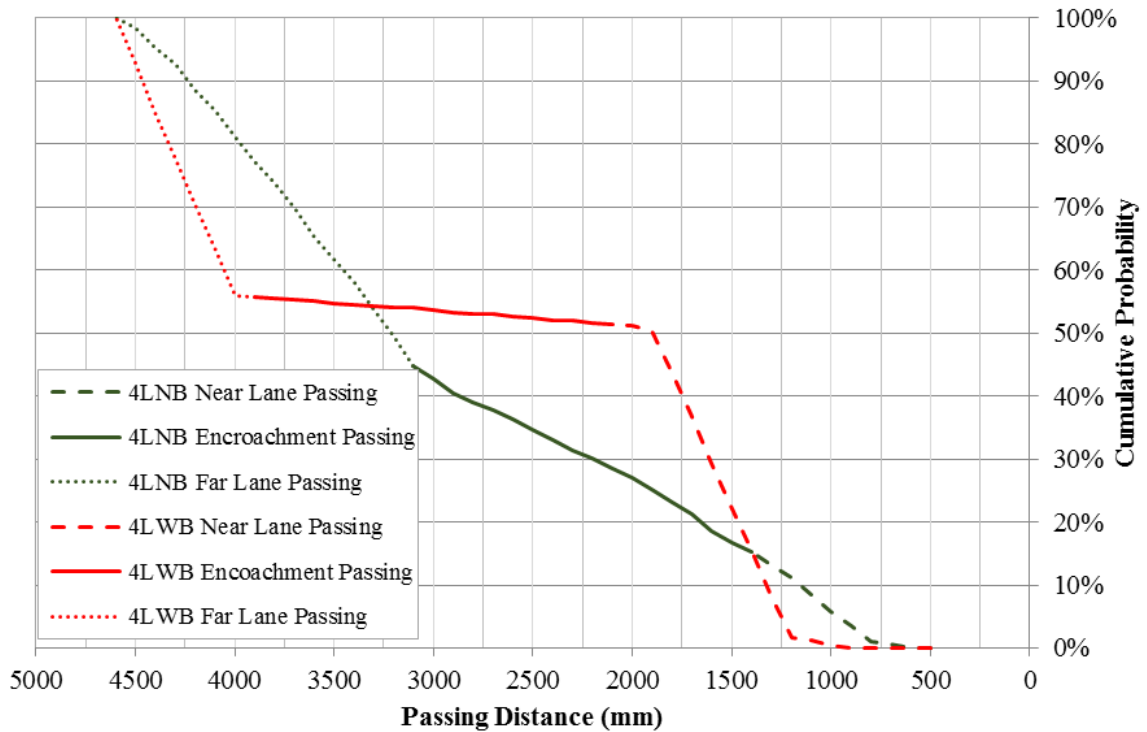
**Table 9: Results of Passing Behavior Analysis**

<b>Facility-Type</b>	<b>% Near Lane Passing</b>	<b>% Encroachment Passing</b>	<b>% Far Lane Passing</b>
<b>2LNB</b>	59 %	41 %	n/a
<b>2LWB</b>	100 %	0 %	n/a
<b>4LNB</b>	15 %	34 %	51 %
<b>4LWB</b>	52 %	4 %	44 %

Figure 23 and Figure 24 show the cumulative relative frequency of the observed passing distances and demonstrate the passing behavior of the vehicles on 2-lane and 4-lane roads, in graphical form. The horizontal axis (passing distance) is reversed to represent the right-hand side driving rule in North America, where the bicycle travels on the right side of the road and vehicles pass from the left side of the bicycle. The 0 mm mark on the horizontal axis represents the left extremity of the bicycle.



**Figure 23: Cumulative Relative Frequency of Passing Distance on 2-Lane Facilities**



**Figure 24: Cumulative Relative Frequency of Passing Distance on 4-Lane Facilities**

### 5.3 Analysis of Passing Speeds

Distributions of vehicle speeds are presented in subsection 5.3.1 and the relationship of passing distances with vehicle speeds are presented in subsection 5.3.2.

#### 5.3.1 Passing Speed Distributions

Figure 25 shows the cumulative relative frequency of the speeds of the passing vehicles on all facility-types. It is important to note that the speed estimations were made for each passing at the location of the passing. Low speeds are typically indicative of a passing event that occurred just downstream of a signalized intersection when vehicles are accelerating or near an intersection when vehicles are slowing to join the tail of a queue or to make a turning movement. Although the geometric features across all four facilities were controlled, slight variations in the geometry and traffic volume at the time of data collection may have factored into the passing speed. However, the impact and significance of these parameters are unknown. Figure 25 shows that the passing speed distributions for both 2-lane facility-types are similar. There appears to be a systematic difference between the distributions of the passing speeds on 4-lane facility-types, however this difference is small and cannot be attributed to the influence of the bike lane.

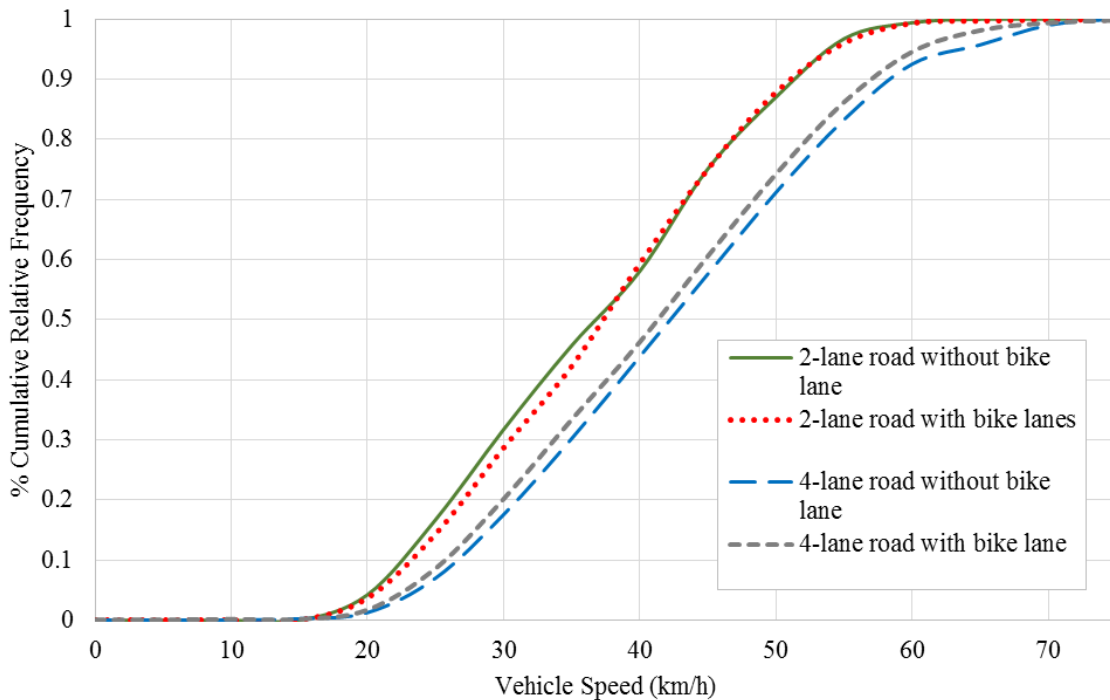


Figure 25: Distribution of Vehicle Speeds at the Time of Passing (all road categories)

#### 5.3.2 Traffic Speed and Passing Distance

Intuitively, it was expected that safety for cyclists is a function of not only the passing distance but also the speed at which the vehicle passes the cyclist. It was hypothesized that drivers would tend to desire to provide a large passing distance when passing at higher speeds. Figure 26 shows the relationships between passing speeds of vehicles and the passing distances on all four facility-

types. These results indicate that the passing distance varies randomly across all categories of passing maneuvers and there is no evidence to support the hypothesis that there is a relationship between passing distance and the speed of the passing vehicle.

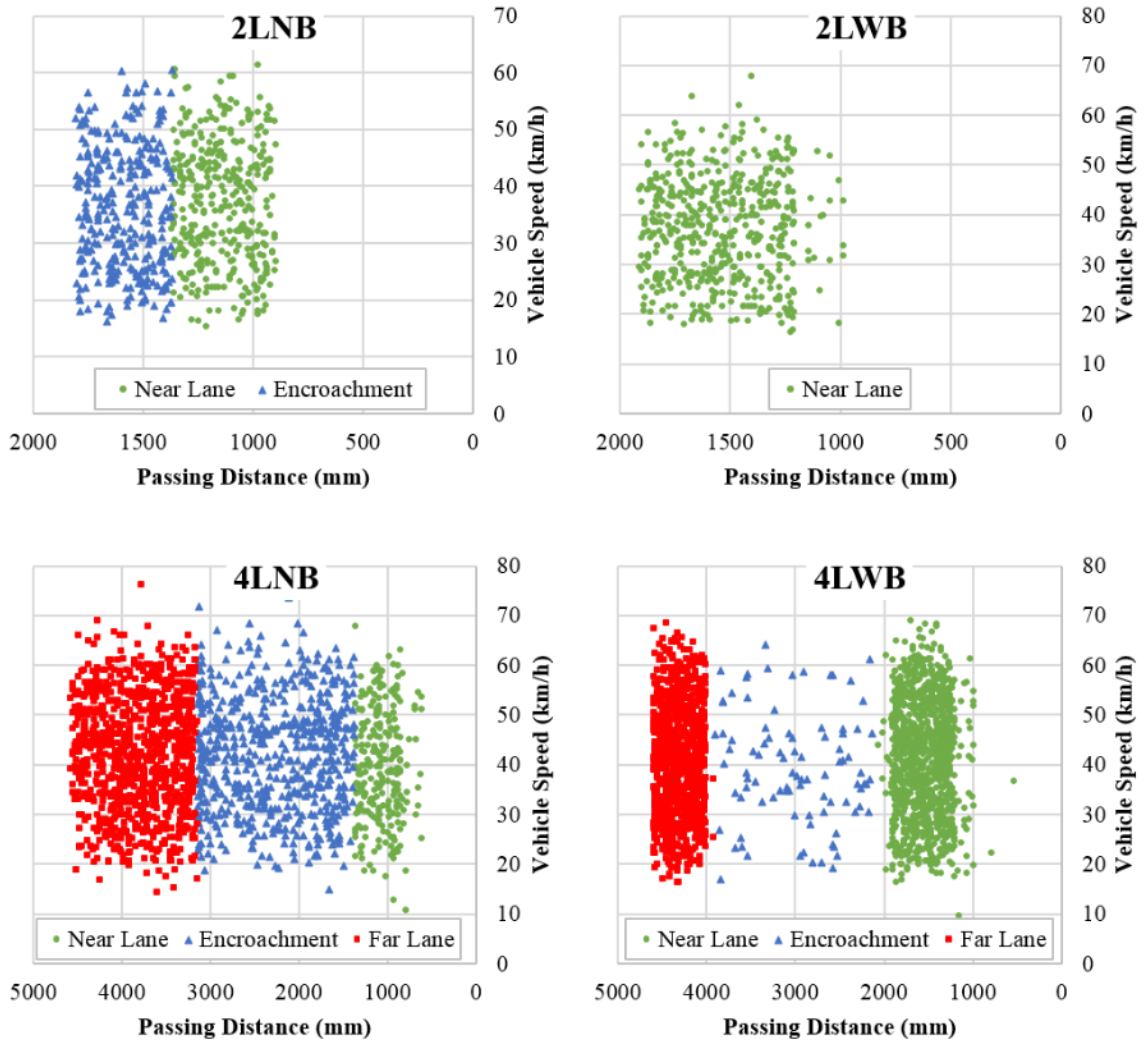
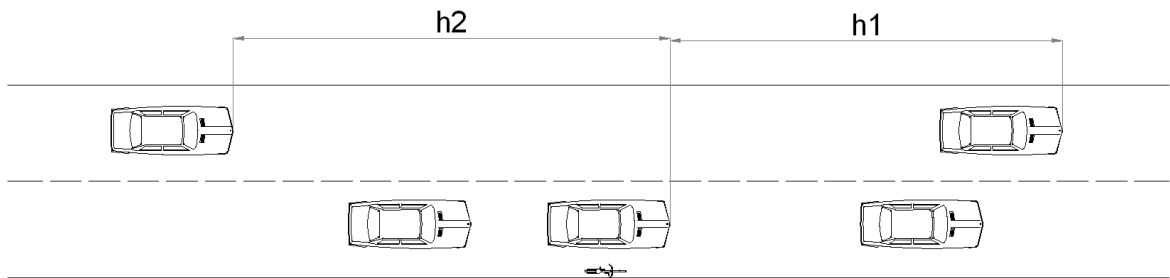


Figure 26: Vehicle Speed vs. Passing Distance (all road categories)

#### 5.4 Passing Opportunity Analyses (4-Lane Roads)

The results presented in Table 9 support the hypothesis that drivers on 4-lane roads without bike lanes attempt to provide adequate passing distance by changing lane or encroaching. The implication of this hypothesis is that smaller passing distances should be observed when drivers are restricted from making lane changes or encroaching due to nearby vehicles. This can be investigated by examining the time headways between the passing vehicle in the near lane and the leading and/or following vehicles in the far lane (Figure 27). In Figure 27,  $h_1$  represents the time headway between the current passing vehicle in the near lane and the immediate leading vehicle in the far lane. Similarly,  $h_2$  represents the time headway between the currently passing near lane vehicle and the immediate following vehicle in the far lane. If both  $h_1$  and  $h_2$  are greater than a threshold, it is concluded that the driver of the passing vehicle was unrestricted and was able to

encroach or make a lane change when passing. If either  $h_1$  or  $h_2$  is less than or equal to the threshold value, a conclusion can be made that the driver was restricted and unable to encroach or make a lane change. A range of values were considered for the threshold and the one that maximized the differences between distributions for restricted and unrestricted passing maneuvers for 4-lane roads without bike lanes was selected. To measure the difference between the restricted and unrestricted passing maneuvers for each value of time headway, the t-test was carried out between the two distributions. The headway with the maximum t-stat value was found to be 1.5 seconds; hence, 1.5 seconds was selected as the threshold time headway. The analysis result for selecting the threshold headway is presented in Table 10. Using this threshold value for the time headways, all passing events on 4-lane roads were classified as restricted or unrestricted.



**Figure 27: Evaluation of Time Headways for Determining Passing Restrictions**

**Table 10: Analysis Results for the Selection of the Threshold Time Headway**

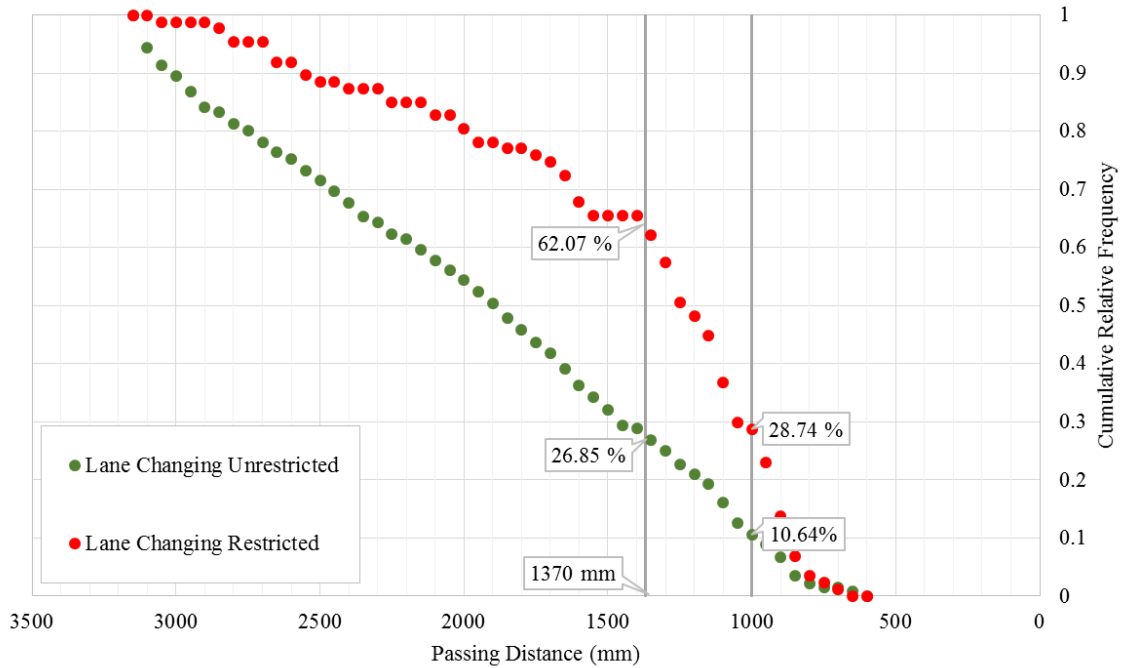
Headway	t-stat	P(T<=t) two-tail
1 sec	-1.741	0.085
1.25 sec	-1.925	0.057
1.4 sec	-2.784	0.006
1.5 sec	<b>-3.267</b>	<b>0.002</b>
1.6 sec	-2.547	0.012
1.75 sec	-2.012	0.047
2 sec	-1.655	0.101

Figure 28 shows the cumulative relative frequency distributions of passing distances on 4-lane facilities without bike lanes, based on the passing opportunities (restricted vs unrestricted) for near lane vehicles. Three observations can be made which support the hypothesis:

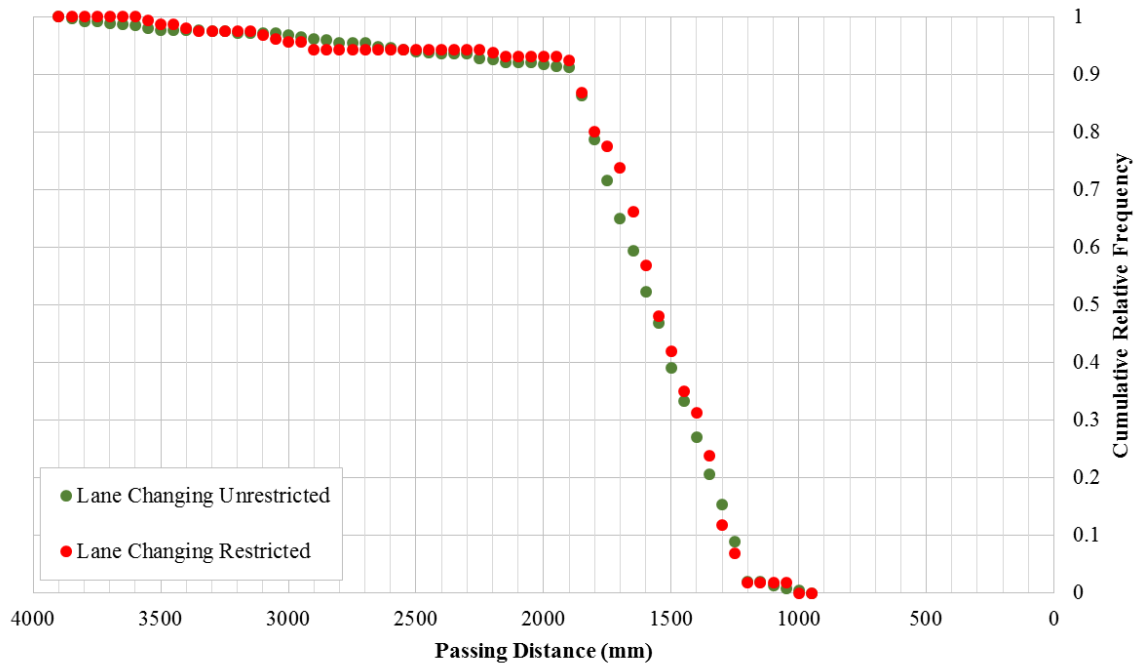
1. Drivers who were restricted when passing the cyclist tend to provide a smaller separation distance.
2. A much higher proportion (29%) of restricted passing maneuvers provided an unsafe passing distance (less than 1m) than unrestricted passing maneuvers (11%).
3. When unrestricted, a much higher proportion of drivers (73%) elected to encroach or change lanes (i.e. passing distance is greater than 1,370mm) than when drivers were restricted (38%).



Figure 29 shows the results for a similar analysis for near lane vehicles on 4-lane roads with bike lanes. Unlike the case of 4-lane roads without bike lanes, the distribution of the passing distances was found to be almost identical for scenarios with and without restricted passing opportunities. For both scenarios, the distribution of passing distances remained the same for the near lane vehicles and the amount of unsafe passing was negligible. These results suggest that when bike lanes are present, drivers in the near lane perceive that they retain sufficient clearance to pass the bikes freely without needing to change or encroach to the other lane.



**Figure 28: Passing Distance as a Function of Passing Opportunity (4-Lane Roads without Bike Lanes)**

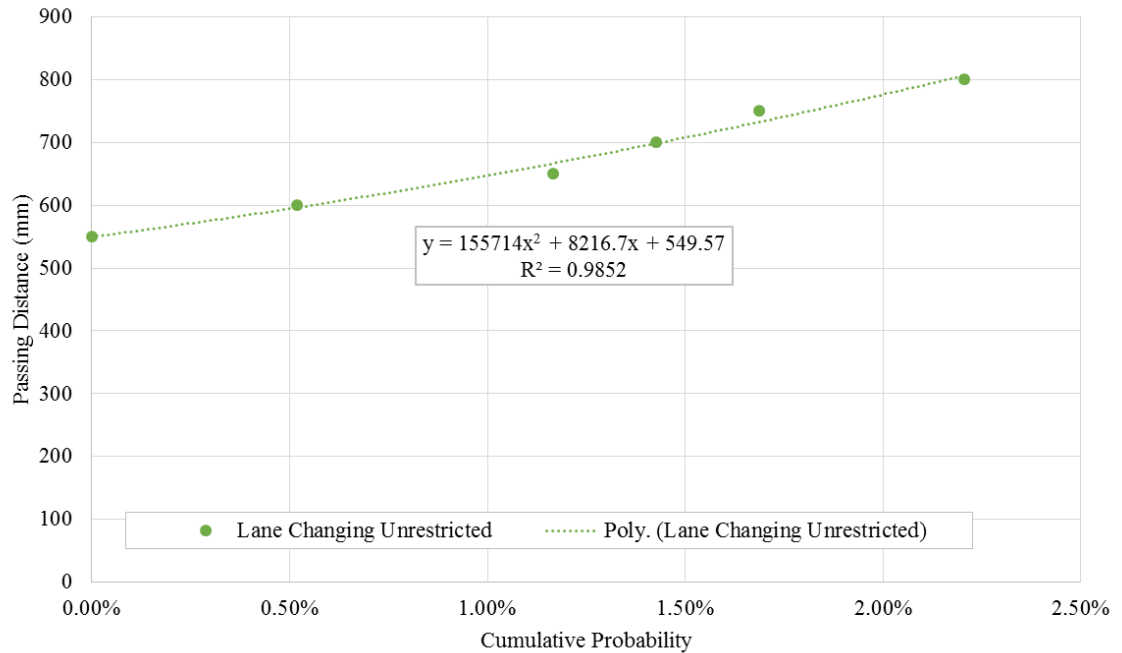


**Figure 29: Passing Distance as a Function of Passing Opportunity (4-Lane Roads with Bike Lanes)**

This analysis was not conducted for 2-lane facilities because passing data for vehicles travelling in the opposite direction was unavailable due to limitations of the ultrasonic sensor. The frequency of the ultrasonic sensor used was 10 Hz (10 measurements per second). The number of measurements that can be made during a passing maneuver is a function of the relative speed between bicycle and vehicle. The relative speed when the vehicles travelling in opposite direction can be calculated by adding the bike speed to the travel speed of the vehicle. For example, if the bike is travelling at 17 km/h and the vehicle is travelling at the speed of 50 km/h, the relative speed between them can be calculated as  $(50 + 17 =) 67$  km/h. At this speed, the vehicle would complete the passing maneuver in 0.27 second, and the number of distance measurements that can be polled is two. For the vehicle speeds higher than 50 km/h, the number of measurements can be even less than that. Comparatively, for the vehicle travelling at 50 km/h in the same direction as the bicycle, the number of distance measurements that can be polled is six. Due to low duration of passing maneuvers for the vehicles travelling in the opposite direction, the ultrasonic sensor failed to detect some of the vehicles as evidenced later in the videos. For this reason, the data obtained for the vehicles travelling in the opposite direction were not considered.

Subsequent analyses were carried out using the results obtained for 4-lane roads without bike lanes (Figure 28) to predict passing distance distributions. Polynomial curves were fitted on the ‘passing restricted’ and ‘passing unrestricted’ categories presented in Figure 28 and the resulting formulations were used for the analyses. The following figures show the results of the curve fitting effort on both passing opportunity categories. Formulations and goodness of fit of these curves are shown and the significance of the coefficients is shown in the subsequent tables. In the formulas,  $y$  is the passing distance in mm (independent variable) and  $x$  is the cumulative probability (dependent variable). It is important to note that two distinct curves were observed for

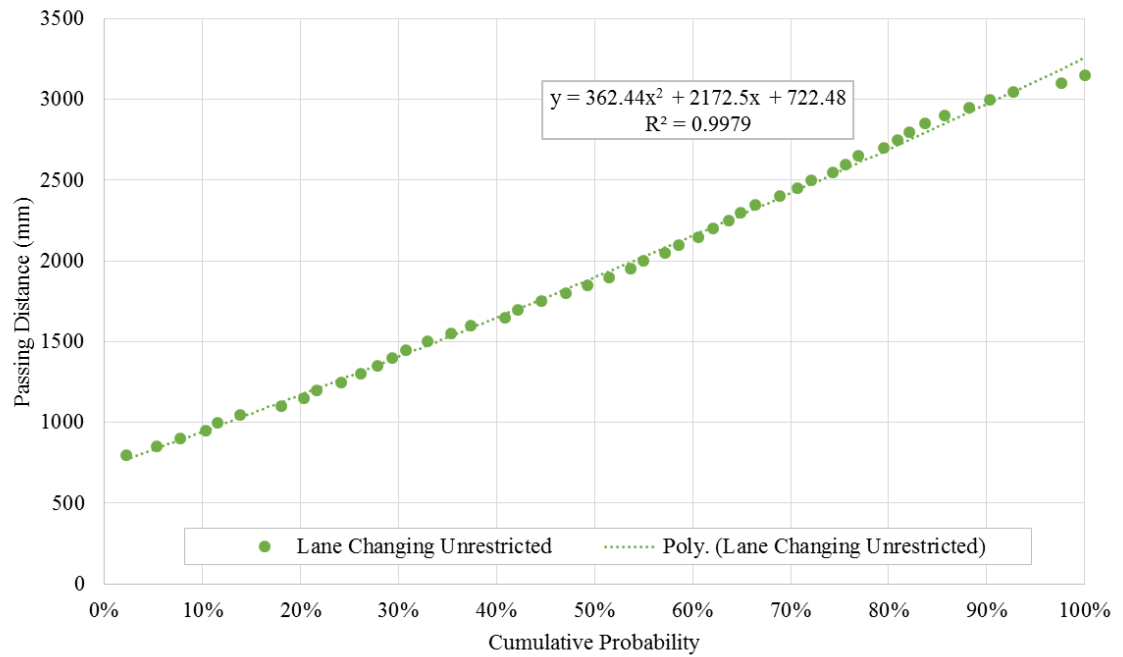
the ‘passing unrestricted’ category, for passing distances above and below 800 mm (cumulative probability of 0.022). Hence, two different formulas were used for the passing unrestricted category for the subsequent analysis.



**Figure 30: Curve Fitting Results for Passing Unrestricted Category (Passing Distance < 800 mm)**

**Table 11: Statistical Significance of the Coefficients for Passing Unrestricted (Passing Distance < 800 mm)**

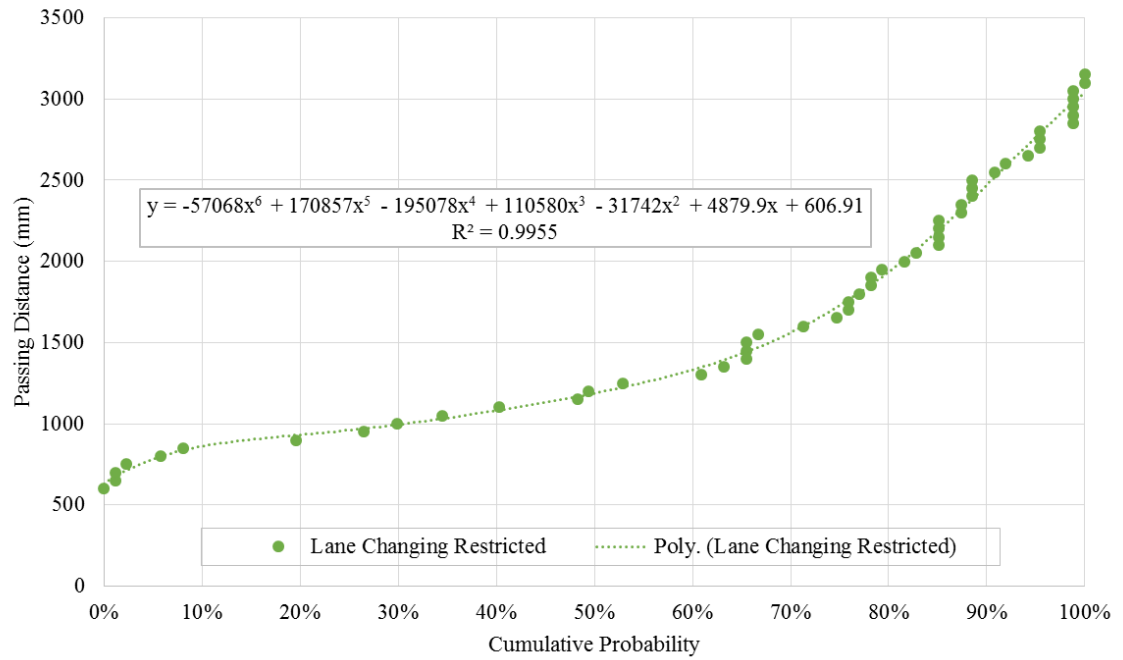
Variable	Coefficient	P(t-Stat)
<b>Intercept</b>	549.57	3.298E-05
<b>x</b>	8216.70	0.038
<b>x<sup>2</sup></b>	155714	0.029



**Figure 31: Curve Fitting Results for Passing Unrestricted Category (Passing Distance > 800 mm)**

**Table 12: Statistical Significance of the Coefficients for Passing Unrestricted (Passing Distance > 800mm)**

Variable	Coefficient	P(t-Stat)
<b>Intercept</b>	722.48	4.879E-39
<b>x</b>	2172.50	1.156E-31
<b>x<sup>2</sup></b>	362.44	3.463E-06



**Figure 32: Curve Fitting Results for Passing Restricted Category**

**Table 13: Statistical Significance of the Coefficients for Passing Restricted**

<b>Variable</b>	<b>Coefficient</b>	<b>P(t-Stat)</b>
<b>Intercept</b>	606.91	5.283E-22
<b>x</b>	4879.90	0.007
<b>x<sup>2</sup></b>	-31742	0.039
<b>x<sup>3</sup></b>	110580	0.022
<b>x<sup>4</sup></b>	-195078	0.049
<b>x<sup>5</sup></b>	170857	0.044
<b>x<sup>6</sup></b>	-57068	0.043

## Chapter 6

### Model Development to Estimate the Probability of Unsafe Passing on 4-Lane Roads without Bicycle Lanes

One of the objectives of this research was to develop a methodology to predict the distribution of passing distances and quantify the unsafe passes on a given facility. In this chapter, a model is proposed to meet this requirement. The core idea was to design a section of a roadway in the simulation software with the characteristics that are similar to the characteristics of the data collection sites. For this analysis, a microscopic simulation model was required where each vehicle and the interactions between two or more vehicles are simulated individually. Due to its popularity for microscopic modelling, the VISSIM software package was used. The following topics are discussed in this chapter.

1. The criteria and development of the VISSIM model is discussed in section 6.1.
2. In section 6.2, the procedure to estimate the probabilities of restricted lane changes for a given set of geometric and traffic-flow parameters are explained. The results for three different test cases are also presented in this section.
3. Section 6.3 describes the procedure to estimate the probability of unsafe passes for a given set of geometric and traffic-flow parameters.
4. In section 6.4, the procedure to estimate the number of unsafe passing using the results obtained in the sections 6.2 and 6.3 is explained.
5. In section 6.5, a comparison is made between the results obtained in the section 6.2 with the current bicycle-facility selection guidelines presented in section 2.2.

#### 6.1 VISSIM Model

Previous sections established the factors related to geometric features and traffic-flow parameters that can affect the passing distances; therefore, it was necessary to include them in the VISSIM model. Following is the list of factors that were considered and their implementation in the VISSIM model is explained.

The following geometric features were considered:

1. Number of lanes: The passing distance distributions vary for 2-lane roads and 4-lane roads as demonstrated Chapter 5. Since model development is based on the results of section 5.4, which only considered 4-lane roads, only the 4-lane roads were considered for modelling.
2. Presence of the bike lane: Similar to the number of lanes, passing distance distributions vary for roads with and without bike lanes. In the analysis results of passing opportunities (section 5.4), the roads without bike lane showed significant differences between 'passing restricted' and 'passing unrestricted' categories; therefore, only a road without a bike lane was modelled.
3. Lane width: One of the criteria for the site selection (section 3.2) was to collect data only on the roads with traffic lane width of 3.65 meter. To maintain the consistency with the collected data and analysis results presented in the previous chapters, only a road with traffic lane widths of 3.65 meter was modelled in VISSIM.

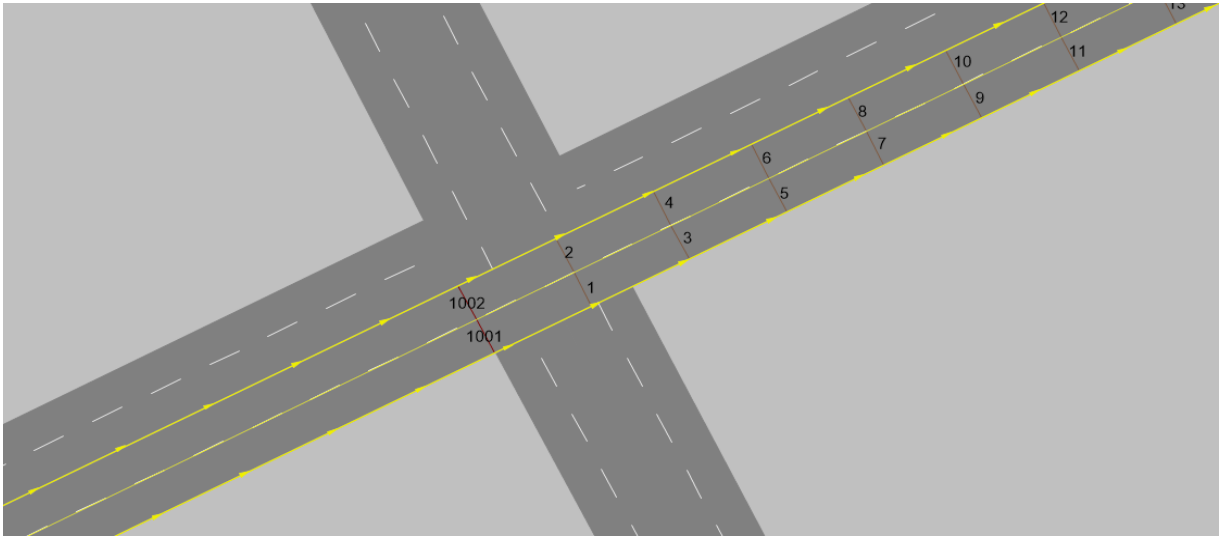
4. Traffic signal-timing: It was hypothesized that passing opportunity (i.e. restricted or unrestricted categories) is a function of platoon dispersion along the section. In urban settings, platoons are formed at the upstream of the intersection when the traffic light is red and the vehicles are queuing. To meet the similar conditions in the VISSIM model, an intersection was modelled with a fixed signal-timing configuration. Different signal-timing configurations with varying cycle times, and red and green interval times were considered for modelling. Cycle length time and green time also govern the capacity of the intersection in the VISSIM model. It is important to note that the modelled intersection did not have any signal-timing coordination with the hypothetical traffic signals located upstream of it. This was important to preserve the random arrival nature of the vehicles on the section in the VISSIM model.
5. Length of the section: Platoons formed at an intersection disperse along the section with varying degrees; hence the passing opportunity is partly dependent on the location of the passing (i.e. how far from the upstream intersection the passing occurs). Since the distance between signalized intersections on most urban arterials is less than 1 km, a length of 1 km was selected for the modelled section.
6. Horizontal and vertical curves: Horizontal and vertical curves can limit the visibility of the cyclist to the driver. The effect of this on the passing distance distribution is unknown. Sites with significant grades were rejected for data collection. To maintain the parity between the filed observations and the results obtained using the model, only a section without horizontal and vertical curves was modelled.

The following traffic-flow parameters were considered:

7. Vehicle speed: The posted speed limit on all 4-lane roads where the data were collected was 50 km/h. To maintain consistency, the modelled section was designed with the posted speed limit of 50 km/h.
8. Flow rate: Similar to the traffic signal-timing, the platoon formation and dispersion is also a function of the demands on the section. The passing opportunities were evaluated for different demands (AADT) by varying their corresponding v/c (volume to capacity) ratios.
9. Vehicular distribution: Vehicles with different dimensions tend to leave different lateral clearances from the cyclists. The passing distance distribution is also a function of the vehicular composition which can vary from region to region. The vehicular distribution for Kitchener-Waterloo Region was presented in Table 6. To keep the consistency with the field data, the same vehicular distribution was used in the VISSIM model.

Using the criteria presented above, a straight section of a roadway was built in VISSIM as shown in Figure 33. The length of the section was 1 km and only one direction of a 4-lane road was used for analysis (only 2 lanes). Each lane was 3.65 meter wide. On the upstream, an intersection was built with fixed signal-timing (signal heads numbered as 1001 and 1002). Only the through movement in one direction from this intersection was considered for analysis (shown between yellow outlines). The turning movements ending on this approach from other approaches of the intersection were disabled. Similarly, the turning movements originating from this

approach to other approaches of the intersection were also disabled and only the through approach was considered. Data collection points were established at every 10 meter interval on each lane at the downstream of the intersection (numbered as 1, 2... 200). The data collection points were configured to collect data regarding the arrival time and vehicle number of each vehicle passing above them.



**Figure 33: VISSIM Model**

The following three test cases based on various traffic signal-timings configurations were evaluated in VISSIM.

1. Case 1: Cycle time (C) = 60 sec, green time (g) = 30 sec (g/C = 0.5)
2. Case 2: Cycle time (C) = 120 sec, green time (g) = 60 sec (g/C = 0.5)
3. Case 3: Cycle time (C) = 60 sec, green time (g) = 18 sec (g/C = 0.3)

## 6.2 Estimation of the Probability of Restricted Lane Changes

As mentioned earlier, the current practice for deciding whether to provide a bike lane or not is based on the expected demand on the section. Furthermore, the passing opportunities also relate to the formation and dispersion of the platoons, which are governed by the demand on the section. The current design guidelines represent the demand as AADT (Annual Average Daily Traffic) and it represents both directions of a section. In VISSIM, for each case, 10 different traffic demands were evaluated based on the volume to capacity ratios (from  $v/c = 0.1$  to  $v/c = 1.0$  in 0.1 increments). The capacity of the intersection can be calculated using the green time (g), the cycle time (C), the saturation flow rate (s) and the number of lanes (n). A saturation flow rate of 1,900 vph/ln was used. The following equation can be used to calculate the intersection capacity for each test case.

$$capacity (c) = s \times n \times \frac{g}{C} \quad (5)$$

Using this equation, the capacities for test cases 1 and 2 were evaluated as 1,900 vph. For test case 3, the capacity was evaluated as 1,140 vph. The VISSIM simulations were carried out using the hourly demands as inputs. The hourly demands can be estimated using the  $v/c$  ratios, where  $c$

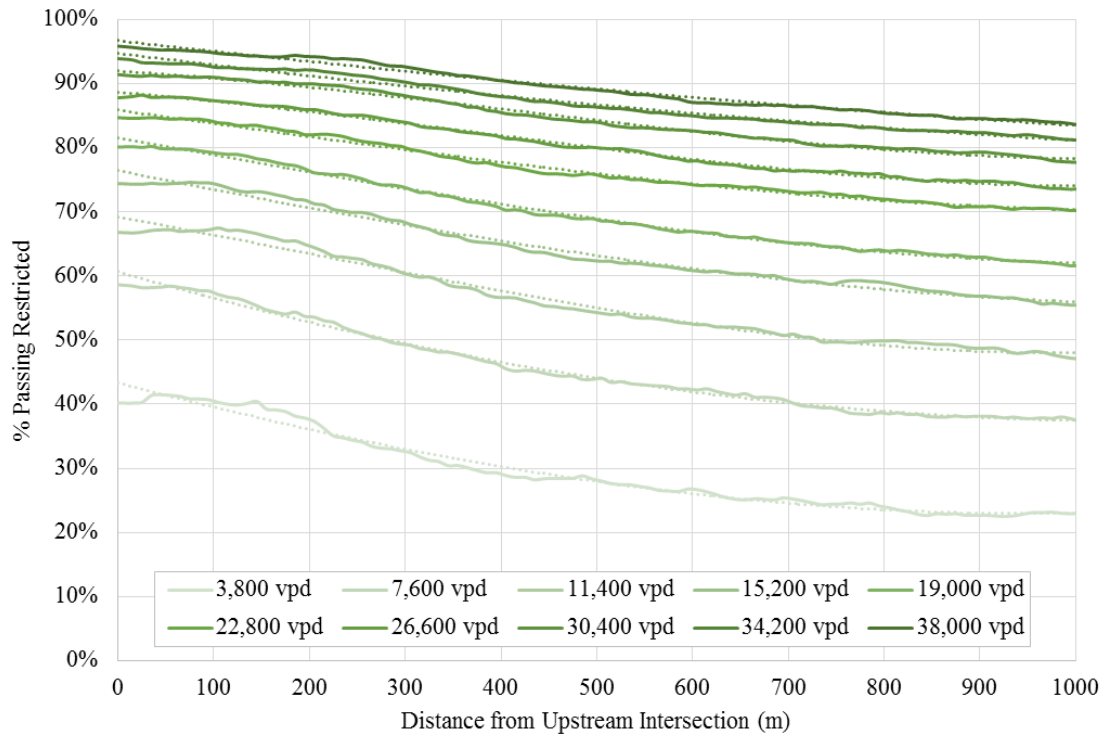


is the capacity (equation (5)) and  $v$  is the hourly demand obtained using a particular  $v/c$  ratio (e.g. for  $v/c = 0.5$  for case 1, the demand  $v = 0.5 \times 1,900 \text{ vph} = 950 \text{ vph}$ ). Assuming that this demand represents the peak-hour flow rate (directional design hourly volume, DDHV) for a hypothetical section, the AADT for that section, can be estimated using equation (6). In equation (6),  $D$  represents the proportion of peak-hour traffic in peak direction (in decimal) on the section. It was assumed that 50% of the total traffic travels in each direction in the peak-hour. The  $k$  factor in the equation represents portion of the AADT that travels through the section in the peak-hour. HCM 2000 recommends using the value of 0.1 for  $k$  for urban arterials. Appendix D presents the  $v/c$  ratios and their corresponding AADT and hourly flow rates.

$$AADT = \frac{DDHV \times D}{k} \quad (6)$$

The length of the each simulation run in VISSIM was one hour (3,600 sec) and 10 simulations were completed for each demand using different random seeds each time. The data for all 10 repetitions were combined for post processing in MATLAB. The MATLAB codes to parse the output data of VISSIM models are presented in Appendix G. In the post processing, the passing opportunities for the vehicles passing from the near lane were calculated at every 10-meter interval on the section for all three test cases. Figure 34, Figure 35 and Figure 36 present the results of passing opportunities for all test cases. The X-axis shows the distance from the upstream intersection in meter and the Y-axis shows the portion of all passes (considering 10 simulation runs) that faced restricted passing condition. Percentage of unrestricted passing for a particular distance from the upstream is a complement of the percentage of restricted passing. The results show that as the section length increases, restriction in passing decreases. This supports the previously stated hypothesis that passing opportunities are functions of platoon dispersion. As the length of the section increases, the vehicles in a platoon become less concentrated, and, in turn, a higher number of unrestricted passes are observed.

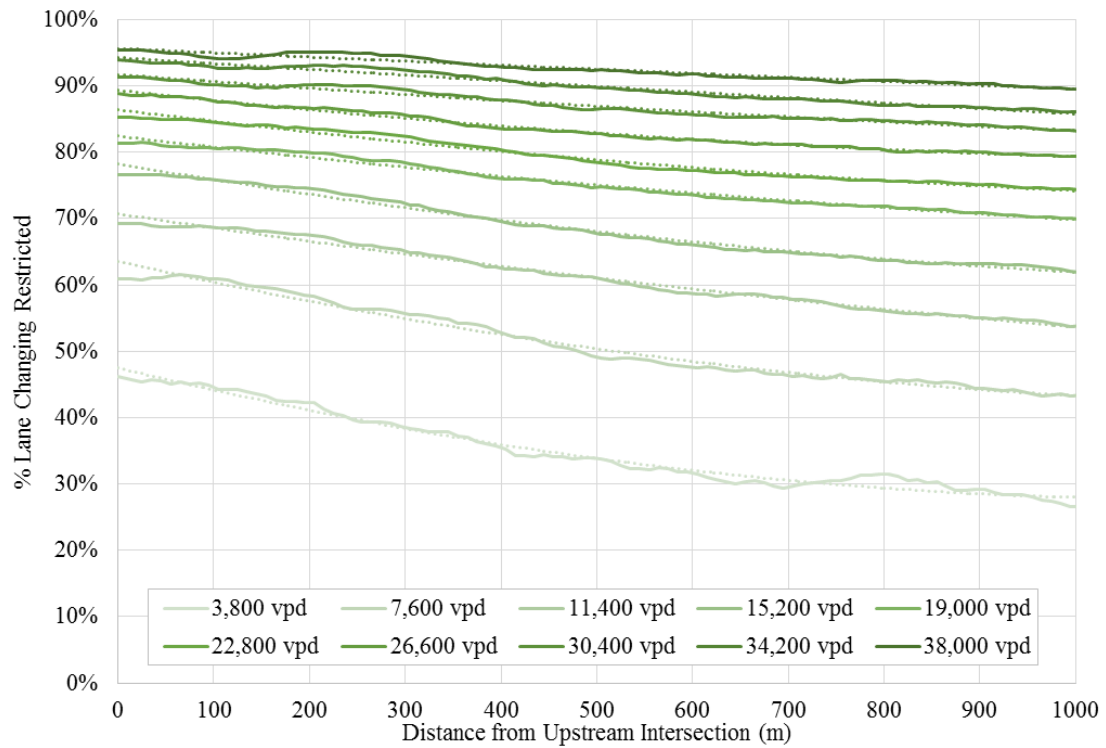
For each of the curves shown in Figure 34, Figure 35 and Figure 36, a 2<sup>nd</sup> order polynomial was fitted and the resulting formulation was used for subsequent analysis. The formulations of these polynomials and their goodness of fit ( $R^2$ ) are presented in the Table 14, Table 15 and Table 16. The term 'y' in the formulas represent the *Percentage Passing Restricted* and the term 'x' represent the *Distance from the Upstream Intersection* in meter. The regression coefficients and their significance are presented in Appendix D.



**Figure 34: Relationship between Restricted Passing Opportunities and Distance from Upstream Intersection for Case 1**

**Table 14: Details of Fitted Polynomials on Restricted Passing Opportunity Curves for Case 1**

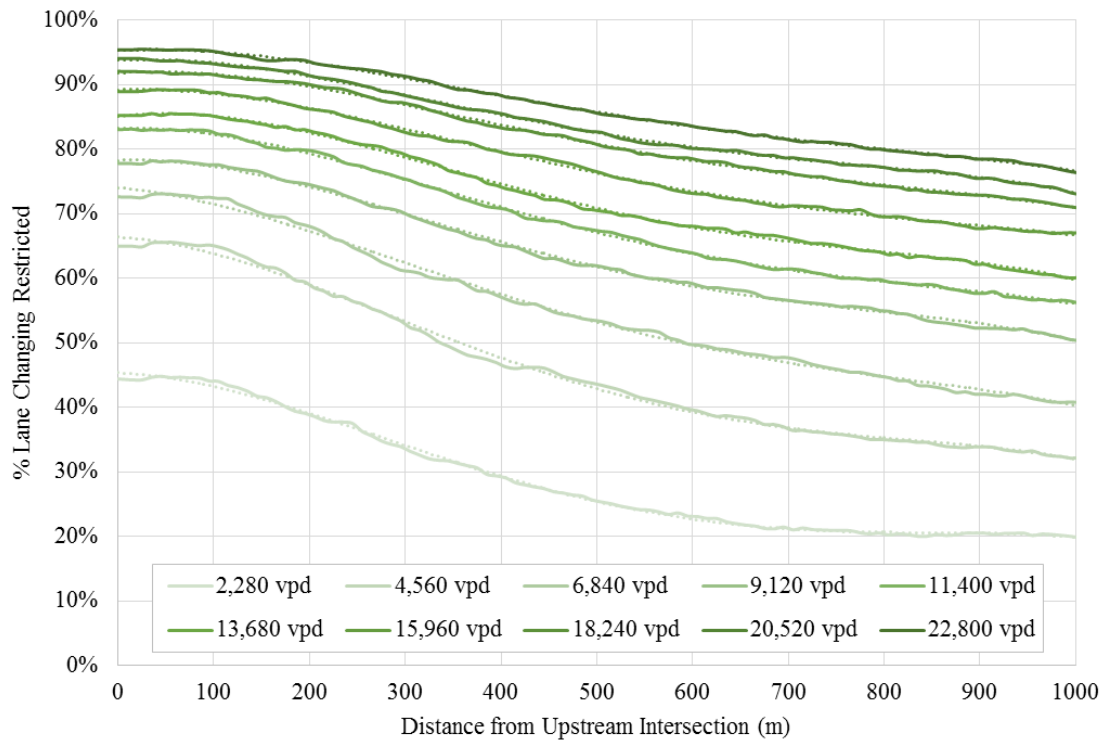
<b>AADT (vph)</b>	<b>2<sup>nd</sup> Order Polynomial Formula (Case 1)</b>	<b>Goodness of Fit - R<sup>2</sup> (Case 1)</b>
<b>3,800</b>	$y = 2E-07x^2 - 0.0005x + 0.4443$	0.986
<b>7,600</b>	$y = 2E-07x^2 - 0.0005x + 0.612$	0.996
<b>11,400</b>	$y = 2E-07x^2 - 0.0004x + 0.7103$	0.989
<b>15,200</b>	$y = 1E-07x^2 - 0.0004x + 0.7734$	0.991
<b>19,000</b>	$y = 1E-07x^2 - 0.0003x + 0.8243$	0.997
<b>22,800</b>	$y = 1E-07x^2 - 0.0003x + 0.8666$	0.993
<b>26,600</b>	$y = 7E-08x^2 - 0.0002x + 0.8991$	0.994
<b>30,400</b>	$y = 5E-08x^2 - 0.0002x + 0.9324$	0.990
<b>34,200</b>	$y = 6E-08x^2 - 0.0002x + 0.9503$	0.989
<b>38,000</b>	$y = 5E-08x^2 - 0.0002x + 0.9698$	0.989



**Figure 35: Relationship between Restricted Passing Opportunities and Distance from Upstream Intersection for Case 2**

**Table 15: Details of Fitted Polynomials on Restricted Passing Opportunity Curves for Case 2**

AADT (vph)	2 <sup>nd</sup> Order Polynomial Formula (Case 2)	Goodness of Fit - R <sup>2</sup> (Case 2)
<b>3,800</b>	$y = 2E-07x^2 - 0.0004x + 0.4779$	0.979
<b>7,600</b>	$y = 1E-07x^2 - 0.0003x + 0.6406$	0.989
<b>11,400</b>	$y = 5E-08x^2 - 0.0002x + 0.7098$	0.992
<b>15,200</b>	$y = 9E-08x^2 - 0.0003x + 0.7854$	0.992
<b>19,000</b>	$y = 5E-08x^2 - 0.0002x + 0.8263$	0.990
<b>22,800</b>	$y = 7E-08x^2 - 0.0002x + 0.8665$	0.987
<b>26,600</b>	$y = 6E-08x^2 - 0.0002x + 0.8946$	0.994
<b>30,400</b>	$y = 2E-08x^2 - 0.0001x + 0.9176$	0.976
<b>34,200</b>	$y = 6E-09x^2 - 0.00009x + 0.9435$	0.973
<b>38,000</b>	$y = 4E-09x^2 - 0.00006x + 0.9567$	0.952



**Figure 36: Relationship between Restricted Passing Opportunities and Distance from Upstream Intersection for Case 3**

**Table 16: Details of Fitted Polynomials on Restricted Passing Opportunity Curves for Case 3**

<b>AADT (vph)</b>	<b>2<sup>nd</sup> Order Polynomial Formula (Case 3)</b>	<b>Goodness of Fit - R<sup>2</sup> (Case 3)</b>
<b>2,280</b>	$y = 4E-07x^2 - 0.0006x + 0.4951$	0.992
<b>4,560</b>	$y = 3E-07x^2 - 0.0007x + 0.7074$	0.994
<b>6,840</b>	$y = 2E-07x^2 - 0.0006x + 0.7725$	0.995
<b>9,120</b>	$y = 2E-07x^2 - 0.0005x + 0.8192$	0.993
<b>11,400</b>	$y = 2E-07x^2 - 0.0005x + 0.8701$	0.993
<b>13,680</b>	$y = 1E-07x^2 - 0.0004x + 0.8921$	0.990
<b>15,960</b>	$y = 1E-07x^2 - 0.0004x + 0.9246$	0.992
<b>18,240</b>	$y = 6E-08x^2 - 0.0003x + 0.9467$	0.992
<b>20,520</b>	$y = 8E-08x^2 - 0.0003x + 0.9629$	0.993
<b>22,800</b>	$y = 4E-08x^2 - 0.0003x + 0.9766$	0.994

### 6.3 Estimation of the Probability of Unsafe Passing

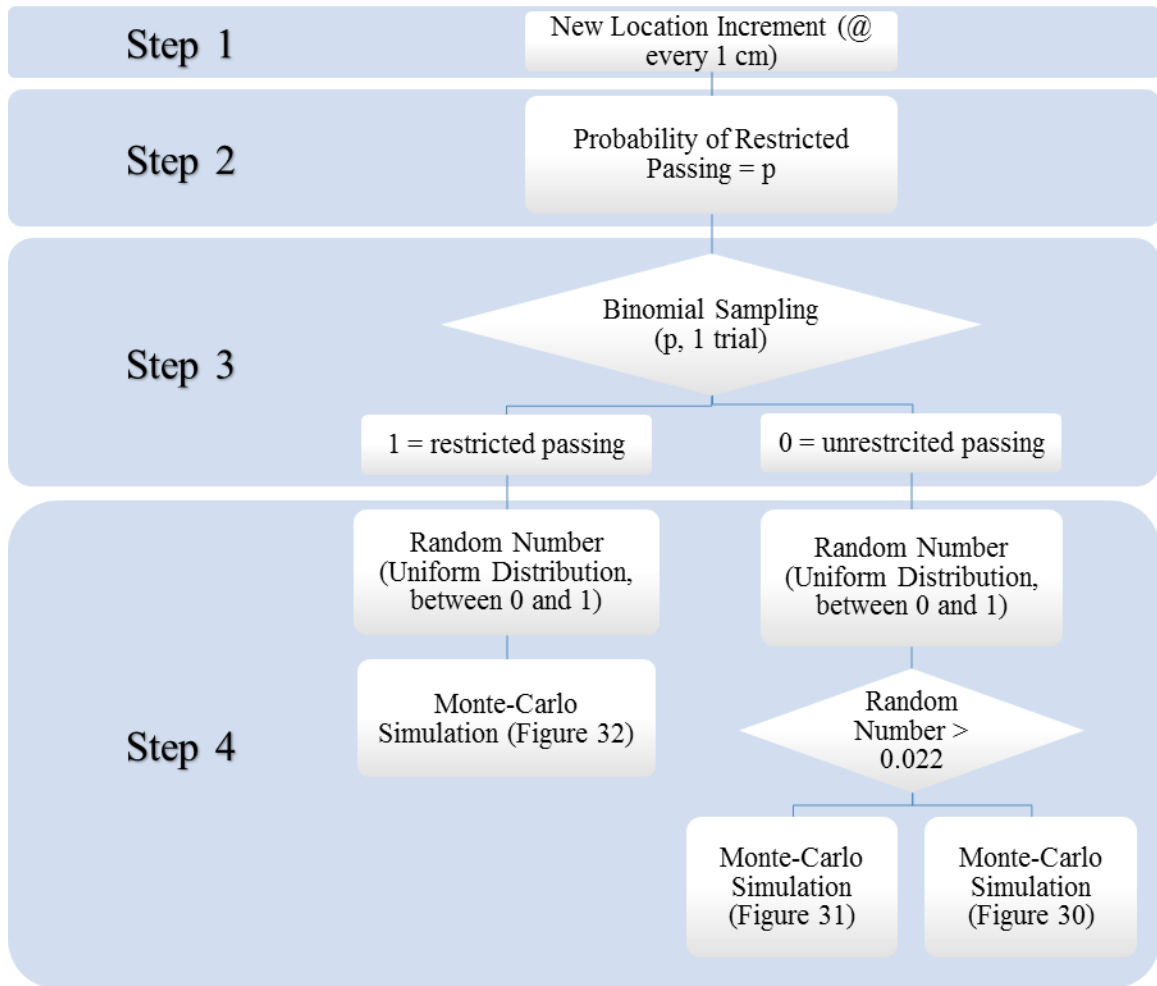
In this subsection, the procedure to estimate the portion (probability) of unsafe passing (passing distance < 1,000 mm) out of all passing events is explained. The results obtained in section 6.1 can be used to determine the probability of unsafe passing for any given 4-lane urban arterial

without bike lane that is less than 1,000 meter long, has the same signal-timing configuration at the upstream intersection as one of the test cases and vehicular distribution similar to the Kitchener-Waterloo Region. It is important to note that, the threshold for unsafe passing distance assumed in these analyses is 1,000 mm.

Results presented in section 6.1 demonstrated that the probabilities of passing being restricted (or unrestricted) are governed by the section length, AADT and the signal-timing configuration. It was hypothesized that the probabilities of unsafe passing are directly proportional to the probabilities of restricted passing. Therefore, in the following analysis the probabilities of unsafe passing were estimated for 20 different section lengths (from 50 meter to 1,000 meter in 50 meter increments) and for 10 different AADT volumes (determined using the v/c ratios from 0.1 to 1.0 in 0.1 increments) for all three signal-timing configuration (test cases). The procedure to estimate these probabilities is explained below.

1. It was assumed that the locations of the passing are uniformly distributed along the entire section. Therefore, for any given section length the passing locations were assumed to be at every one-centimeter interval along the section. For each passing location, one value of passing distance was stochastically determined using the steps 2 through 4.
2. Using the location of the passing, volume and signal-timing as inputs, the probability of that passing being from the 'passing restricted' category was calculated using the equations from section 6.1 (Table 14, Table 15 or Table 16).
3. The probability value found in step 1 was later used to stochastically decide whether that individual passing is restricted or not using binomial sampling (number of trials = 1). In this step, there are two possible outcomes, namely *pass* (passing restricted) or *fail* (passing unrestricted).
4. The passing distance for that passing observation was estimated using Monte-Carlo simulation (one iteration). The term  $x$  in the formulas shown in Figure 30 through Figure 32 represents the cumulative probability for which passing distance found. The value for the term  $x$  was generated from uniform distribution ranging between 0 and 1. This value was used as an input in the Monte-Carlo simulation model. If the passing opportunity for that passing was determined to be of 'restricted' category in step 2, the formula shown in Figure 32 was used. Alternatively, if the passing opportunity was determined 'unrestricted', the formulas in Figure 30 and Figure 31 were used to estimate the passing distance. Steps 1 to 3 were repeated for each passing location determined in step 1. For example, if the section length for a given section was 700 meter, the steps 2 to 4 were repeated (700 m X 100 cm/m =) 70,000 times in one iteration.
5. Once the passing distance was known for each one-centimeter interval, a passing distance distribution was prepared and the cumulative probability associated with the passing distance of 1,000 mm (critical passing distance) was found.
6. Steps 1 through 5 were repeated 10 times (total 10 iterations) for each combination of the section length, AADT and signal-timing configuration. Arithmetic average of the resulting ten probability values was used as the final value for the probability of unsafe passing.

Using the procedure explained above, the probability of unsafe passing was found for (three signal-timing configurations X twenty section lengths X ten volumes => 600 unique combinations). Following flowchart presents the steps 1 through 4 in the above procedure using graphical form.



**Figure 37: Flowchart of the Process to Stochastically Estimate Passing Distance**

The following tables present the probabilities of unsafe passing (portion of passing which are unsafe out of all passing events) for each signal-timing scenario (Case 1 through Case 3).

**Table 17: Probabilities of Unsafe Passing for Case 1 (unsafe passing distance threshold = 1,000 mm)**

Probability of Unsafe Passing																				
AADT	Section Length (m)																			
	50	100	150	200	250	300	350	400	450	500	550	600	650	700	750	800	850	900	950	1000
<b>3,800</b>	0.123	0.121	0.120	0.119	0.118	0.117	0.116	0.115	0.114	0.113	0.112	0.111	0.110	0.110	0.108	0.108	0.107	0.106	0.106	0.105
<b>7,600</b>	0.140	0.140	0.137	0.138	0.136	0.135	0.134	0.133	0.131	0.130	0.130	0.129	0.128	0.127	0.126	0.126	0.125	0.124	0.124	0.123
<b>11,400</b>	0.150	0.150	0.150	0.147	0.148	0.147	0.147	0.145	0.144	0.144	0.143	0.142	0.141	0.141	0.141	0.140	0.139	0.140	0.138	0.138
<b>15,200</b>	0.158	0.158	0.156	0.155	0.154	0.153	0.152	0.151	0.150	0.149	0.148	0.148	0.147	0.146	0.145	0.144	0.144	0.143	0.142	0.142
<b>19,000</b>	0.163	0.164	0.161	0.161	0.160	0.159	0.159	0.159	0.158	0.156	0.156	0.156	0.156	0.155	0.155	0.154	0.154	0.153	0.153	0.152
<b>22,800</b>	0.168	0.167	0.166	0.166	0.165	0.164	0.163	0.163	0.162	0.162	0.161	0.160	0.160	0.159	0.159	0.158	0.158	0.157	0.157	0.156
<b>26,600</b>	0.170	0.172	0.170	0.169	0.170	0.169	0.169	0.168	0.167	0.167	0.166	0.166	0.166	0.166	0.166	0.165	0.165	0.165	0.164	0.164
<b>30,400</b>	0.175	0.174	0.174	0.174	0.173	0.172	0.173	0.171	0.171	0.171	0.170	0.170	0.170	0.169	0.169	0.168	0.168	0.167	0.167	0.167
<b>34,200</b>	0.178	0.177	0.176	0.174	0.175	0.174	0.174	0.174	0.173	0.173	0.172	0.172	0.171	0.172	0.170	0.170	0.170	0.170	0.169	0.169
<b>38,000</b>	0.180	0.177	0.179	0.178	0.177	0.177	0.176	0.176	0.175	0.175	0.174	0.174	0.174	0.173	0.173	0.172	0.172	0.171	0.171	0.171

**Table 18: Probabilities of Unsafe Passing for Case 2 (unsafe passing distance threshold = 1,000 mm)**

Probability of Unsafe Passing																				
AADT	Section Length (m)																			
	50	100	150	200	250	300	350	400	450	500	550	600	650	700	750	800	850	900	950	1000
<b>3,800</b>	0.127	0.127	0.125	0.123	0.122	0.121	0.121	0.121	0.121	0.119	0.118	0.118	0.117	0.117	0.115	0.115	0.115	0.114	0.114	0.114
<b>7,600</b>	0.144	0.144	0.143	0.141	0.143	0.140	0.140	0.139	0.138	0.139	0.138	0.136	0.137	0.135	0.136	0.136	0.134	0.134	0.133	0.133
<b>11,400</b>	0.150	0.151	0.151	0.151	0.149	0.150	0.149	0.147	0.147	0.148	0.148	0.146	0.145	0.146	0.144	0.144	0.144	0.144	0.143	0.142
<b>15,200</b>	0.161	0.158	0.158	0.157	0.156	0.156	0.155	0.155	0.154	0.155	0.153	0.152	0.151	0.152	0.150	0.147	0.149	0.150	0.148	0.148
<b>19,000</b>	0.164	0.164	0.164	0.162	0.163	0.162	0.160	0.161	0.161	0.160	0.159	0.159	0.158	0.159	0.159	0.157	0.157	0.156	0.157	0.156
<b>22,800</b>	0.168	0.167	0.168	0.167	0.165	0.166	0.165	0.164	0.165	0.164	0.162	0.164	0.163	0.163	0.163	0.161	0.163	0.161	0.161	0.161
<b>26,600</b>	0.172	0.171	0.171	0.169	0.170	0.169	0.169	0.167	0.168	0.166	0.166	0.165	0.165	0.162	0.164	0.164	0.163	0.163	0.164	0.163
<b>30,400</b>	0.173	0.173	0.174	0.175	0.172	0.172	0.172	0.172	0.172	0.171	0.172	0.171	0.172	0.170	0.171	0.171	0.170	0.170	0.170	0.171
<b>34,200</b>	0.177	0.176	0.176	0.177	0.176	0.175	0.175	0.175	0.176	0.175	0.174	0.174	0.174	0.174	0.172	0.173	0.172	0.172	0.173	0.171
<b>38,000</b>	0.179	0.178	0.178	0.179	0.176	0.177	0.177	0.177	0.177	0.177	0.177	0.176	0.176	0.175	0.176	0.175	0.174	0.177	0.175	0.176



**Table 19: Probabilities of Unsafe Passing for Case 3 (unsafe passing distance threshold = 1,000 mm)**

Probability of Critical Passing																				
AADT	Section Length (m)																			
	50	100	150	200	250	300	350	400	450	500	550	600	650	700	750	800	850	900	950	1000
<b>2,280</b>	0.128	0.128	0.124	0.124	0.123	0.122	0.121	0.120	0.118	0.118	0.117	0.116	0.116	0.115	0.114	0.114	0.113	0.113	0.113	0.112
<b>4,560</b>	0.150	0.149	0.146	0.145	0.143	0.142	0.139	0.139	0.138	0.136	0.135	0.134	0.132	0.131	0.131	0.130	0.128	0.128	0.127	0.125
<b>6,840</b>	0.159	0.156	0.155	0.152	0.152	0.150	0.149	0.147	0.147	0.145	0.144	0.142	0.141	0.141	0.139	0.138	0.137	0.136	0.135	0.135
<b>9,120</b>	0.162	0.161	0.160	0.159	0.157	0.157	0.155	0.155	0.153	0.153	0.151	0.151	0.150	0.149	0.148	0.147	0.147	0.146	0.145	0.144
<b>11,400</b>	0.167	0.164	0.163	0.163	0.163	0.161	0.160	0.158	0.159	0.158	0.157	0.156	0.155	0.154	0.153	0.152	0.152	0.151	0.150	0.150
<b>13,680</b>	0.169	0.170	0.167	0.168	0.167	0.165	0.164	0.164	0.161	0.162	0.160	0.160	0.159	0.158	0.157	0.156	0.156	0.156	0.155	0.154
<b>15,960</b>	0.176	0.173	0.171	0.170	0.171	0.168	0.168	0.167	0.167	0.166	0.164	0.164	0.163	0.163	0.161	0.160	0.159	0.159	0.158	0.157
<b>18,240</b>	0.178	0.175	0.173	0.174	0.172	0.172	0.171	0.172	0.171	0.170	0.169	0.168	0.168	0.167	0.167	0.166	0.165	0.164	0.164	0.164
<b>20,520</b>	0.178	0.177	0.175	0.176	0.175	0.175	0.174	0.173	0.172	0.172	0.171	0.170	0.170	0.169	0.169	0.168	0.167	0.167	0.167	0.165
<b>22,800</b>	0.179	0.178	0.176	0.176	0.177	0.175	0.175	0.174	0.174	0.173	0.172	0.171	0.171	0.170	0.169	0.169	0.168	0.166	0.167	0.166

Alternatively, the following regression models for each case can represent the results in the above tables. In these models, the units for the terms AADT and Section Length are number of vehicles and meters, respectively. The adjusted R<sup>2</sup> values were 0.90, 0.90 and 0.93 for Case 1, Case 2 and Case 3, respectively. The analysis of variance (ANOVA) for these models showed that the F-significance was 1.3E-99 for Case 1, 2.41E-99 for Case 2 and 6.8E-118 for Case 3. F-significance is the probability that the regression equations below do not explain the variance in ‘% Unsafe Passing’; i.e. the fitting of the regression models is by chance. For 95<sup>th</sup> percentile confidence, the F-significance values should be less than 0.05. Since the F-significance value for each case was less than 0.05, the models were accepted.

Case 1:

$$\% \text{ Unsafe Passing} = 0.126 + 1.66E - 06 \times \text{AADT} - 1.3E - 05 \times \text{Section Length} \quad (7)$$

Case 2:

$$\% \text{ Unsafe Passing} = 0.130 + 1.49E - 06 \times \text{AADT} - 8.59E - 06 \times \text{Section Length} \quad (8)$$

Case 3:

$$\% \text{ Unsafe Passing} = 0.134 + 2.38E - 06 \times \text{AADT} - 1.8E - 05 \times \text{Section Length} \quad (9)$$

**Table 20: Statistical Significance of the Coefficients of Regression Models for Probabilities of Unsafe Passing (All Cases)**

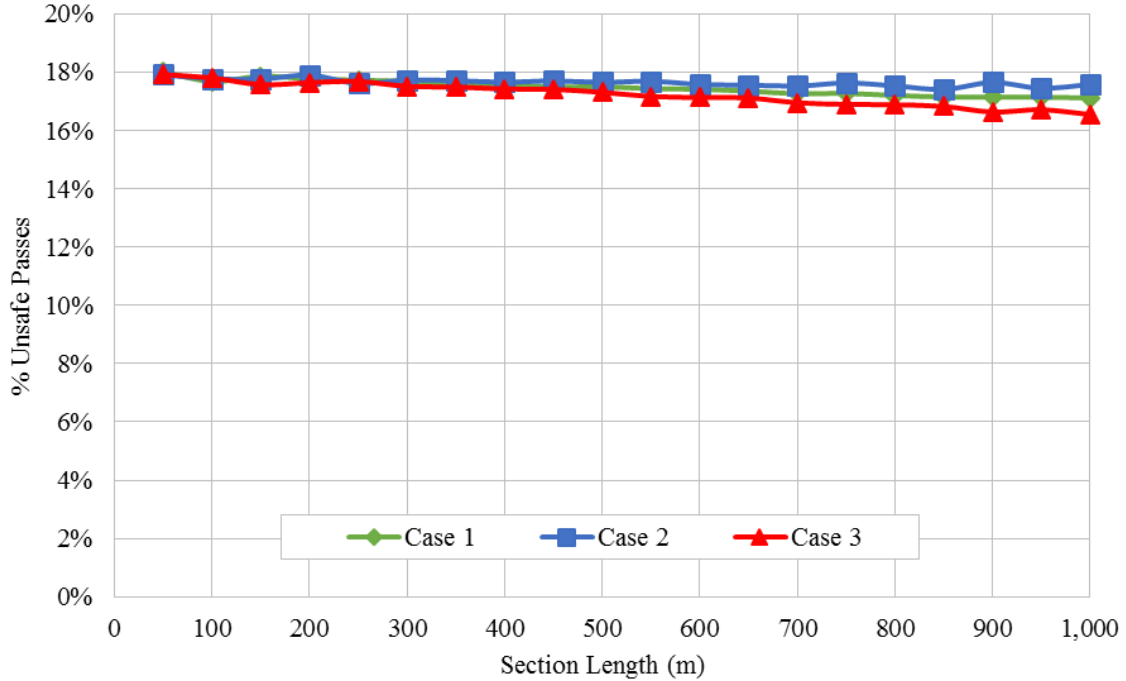
Variable	Case 1		Case 2		Case 3	
	Coefficients	P (t > t-Stat)	Coefficients	P (t > t-Stat)	Coefficients	P (t > t-Stat)
<b>Intercept</b>	0.126	1.8E-172	0.130	1E-184	0.134	1.3E-185
<b>AADT</b>	1.66E-06	2.30E-99	1.49E-06	1.09E-99	2.38E-06	9.22E-95
<b>Section Length (m)</b>	-1.30E-05	2.05E-14	-8.59E-06	1.62E-09	-1.80E-05	1.08E-27

The above tables and regression models demonstrate that for each test case, the probability of unsafe passing is inversely proportional to the section length. This was anticipated, because platoons become more dispersed the further downstream they travel and lane changing is less restricted when the platoon is more dispersed. Furthermore, as demonstrated in Figure 28, unrestricted passing is associated with a smaller proportion of unsafe passes.

The relationship between section length and probability of unsafe passes for *v/c* ratio of 1.0 (the largest volumes analyzed for each test case) is shown in Figure 38. Several observations can be made from these results:

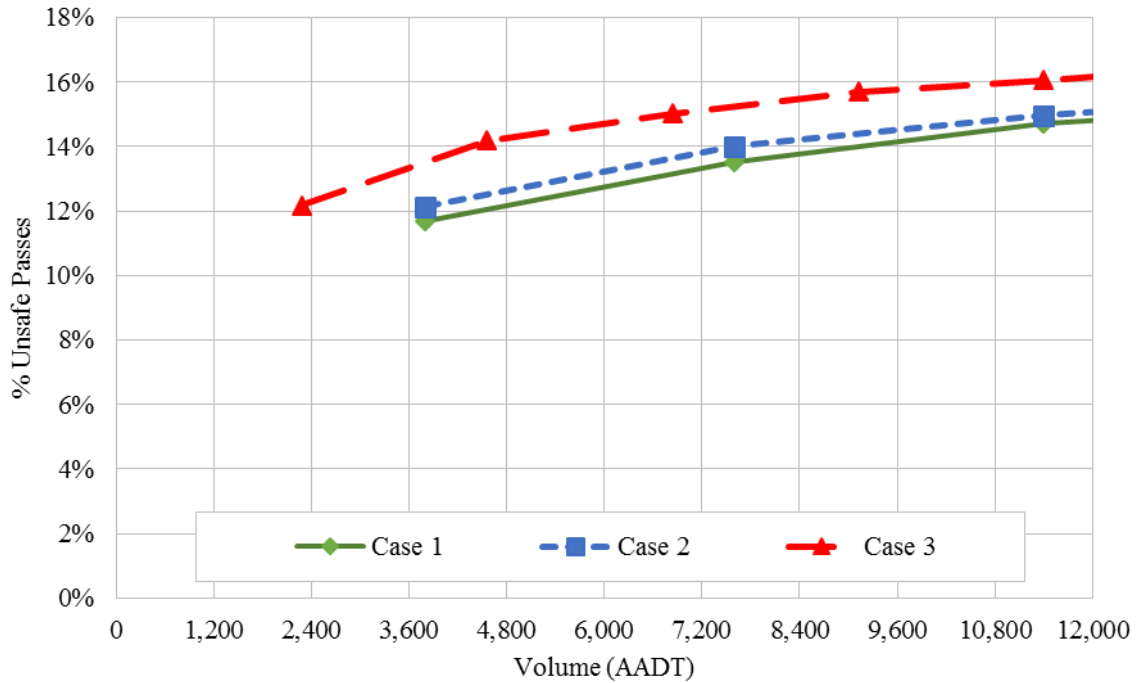
1. As expected, the probability of unsafe passes is largest for short section length and decreases linearly as section length increases.

- The impact of the signal-timing scenario is negligible for section lengths less than approximately 600m. For the section length of 1,000m, the probabilities of unsafe passes are 17.1%, 17.6% and 16.6% for Case 1, Case 2 and Case 3, respectively.



**Figure 38: Relationship between Section Length and % Unsafe Passing for v/c ratio of 1.0**

The regression models suggest that the probability of unsafe passing is directly proportional to the AADT. For the same section length, the probability of unsafe passing increases as the AADT increases. For a higher AADT, bigger platoons are formed (bigger queues are generated at the upstream intersection) and the vehicles travel in close proximity for a longer time and distance as compared to in the case of lower AADT. Due to increased proximity between vehicles, the proportion of restricted passes increases, and in turn, the probability of unsafe passes increases. The relationship between volume and probability of unsafe passes for a 300-meter long section (typical section length on urban arterials) is shown in Figure 39. The figure confirms the above finding that as the volume increases; the proportion of unsafe passes also increases. It can be observed that for the same traffic volume, the probability of unsafe passes is significantly higher in Case 3. This is because the capacity for Case 3 is smaller than for Cases 1 and 2 and therefore for a given AADT, the  $v/c$  ratio is larger for Case 3 than for Cases 1 and 2. For Case 3, the cycle time ( $C$ ) is 60 seconds and the green time to cycle time ratio ( $g/C$ ) is 0.3. For Case 1 and Case 2, the cycle times are 60 seconds and 120 seconds and the  $g/C$  ratio is 0.5. This means, for the same flow rate, the discharge through each cycle is higher in Case 3, as compared to Case 1 and Case 2. Higher discharge indicates bigger platoons forming at the upstream of the intersection, which leads to the higher probability of unsafe passes for Case 3.

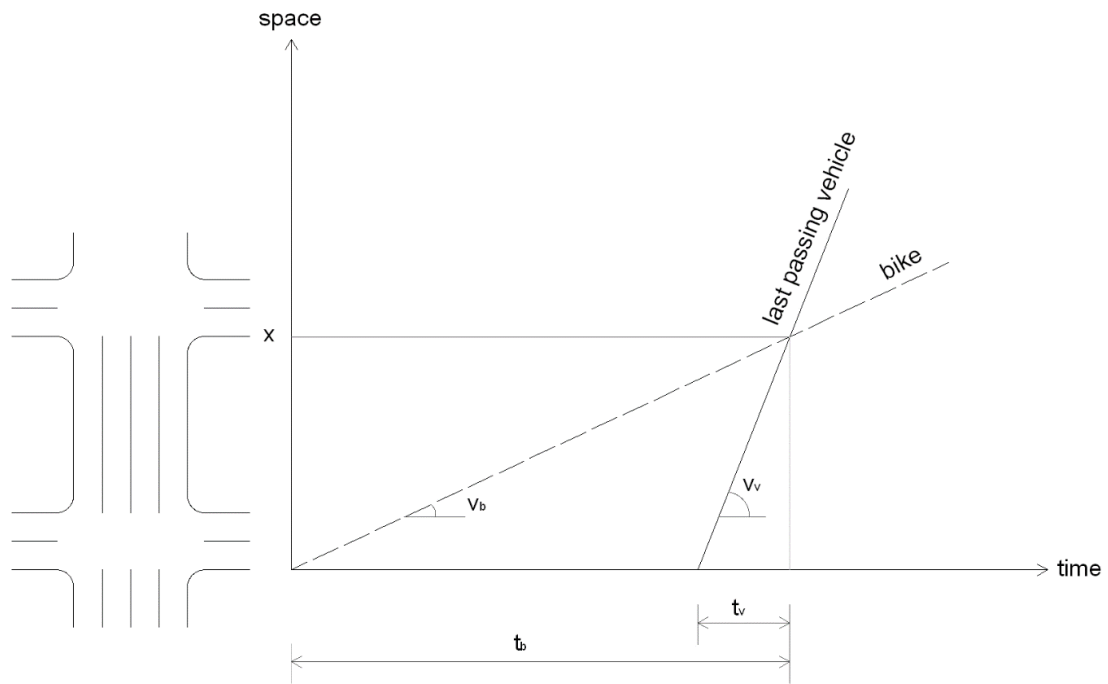


**Figure 39: Relationship between Volume and % Unsafe Passing for Section Length of 300 m**

## 6.4 Estimation of Number of Unsafe Passing

Using the results obtained in Section 6.3, the expected number of unsafe passing can be obtained for a given roadway section. In order to estimate the number of unsafe passing, the section length, expected vehicular volume, bike volume and the signal-timing configuration of the upstream intersection must be known.

Hourly demands of bikes and vehicles are required to estimate the expected number of near lane and encroachment passing, the procedure for which is illustrated in Figure 40. A section of length  $x$  of an urban arterial is shown. A bike travelling at a constant speed of  $v_b$  takes time  $t_b$  to traverse the entire section. To travel the same section, a vehicle travelling at a constant speed of  $v_v$  requires time  $t_v$ . Therefore, the last vehicle that can overtake the bike on this section has to enter the section no later than time  $t_b - t_v$ . Any vehicle entering the section after this time will not be able to overtake the bicycle on this section.



**Figure 40: Estimation of Number of Near Lane Passing**

The expected AADT is also known for the given section and the hourly vehicular volume can be estimated using the following equation.

$$DDHV = AADT \times k \times D \quad (10)$$

Where,  $DDHV$  is the directional design hourly volume,  $k$  is the design hour factor and  $D$  is the proportion of traffic in the design direction. For the analysis, it was assumed that the design hour is same as the peak-hour and the value of 0.1 was used for  $k$ . In addition, it was assumed that in peak-hour, the directional traffic split is 50% in each direction and the constant value of 0.5 was used for  $D$ . The average headway  $h$  that can be observed between any two vehicles in the design hour can be calculated using the equation below. The  $h$  in the equation represents the average time headway between two consecutive vehicles.  $DDHV$  is divided by two in this equation to include only the near lane and encroachment passing. It was assumed that the 50% of all vehicles were travelling in the far lane at the time of passing. This assumption is consistent with the principle of *user equilibrium*, which states that the travelers will only travel on the cheapest route in terms of their generalized non-additive travel cost. Results in Table 9 also show that for 4-lane roads without bike lanes, 51% of all vehicles pass from the far lane.

$$h = \frac{3600}{\frac{DDHV}{2}} \quad (11)$$

The number of near lane passing that can be encountered by a single bike can be given by-

$$\text{near lane passing per bike trip} = \frac{t_b - t_v}{h} \quad (12)$$

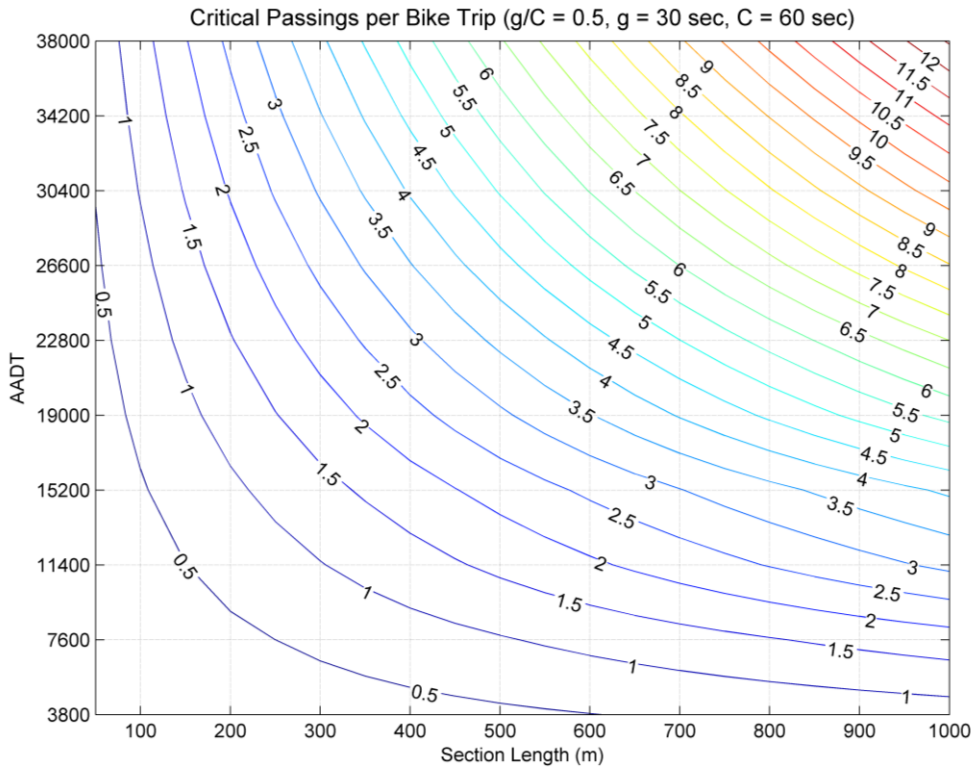
The total number of near lane passing occurrences observed by all vehicles in one hour can simply be obtained by multiplying the expected number of bikes in one hour with the number of near lane passing per bike.

$$\begin{aligned} \text{total near lane passing per hour} &= \text{number of bikes per hour} \times \\ \text{near lane passing per bike} & \end{aligned} \quad (13)$$

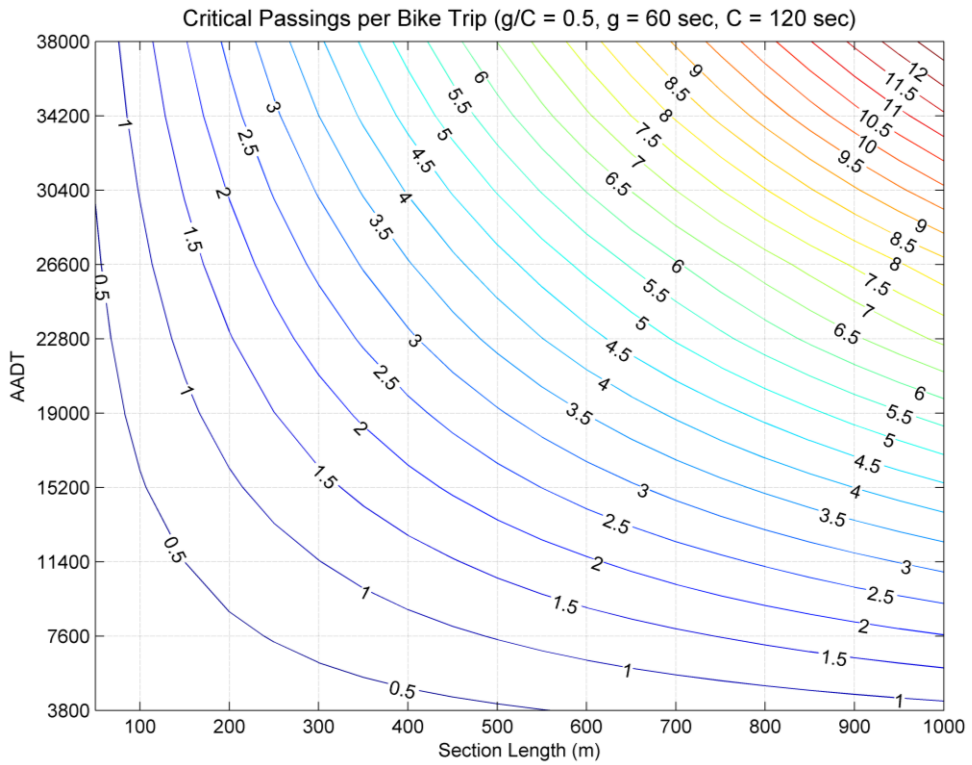
Subsequently, the number of unsafe passing per hour can be found using the results from Section 6.3. The appropriate probability of unsafe passing can be found using the signal-timing configuration, AADT and the section length values in Table 17, Table 18, or Table 19. By multiplying this probability of unsafe passing with the total number of near lane passing per hour obtained in the previous step, the number of unsafe (critical) passing per hour can be estimated.

$$\begin{aligned} \text{number of critical passing} \\ &= \text{proportion of critical passing} \times \text{total number of passing per hour} \end{aligned} \quad (14)$$

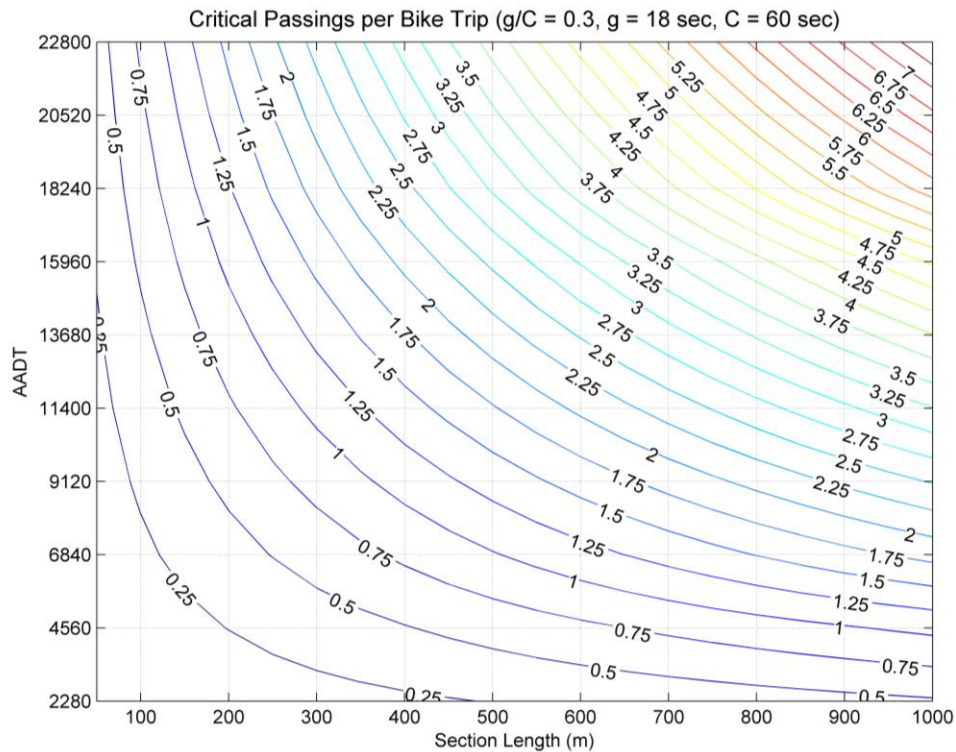
For this analysis, constant speeds of 50 km/h and 17 km/h were assumed for  $v_v$  and  $v_b$ , respectively. The procedure for estimating the number of unsafe passing per hour is straightforward; however, it is time intensive. Alternatively, Figure 41 through Figure 43 can be used to estimate the number of unsafe passing per bike for an appropriate signal-timing configuration in the peak-hour. Multiplying the number of unsafe passing per bike with the expected hourly volume of bikes, the number of unsafe passing can be obtained. It is important to note that these figures are based on the critical passing distance of 1,000 mm. Similar figures can be produced for other values of critical passing distance.



**Figure 41: Number of Unsafe Passings per Bike Trip per Hour (Case 1)**



**Figure 42: Number of Unsafe Passings per Bike Trip per Hour (Case 2)**



**Figure 43: Number of Unsafe Passings per Bike Trip per Hour (Case 3)**

A hypothetical case is presented here to show an example of the usage of the above charts. A hypothetical section is 1,000 meter long and the expected AADT is 9,120 vehicles. The upstream signal-timing configuration matches the signal-timing scenario of Case 3. For these conditions, the expected number of unsafe passing per bike trip per hour is 2.5. If in the peak-hour, 100 bikes are expected to travel through this section, the number of unsafe passes is  $(2.5 \times 100 =) 250$ .

## 6.5 Comparison with Existing Guidelines

Section 2.2 described various bicycle-facility selection guidelines from different jurisdictions. In this section, a comparison is made between these guidelines and the results obtained in Section 6.3 (probability of unsafe passing). It is important to note that the estimation of unsafe passing was based on the critical passing distance of 1,000 mm. This passing distance can be subjective to a specific jurisdiction and may vary from one jurisdiction to the other. Presently no study exists that can conclude any one passing distance as a safe passing distance. In addition, the existing guidelines do not specify the goals expected to be met by implementing them. It is unclear whether the end goal of some or all of these guidelines is to reduce unsafe passing maneuvers to a certain degree or to eliminate them. Furthermore, as explained in Section 2.2, the existing guidelines only consider traffic volumes and traffic speed as thresholds to select a particular bicycle-facility. These thresholds are not classified by other factors such as section length and the signal-timing configuration at the upstream intersection.

For these reasons, instead of making a direct comparison of the existing guidelines with the results obtained in the Section 6.3, Table 21 states the probabilities of unsafe passing that can be observed if a specific guideline is implemented. The probabilities of unsafe passes were estimated



only for 4-lane roadways; therefore, the comparison is only made with the guidelines that are applicable to the 4-lane roadways. If the application of a specific guideline on 4-lane roadways was unknown/uncertain, the guideline was excluded from the comparison. The probabilities of unsafe passes for the section length of 300m (typical section length on urban arterials) were selected. In the VISSIM model, the width of the designed lanes was 3.65 meter to maintain consistency with the data collection sites. The 3.65-meter wide lanes are defined as ‘Narrow Lanes’ in bicycle-facility selection guidelines. For this reason, the comparison was only made with the maximum allowed volumes of Narrow Lane category. As described in Section 2.2, in the existing guidelines, the stated traffic speeds are either design speed limits or the 85<sup>th</sup> percentile of traffic speed. Using the data collected from the VISSIM simulation results, the 85<sup>th</sup> percentile vehicle speed was found to be 52.4 km/h. The nearest speed threshold in the design guidelines presented in Section 2.2.2 is 50 km/h. For this reason, the comparison was only made with the AADT thresholds stated for 50 km/h design speed. For the comparison with the nomograph presented in the OTM Book 18 (Section 2.2.1, Figure 9), the threshold for AADT was found using the vehicle speed of 52.4 km/h.

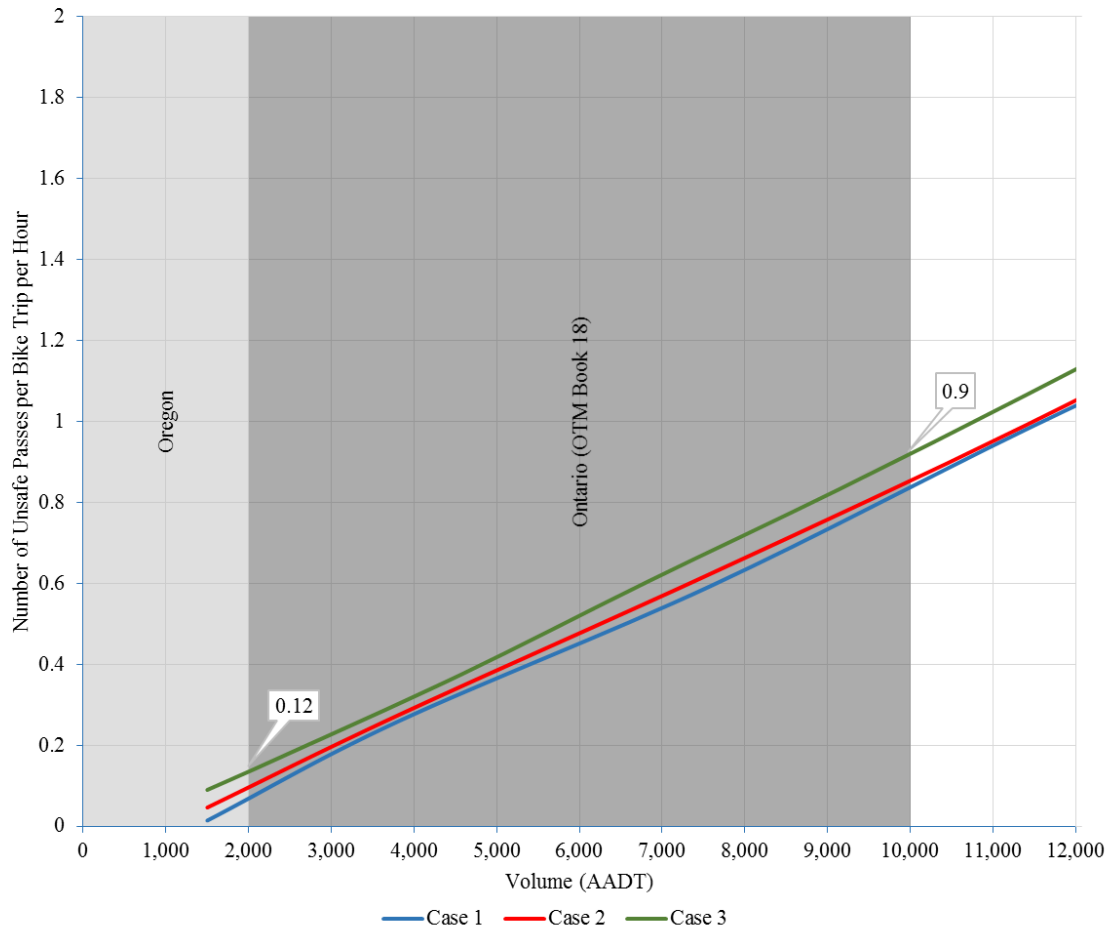
It is important to note that the nomograph presented in the OTM Book 18 combines the Narrow Lane and Wide Lane facility-types under the same category (Shared Lane). The nomograph does not contain a well-defined borderline between the two shared lane facility-types. It is up to the planner to assess the site-specific parameters and select the most appropriate facility-type for a given roadway section. The final selection of the facility-type made using the site-specific characteristics may differ than the one obtained using the nomograph. In Table 21, the comparison between the OTM Book 18 and the analysis results was made using the results obtained using only the nomograph and any site-specific characteristics were not considered. It was also assumed that the selected facility-type was of Narrow Lane category and not the Wide Lane category.

**Table 21: Comparison of Existing Bicycle-facility Selection Guideline with Modelling Results**

Jurisdiction	Threshold AADT in Guidelines	% Unsafe Passing		
		Case 1	Case 2	Case 3
<b>Ontario (OTM Book 18)</b>	<10,000	<14.3	<14.6	<15.8
<b>USA (FHWA)</b>	Narrow lane not recommended for any AADT	n/a	n/a	n/a
<b>Minnesota</b>	Narrow lane not recommended for any AADT	n/a	n/a	n/a
<b>Oregon</b>	<2,000	<10.8	<11.2	<11.9

The results in the Table 21 show the probabilities of unsafe passing that can be observed on roadways with lane width of 3.65 meter (Narrow Lane). The guidelines for FHWA (USA) and Minnesota do not recommend a narrow lane facility regardless of demand (AADT) on roadways where the 85<sup>th</sup> percentile speed is 50 km/h or higher. The design guideline for Oregon and the nomograph from the OTM Book 18 allow the use of Narrow Lanes when AADT is less than 2,000 and 10,000, respectively. If, the design guideline for Oregon is followed to select a cycling facility-type, then up to 11.9% passes are expected to be unsafe (i.e. passing distance < 1,000

mm). If the nomograph in the OTM Book 18 is followed, up to 15.8% of total passes are expected to be unsafe.



**Figure 44: Comparison of Design Guidelines with Model Results**

Figure 44 presents the relationship between ‘number of unsafe passes per bike trip per hour’ and volume (AADT) on a 300-meter long section for all three signal-timing cases. The thresholds for OTM Book 18 and Oregon guideline are also shown on the plot. The guidelines for FHWA (USA) and Minnesota do not recommend Narrow Lane facility-type for vehicle speed of 50 km/h; hence, they were not included in this comparison. Up to 0.9 and 0.12 unsafe passes per bike trip per hour are expected to occur for signal-timing scenario Case 3 when using the OTM Book 18 nomograph and Oregon Bicycle Facility Design Guideline, respectively.

It is important to note that the Step 2 of the OTM Book 18, which uses site-specific parameters to recommend facility-types, recommends usage of on-street bike lanes for multi-lane roads where the hourly motor-vehicle flow rate exceed 250 vph in the curb lane (equivalent AADT for 4-lane roadways is 10,000 vpd). From this, it can be inferred that the usage of shared lanes may be appropriate for 4-lane roadways where the AADT is less than or equal to 10,000 vpd. This means, the thresholds for motor-vehicle volume in Step 1 (nomograph) and Step 2 (site-specific criteria) to warrant the provision of dedicated bike lane are the same. If a ‘narrow lane’ facility-

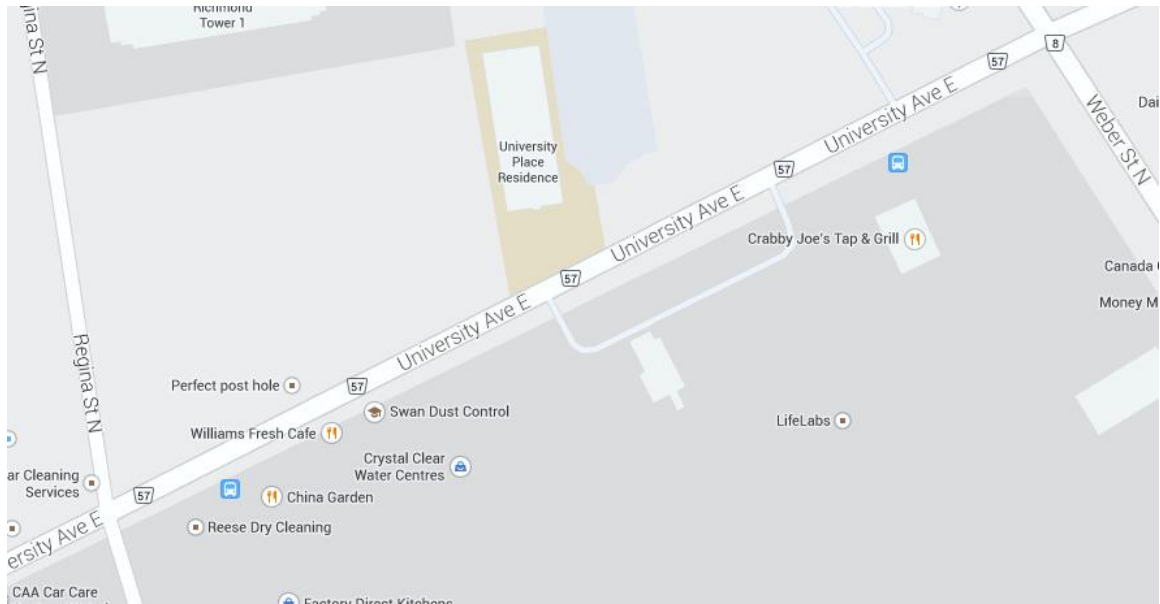
type is selected using the method presented in Step 2, the estimation of probability of unsafe passes (or the number of unsafe passes per bike trip per hour) also remains the same for Step 1 and Step 2.

The results suggest that ‘narrow lane’ facility-type may not be appropriate for similar roadways where design motor-vehicle speed (or 85<sup>th</sup> percentile speed) is 50 km/h or higher and a high number of cyclists are expected to travel. It is important to note that the three signal-timing configurations selected for this analysis do not represent all the possible signal-timing configurations. The probability of unsafe passes may be larger for other signal-timing configurations.

This study does not evaluate the relationship between unsafe passing and bicycle/motor-vehicle collisions. However, it is clear that all collisions (that occur during the overtaking maneuver) are associated with an unsafe passing distance and an assumption can be made that an increased probability of unsafe passes indicates a higher likelihood of bicycle/motor-vehicle collisions. Additionally, the occurrence of unsafe passes also influences cyclists’ perceived risk and satisfaction. A roadway with a high number of unsafe passes is likely to be perceived by cyclists to be less safe. Since it is expected that the modal share of cycling will increase if safety and the perception of safety improves, the goal of the cycling facility-type selection guidelines should be to create a safe cycling environment by eliminating (or significantly reducing) the occurrence of unsafe passes. It is recommended that the thresholds for AADT and/or vehicle speed in these guidelines be determined using a more quantitative approach, such as the method developed in Chapter 6. It is important to note that if the model developed in Chapter 6 is used to determine AADT and vehicle speed thresholds, the final decision will depend on two factors: (1) the threshold for defining unsafe passes (e.g. 1,000 mm), (2) threshold value for acceptable number of unsafe passes per bike trip (or probability of unsafe passes). It is preferable that additional research is conducted to determine the acceptable quantities for these two factors scientifically (rather than relying on preferences based on engineering judgment).

## **6.6 Model Application**

In this section, the proposed methodology to estimate the number of unsafe passings per bike trip per hour was applied for a section of University Ave in Waterloo. Specifically, the segment between Regina St N and Weber St N on University Ave E was selected for application. This section is a 4-lane roadway of narrow lane facility-type with lane widths of 3.65 meter. The length of this section is 350 meter and the posted speed limit is 50 km/h. The AADT on this section, which was obtained from the Region of Waterloo (Transportation and Environmental Services) for the year 2012, was 22,375 vpd. For the signal-timing configuration at the upstream intersection (at Regina St N and University Ave E), the three signal-timing scenarios used for the VISSIM modeling were considered.



**Figure 45: Selected Roadway for Model Application (source: [www.maps.google.com](http://www.maps.google.com))**

For this roadway, the design guideline for Oregon (Figure B1) recommends provision of on-street bike lane and the nomograph presented in the OTM Book 18 (Figure 9) recommends a separated path facility-type. Using the methodology developed in Chapter 6 and the plots presented in Figure 41, Figure 42 and Figure 43 the numbers of unsafe passes per bike trip per hour were estimated as 2.45, 2.45 and 2.70 for the three signal timing cases, respectively. These values are more than 20 times higher than the maximum permitted by the Oregon guidelines and 3 times higher than the maximum permitted by the OTM Book 18 (as per Figure 44). Ironically, this section of University Ave does not have any dedicated cycling infrastructure.

It is suggested that the results from the proposed model can be used to assist in quantitatively comparing and prioritizing candidate road segments for implementation of dedicated cycling infrastructure. Further work should also be done to identify appropriate thresholds so that the model estimates can be used directly for selecting recommended cycling treatments.

The results above also indicate the lack of consistency between the two guidelines. For the 85<sup>th</sup> percentile vehicle speed (or design vehicle speed) of 50 km/h the Oregon guideline permits the usage of narrow lane facility-type up to the AADT of 2,000 vpd. For AADT greater than 2,000 vpd, provision of bike lane is recommended in this guideline. The Oregon guideline does not recommend separated path facility-type for any AADT for 50 km/h vehicle speed. In contrast, the nomograph presented in the OTM Book 18 permits narrow lanes up to the AADT of 10,000 vpd. For AADT between 10,000 and 14,000 vpd it recommends bike lanes and for AADT greater than 14,000 vpd the nomograph recommends provision of separated path. Similar inconsistencies can also be seen between other guidelines, which are not included for this analysis. The lack of consistency between different guidelines signifies the need for an empirical foundation for developing these guidelines.

## Chapter 7

### Conclusions and Recommendations

An analysis was presented to measure and investigate the distribution of the passing distances and the passing behavior of motorized vehicles when overtaking cyclists across different categories of urban arterials. A sensor array was developed to collect field data, which were used for this analysis. The analysis further investigated the relationship between the passing behavior of the drivers and traffic-flow conditions at the time of the passing maneuvers. Subsequently, a model was developed to estimate the probability of unsafe passing on 4-lane roads without bike lanes for given traffic conditions. The study has led to the following conclusions:

1. The sensor array developed as part of this study was capable of collecting data from which the following quantities could be determined: number of passing events, passing distance, category of passing maneuver, speed and location of the cyclist at the time of the passing event, speed of the passing vehicle at the time of the passing event.
2. It was found that the lateral separation between cyclists and motorized vehicles is significantly smaller on the facilities without exclusive bike lanes where the cyclists share the traffic lane with motorized vehicles. For 2-lane roadways without bike lanes 12% of passing events were unsafe (less than 1 meter). When bike lanes were present, only 0.2% of passing events were unsafe. For 4-lane roadways without bike lanes, 6% of passing events were unsafe, and when a bike lane is present, only 0.5% of passing events were unsafe.
3. It was hypothesized that on roads without bike lanes, many drivers attempt to provide increased passing distance by encroaching on the adjacent lane or changing lanes completely. Field data for 4-lane roadways without bike lanes was examined and evidence was found to support this hypothesis.
4. The ability of drivers to encroach or change lanes is determined by the proximity of vehicles in the adjacent lane. Analysis results showed that when drivers on 4-lane roadways without bike lanes are restricted from encroaching or changing lanes, the passing distance tends to be smaller and a higher proportion of passes are unsafe.
5. It was hypothesized that the probability of a passing event being restricted or unrestricted is a function of platoon formation and dispersion. Formation and dispersion of platoons are governed by the demand volume and the section length. Evidence to support this hypothesis was found from the analysis results of the VISSIM model. The results have showed that for longer sections, the proportion of restricted passes is smaller when compared to the proportion of restricted passes on a shorter section. Similarly, when the AADT is increased, the proportion of restricted passes also increases.
6. It was hypothesized that the proportion of unsafe passes should be higher for higher volumes as compared to the proportion of unsafe passes on sections with lower volumes. Similarly, it was hypothesized that the proportion of unsafe passes should be higher on shorter sections as compared to the proportion of unsafe passes on longer sections. The model results provide evidence supporting both these hypotheses.
7. The comparison of probabilities of unsafe passes estimated using the proposed model with the nomograph provided in the OTM Book 18 showed that up to 15.8% of all passing events can be unsafe if the facility is selected using the nomograph. A similar comparison

between the design guidelines from other jurisdictions and the proposed model showed that following the Oregon design guideline may result in up to 11.9 % unsafe passes, while following the FHWA (USA) and Minnesota guidelines is expected to result in almost no unsafe passes because these guidelines do not recommend narrow lanes ( $\leq 3.65$  meter lane width) for any level of AADT when the 85<sup>th</sup> percentile motor-vehicle speed is 50 km/h or higher.

## 7.1 Recommendations

The following recommendations are made for the future extensions of this study:

1. The proposed design of the sensor array failed to capture the information regarding the dimensions of the overtaking vehicle. The traffic-flow parameters such as vehicle speed and headway were estimated by using an average vehicle length. Furthermore, the passing behaviors were categorized using an average vehicle width. Such simplifications limited the opportunity to study the vehicle-bicycle interactions considering different vehicle types such as sedans, buses and heavy vehicles. Alternatively, an improved version of the sensor array should be developed to facilitate the acquisition of information regarding passing vehicle dimensions. It can be achieved by using two ultrasonic sensors simultaneously, mounted on the front and the rear of the bike at a fixed known distance from each other.
2. The ultrasonic sensor used in the sensor array failed to obtain the passing distance information from vehicles travelling in the opposite direction on 2-lane roads. Consequently it was not possible to investigate the influence that passing opportunities had on the passing distance. It is recommended to use a different model of ultrasonic sensor with a higher measuring range and refresh rate (frequency). Albeit, such a sensor would be significantly more expensive than the one used in this study. If sufficient budget is available, the ultrasonic sensor should be replaced with a high frequency and high fidelity laser range finder.
3. One of the goals of this study was to compare the passing distance distributions on roadways with and without bike lanes. The data was collected in the Kitchener-Waterloo Region where legislation requiring drivers to keep a minimum passing distance from the cyclists (such as 1-meter rule) does not exist. As such, it was not possible to evaluate the impact that such legislation has on the distribution of passing distances. It is recommended that a similar study should be carried out in a location in which minimum safe passing distance legislation exists in order to quantify the effectiveness of such legislation.
4. Three different models were developed in this study based on different signal-timing scenarios and their effects on distributions of unsafe passes were examined. However, these three scenarios do not represent the entire domain of possible signal-timing configurations that are typically used for urban intersections. Consequently, it was not possible to conduct a sensitivity analysis of the effects of the entire range of signal-timing configurations. A study should be conducted to include a wider range of signal-timing configurations that are typically found in urban settings and a sensitivity analysis should be carried out between their respective passing distance distributions.
5. Finally, effort should be made to establish threshold values of the number of unsafe passing maneuvers per bike per hour which can be incorporated within existing guidelines for selecting appropriate cycling treatments.

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## Appendix A

This appendix presents the relevant results of “City of Toronto Bicycle/Motor-Vehicle Collision Study” (City of Toronto, 2003) and “City of Toronto Cycling Study – Tracking Report (1999 and 2009)” (Ipsos, 2009).

**Table A-1: Car-Bike Collision Types, Major Injuries and Fatalities (City of Toronto, 2003)**

Collision Type	Number of Cases	% of Total	Cyclist's Position		Major Injuries	Fatal
			Sidewalk	Road		
Drive Out At Controlled Intersection	284	12.2%	51%	49%	8	0
<b>Motorist Overtaking</b>	<b>277</b>	<b>11.9%</b>	<b>0</b>	<b>100%</b>	<b>7</b>	<b>4</b>
Motorist Opens Vehicle Door	276	11.9%	0	100%	8	1
Motorist Left Turn Facing Cyclist	248	10.7%	18%	82%	11	0
Motorist Right Turn (Not at Red Light)	224	9.6%	35%	65%	3	0
Motorist Right Turn At Red Light	179	7.7%	86%	14%	4	0
Drive Out From Lane or Driveway	179	7.7%	81%	19%	3	0
Ride Out At Controlled Intersection	65	2.8%	0	100%	3	2
Wrong Way Cyclist	59	2.5%	0	100%	2	0
Ride Out At Mid-block	51	2.2%	100%	0	4	1
Motorist Left Turn – In Front Of Cyclist	48	2.1%	48%	52%	2	0
Ride Out From Sidewalk	44	1.9%	100%	0	5	0
Cyclist Lost Control	44	1.9%	11%	89%	2	0
Cyclist Left Turn In Front Of Motorist	41	1.8%	0	100%	6	0
Cyclist Strikes Stopped Vehicle	39	1.7%	0	100%	1	0
Motorist Reversing	37	1.6%	46%	54%	0	0
Cyclist Overtaking	31	1.3%	0	100%	0	0
Cyclist Caught in Intersection	30	1.3%	3%	97%	0	0
Ride Out From Lane or Driveway	29	1.2%	Unknown		1	0
Drive Into/Out of On-Street Parking	28	1.2%	0	100%	0	0
Cyclist Left Turn – Facing Traffic	11	0.5%	0	100%	2	0
Non Classified	101	4.3%	Unknown		9	2
Unknown (Insufficient Information)	247	-	Unknown		4	0
	2572		30%	70%	85	10

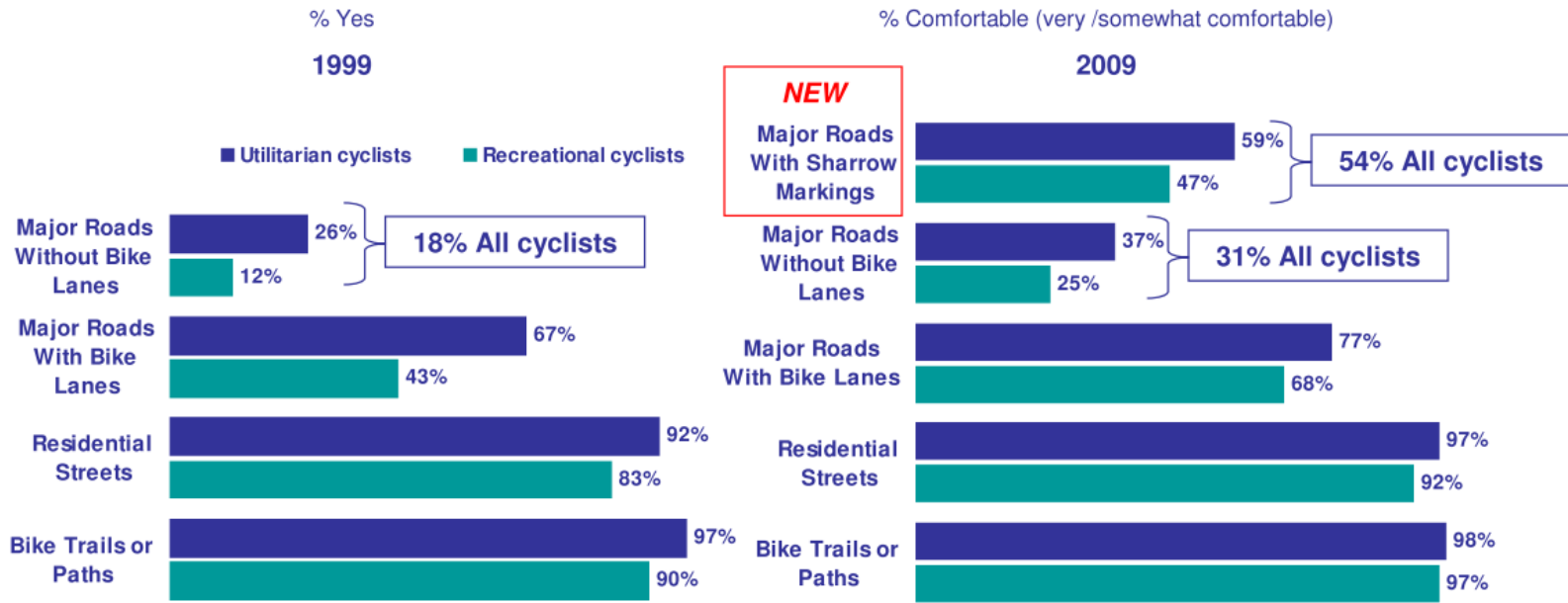


Figure A-1: Cycling Comfort Level Survey (Ipsos, 2009)

## Appendix B

In this appendix the supporting material for design guidelines presented in Section 2.2 are shown. The following thirteen tables present the ‘Application Heuristics’ explained in Section 2.2.1 (OTM Book 18).

**Table B-1: 85th Percentile Motor-Vehicle Operating Speeds (MTO, 2013)**

As the speed differential between motorists and cyclists increases, so does the collision risk for cyclists using that roadway. Therefore, when selecting a bicycle facility type, the 85 <sup>th</sup> percentile operating speed should be considered. Higher motor vehicle speeds may negatively influence a cyclist’s ability to control their bicycle.	
Site Characteristics	Design Considerations and Application Heuristics
Low (30 to 49 km/h)	Speed differential between bicycles and motor vehicles is within 30 km/h, suggesting integration of the two modes as mixed traffic, in standard or wide curb lanes, may be appropriate.
Moderate (50 to 69 km/h)	Exclusive operating space for both bicycles and motor vehicles, in the form of paved shoulders, bicycle lanes or separated facilities is recommended.
High (70 to 89 km/h)	Speed differential between bicycles and motor vehicles exceeds 40 km/h, suggesting physical separation of the two modes is most appropriate such as buffered paved shoulders.
Very high (90 km/h and greater)	Physical separation is preferable, particularly in an urban environment. In rural areas of the province, it may not be practical to provide physically separated facilities on very high speed roadways where bicycles are currently allowed. A painted buffer between the roadway and the paved shoulder is an alternative treatment for such cases. If this is not feasible, provision of a parallel bicycle route should be explored.

**Table B-2: Motor-vehicle Volumes (MTO, 2013)**

<p>As motor vehicle volume increases, so does the collision risk for cyclists using that roadway. For planning purposes, the future year traffic volumes should be used when selecting an appropriate bicycle facility type for a given roadway section. Where AADT volumes are unavailable, rush hour volumes may be used. Some municipalities suggest that as a rule of thumb, rush hour volumes typically represent 10% of the daily volume.</p>	
Site Characteristics	Design Considerations and Application Heuristics
Very Low Volume: where two-way daily average volume is less than 500 vpd on a two-lane road	No facility type is typically required.
Low Volume: where two-way daily average volume is 500 to 2,000 vpd on a two-lane road	Mixed traffic may be appropriate if vehicle speeds are low. Lanes should be wide enough to comfortably accommodate shared use by cyclists and motorists. If speeds are moderate, paved shoulders or bicycle lanes should be considered.
Moderate Volume: where two-way daily average volume is 2,000 to 10,000 vpd on a two-lane road	Some level of formal bicycle facility such as a conventional bicycle lane is recommended. If this is not feasible, a signed bicycle route with a paved shoulder may be considered.
High Volume: where two-way daily average volume is greater than 10,000 vpd on a two-lane road	Physical separation of motor vehicle and bicycle traffic may be most appropriate.
Hourly one-way volume in the curb lane exceeds 250 vph	Some level of formal bicycle facility such as a 'signed only' bike route with a paved shoulder or bicycle lanes are recommended.

**Table B-3: Function of Street or Road or Highway (MTO, 2013)**

<p>While generally reflected in motor vehicle volumes, the function of a roadway should also be considered in bicycle facility decisions. The significance of this factor will be higher in cases where volume or speed data are unavailable.</p>	
Site Characteristics	Design Considerations and Application Heuristics
Access roads such as local roads and residential streets	Mixed traffic may be appropriate if speeds and volumes are low. Where feasible, design features associated with Bicycle Priority Streets should be applied, as described in <b>section 5.1</b> . Otherwise, curb lanes should be wide enough to comfortably accommodate shared use by cyclists and motorists, with dimensions as indicated in <b>Table 4.1</b> for a Wide Signed Bicycle Route.
Both mobility and access roads such as minor collectors plus similar roads and streets	Some level of formal bicycle facility such as a signed bike route with paved shoulder or bicycle lane is appropriate. A Narrow Signed Bicycle Route may be implemented, with dimensions as indicated in <b>Table 4.1</b> .
Mobility roads such as arterials and major collectors	Some level of formal bicycle facility such as a bicycle lane or separated facility is appropriate.
Motor vehicle commuter route	Separated bicycle facilities should be considered to minimize conflicts with aggressive drivers on the roadway.

**Table B-4: Vehicle Mix (MTO, 2013)**

<p>Heavy vehicles, such as transport trucks and buses have a greater influence on cyclists than passenger vehicles. This is partly due to the larger difference in mass between cyclists and heavy commercial vehicles, and the increased severity of any resulting collision. Air turbulence generated by these high-sided vehicles also has a more significant impact on the difficulty of controlling a bicycle, which requires both greater skill and more caution on the part of the cyclist than in the presence of passenger vehicles. As the volume of heavy vehicles increases, so too does the desirability of providing buffers or physical separation of cyclists from motorized traffic. Stationary trucks and buses may also interfere with cyclist movements, creating a need for lane changes on the part of cyclists. This increases the interaction with vehicular traffic, and at times may obstruct other drivers' view of the cyclist on the road at inopportune moments.</p>	
Site Characteristics	Design Considerations and Application Heuristics
More than 30 trucks or buses per hour are present in a single curb lane	Separated bicycle facilities may be preferred by many cyclists. If paved shoulders, wide curb lanes or bicycle lanes are considered, additional width should be provided as a buffer.
Bus stops are located along the route	Facilities should be designed to minimize and clearly mark cyclist conflict areas with buses or pedestrians at stop locations. See <b>Section 5.4.2</b> for more details.

**Table B-5: Collision History (MTO, 2013)**

<p>Where there is evidence of the involvement of cyclists in collisions, historical patterns can sometimes provide valuable indicators of the factors that are present and pose particular challenges for the accommodation of cycling facilities, as well as the mitigating measures that can help resolve them.</p>	
Site Characteristics	Design Considerations and Application Heuristics
Bicycle collisions are relatively frequent along the route	A detailed safety study is recommended. Alternate routes should be considered. Separated facilities may be appropriate to address midblock conflicts. If on-road facilities are considered, the operating and buffer space provided to cyclists should be considered.
Bicycle collisions are relatively frequent at specific locations	Localized design improvements should be considered to address contributing factors at high-collision locations, often near intersection and driveway locations.
Noticeable trends emerge from bicycle collisions	The proposed facility and its design should attempt to address noticeable collision trends. For each facility type, safety countermeasures* can be developed. These can be based on road user behaviour and manoeuvres that resulted in the collision, or specific design and policy objectives.
Conflict areas exist between cyclists and motor vehicles or pedestrians	Facilities and crossings should be designed to minimize conflict between different types of users and the conflict area should be clearly marked.

\*For detailed scenario-based information, refer to the Bicycle Countermeasure Selection System in the FHWA's BikeSafe guide.

**Table B-6: Available Space (MTO, 2013)**

<p>The space available to serve all functions and users of a roadway is finite. Consequently, practitioners should consider the constraints imposed by curbs, pinch points and physical barriers when choosing the most appropriate facility for a particular section of roadway. Once the facility type has been selected, the adequacy of sightlines, both at intersections and continuously along a roadway should be considered. Please refer to <b>Section 5.4</b> for more details.</p>	
Site Characteristics	Design Considerations and Application Heuristics
<p>Sufficient curb-to-curb width exists to adequately accommodate motorists and cyclists.</p>	<p>Redistribute roadway space to accommodate bicycle lanes by narrowing or eliminating parking lanes, narrowing travel lanes, or eliminating unnecessary travel or turn lanes. Where bicycle lanes are not feasible, wide curb lanes may be provided. Please refer to <b>Section 5.2</b> for guidance on integrating bicycle facilities through road retrofits.</p>
<p>Sufficient curb-to-curb width exists, but pinch points are created where turn lanes are developed at intersections.</p>	<p>There is a higher risk of collisions at intersection compared to other sections of road and less confident cyclists may be deterred by a lack of designated bicycle facilities on the immediate approach to an intersection. Where feasible, localized widening should be undertaken to provide continuous bicycle facilities of constant width entering, through and exiting the intersection. Where this is not possible, bike lanes may be discontinued with appropriate positive guidance or warning measures upstream of the merge point or intersection. Practitioners should carefully and practically consider the way in which cyclists and general traffic will merge. Pavement markings and signage should encourage cooperative merging of cyclists and motorists into a single traffic lane. Sharrow markings can be used to denote a desirable cyclist path, particularly through narrow or atypical intersections. Refer to <b>Section 4.2.1.4</b> for design recommendations.</p>
<p>Physical barriers include those created by steep grades, rivers, freeways, railways, narrow bridges.</p>	<p>Separated facilities should be considered to bypass or overcome barriers.</p>
<p>Curb-to-curb width is not adequate to provide sufficient operating space for both motorists and cyclists.</p>	<p>Provide separated facilities adjacent to the roadway or within an independent right-of-way, provide paved shoulders, widen roadway platform to accommodate bicycle lanes. Where this is not feasible, wide curb lanes may be considered or alternate routes may be investigated. If on-street parking is present, explore opportunities for it to be eliminated or reduced.</p>
<p>Adequate sightlines for road users including both motorists and cyclists on rural roads given design and operating speeds.</p>	<p>Horizontal and vertical curves along the roadway as well as roadway width should be considered when providing adequate sightlines for road users. Regular maintenance of vegetation is also important in preserving sightlines throughout the year.</p>
<p>Sight distance is limited at intersections, crossing locations or where cyclists and motor vehicles share limited road space.</p>	<p>Improve sightlines by improving roadway geometry, removing or relocating roadside furniture and vegetation; provide adequate space for cyclists either on or off the roadway. Design intersection crossings to minimize and clearly mark conflicts, and restrict parking in close proximity to intersections.</p>



**Table B-7: Costs (MTO, 2013)**

<p>In reality, provisions for cyclists on roadway projects will be affected by the availability of funding. Designers should seek to ensure that their solutions are cost-effective, meet project objectives and are appropriate for the intended users given the characteristics of the site. However, cost should not eliminate the need for due diligence in providing safe and effective cycling facilities that encourage use.</p>	
Site Characteristics	Design Considerations and Application Heuristics
<p>More than one type of bicycle facility appears appropriate</p>	<p>Benefit/cost analysis of alternatives should be conducted.*</p>
<p>Funding levels are not available to provide preferred type of facility</p>	<p>Consider alternate routes or focus on cost-effective improvements to existing facilities such as improved maintenance, pavement and drainage rehabilitation as well as removal of barriers. Poorly designed or constructed facilities may result in increased safety risks for cyclists, and are unlikely to encourage additional use.</p>

\*Refer to NCHRP Report 552 - Guidelines for Analysis of Investments in Bicycle Facilities.

**Table B-8: Anticipated Users in Terms of Skill and Trip Purpose (MTO, 2013)**

<p>It is important to consider different user skill levels and trip purposes in the design of bicycle facilities. Therefore, providing a variety of facility types, whose distinguishing feature is the presence of different degrees of separation between motorists and cyclists, helps encourage new or less experienced cyclists. This in turn improves overall cyclist safety within a road network. Research shows that one of the most effective measures for doing this is increasing the number of cyclists using the system. The appropriateness of the existing provision on a particular link can be assessed by undertaking cyclist counts. In addition to recording the number of cyclists, the hourly and daily profile will give an indication as to trip purpose; for example, peaks in use during weekday periods demonstrate commuter demand whereas high volumes on the weekend suggests recreational use.</p>	
Site Characteristics	Design Considerations and Application Heuristics
<p>Experienced cyclists (commuter or other utilitarian)</p>	<p>This group generally prefers direct, continuous facilities with minimal delay as is generally provided by the arterial road network. Experienced cyclists may be comfortable on shared use roadways with low motor vehicle volumes and speeds. However, users in this group typically prefer on-street bike lanes or separated facilities where the context warrants it.</p>
<p>Novice cyclists (recreational / beginner utilitarian)</p>	<p>This group generally prefers routes on residential streets with light traffic and low speeds. Bicycle lanes, paved shoulders (with or without buffers) and separated facilities should be considered.</p>
<p>Child cyclists</p>	<p>This group generally requires separated facilities free of conflicts with motor vehicle traffic. Separated facilities should be considered near schools, parks and neighbourhoods. Children under the age of 11 should be permitted to cycle on sidewalks since they may not have the cognitive ability or experience to ride on roads with motor vehicles by themselves.</p>

**Table B-9: Level of Bicycle Use (MTO, 2013)**

As cyclist volumes increase, so does the risk of interactions with motor vehicles. Therefore, as cyclist volume increases, practitioners should consider increased separation between motorists and cyclists.	
Site Characteristics	Design Considerations and Application Heuristics
Low bicycle volumes (< 10 cyclists per hour)	Wide curb lanes may be adequate in some cases. However, practitioners should carefully consider whether the low bicycle volumes represent a lack of cyclist demand or inadequate existing facilities. As improvements are made to cycling infrastructure, bicycle volumes tend to increase.
High bicycle volumes (> 50 cyclists per hour)	Paved shoulders, bicycle lanes or separated facilities may be appropriate. The width provided for urban bicycle facilities should accommodate bicycle volumes during peak periods both midblock and at intersections.
Significant bicycle traffic generators are nearby	Latent bicycle demand may exist if there are employment centres, neighbourhoods, schools, parks, recreational or shopping facilities along the route. Transit nodes also provide the opportunity for multi-modal travel, with bicycle trips to and from the node where appropriate end-of-trip facilities are provided (see <b>Section 7</b> ). Bicycle lanes and separated facilities should be considered to accommodate the anticipated volume of cyclists.

**Table B-10: Function of Route within the Bicycle-facility Network (MTO, 2013)**

The function of the route within the bicycle facility network is very important. Bicycle facilities depend on accessibility and connections between routes, major destinations, residential areas and recreational services. Route segments should be identified as primary or secondary routes, and ease of access to and from such facilities should be a major planning and design consideration.	
Site Characteristics	Design Considerations and Application Heuristics
Parallel bicycle routes already exist with bicycle facilities present	Redundancy of bicycle routes may provide an opportunity to provide different types of bicycle facilities within the same travel corridor. This would give cyclists with different skill levels and trip purposes the opportunity to choose the facility most appropriate to their needs.
New route provides a connection between adjacent existing facilities	Facility selection should provide continuity with adjacent bicycle facilities to the extent possible.
New route provides access to a neighbourhood, suburb or other locality.	Bicycle lanes and separated facilities should be considered to encourage cycling for all users.



**Table B-11: Type of Roadway Improvement Project (MTO, 2013)**

<p>The type of roadway improvement project can and most often does affect the type of bicycle facility that is appropriate for a given context. For example, retrofitting existing roads and intersections, platform width and other existing constraints will play a role in selecting the appropriate bicycle facility type. Therefore, consideration must be given to the type of roadway improvement project whether it is new construction, reconstruction or a retrofit. Combining works in this way allows bike facilities to be installed while achieving cost efficiencies. However, practitioners should consider the completeness of the resulting bikeway network. The implementation of small sections of disconnected bicycle facilities is unlikely to provide meaningful connections for cyclists since those facilities may suffer from low cycling volumes. Practitioners should consider using some the resources saved through the aforementioned synergies to provide additional links which will properly integrate the new facilities into the network.</p>	
<b>Site Characteristics</b>	<b>Design Considerations and Application Heuristics</b>
New construction	Appropriate bicycle facilities should be planned and integrated with the design and construction of new roads and communities.
Reconstruction	Major roadway reconstruction provides an opportunity to improve provisions for cyclists through the redistribution of existing road space (if reconstruction only involves work between the curbs) or increased roadway width or off-road space. Efficiencies where the two projects overlap will reduce the cost of providing context-appropriate bike facilities.
Resurfacing	Affordable solutions may be limited to redistributing existing road space. Fully paved shoulders may be considered along rural arterials or collectors used by cyclists.

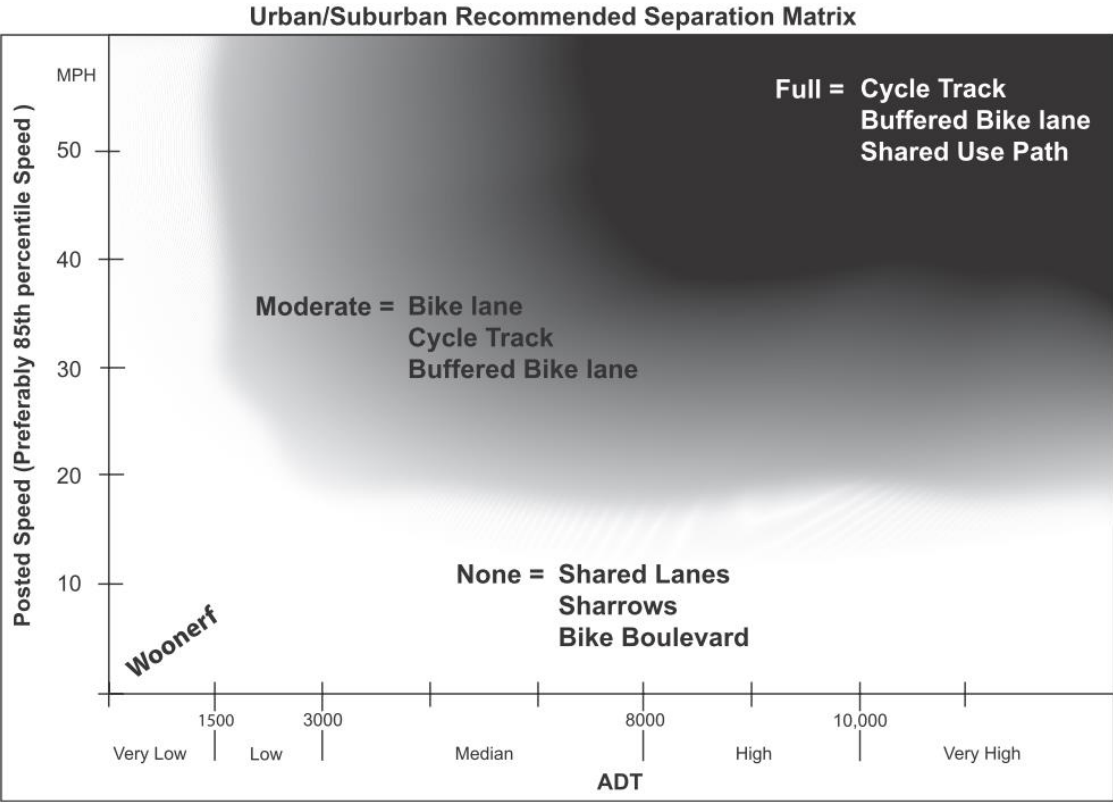
**Table B-12: On-street Parking (for urban situations) (MTO, 2013)**

<p>The presence of on-street parking has a considerable influence on both the safety and comfort of a cyclist using a bicycle facility. In particular, the configuration of on-street parking, its degree of utilization and its separation from the bicycle facility are of concern selecting a bicycle facility type. Sound engineering judgement must be applied in the design of these facilities. The designer must assess the potential for conflict between cyclists and motor vehicles as a result of vehicles entering or leaving parking spaces. The potential severity and number of conflicts will vary based on the volume of cyclists as well as the parking demand and turnover. In each case, the objective should be to avoid or mitigate conflicts to the extent possible, while recognizing parking needs and alternatives.</p>	
Site Characteristics	Design Considerations and Application Heuristics
Parallel on-street parking is not permitted	Opportunities to provide bicycle lanes or, if not feasible, wide curb lanes should be explored and their appropriateness should be evaluated.
Parallel on-street parking is permitted in localized areas along the route	Consistent bicycle lanes may prove difficult to provide since available roadway width is likely to change where parking is provided. Wide curb lanes may be a compromise solution.
Parallel on-street parking is permitted but demand is low	Opportunities to remove, restrict or relocate parking in favour of providing bicycle lanes should be considered.
Parallel on-street parking is permitted but turnover is low	Bicycle lanes may be appropriate. Additional buffer space between bicycle and parking lanes should be provided.
Parallel on-street parking is permitted; turnover and demand is high	Separated bicycle facilities between on-street parking and the edge of the roadway may be most appropriate. Bicycle lanes between vehicle travel lanes and on-street parking are not desirable in this situation. This is due to the frequent occurrence of conflicts between cyclists and vehicles manoeuvring in and out of the parking area. Where separated facilities cannot be accommodated, potential provision for cyclists on alternate routes should be investigated.
Perpendicular or diagonal parking is permitted	On-road facilities are not appropriate unless parking is reconfigured or removed. Alternate routes or opportunities to provide a separated facility should be explored.

**Table B-13: Frequency of Intersections (for urban situations) (MTO, 2013)**

<p>The more intersections and access points along a bicycle route, the more conflict points that are present. Therefore, locations with increased intersection and access density require careful consideration when selecting a bicycle facility type for the area. Sound engineering judgement must be applied to determine the characteristics of a particular site and a corresponding facility design. The designer must assess the potential for conflict between cyclists and motor vehicles as a result of vehicles entering and exiting the road. The potential severity and number of conflicts will vary based on cyclist and vehicle turning movement volumes. In each case, the objective should be to avoid or mitigate conflicts to the extent possible. This may involve the application of conflict pavement markings, as described in <b>Section 4.2.1.4</b> and <b>4.2.2.4</b>.</p>	
<b>Site Characteristics</b>	<b>Design Considerations and Application Heuristics</b>
Limited intersection and driveway crossings are present along the route	Separated facilities or bicycle lanes are well suited to routes with few driveways and intersections.
Numerous low volume driveways or unsignalized intersections are encountered	Bicycle lanes may be more appropriate than separated facilities since motorists are more likely to be aware of cyclists on the roadway rather than adjacent to the road. If bicycle lanes are not feasible, wide curb lanes may be provided.
Numerous high volume driveways or unsignalized intersections are present along the route	Separated facilities are generally not preferred in this situation; bicycle lanes may be more appropriate. Crossings should be designed to minimize conflicts; additional positive guidance should be considered to warn cyclists and motorists of conflicts. If bicycle lanes are not feasible, wide curb lanes may be provided.
Major intersections with high speed and traffic volumes are encountered	Consider provision of bicycle lanes, bike boxes, intersection and conflict zone markings as well as special bicycle signal phases at major intersections. Consider indirect left-turn treatments if there is significant bicycle left turn demand conflicting with through motor vehicle traffic. If a separated facility is being considered, crossings should have bicycle traffic signals with exclusive phases, and conflicts should be clearly marked.

Following are the volume-speed matrices presented in the other guidelines.



**Figure B-1: Oregon Urban/Suburban Recommended Separation Matrix (Oregon Department of Transportation, 2011)**

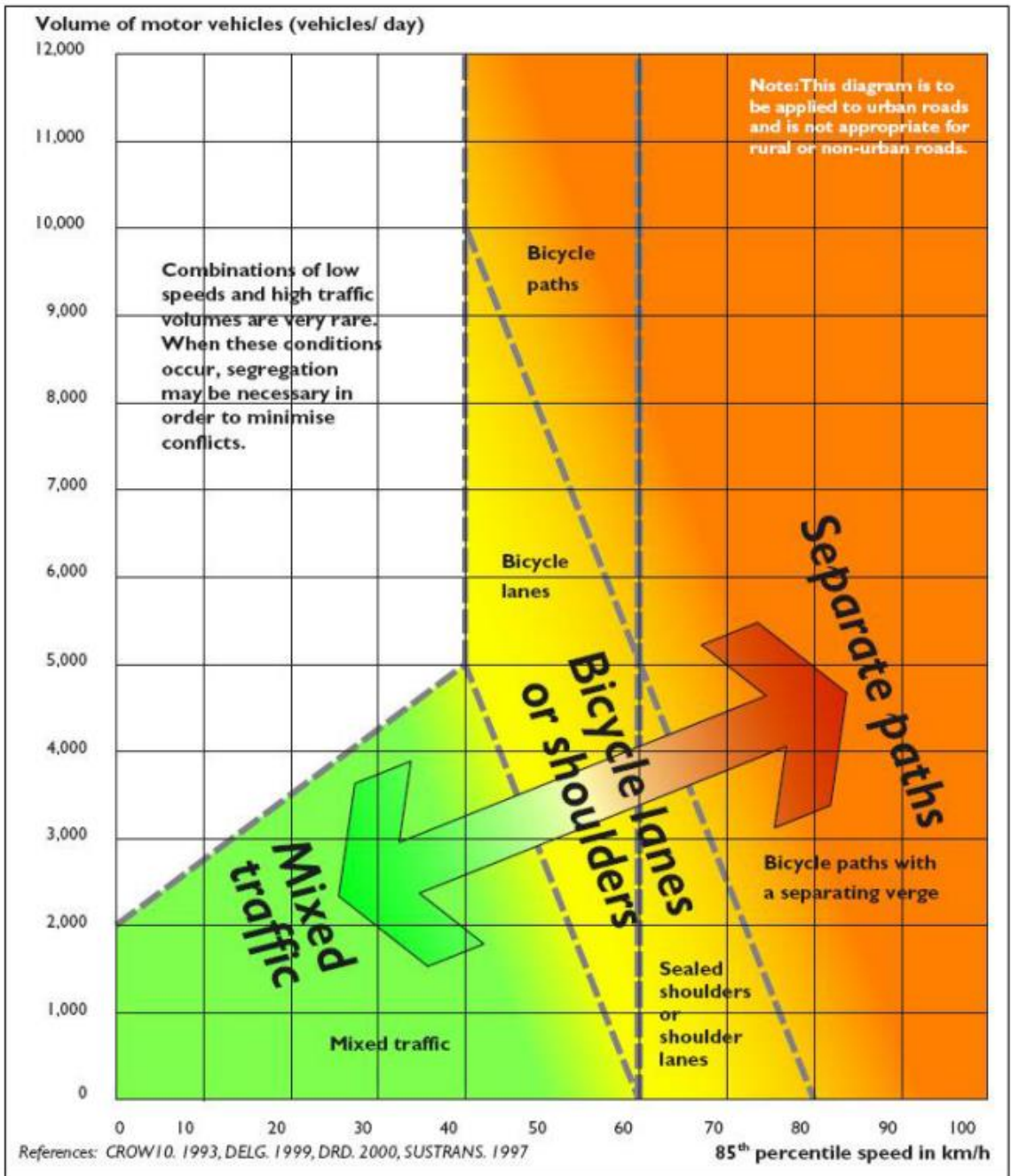


Figure B-2: Separation of Cyclists and Motor-vehicles by Speed and Volume (Veith & Eady, 2011)

**Table B-14: Bicycle-facility Selection Guide (Wilkinson, 1994)**

average motor vehicle operating speed	average annual daily traffic (AADT) volume											
	less than 2,000				2,000-10,000				over 10,000			
	adequate sight distance		inadequate sight distance		adequate sight distance		inadequate sight distance		adequate sight distance		inadequate sight distance	
less than 30 mi/h	we 14	truck, bus, rv		we 14	we 14	truck, bus, rv		we 14	bl 5	truck, bus, rv		bl 5
		we 14	we 14			we 14	we 14			bl 5	bl 5	
30-40 mi/h	bl 5	bl 5	bl 5	bl 5	bl 5	bl 6	bl 6	bl 5	bl 5	bl 6	bl 6	bl 5
41-50 mi/h	bl 5	bl 5	bl 5	bl 5	bl 6	bl 6	bl 6	bl 6	bl 6	bl 6	bl 6	bl 6
over 50 mi/h	bl 6	bl 6	bl 6	bl 6	bl 6	bl 6	bl 6	bl 6	bl 6	bl 6	bl 6	bl 6

1 mi/h - 1.61 km/h

Key:\* we - wide curb lane\*\* sh - shoulder sl - shared lane bl - bike lane\*\* na - not applicable

**Table B-15: Bikeway Design Selection (Minnesota Department of Transportation, 2007)**

<b>Table 4-1: Bikeway Design Selection for Urban (Curb and Gutter) Cross Section - English Units</b>							
<b>Motor Vehicle ADT (2 Lane)</b>		<500	500-1,000	1,000-2,000	2,000-5,000	5,000-10,000	>10,000
<b>Motor Vehicle ADT (4 Lane)</b>		N/A	N/A	2,000-4,000	4,000-10,000	10,000-20,000	>20,000
<b>Motor Vehicle Speed</b>	25 mph	SL	WOL	WOL	WOL	BL = 5 ft	Not Applicable
	30 mph	SL with sign	WOL	BL = 5 ft	BL = 5 ft	BL = 6 ft	BL = 6 ft
	35 - 40 mph	WOL	BL = 5 ft	BL = 5 ft	BL = 6 ft	BL = 6 ft	BL = 6 ft or PS = 8 ft
	45 mph and greater	BL = 5 ft	BL = 5 ft	BL = 6 ft	BL = 6 ft	BL = 6 ft or PS = 8 ft	SUP or PS = 10 ft
BL = Bicycle Lane, SL = Shared Lane, WOL = Wide Outside Lane, SUP = Shared-Use Path, PS = Paved Shoulder							



Table B-16: Bicycle Compatible Roadway Pavement Widths (New Jersey Dept. of Transportation et al., 1996)

**Condition I  
AADT 1200\* -2000**

	URBAN W/PARKING	URBAN W/O PARKING	RURAL
<50 km/h (30 mph)	SL 3.6m (12 ft.)	SL 3.3m (11 ft.)	SL 3.0m (10 ft.)
50 km/h-65 km/h (31-40 mph)	SL 4.2m (14 ft.)	SL 4.2m (14 ft.)	SL 3.6m (12 ft.)
65 km/h-80 km/h (41-50 mph)	SL 4.5m (15 ft.)	SL 4.5m (15 ft.)	SH 0.9m (3 ft.)
>80 km/h (50 mph)	NA	SH 1.2m (4 ft.)	SH 1.2m (4 ft.)

\* For volumes less than 1200 a shared lane is acceptable.

KEY: SH=shoulder SL=shared lane

**Condition II  
AADT 2000-10,000**

	URBAN W/PARKING	URBAN W/O PARKING	RURAL
<50 km/h (30 mph)	SL 4.2m (14 ft.)	SL 3.6m (12 ft.)	SL 3.6m (12 ft.)
50 km/h-65 km/h (31-40 mph)	SL 4.2m (14 ft.)	SL 4.2m (14 ft.)	SH 0.9m (3 ft.)
65 km/h-80 km/h (41-50 mph)	SL 4.5m (15 ft.)	SL 4.5m (15 ft.)	SH 1.2m (4 ft.)
>80 km/h 50 mph	NA	SH 1.8m (6 ft.)	SH 1.8m (6 ft.)

**Condition III  
AADT over 10,000 or Trucks over 5%**

	URBAN W/PARKING	URBAN W/O PARKING	RURAL
<50 km/h (30 mph)	SL 4.2m (14 ft.)	SL 4.2m (14 ft.)	SL 4.2m (14 ft.)
50 km/h-65 km/h (31-40 mph)	SL 4.2m (14 ft.)	SH 1.2m (4 ft.)	SH 1.2m (4 ft.)
65 km/h-80 km/h (41-50 mph)	SL 4.5m (15 ft.)	SH 1.8m (6 ft.)	SH 1.8m (6 ft.)
>80 km/h (50 mph)	NA	SH 1.8m (6 ft.)	SH 1.8m (6 ft.)

**NOTE:** NJDOT minimum shoulder width of 2.4 meters (8 feet) should be provided wherever possible on roadways having an AADT greater than 10,000 vehicles.

## Appendix C

In this appendix, the information about GPS data conversion is presented.

The GPS collects data regarding the longitude and latitude in NMEA mandated (National Marine Electronics Association) format. To convert from the NMEA format to decimal degree format the following method can be used.

In the example below,  $d$  denotes degree and  $m$  denotes minute. The format of the longitude is ‘ $ddmm.mmmm$ ’ and for latitude is ‘ $dddmm.mmmm$ ’. First, the segment representing the degree in the NMEA format is separated. Then the segment representing the minute is converted to decimal format by dividing it by 60. Finally, the converted minute segment is added to the degree segment. Following table illustrates this method using a set of longitude and latitude values.

**Table C-1: Conversion of Longitude and Latitude from NMEA to Decimal Degree**

	NMEA Format	Conversion	Decimal Degree Format
<b>Latitude</b>	4327.9048 (ddmm.mmmm)	43 + 27.9048/60	43.46508
<b>Longitude</b>	08032.4669 (dddmm.mmmm)	080 + 32.4669/60	080.541115

Each degree of latitudes is 111 km apart. The distance between each degree of longitudes varies and is maximum at the equator (111 km) and 0 at the north and south poles. Using this information the distance between any two sets of coordinates can be calculated using the following equations.

$$\Delta Lat = (Lat_{i+1} - Lat_i) * 111000 \tag{15}$$

$$\Delta Lon = (Lon_{i+1} - Lon_i) * 111000 * \cos Lat_i \tag{16}$$

$$Distance (m) = \sqrt{\Delta Lat^2 + \Delta Lon^2} \tag{17}$$

Where,  $\Delta Lat$  is the difference between two latitudes in meter,  $\Delta Lon$  is the difference between two longitudes in meter and  $Distance$  is the straight-line distance between two sets of coordinates in meter. It is important to note that, these equations omit the effect of the curvature of the earth’s surface and are only applicable to relatively smaller distances. For smaller distances, the error caused by omitting the curvature of the earth’s surface is insignificant. For larger distances, the effect of the curvature should also be included.

The GPS collects speed information in knots. To convert the speed to m/s and km/h units, the following equations can be used.



$$\text{speed} \left( \frac{m}{s} \right) = \text{speed} (\text{knots}) * 0.5144 \quad (18)$$

$$\text{speed} \left( \frac{km}{h} \right) = \text{speed} (\text{knots}) * 1.8518 \quad (19)$$

## Appendix D

In this appendix, the hourly and daily flow rates obtained from their respective v/c ratios are presented for the included signal-timing configurations (Case 1, Case 2 and Case 3). The hourly flow rates were used as inputs in the VISSIM models. The daily flow rates (AADT) were used to compare the results with the bicycle-facility selection guidelines. On the latter part of this appendix, the regression models representing the relationships between ‘probabilities of restricted lane change’ and ‘distance from the upstream intersection’ are presented in terms of the significance of their coefficients.

**Table D-1: Hourly and Daily Flow Rates as Calculated from their respective v/c ratios**

v/c	Flow Rate-Case 1		Flow Rate-Case 2		Flow Rate-Case 3	
	Hourly (vph)	AADT (vpd)	Hourly (vph)	AADT (vpd)	Hourly (vph)	AADT (vpd)
<b>0.1</b>	190	3800	190	3800	114	2280
<b>0.2</b>	380	7600	380	7600	228	4560
<b>0.3</b>	570	11400	570	11400	342	6840
<b>0.4</b>	760	15200	760	15200	456	9120
<b>0.5</b>	950	19000	950	19000	570	11400
<b>0.6</b>	1140	22800	1140	22800	684	13680
<b>0.7</b>	1330	26600	1330	26600	798	15960
<b>0.8</b>	1520	30400	1520	30400	912	18240
<b>0.9</b>	1710	34200	1710	34200	1026	20520
<b>1</b>	1900	38000	1900	38000	1140	22800

## Regression Models for Case 1

### **AADT = 3,800 vpd**

<i>Regression Statistics</i>								
Multiple R	0.993136							
R Square	0.986318							
Adjusted R Square	0.986036							
Standard Error	0.007203							
Observations	100							
<i>ANOVA</i>								
	<i>df</i>	<i>SS</i>	<i>MS</i>	<i>F</i>	<i>Significance F</i>			
Regression	2	0.362822	0.181411	3496.404	4.01E-91			
Residual	97	0.005033	5.19E-05					
Total	99	0.367855						
	<i>Coefficients</i>	<i>Standard Error</i>	<i>t Stat</i>	<i>P-value</i>	<i>Lower 95%</i>	<i>Upper 95%</i>	<i>Lower 95.0%</i>	<i>Upper 95.0%</i>
Intercept	0.444255	0.002432	182.6574	6.7E-125	0.439428	0.449082	0.439428	0.449082
x	-0.00045	1.05E-05	-42.802	8.67E-65	-0.00047	-0.00043	-0.00047	-0.00043
x2	2.38E-07	9.67E-09	24.58814	1.83E-43	2.18E-07	2.57E-07	2.18E-07	2.57E-07

### **AADT = 7,600 vpd**

<i>Regression Statistics</i>								
Multiple R	0.997953							
R Square	0.995909							
Adjusted R Square	0.995825							
Standard Error	0.004321							
Observations	100							
<i>ANOVA</i>								
	<i>df</i>	<i>SS</i>	<i>MS</i>	<i>F</i>	<i>Significance F</i>			
Regression	2	0.440972	0.22048 6	11807.9	1.5E-116			
Residual	97	0.001811	1.87E-05					
Total	99	0.442784						
	<i>Coefficients</i>	<i>Standard Error</i>	<i>t Stat</i>	<i>P-value</i>	<i>Lower 95%</i>	<i>Upper 95%</i>	<i>Lower 95.0%</i>	<i>Upper 95.0%</i>
Intercept	0.611978	0.001459	419.428 3	7.2E-160 9.38E-	0.609082	0.614874	0.609082	0.614874
x	-0.00045	6.33E-06	71.5587 37.3470	86 2.27E-	-0.00047	-0.00044	-0.00047	-0.00044
x2	2.17E-07	5.8E-09	9	59	2.05E-07	2.28E-07	2.05E-07	2.28E-07

**AADT = 11,400 vpd**

<i>Regression Statistics</i>	
Multiple R	0.994645
R Square	0.989319
Adjusted R Square	0.989099
Standard Error	0.006945
Observations	100

ANOVA								
	<i>df</i>	<i>SS</i>	<i>MS</i>	<i>F</i>	<i>Significance F</i>			
Regression	2	0.433336	0.216668	4492.318	2.44E-96			
Residual	97	0.004678	4.82E-05					
Total	99	0.438014						
	<i>Coefficients</i>	<i>Standard Error</i>	<i>t Stat</i>	<i>P-value</i>	<i>Lower 95%</i>	<i>Upper 95%</i>	<i>Lower 95.0%</i>	<i>Upper 95.0%</i>
Intercept	0.710326	0.002345	302.9158	3.6E-146	0.705672	0.71498	0.705672	0.71498
x	-0.00041	1.02E-05	40.5962	1.12E-62	-0.00043	-0.00039	-0.00043	-0.00039
x2	1.79E-07	9.32E-09	19.17603	9.05E-35	1.6E-07	1.97E-07	1.6E-07	1.97E-07

**AADT = 15,200 vpd**

<i>Regression Statistics</i>	
Multiple R	0.995593
R Square	0.991205
Adjusted R Square	0.991024
Standard Error	0.00576
Observations	100

ANOVA								
	<i>df</i>	<i>SS</i>	<i>MS</i>	<i>F</i>	<i>Significance F</i>			
Regression	2	0.362698	0.181349	5465.917	2E-100			
Residual	97	0.003218	3.32E-05					
Total	99	0.365916						
	<i>Coefficients</i>	<i>Standard Error</i>	<i>t Stat</i>	<i>P-value</i>	<i>Lower 95%</i>	<i>Upper 95%</i>	<i>Lower 95.0%</i>	<i>Upper 95.0%</i>
Intercept	0.773437	0.001945	397.672	1.3E-157	0.769577	0.777297	0.769577	0.777297
x	-0.00036	8.43E-06	42.2233	3.04E-64	-0.00037	-0.00034	-0.00037	-0.00034
x2	1.42E-07	7.73E-09	18.3914	2.19E-33	1.27E-07	1.58E-07	1.27E-07	1.58E-07

### AADT = 19,000 vpd

<i>Regression Statistics</i>	
Multiple R	0.998463
R Square	0.996928
Adjusted R Square	0.996864
Standard Error	0.00327
Observations	100

ANOVA								
	<i>df</i>	<i>SS</i>	<i>MS</i>	<i>F</i>	<i>Significance F</i>			
Regression	2	0.336646	0.16832	15738.3	1.4E-122			
Residual	97	0.001037	1.07E-05					
Total	99	0.337683						
	<i>Coefficients</i>	<i>Standard Error</i>	<i>t Stat</i>	<i>P-value</i>	<i>Lower 95%</i>	<i>Upper 95%</i>	<i>Lower 95.0%</i>	<i>Upper 95.0%</i>
Intercept	0.824316	0.001104	746.497	3.8E-184	0.822125	0.826508	0.822125	0.826508
x	-0.00034	4.79E-06	70.3029	5.06E-85	-0.00035	-0.00033	-0.00035	-0.00033
x2	1.31E-07	4.39E-09	29.7627	1.42E-50	1.22E-07	1.39E-07	1.22E-07	1.39E-07

### AADT = 22,800 vpd

<i>Regression Statistics</i>	
Multiple R	0.996701
R Square	0.993412
Adjusted R Square	0.993276
Standard Error	0.003831
Observations	100

ANOVA								
	<i>df</i>	<i>SS</i>	<i>MS</i>	<i>F</i>	<i>Significance F</i>			
Regression	2	0.214699	0.10735	7313.28	1.6E-106			
Residual	97	0.001424	1.47E-05					
Total	99	0.216123						
	<i>Coefficients</i>	<i>Standard Error</i>	<i>t Stat</i>	<i>P-value</i>	<i>Lower 95%</i>	<i>Upper 95%</i>	<i>Lower 95.0%</i>	<i>Upper 95.0%</i>
Intercept	0.866574	0.001294	669.866	1.4E-179	0.864007	0.869142	0.864007	0.869142
x	-0.00027	5.61E-06	-47.359	7.4E-69	-0.00028	-0.00025	-0.00028	-0.00025
x2	1.01E-07	5.14E-09	19.6826	1.2E-35	9.1E-08	1.11E-07	9.1E-08	1.11E-07

### AADT = 26,600 vpd

<i>Regression Statistics</i>								
Multiple R	0.996862							
R Square	0.993734							
Adjusted R Square	0.993605							
Standard Error	0.003735							
Observations	100							
<i>ANOVA</i>								
	<i>df</i>	<i>SS</i>	<i>MS</i>	<i>F</i>	<i>Significance F</i>			
Regression	2	0.214649	0.10732	7692.22	1.4E-107			
Residual	97	0.001353	1.4E-05					
Total	99	0.216002						
	<i>Coefficients</i>	<i>Standard Error</i>	<i>t Stat</i>	<i>P-value</i>	<i>Lower 95%</i>	<i>Upper 95%</i>	<i>Lower 95.0%</i>	<i>Upper 95.0%</i>
Intercept	0.899141	0.001261	712.904	3.3E-182	0.896638	0.901644	0.896638	0.901644
x	-0.00024	5.47E-06	43.1728	3.91E-65	-0.00025	-0.00023	-0.00025	-0.00023
x2	7.23E-08	5.01E-09	14.4331	6.86E-26	6.24E-08	8.23E-08	6.24E-08	8.23E-08

### AADT = 30,400 vpd

<i>Regression Statistics</i>								
Multiple R	0.994965							
R Square	0.989955							
Adjusted R Square	0.989748							
Standard Error	0.004475							
Observations	100							
<i>ANOVA</i>								
	<i>df</i>	<i>SS</i>	<i>MS</i>	<i>F</i>	<i>Significance F</i>			
Regression	2	0.191449	0.09572	4779.81	1.24E-97			
Residual	97	0.001943	2E-05					
Total	99	0.193392						
	<i>Coefficients</i>	<i>Standard Error</i>	<i>t Stat</i>	<i>P-value</i>	<i>Lower 95%</i>	<i>Upper 95%</i>	<i>Lower 95.0%</i>	<i>Upper 95.0%</i>
Intercept	0.932443	0.001511	617.081	4E-176	0.929444	0.935442	0.929444	0.935442
x	-0.00021	6.55E-06	31.7217	5.19E-53	-0.00022	-0.00019	-0.00022	-0.00019
x2	5.37E-08	6.01E-09	8.93728	2.64E-14	4.18E-08	6.56E-08	4.18E-08	6.56E-08

### AADT = 34,200 vpd

<i>Regression Statistics</i>	
Multiple R	0.994502
R Square	0.989034
Adjusted R Square	0.988808
Standard Error	0.004171
Observations	100

<i>ANOVA</i>					
	<i>df</i>	<i>SS</i>	<i>MS</i>	<i>F</i>	<i>Significance F</i>
Regression	2	0.152234	0.07611	4374.23	8.76E-96
Residual	97	0.001688	1.74E-05		
Total	99	0.153921			

	<i>Coefficients</i>	<i>Standard Error</i>	<i>t Stat</i>	<i>P-value</i>	<i>Lower 95%</i>	<i>Upper 95%</i>	<i>Lower 95.0%</i>	<i>Upper 95.0%</i>
Intercept	0.950259	0.001409	674.651	6.9E-180	0.947463	0.953054	0.947463	0.953054
x	-0.0002	6.11E-06	32.0793	1.92E-53	-0.00021	-0.00018	-0.00021	-0.00018
x2	5.81E-08	5.6E-09	10.3789	2.04E-17	4.7E-08	6.92E-08	4.7E-08	6.92E-08

### AADT = 38,000 vpd

<i>Regression Statistics</i>	
Multiple R	0.994475
R Square	0.988981
Adjusted R Square	0.988754
Standard Error	0.004091
Observations	100

<i>ANOVA</i>					
	<i>df</i>	<i>SS</i>	<i>MS</i>	<i>F</i>	<i>Significance F</i>
Regression	2	0.145715	0.07285	4352.92	1.11E-95
Residual	97	0.001624	1.67E-05		
Total	99	0.147339			

	<i>Coefficients</i>	<i>Standard Error</i>	<i>t Stat</i>	<i>P-value</i>	<i>Lower 95%</i>	<i>Upper 95%</i>	<i>Lower 95.0%</i>	<i>Upper 95.0%</i>
Intercept	0.969841	0.001381	702.069	1.5E-181	0.967099	0.972582	0.967099	0.972582
x	-0.00018	5.99E-06	30.0099	6.89E-51	-0.00019	-0.00017	-0.00019	-0.00017
x2	4.53E-08	5.49E-09	8.25298	7.76E-13	3.44E-08	5.62E-08	3.44E-08	5.62E-08

## Regression Models for Case 2

### AADT = 3,800 vpd

Regression Statistics	
Multiple R	0.9894826
R Square	0.9790758
Adjusted R Square	0.9786488
Standard Error	0.0083942
Observations	15

ANOVA					
	df	SS	MS	F	Significance F
Regression	2	0.32311286	0.1615564	2292.7890	5.14953E-83
Residual	98	0.00690535	7.04628E-05		
Total	100	0.33001822			

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%	Lower 95.0%	Upper 95.0%
Intercept	0.4778991	0.00271057	176.30930	1.8794E-124	0.47252006	0.4832781	0.4725200	0.4832781
x	0.0003615	1.18878E-05	30.412703	1.03325E-51	0.00038513	0.0003379	0.0003851	0.0003379
x2	1.6411E-07	1.0988E-08	14.935324	5.36423E-27	1.42304E-07	1.85915E-07	1.42304E-07	1.85915E-07

### AADT = 7,600 vpd

Regression Statistics	
Multiple R	0.99429209
R Square	0.98861677
Adjusted R Square	0.98838445
Standard Error	0.00643704
Observations	7

ANOVA					
	df	SS	MS	F	Significance F
Regression	2	0.352664643	0.1763323	4255.5778	5.71492E-96
Residual	98	0.004060687	4.14356E-05		
Total	100	0.356725329			

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%	Lower 95.0%	Upper 95.0%
Intercept	0.64055656	0.002078584	308.16966	3.5658E-148	0.63643168	0.64468144	0.63643168	0.64468144
x	0.00034336	9.11608E-06	37.665551	4.22187E-60	0.00036145	0.00032527	0.00036145	0.00032527
x2	1.37005E-07	8.42609E-09	16.259564	1.39158E-29	1.20283E-07	1.53726E-07	1.20283E-07	1.53726E-07



### AADT = 11,400 vpd

Regression Statistics	
Multiple R	0.99618789
R Square	0.992390311
Adjusted R Square	0.992235012
Standard Error	0.004419158
Observations	100

ANOVA					
	<i>df</i>	<i>SS</i>	<i>MS</i>	<i>F</i>	<i>Significance F</i>
Regression	2	0.249586303	0.124793152	6390.159681	1.5381E-104
Residual	98	0.001913838	1.9529E-05		
Total	100	0.251500141			

	<i>Coefficients</i>	<i>Standard Error</i>	<i>t Stat</i>	<i>P-value</i>	<i>Lower 95%</i>	<i>Upper 95%</i>	<i>Lower 95.0%</i>	<i>Upper 95.0%</i>
Intercept	0.70979964	0.001426988	497.4109608	1.5447E-168	0.706967828	0.712631452	0.706967828	0.712631452
x	0.000225153	6.25836E-06	35.97628577	2.80553E-58	0.000237572	0.000212733	0.000237572	0.000212733
x2	5.25698E-08	5.78467E-09	9.087769953	1.1547E-14	4.10903E-08	6.40493E-08	4.10903E-08	6.40493E-08

### AADT = 15,200 vpd

Regression Statistics	
Multiple R	0.996009475
R Square	0.992034875
Adjusted R Square	0.991872321
Standard Error	0.004305622
Observations	100

ANOVA					
	<i>df</i>	<i>SS</i>	<i>MS</i>	<i>F</i>	<i>Significance F</i>
Regression	2	0.22627274	0.11313637	6102.81792	1.4402E-103
Residual	98	0.001816761	1.85384E-05		
Total	100	0.228089502			

	<i>Coefficients</i>	<i>Standard Error</i>	<i>t Stat</i>	<i>P-value</i>	<i>Lower 95%</i>	<i>Upper 95%</i>	<i>Lower 95.0%</i>	<i>Upper 95.0%</i>
Intercept	0.785437202	0.001390327	564.9300171	5.9341E-174	0.782678144	0.788196206	0.782678144	0.788196206
x	0.000255893	6.09758E-06	41.96632391	1.95053E-64	0.000267993	0.000243792	0.000267993	0.000243792
x2	9.07413E-08	5.63605E-09	16.10014406	2.8169E-29	7.95567E-08	1.01926E-07	7.95567E-08	1.01926E-07

### AADT = 19,000 vpd

Regression Statistics	
Multiple R	0.9952183
R Square	0.9904596
Adjusted R Square	0.9902649
Standard Error	0.0036447
Observations	100

ANOVA					
	<i>df</i>	<i>SS</i>	<i>MS</i>	<i>F</i>	<i>Significance F</i>
Regression	2	0.13515463	0.0675773	5087.0806	9.9689E-100
Residual	98	0.00130184	1.32841E-05		
Total	100	0.13645647			

	<i>Coefficients</i>	<i>Standard Error</i>	<i>t Stat</i>	<i>P-value</i>	<i>Lower 95%</i>	<i>Upper 95%</i>	<i>Lower 95.0%</i>	<i>Upper 95.0%</i>
Intercept	0.8262929	0.00117692	702.08060	3.3511E-183	0.82395736	0.8286284	0.8239573	0.8286284
x	0.0001759	5.16164E-06	34.078313	3.85178E-56	0.00018614	0.0001656	0.0001861	0.0001656
x2	4.86389E-08	4.77096E-09	10.194786	4.57394E-17	3.91711E-08	5.81067E-08	3.91711E-08	5.81067E-08

### AADT = 22,800 vpd

Regression Statistics	
Multiple R	0.9933647
R Square	0.9867735
Adjusted R Square	0.9865035
Standard Error	0.0041667
Observations	100

ANOVA					
	<i>df</i>	<i>SS</i>	<i>MS</i>	<i>F</i>	<i>Significance F</i>
Regression	2	0.12693668	0.0634683	3655.6846	8.92888E-93
Residual	98	0.00170143	1.73615E-05		
Total	100	0.12863811			

	<i>Coefficients</i>	<i>Standard Error</i>	<i>t Stat</i>	<i>P-value</i>	<i>Lower 95%</i>	<i>Upper 95%</i>	<i>Lower 95.0%</i>	<i>Upper 95.0%</i>
Intercept	0.8665297	0.00134547	644.03333	1.5751E-179	0.86385966	0.8691997	0.8638596	0.8691997
x	0.0001888	5.90086E-06	31.999737	1.11019E-53	0.00020054	0.0001771	0.0002005	0.0001771
x2	6.51635E-08	5.45423E-09	11.947335	7.76434E-21	5.43398E-08	7.59873E-08	5.43398E-08	7.59873E-08

### AADT = 26,600 vpd

Regression Statistics	
Multiple R	0.9969650
R Square	0.9939392
Adjusted R Square	0.9938155
Standard Error	0.0022835
Observations	100

ANOVA					
	<i>df</i>	<i>SS</i>	<i>MS</i>	<i>F</i>	<i>Significance F</i>
Regression	2	0.08380738	0.0419036	8035.7582	2.2076E-109
Residual	98	0.00051103	5.21465E-06		
Total	100	0.08431842			

	<i>Coefficients</i>	<i>Standard Error</i>	<i>t Stat</i>	<i>P-value</i>	<i>Lower 95%</i>	<i>Upper 95%</i>	<i>Lower 95.0%</i>	<i>Upper 95.0%</i>
Intercept	0.8946007	0.00073738	1213.2090	1.7709E-206	0.89313743	0.8960640	0.8931374	0.8960640
x	0.0001623	3.23396E-06	50.185422	1.0339E-71	0.00016872	0.0001558	0.0001687	0.0001558
x2	6.17274E-08	2.98918E-09	20.650298	1.79613E-37	5.57955E-08	6.76594E-08	5.57955E-08	6.76594E-08

### AADT = 30,400 vpd

Regression Statistics	
Multiple R	0.9877519
R Square	0.9756538
Adjusted R Square	0.9751570
Standard Error	0.0039235
Observations	100

ANOVA					
	<i>df</i>	<i>SS</i>	<i>MS</i>	<i>F</i>	<i>Significance F</i>
Regression	2	0.06045678	0.0302283	1963.6402	8.61125E-80
Residual	98	0.00150861	1.53941E-05		
Total	100	0.06196540			

	<i>Coefficients</i>	<i>Standard Error</i>	<i>t Stat</i>	<i>P-value</i>	<i>Lower 95%</i>	<i>Upper 95%</i>	<i>Lower 95.0%</i>	<i>Upper 95.0%</i>
Intercept	0.9176440	0.00126694	724.29718	1.5831E-184	0.91512983	0.9201582	0.9151298	0.9201582
x	0.0001084	5.55646E-06	19.509328	1.60198E-35	0.00011942	-9.73761E-05	0.0001194	-9.73761E-05
x2	2.35332E-08	5.13589E-09	4.5821063	1.3571E-05	1.33412E-08	3.37252E-08	1.33412E-08	3.37252E-08

### AADT = 34,200 vpd

Regression Statistics	
Multiple R	0.9866024
R Square	0.9733843
Adjusted R Square	0.9728411
Standard Error	0.0041616
Observations	100

ANOVA					
	<i>df</i>	<i>SS</i>	<i>MS</i>	<i>F</i>	<i>Significance F</i>
Regression	2	0.06207324	0.0310366	1792.0223	6.78756E-78
Residual	98	0.00169729	1.73193E-05		
Total	100	0.06377054			

	<i>Coefficients</i>	<i>Standard Error</i>	<i>t Stat</i>	<i>P-value</i>	<i>Lower 95%</i>	<i>Upper 95%</i>	<i>Lower 95.0%</i>	<i>Upper 95.0%</i>
Intercept	0.943483703	0.001343836	702.0822188	3.3503E-183	0.940816903	0.946150503	0.940816903	0.946150503
x	-9.1778E-05	5.89368E-06	15.57226004	2.97727E-28	0.000103474	-8.00821E-05	0.000103474	-8.00821E-05
x2	6.44058E-09	5.44759E-09	1.182280156	0.239955209	-4.36999E-09	1.72512E-08	-4.36999E-09	1.72512E-08

### AADT = 38,000 vpd

Regression Statistics	
Multiple R	0.9757850
R Square	0.9521563
Adjusted R Square	0.9511799
Standard Error	0.0040582
Observations	100

ANOVA					
	<i>df</i>	<i>SS</i>	<i>MS</i>	<i>F</i>	<i>Significance F</i>
Regression	2	0.03212160	0.0160608	975.169817	2.04824E-65
Residual	98	0.00161403	1.64697E-05		
Total	100	0.03373563			

	<i>Coefficient</i>	<i>Standard Error</i>	<i>t Stat</i>	<i>P-value</i>	<i>Lower 95%</i>	<i>Upper 95%</i>	<i>Lower 95.0%</i>	<i>Upper 95.0%</i>
Intercept	0.956691662	0.001310462	730.0415882	7.3006E-185	0.954091093	0.959292231	0.954091093	0.959292231
x	-6.49825E-05	5.74731E-06	11.3065935	1.81736E-19	-7.63879E-05	-5.35772E-05	-7.63879E-05	-5.35772E-05
x2	3.63932E-09	5.3123E-09	0.685074595	0.494914056	-6.90277E-09	1.41814E-08	-6.90277E-09	1.41814E-08

## Regression Models for Case 2

**AADT = 2,280 vpd**

Regression Statistics	
Multiple R	0.9962270
R Square	0.9924684
Adjusted R Square	0.9923147
Standard Error	0.0075072
Observations	100

ANOVA					
	df	SS	MS	F	Significance F
Regression	2	0.72781078	0.3639053	6456.9383	9.2773E-105
Residual	98	0.00552316	5.63588E-05		
Total	100	0.73333394			

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%	Lower 95.0%	Upper 95.0%
Intercept	0.4951455	0.00242416	204.25421	1.0693E-130	0.49033484	0.4999561	0.4903348	0.4999561
x	0.0006473	1.06317E-05	60.893056	1.09163E-79	0.00066849	0.0006262	0.0006684	0.0006262
x2	3.5353E-07	9.82698E-09	35.975428	2.81163E-58	3.34029E-07	3.73031E-07	3.34029E-07	3.73031E-07

**AADT = 4,560 vpd**

Regression Statistics	
Multiple R	0.99704152
R Square	0.99409179
Adjusted R Square	0.99397122
Standard Error	0.00860614
Observations	100

ANOVA					
	df	SS	MS	F	Significance F
Regression	2	1.221277904	0.61063895	8244.5532	6.3287E-110
Residual	98	0.007258443	7.40657E-05		
Total	100	1.228536347			

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%	Lower 95.0%	Upper 95.0%
Intercept	0.70741847	0.002779007	254.558033	4.7463E-140	0.70190362	0.7129333	0.70190362	0.7129333
x	0.00070571	1.21879E-05	57.9028938	1.32952E-77	0.00072990	0.0006815	0.00072990	0.0006815
x2	3.21908E-07	1.12654E-08	28.5748524	2.51694E-49	2.99552E-07	3.44264E-07	2.99552E-07	3.44264E-07

### AADT = 6,840 vpd

Regression Statistics	
Multiple R	0.9977669
R Square	0.9955388
Adjusted R Square	0.9954478
Standard Error	0.0071500
Observations	100

ANOVA					
	df	SS	MS	F	Significance F
Regression	2	1.11803675	0.5590183	10934.745	6.6502E-116
Residual	98	0.00501006	5.11231E-05		
Total	100	1.12304682			

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%	Lower 95.0%	Upper 95.0%
Intercept	0.7725106	0.00230881	334.59149	1.1335E-151	0.76792892	0.7770924	0.7679289	0.7770924
x	0.0005784	1.01258E-05	57.129993	4.77903E-77	0.00059858	0.0005583	0.0005985	0.0005583
x2	2.11277E-07	9.3594E-09	22.573786	1.30688E-40	1.92704E-07	2.2985E-07	1.92704E-07	2.2985E-07

### AADT = 9,120 vpd

Regression Statistics	
Multiple R	0.9967397
R Square	0.9934901
Adjusted R Square	0.9933572
Standard Error	0.0073590
Observations	100

ANOVA					
	df	SS	MS	F	Significance F
Regression	2	0.80994679	0.4049733	7478.0358	7.3288E-108
Residual	98	0.00530719	5.4155E-05		
Total	100	0.81525398			

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%	Lower 95.0%	Upper 95.0%
Intercept	0.8192499	0.00237629	344.75936	6.0445E-153	0.81453431	0.8239656	0.8145343	0.8239656
x	0.0004707	1.04218E-05	45.168357	2.05637E-67	0.00049141	0.0004500	0.0004914	0.0004500
x2	1.58447E-07	9.63294E-09	16.448419	6.06051E-30	1.3933E-07	1.77563E-07	1.3933E-07	1.77563E-07

### AADT = 11,400 vpd

Regression Statistics	
Multiple R	0.9964553
R Square	0.9929232
Adjusted R Square	0.9927787
Standard Error	0.0076768
Observations	100

ANOVA					
	df	SS	MS	F	Significance F
Regression	2	0.81035608	0.4051780	6875.0477	4.385E-106
Residual	98	0.00577558	5.89346E-05		
Total	100	0.81613167			

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%	Lower 95.0%	Upper 95.0%
Intercept	0.870133203	0.00247894	351.0102078	1.0404E-153	0.865213827	0.875052578	0.865213827	0.875052578
x	0.00046861	1.08719E-05	43.10277483	1.62479E-65	0.000490185	0.000447035	0.000490185	0.000447035
x2	1.56277E-07	1.0049E-08	15.55145828	3.26952E-28	1.36335E-07	1.76219E-07	1.36335E-07	1.76219E-07

### AADT = 13,680 vpd

Regression Statistics	
Multiple R	0.9949991
R Square	0.9900232
Adjusted R Square	0.9898196
Standard Error	0.0085586
Observations	100

ANOVA					
	df	SS	MS	F	Significance F
Regression	2	0.71235584	0.3561779	4862.4203	8.9219E-99
Residual	98	0.00717861	7.32512E-05		
Total	100	0.71953445			

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%	Lower 95.0%	Upper 95.0%
Intercept	0.892058685	0.002763683	322.7790036	3.8262E-150	0.886574247	0.897543123	0.886574247	0.897543123
x	0.000416187	1.21207E-05	34.33679688	1.94384E-56	0.000392134	0.00044024	0.000392134	0.00044024
x2	1.23755E-07	1.12033E-08	11.04628255	6.59492E-19	1.01522E-07	1.45988E-07	1.01522E-07	1.45988E-07

### AADT = 15,960 vpd

Regression Statistics	
Multiple R	0.9961644
R Square	0.9923435
Adjusted R Square	0.9921873
Standard Error	0.0067152
Observations	100

ANOVA		df	SS	MS	F	Significance F			
Regression	2	0.57277179	0.2863858	6350.8605	2.0761E-104				
Residual	98	0.00441921	4.5094E-05						
Total	100	0.57719101							

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%	Lower 95.0%	Upper 95.0%
Intercept	0.924625409	0.002168405	426.4080491	5.5088E-162	0.920322279	0.928928538	0.920322279	0.928928538
x	0.000373437	9.51001E-06	39.26775858	9.15403E-62	0.000392309	0.000354564	0.000392309	0.000354564
x2	1.11211E-07	8.7902E-09	12.65169953	2.5213E-22	9.37671E-08	1.28655E-07	9.37671E-08	1.28655E-07

### AADT = 18,240 vpd

Regression Statistics	
Multiple R	0.9961626
R Square	0.9923400
Adjusted R Square	0.9921837
Standard Error	0.0061598
Observations	100

ANOVA		df	SS	MS	F	Significance F			
Regression	2	0.48173357	0.2408667	6347.9184	2.1234E-104				
Residual	98	0.00371853	3.79442E-05						
Total	100	0.48545210							

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%	Lower 95.0%	Upper 95.0%
Intercept	0.94672773	0.001989087	475.9610635	1.1593E-166	0.942780495	0.95067505	0.942780495	0.95067505
x	0.000303645	8.72357E-06	34.80745227	5.65864E-57	0.000320957	0.000286333	0.000320957	0.000286333
x2	6.41463E-08	8.06329E-09	7.955351807	3.15863E-12	4.81449E-08	8.01476E-08	4.81449E-08	8.01476E-08



### AADT = 20,520 vpd

Regression Statistics	
Multiple R	0.9964626
R Square	0.9929378
Adjusted R Square	0.9927937
Standard Error	0.0055993
Observations	100

ANOVA					
	df	SS	MS	F	Significance F
Regression	2	0.43200662	0.2160033	6889.3857	3.9623E-106
Residual	98	0.0030726	3.13531E-05		
Total	100	0.43507922			

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%	Lower 95.0%	Upper 95.0%
Intercept	0.9629217	0.00180809	532.56194	1.922E-171	0.95933362	0.9665098	0.9593336	0.9665098
x	0.0003044	7.92978E-06	38.396108	7.23227E-61	0.00032020	0.0002887	0.0003202	0.0002887
x2	7.71941E-08	7.32958E-09	10.531859	8.51131E-18	6.26488E-08	9.17395E-08	6.26488E-08	9.17395E-08

### AADT = 22,800 vpd

Regression Statistics	
Multiple R	0.99681646
R Square	0.99364306
Adjusted R Square	0.99351333
Standard Error	0.00497653
Observations	100

ANOVA					
	df	SS	MS	F	Significance F
Regression	2	0.37937026	0.18968513	7659.1217	2.2863E-108
Residual	98	0.002427059	2.47659E-05		
Total	100	0.381797319			

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%	Lower 95.0%	Upper 95.0%
Intercept	0.97657595	0.001606971	607.712217	4.6484E-177	0.97338697	0.97976493	0.97338697	0.97976493
x	0.00025449	7.04772E-06	36.1105609	1.99742E-58	0.00026848	0.00024051	0.00026848	0.00024051
x2	4.24521E-08	6.51428E-09	6.51676985	3.12037E-09	2.95247E-08	5.53794E-08	2.95247E-08	5.53794E-08

## Appendix E

In this appendix, the code for the sensor array is presented. The code was written and compiled using the open-sourced Arduino IDE (V 1.0.4). The programming syntax is based on C/C++ programming language and is slightly modified to work with the Arduino environment. The code consists of the instructions to communicate with the GPS and ultrasonic sensor to collect data as well as to store the collected data on the flash memory (micro-sd card). The following code was uploaded and stored in the ROM of the Arduino UNO board to run it without needing the persistent connection to a computer.

```
/* Start Code */
#include <SD.h>
#include <SoftwareSerial.h>

// power saving modes

#define LOG_RMC_FIXONLY 0 // set to 1 to only log to SD when GPS has a fix
#define SHOW_SERIAL 1 // 0 if no serial view is required i.e. when biking, when connected to
computer use 1.
#define SENSOR_FILTER 10 // number of readings to average for filtering
#define SENSOR_READINGS 10 // number of sensor readings between two GPS readings

/* EXAMPLE

$PSRF103,<msg>,<mode>,<rate>,<cksumEnable>*CKSUM<CR><LF>

<msg> 00=GGA,01=GLL,02=GSA,03=GSV,04=RMC,05=VTG
<mode> 00=SetRate,01=Query
<rate> Output every <rate>seconds, off=00,max=255
<cksumEnable> 00=disable Checksum,01=Enable checksum for specified message
Note: checksum is required

Example 1: Query the GGA message with checksum enabled
$PSRF103,00,01,00,01*25

Example 2: Enable VTG message for a 1Hz constant output with checksum enabled
$PSRF103,05,00,01,01*20

Example 3: Disable VTG message
$PSRF103,05,00,00,01*21

*/
// Following are the configurations for GPS. DO NOT DELETE.
#define SERIAL_SET "$PSRF100,01,4800,08,01,00*0E\r\n"

#define GGA_ON "$PSRF103,00,00,01,01*25\r\n"// GGA-Global Positioning System Fixed Data,
message 103,00
#define GGA_OFF "$PSRF103,00,00,00,01*24\r\n"

#define GLL_ON "$PSRF103,01,00,01,01*26\r\n"// GLL-Geographic Position-Latitude/Longitude,
message 103,01
```

```

#define GLL_OFF "$PSRF103,01,00,00,01*27\r\n"

#define GSA_ON "$PSRF103,02,00,01,01*27\r\n"// GSA-GNSS DOP and Active Satellites, message
103,02
#define GSA_OFF "$PSRF103,02,00,00,01*26\r\n"

#define GSV_ON "$PSRF103,03,00,01,01*26\r\n"// GSV-GNSS Satellites in View, message 103,03
#define GSV_OFF "$PSRF103,03,00,00,01*27\r\n"

#define RMC_ON "$PSRF103,04,00,01,01*21\r\n"// RMC-Recommended Minimum Specific GNSS
Data, message 103,04
#define RMC_OFF "$PSRF103,04,00,00,01*20\r\n"

#define VTG_ON "$PSRF103,05,00,01,01*20\r\n"// VTG-Course Over Ground and Ground Speed,
message 103,05
#define VTG_OFF "$PSRF103,05,00,00,01*21\r\n"

#define DDM_ON "$PSRF105,01*3E\r\n"// Switch Development Data Messages On/Off, message 105
#define DDM_OFF "$PSRF105,00*3F\r\n"

#define WAAS_ON "$PSRF151,01*3F\r\n"// useful in US, but slower fix
#define WAAS_OFF "$PSRF151,00*3E\r\n"

// Use pins 2 and 3 to talk to the GPS. 2 is the TX pin, 3 is the RX pin
SoftwareSerial gpsSerial = SoftwareSerial(2, 3);
// Set the GPSRATE to the baud rate of the GPS module. Most are 4800
#define GPSRATE 4800

// Set the pins used
#define powerPin 4
#define chipSelect 10

#define BUFFSIZE 90
char buffer[BUFFSIZE];
bool fix = false; // current fix data
bool gotGPRMC; //true if current data is a GPRMC string
uint8_t i;

const int zpin = A2; // z-axis
const int Sonarpin = 9; // Sonar sensor, PW pin
//char stringSensor[20];
File logfile;

void setup() {
  Serial.begin(9600);
  Serial.println("\r\nGPSlogger");
  pinMode(powerPin, OUTPUT);
  digitalWrite(powerPin, LOW);

  // make sure that the default chip select pin is set to
  // output, even if you don't use it:

```

```

pinMode(10, OUTPUT);

// see if the card is present and can be initialized:
if (!SD.begin(chipSelect)) {
  Serial.println("Card init. failed!");
}

strcpy(buffer, "LOG00.TXT");
for (i = 0; i < 100; i++) {
  buffer[3] = '0' + i/10;
  buffer[4] = '0' + i%10;
  // create if does not exist, do not open existing, write, sync after write
  if (!SD.exists(buffer)) {
    break;
  }
}

logfile = SD.open(buffer, FILE_WRITE);
Serial.println(buffer);

// connect to the GPS at the desired rate
gpsSerial.begin(GPSRATE);

gpsSerial.print(SERIAL_SET);
delay(250);

//Write following configurations to GPS module
gpsSerial.print(DDM_OFF);
delay(250);
gpsSerial.print(GGA_OFF);
delay(250);
gpsSerial.print(GLL_OFF);
delay(250);
gpsSerial.print(GSA_OFF);
delay(250);
gpsSerial.print(GSV_OFF);
delay(250);
gpsSerial.print(RMC_ON);
delay(250);
gpsSerial.print(VTG_OFF);
delay(250);
gpsSerial.print(WAAS_OFF);
}

void loop() {
  //Serial.println(Serial.available(), DEC);
  char inBuffer[BUFFSIZE]; // buffer used to read NMEA lines from GPS
  memset(inBuffer, 0, sizeof(inBuffer));
  /* inBuffer = ;
  outBuffer[0] = '\0';*/
  int sizeBuffer = 0;

  // read one 'line'

```

```

while (!gpsSerial.available()){
}

char c = gpsSerial.read();
if (c != '$') {
    return;
}

    sizeBuffer = gpsSerial.readBytesUntil('\n', inBuffer, BUFFSIZE); // read one NMEA line from GPS
until end of line

    // find out if we got a fix
char *p = inBuffer;
p = strchr(p, ',')+1;
p = strchr(p, ',')+1;    // skip to 3rd item

if (p[0] == 'A') {
    fix = true;
} else {
    fix = false;
}

if (LOG_RMC_FIXONLY) {
    if (!fix) {
        return;
    } //if (!fix)
} //if (LOG_RMC_FIXONLY)

if (SHOW_SERIAL) {
    Serial.println(inBuffer);
}

// Lets log it!
logfile.write((uint8_t *) inBuffer, sizeBuffer); //write the string to the SD file
logfile.write('\n');
logfile.flush();

for (uint8_t cnt = 0; cnt < SENSOR_READINGS; cnt++) {
    String stringSensor = "";
    int Zvolts = 0;
    int Sonarmm = analogRead(A0);
    delay(10);
    //int Sonarmm = pulseIn(Sonarpin, HIGH);
    for (uint8_t cntf = 0; cntf < SENSOR_FILTER; cntf++) {
        Zvolts = Zvolts + analogRead(A2);
        delay(5);
    }
    stringSensor += String(Zvolts);
    stringSensor += ",";
    stringSensor += String(Sonarmm);
    logfile.println(stringSensor);
    logfile.flush();

if (SHOW_SERIAL) {
    Serial.println(stringSensor);
}

```

```
    }//if (SHOW_SERIAL)
  }
}

/* End code */
```

## Appendix F

This appendix presents the MATLAB codes to parse the data collected by the sensor array. The codes are written using the MATLAB programming language. Each of the following four codes are specific to one of the four facility types on which the data were collected.

### 1. 2-Lane Road without Bicycle Lane (2LNB)

```
%BEGIN

clear %Clear workspace. Delete all the variables
clc % Clear Command Window.

% Data import and preparation

logfile = fopen('LOG.TXT'); % Open the log file. Name of the file should be changed before each run.
gpsdata = fopen('GPS.csv','w'); % Make new file called GPS.csv to store GPS data.
sensordata = fopen('sensor.dat','w'); % Make new file called sensor.dat to store Sensor data.

tline = fgets(logfile); % Read first line of the logfile and -
lineLength = length (tline); % measure the length of the new line
while ischar(tline) % Check if the line is a character array (i.e. the line is not empty, or any other
array)
    if tline(1) == 'G' % If the fist character is 'G' -
        fprintf(gpsdata,tline); % Print the line in GPS.csv file -
    else % Otherwise -
        fprintf(sensordata,tline); % Print the line in sensor.dat file-
    end
    tline = fgets(logfile); % Read the next line and go back to the begining of this while statement.
end % End the while statement if there is no more line to be read.

fclose(logfile); % Close the logfile
fclose(gpsdata); % Close the gpsdata file
fclose(sensordata); % Close the sensordata file

header = 'Z_axis,usDistance'; % Make the header row for sensor.dat file.
outf3 = fopen('sensortemp.dat','w'); % create a new file called sensortemp.dat which will temporarily
store the data from sensor.dat
fwrite(outf3,header); % Write the prepared header in the sensortemp.dat file
fprintf(outf3,'\n');
fwrite(outf3,file('sensor.dat')); % Write all the data from the sensor.dat file to sensortemp.dat file.
fclose(outf3); % Close sensortemp.dat file
movefile('sensortemp.dat', 'sensor.dat'); % Replace sensor.dat file with sensortemp.dat file. The new file is
named sensor.dat which now has header row as well.
```

```

sensorData=importdata('sensor.dat'); % Store all the info in sensor.dat file to sensorData 2D array.

for i = 1:size(sensorData.colheaders, 2) % Make 1 dimensional vectors for each sensor type out of
sensorData array. Name of the vector is the header above it.
    assignin('base', genvarname(sensorData.colheaders{i}), sensorData.data(:,i));
end

% Sensor data processing

zaxis = Z_axis/10; % Copy value of Z_axis in array zaxis before processing for later use in
classification.
% rowszaxis = size(zaxis,1);
% for i = 1:rowszaxis
%     if zaxis(i) > 590.7 && zaxis(i) < 624.7
%         zaxis(i) = 607.7;
%     end
% end
% plot(zaxis)
Z_axis = (zaxis-507.15)/100.55; % The difference between 1g is 100.55. For Z axis the 0g value is 507.15,
1g is 607.7 and -1g is 406.6

maxDis = 4.0; % Maximum measurement range is 4 m
minDis = 0.3; % Minimum measurement range is 30 cm
usDistance = usDistance / 200; % usDistance * 5 will give measurements in mm and dividing it by
1000 will give results in meters.
usDistance(usDistance(:,1) > maxDis) = 0;
usDistance(usDistance(:,1) < minDis) = 0;
usDistance = maxDis - usDistance;

%GPS data processing

[num txt raw] = xlsread('GPS.csv');

rawGPS = cell2mat(raw(1:end,[4 6 8])); % rawGPS contains raw Latitude, Longitude and Speed data of
NMEA format
NLL=rawGPS(~any(isnan(rawGPS),2),:); % NLL (NMEA Latitude Longitude) contains coordinates in
NMEA format. They will be converted to Google Earth format.
rowsNLL = size(NLL,1); % Find number of rows in NLL array

Coord = zeros(rowsNLL,3);
Coord(:,3) = NLL(:,3)*0.5144444; % Convert speed from knots to m/s
for j=1:rowsNLL % Convert NMEA Latitude Longitude values to google earth supported
format
    numberx=NLL(j,1)/100;

```



```

integx=floor(numberx);
fractx=(numberx-integx)*1.66667;
Coord(j,1) = integx+fractx;

numbery=NLL(j,2)/100;
integy=floor(numbery);
fracty=(numbery-integy)*1.66667;
Coord(j,2) = -1*(integy+fracty);
end

iCoord = zeros((rowsNLL-1)*10,4);           % iCoord array contains interpolated coordinates,
acceleration and speed
iCoord(:,4) = zaxis;                       % Copy Z axis values to 4th column of iCoord
iCoord(:,5) = abs(iCoord(:,4) - 607.7);
slope = cumsum(iCoord(:,5));

p=0;                                       % Interpolation of coordinates and speed
for n = 1:rowsNLL-1
    x1 = Coord(n,1);
    x2 = Coord(n+1,1);
    y1 = Coord(n,2);
    y2 = Coord(n+1,2);
    s1 = Coord(n,3);
    s2 = Coord(n+1,3);
    dx = x2-x1;
    if dx==0
        dx=0.000001;
    end
    ds = s2-s1;

    m = (y2-y1)/dx;
    b = y1-m*x1;
    for i=(p+1):(p+10)
        iCoord(i,1) = x1+(dx/10)*(i-p);
        iCoord(i,2) = y1+m*(iCoord(i,1)-x1);
        iCoord(i,3) = s1+(ds/10)*(i-p);
    end

    p=p+10;
end

rowsiCoord = size(iCoord,1);
classSeg = 2;                             % This is the specified segment length in meters by which the classification will be
made for the entire route

```

```

length = 0;          % This is the calculated distance between two points. It will be compared with
classSeg
o = 1;              % Counter register for classMatrix array
m = 1;
length1=0;

% classMatrix is an array that stores values for classifications based on
% accelerometer data.
% 1st column >> Latitude
% 2nd column >> Longitude
% 3rd column >> Class Number (Positive integers only)
% 4th column >> Mean speed
% 5th column >> Maximum acceleration (Z axis)
% 6th column >> Minimum acceleration (Z axis)
% 7th column >> Mean acceleration (Z axis)
% 8th column >> Variance in acceleration (Z axis)
while m < rowsiCoord-1
    n = m;
    while length < classSeg
        if n < rowsiCoord-1
            n = n+1;
            dx = (iCoord(n,1)-iCoord(m,1)) * 111106;          % 111 km between two consecutive
latitude (always a constant)
            dy = (iCoord(n,2)-iCoord(m,2)) * (40075900/360) * cosd(iCoord(n,1)); % Distance between two
consecutive longitude changes according to the latitude
            length = sqrt((dx^2)+(dy^2));
        else
            break;
        end
    end
    classMatrix(o,1) = iCoord(m,1);
    classMatrix(o,2) = iCoord(m,2);
    classMatrix(o,4) = mean(iCoord(m:n,3));
    classMatrix(o,7) = mean(iCoord(m:n,4));
    sqdiff = 0;          % Squared difference of segment mean and current value to calculate
variance over segment length
    absdiff = 0;
    for p = m:n
        sqdiff = sqdiff + (iCoord(p,4) - classMatrix(o,7))^2;
        absdiff = absdiff + abs(iCoord(p,4) - 607.7);
    end
    classMatrix(o,8) = sqdiff/(n-m);
    classMatrix(o,9) = absdiff;
    m = n;
    o = o + 1;
end

```

```

    length = 0;
end
classSlope = cumsum(classMatrix(:,9));

% length1
% rowsclassMatrix = size(classMatrix,1);
% for i = 1:rowsclassMatrix
%   if classMatrix(i,4) < 2.78           % If speed is less than 10 km/h (2.78 m/s)
%     if classMatrix(i,8) < 50           % Smooth-slow
%       classMatrix(i,3) = 5;
%     elseif classMatrix(i,8) > 200      % Sidewalk-slow
%       classMatrix(i,3) = 20;
%     else                                % Uneven-slow
%       classMatrix(i,3) = 35;
%     end
%   elseif classMatrix(i,4) > 5.56      % If speed is greater than or equal to 20 km/h (5.56 m/s)
%     if classMatrix(i,8) < 100         % Smooth-medium
%       classMatrix(i,3) = 10;
%     elseif classMatrix(i,8) > 525     % Uneven-medium
%       classMatrix(i,3) = 40;
%     else                                % Sidewalk-medium
%       classMatrix(i,3) = 25;
%     end
%   else
%     classMatrix(i,3) = 6;
%   else
%     classMatrix(i,3) = 11;
%   end
% end

% Generate KML files for Google Earth
% KML commands accept Longitude first and Latitude is followed..
% Z_axis = Z_axis + 5;           % Here 5 is added to all values but it is not necessary. This is just for
% better visibility in Google Earth.

myRoute = kml('Route');
myRoute.plot(iCoord(:,2),iCoord(:,1),'lineColor','ff1400ff','lineWidth',2);
%
% k2 = kml('Z Axis');
%
k2.plot3(iCoord(:,2),iCoord(:,1),Z_axis,'lineColor','ff1400ff','lineWidth',5,'polyColor','ff660033','altitudeM
ode','relativeToGround');
%
distance = kml('Ultrasonic Distance');
```

```

distance.plot3(iCoord(:,2),iCoord(:,1),usDistance,'lineColor','ff33ff99','lineWidth',5,'polyColor','5833ff99','
altitudeMode','relativeToGround');
%
% k4 = kml('Velocity');
%
k4.plot3(Coord(:,2),Coord(:,1),Coord(:,3),'lineColor','ffff0000','lineWidth',5,'polyColor','ff660033','altitude
Mode','relativeToGround');

% k5 = kml('Surface');
%
k5.plot3(classMatrix(:,2),classMatrix(:,1),classMatrix(:,3),'lineColor','ffff0000','lineWidth',5,'polyColor','ff6
60033','altitudeMode','relativeToGround');

myRoute.run;
% k2.run;
distance.run;
% k4.run;
% k5.run;

%END

```

## **2. 2-Lane Road with Bicycle Lane (2LWB)**

```

%BEGIN

clear %Clear workspace. Delete all the variables
clc % Clear Command Window.

% Data import and preparation

logfile = fopen('LOG.TXT'); % Open the log file. Name of the file should be changed before each run.
gpsdata = fopen('GPS.csv','w'); % Make new file called GPS.csv to store GPS data.
sensordata = fopen('sensor.dat','w'); % Make new file called sensor.dat to store Sensor data.

tline = fgets(logfile); % Read first line of the logfile and -
lineLength = length (tline); % measure the length of the new line
while ischar(tline) % Check if the line is a character array (i.e. the line is not empty, or any other
array)
    if tline(1) == 'G' % If the fist character is 'G' -
        fprintf(gpsdata,tline); % Print the line in GPS.csv file -
    else % Otherwise -
        fprintf(sensordata,tline); % Print the line in sensor.dat file-
    end
    tline = fgets(logfile); % Read the next line and go back to the begining of this while statement.
end % End the while statement if there is no more line to be read.

```

```

fclose(logfile); % Close the logfile
fclose(gpsdata); % Close the gpsdata file
fclose(sensordata); % Close the sensordata file

header = 'Z_axis,usDistance'; % Make the header row for sensor.dat file.
outf3 = fopen('sensortemp.dat','w'); % create a new file called sensortemp.dat which will temporarily
store the data from sensor.dat
fwrite(outf3,header); % Write the prepared header in the sensortemp.dat file
fprintf(outf3,'\n');
fwrite(outf3,fileread('sensor.dat')); % Write all the data from the sensor.dat file to sensortemp.dat file.
fclose(outf3); % Close sensortemp.dat file
movefile('sensortemp.dat', 'sensor.dat'); % Replace sensor.dat file with sensortemp.dat file. The new file is
named sensor.dat which now has header row as well.

sensorData=importdata('sensor.dat'); % Store all the info in sensor.dat file to sensorData 2D array.

for i = 1:size(sensorData.colheaders, 2) % Make 1 dimensional vectors for each sensor type out of
sensorData array. Name of the vector is the header above it.
    assignin('base', genvarname(sensorData.colheaders{i}), sensorData.data(:,i));
end

% Sensor data processing

zaxis = Z_axis/10; % Copy value of Z_axis in array zaxis before processing for later use in
classification.
% rowszaxis = size(zaxis,1);
% for i = 1:rowszaxis
%     if zaxis(i) > 590.7 && zaxis(i) < 624.7
%         zaxis(i) = 607.7;
%     end
% end
% plot(zaxis)
Z_axis = (zaxis-507.15)/100.55; % The difference between 1g is 100.55. For Z axis the 0g value is 507.15,
1g is 607.7 and -1g is 406.6

maxDis = 4.0; % Maximum measurement range is 4 m
minDis = 0.3; % Minimum measurement range is 30 cm
usDistance = usDistance / 200; % usDistance * 5 will give measurements in mm and dividing it by
1000 will give results in meters.
usDistance(usDistance(:,1) > maxDis) = 0;
usDistance(usDistance(:,1) < minDis) = 0;
usDistance = maxDis - usDistance;

%GPS data processing

```

```

[num txt raw] = xlsread('GPS.csv');

rawGPS = cell2mat(raw(1:end,[4 6 8])); % rawGPS contains raw Latitude, Longitude and Speed data of
NMEA format
NLL=rawGPS(~any(isnan(rawGPS),2),:); % NLL (NMEA Latitude Longitude) contains coordinates in
NMEA format. They will be converted to Google Earth format.
rowsNLL = size(NLL,1); % Find number of rows in NLL array

Coord = zeros(rowsNLL,3);
Coord(:,3) = NLL(:,3)*0.5144444; % Convert speed from knots to m/s
for j=1:rowsNLL % Convert NMEA Latitude Longitude values to google earth supported
format
    numberx=NLL(j,1)/100;
    integx=floor(numberx);
    fractx=(numberx-integx)*1.66667;
    Coord(j,1) = integx+fractx;

    numbery=NLL(j,2)/100;
    integy=floor(numbery);
    fracty=(numbery-integy)*1.66667;
    Coord(j,2) = -1*(integy+fracty);
end

iCoord = zeros((rowsNLL-1)*10,4); % iCoord array contains interpolated coordinates,
acceleration and speed
iCoord(:,4) = zaxis; % Copy Z axis values to 4th column of iCoord
iCoord(:,5) = abs(iCoord(:,4) - 607.7);
slope = cumsum(iCoord(:,5));

p=0; % Interpolation of coordinates and speed
for n = 1:rowsNLL-1
    x1 = Coord(n,1);
    x2 = Coord(n+1,1);
    y1 = Coord(n,2);
    y2 = Coord(n+1,2);
    s1 = Coord(n,3);
    s2 = Coord(n+1,3);
    dx = x2-x1;
    if dx==0
        dx=0.000001;
    end
    ds = s2-s1;

    m = (y2-y1)/dx;

```

```

b = y1-m*x1;
for i=(p+1):(p+10)
    iCoord(i,1) = x1+(dx/10)*(i-p);
    iCoord(i,2) = y1+m*(iCoord(i,1)-x1);
    iCoord(i,3) = s1+(ds/10)*(i-p);
end

p=p+10;
end

rowsiCoord = size(iCoord,1);
classSeg = 2;          % This is the specified segment length in meters by which the classification will be
                        % made for the entire route
length = 0;           % This is the calculated distance between two points. It will be compared with
classSeg
o = 1;                % Counter register for classMatrix array
m = 1;
length1=0;

% classMatrix is an array that stores values for classifications based on
% acclerometer data.
% 1st column >> Latitude
% 2nd column >> Longitude
% 3rd column >> Class Number (Positive integers only)
% 4th column >> Mean speed
% 5th column >> Maximum acceleration (Z axis)
% 6th column >> Minimum acceleration (Z axis)
% 7th column >> Mean acceleration (Z axis)
% 8th column >> Variance in acceleration (Z axis)
while m < rowsiCoord-1
    n = m;
    while length < classSeg
        if n < rowsiCoord-1
            n = n+1;
            dx = (iCoord(n,1)-iCoord(m,1)) * 111106;          % 111 km between two consecutive
            latitude (always a constant)
            dy = (iCoord(n,2)-iCoord(m,2)) * (40075900/360) * cosd(iCoord(n,1)); % Distance between two
            consecutive longitude changes according to the latitude
            length = sqrt((dx^2)+(dy^2));
        else
            break;
        end
    end
    classMatrix(o,1) = iCoord(m,1);
    classMatrix(o,2) = iCoord(m,2);

```

```

classMatrix(o,4) = mean(iCoord(m:n,3));
classMatrix(o,7) = mean(iCoord(m:n,4));
sqdiff = 0; % Squared difference of segment mean and current value to calculate
variance over segment length
absdiff = 0;
for p = m:n
    sqdiff = sqdiff + (iCoord(p,4) - classMatrix(o,7))^2;
    absdiff = absdiff + abs(iCoord(p,4) - 607.7);
end
classMatrix(o,8) = sqdiff/(n-m);
classMatrix(o,9) = absdiff;
m = n;
o = o + 1;
length = 0;
end
classSlope = cumsum(classMatrix(:,9));

% length1
% rowclassMatrix = size(classMatrix,1);
% for i =1:rowclassMatrix
%     if classMatrix(i,4) < 2.78 % If speed is less than 10 km/h (2.78 m/s)
%         if classMatrix(i,8) < 50 % Smooth-slow
%             classMatrix(i,3) = 5;
%         elseif classMatrix(i,8) > 200 % Sidewalk-slow
%             classMatrix(i,3) = 20;
%         else % Uneven-slow
%             classMatrix(i,3) = 35;
%         end
%     elseif classMatrix(i,4) > 5.56 % If speed is greater than or equal to 20 km/h (5.56 m/s)
%         if classMatrix(i,8) < 100 % Smooth-medium
%             classMatrix(i,3) = 10;
%         elseif classMatrix(i,8) > 525 % Uneven-medium
%             classMatrix(i,3) = 40;
%         else % Sidewalk-medium
%             classMatrix(i,3) = 25;
%         end
%     classMatrix(i,3) = 6;
%     else
%         classMatrix(i,3) = 11;
%     end
% end

% Generate KML files for Google Earth
% KML commands accept Longitude first and Latitude is followed..

```



```
% Z_axis = Z_axis + 5;          % Here 5 is added to all values but it is not necessary. This is just for
better visibility in Google Earth.
```

```
myRoute = kml('Route');
myRoute.plot(iCoord(:,2),iCoord(:,1),'lineColor','ff1400ff','lineWidth',2);
%
% k2 = kml('Z Axis');
%
k2.plot3(iCoord(:,2),iCoord(:,1),Z_axis,'lineColor','ff1400ff','lineWidth',5,'polyColor','ff660033','altitudeM
ode','relativeToGround');
%
distance = kml('Ultrasonic Distance');
distance.plot3(iCoord(:,2),iCoord(:,1),usDistance,'lineColor','ff33ff99','lineWidth',5,'polyColor','5833ff99','
altitudeMode','relativeToGround');
%
% k4 = kml('Velocity');
%
k4.plot3(Coord(:,2),Coord(:,1),Coord(:,3),'lineColor','ffff0000','lineWidth',5,'polyColor','ff660033','altitude
Mode','relativeToGround');

% k5 = kml('Surface');
%
k5.plot3(classMatrix(:,2),classMatrix(:,1),classMatrix(:,3),'lineColor','ffff0000','lineWidth',5,'polyColor','ff6
60033','altitudeMode','relativeToGround');

myRoute.run;
% k2.run;
distance.run;
% k4.run;
% k5.run;

%END
```

### **3. 4-Lane Road without Bicycle Lane (4LNB)**

```
%BEGIN
```

```
clear %Clear workspace. Delete all the variables
```

```
clc % Clear Command Window.
```

```
% Data import and preparation
```

```
logfile = fopen('LOG.TXT'); % Open the log file. Name of the file should be changed before each run.
```

```
gpsdata = fopen('GPS.csv','w'); % Make new file called GPS.csv to store GPS data.
```

```
sensordata = fopen('sensor.dat','w'); % Make new file called sensor.dat to store Sensor data.
```

```

tline = fgets(logfile); % Read first line of the logfile and -
lineLength = length (tline); % measure the length of the new line
while ischar(tline) % Check if the line is a character array (i.e. the line is not empty, or any other
array)
    if tline(1) == 'G' % If the fist character is 'G' -
        fprintf(gpsdata,tline); % Print the line in GPS.csv file -
    else % Otherwise -
        fprintf(sensordata,tline); % Print the line in sensor.dat file-
    end
    tline = fgets(logfile); % Read the next line and go back to the begining of this while statement.
end % End the while statement if there is no more line to be read.

fclose(logfile); % Close the logfile
fclose(gpsdata); % Close the gpsdata file
fclose(sensordata); % Close the sensordata file

header = 'Z_axis,usDistance'; % Make the header row for sensor.dat file.
outf3 = fopen('sensortemp.dat','w'); % create a new file called sensortemp.dat which will temporarily
store the data from sensor.dat
fwrite(outf3,header); % Write the prepared header in the sensortemp.dat file
fprintf(outf3,'\n');
fwrite(outf3,fileread('sensor.dat')); % Write all the data from the sensor.dat file to sensortemp.dat file.
fclose(outf3); % Close sensortemp.dat file
movefile('sensortemp.dat', 'sensor.dat'); % Replace sensor.dat file with sensortemp.dat file. The new file is
named sensor.dat which now has header row as well.

sensorData=importdata('sensor.dat'); % Store all the info in sensor.dat file to sensorData 2D array.

for i = 1:size(sensorData.colheaders, 2) % Make 1 dimensional vectors for each sensor type out of
sensorData array. Name of the vector is the header above it.
    assignin('base', genvarname(sensorData.colheaders{i}), sensorData.data(:,i));
end

% Sensor data processing

zaxis = Z_axis/10; % Copy value of Z_axis in array zaxis before processing for later use in
classification.
% rowszaxis = size(zaxis,1);
% for i = 1:rowszaxis
%     if zaxis(i) > 590.7 && zaxis(i) < 624.7
%         zaxis(i) = 607.7;
%     end
% end
% plot(zaxis)

```

```
Z_axis = (zaxis-507.15)/100.55; % The difference between 1g is 100.55. For Z axis the 0g value is 507.15,
1g is 607.7 and -1g is 406.6
```

```
maxDis = 4.0; % Maximum measurement range is 4 m
minDis = 0.3; % Minimum measurement range is 30 cm
usDistance = usDistance / 200; % usDistance * 5 will give measurements in mm and dividing it by
1000 will give results in meters.
usDistance(usDistance(:,1) > maxDis) = 0;
usDistance(usDistance(:,1) < minDis) = 0;
usDistance = maxDis - usDistance;
```

```
%GPS data processing
```

```
[num txt raw] = xlsread('GPS.csv');
```

```
rawGPS = cell2mat(raw(1:end,[4 6 8])); % rawGPS contains raw Latitude, Longitude and Speed data of
NMEA format
```

```
NLL=rawGPS(~any(isnan(rawGPS),2),:); % NLL (NMEA Latitude Longitude) contains coordinates in
NMEA format. They will be converted to Google Earth format.
```

```
rowsNLL = size(NLL,1); % Find number of rows in NLL array
```

```
Coord = zeros(rowsNLL,3);
```

```
Coord(:,3) = NLL(:,3)*0.5144444; % Convert speed from knots to m/s
```

```
for j=1:rowsNLL % Convert NMEA Latitude Longitude values to google earth suppoertd
format
```

```
numberx=NLL(j,1)/100;
```

```
integx=floor(numberx);
```

```
fractx=(numberx-integx)*1.66667;
```

```
Coord(j,1) = integx+fractx;
```

```
numbery=NLL(j,2)/100;
```

```
integy=floor(numbery);
```

```
fracty=(numbery-integy)*1.66667;
```

```
Coord(j,2) = -1*(integy+fracty);
```

```
end
```

```
iCoord = zeros((rowsNLL-1)*10,4); % iCoord array contains interpolated coordinates,
acceleration and speed
```

```
iCoord(:,4) = zaxis; % Copy Z axis values to 4th column of iCoord
```

```
iCoord(:,5) = abs(iCoord(:,4) - 607.7);
```

```
slope = cumsum(iCoord(:,5));
```

```
p=0; % Interpolation of coordinates and speed
```

```
for n = 1:rowsNLL-1
```

```
 x1 = Coord(n,1);
```

```

x2 = Coord(n+1,1);
y1 = Coord(n,2);
y2 = Coord(n+1,2);
s1 = Coord(n,3);
s2 = Coord(n+1,3);
dx = x2-x1;
if dx==0
    dx=0.000001;
end
ds = s2-s1;

m = (y2-y1)/dx;
b = y1-m*x1;
for i=(p+1):(p+10)
    iCoord(i,1) = x1+(dx/10)*(i-p);
    iCoord(i,2) = y1+m*(iCoord(i,1)-x1);
    iCoord(i,3) = s1+(ds/10)*(i-p);
end

p=p+10;
end

rowsiCoord = size(iCoord,1);
classSeg = 2;          % This is the specified segment length in meters by which the classification will be
                        % made for the entire route
length = 0;           % This is the calculated distance between two points. It will be compared with
classSeg
o = 1;                % Counter register for classMatrix array
m = 1;
length1=0;

% classMatrix is an array that stores values for classifications based on
% acclerometer data.
% 1st column >> Latitude
% 2nd column >> Longitude
% 3rd column >> Class Number (Positive integers only)
% 4th column >> Mean speed
% 5th column >> Maximum acceleration (Z axis)
% 6th column >> Minimum acceleration (Z axis)
% 7th column >> Mean acceleration (Z axis)
% 8th column >> Variance in acceleration (Z axis)
while m < rowsiCoord-1
    n = m;
    while length < classSeg
        if n < rowsiCoord-1

```

```

        n = n+1;
        dx = (iCoord(n,1)-iCoord(m,1)) * 111106;           % 111 km between two consecutive
latitude (always a constant)
        dy = (iCoord(n,2)-iCoord(m,2)) * (40075900/360) * cosd(iCoord(n,1)); % Distance between two
consecutive longitude changes according to the latitude
        length = sqrt((dx^2)+(dy^2));
    else
        break;
    end
end
classMatrix(o,1) = iCoord(m,1);
classMatrix(o,2) = iCoord(m,2);
classMatrix(o,4) = mean(iCoord(m:n,3));
classMatrix(o,7) = mean(iCoord(m:n,4));
sqdiff = 0;           % Squared difference of segment mean and current value to calculate
variance over segment length
absdiff = 0;
for p = m:n
    sqdiff = sqdiff + (iCoord(p,4) - classMatrix(o,7))^2;
    absdiff = absdiff + abs(iCoord(p,4) - 607.7);
end
classMatrix(o,8) = sqdiff/(n-m);
classMatrix(o,9) = absdiff;
m = n;
o = o + 1;
length = 0;
end
classSlope = cumsum(classMatrix(:,9));

% length1
% rowclassMatrix = size(classMatrix,1);
% for i = 1:rowclassMatrix
%     if classMatrix(i,4) < 2.78           % If speed is less than 10 km/h (2.78 m/s)
%         if classMatrix(i,8) < 50       % Smooth-slow
%             classMatrix(i,3) = 5;
%         elseif classMatrix(i,8) > 200   % Sidewalk-slow
%             classMatrix(i,3) = 20;
%         else                             % Uneven-slow
%             classMatrix(i,3) = 35;
%         end
%     elseif classMatrix(i,4) > 5.56     % If speed is greater than or equal to 20 km/h (5.56 m/s)
%         if classMatrix(i,8) < 100     % Smooth-medium
%             classMatrix(i,3) = 10;
%         elseif classMatrix(i,8) > 525  % Uneven-medium
%             classMatrix(i,3) = 40;

```

```

%     else                                % Sidewalk-medium
%         classMatrix(i,3) = 25;
%     end
%     classMatrix(i,3) = 6;
%     else
%         classMatrix(i,3) = 11;
%     end
% end

% Generate KML files for Google Earth
% KML commands accept Longitude first and Latitude is followed..
% Z_axis = Z_axis + 5;                    % Here 5 is added to all values but it is not necessary. This is just for
better visibility in Google Earth.

myRoute = kml('Route');
myRoute.plot(iCoord(:,2),iCoord(:,1),'lineColor','ff1400ff','lineWidth',2);
%
% k2 = kml('Z Axis');
%
k2.plot3(iCoord(:,2),iCoord(:,1),Z_axis,'lineColor','ff1400ff','lineWidth',5,'polyColor','ff660033','altitudeM
ode','relativeToGround');
%
distance = kml('Ultrasonic Distance');
distance.plot3(iCoord(:,2),iCoord(:,1),usDistance,'lineColor','ff33ff99','lineWidth',5,'polyColor','5833ff99','
altitudeMode','relativeToGround');
%
% k4 = kml('Velocity');
%
k4.plot3(Coord(:,2),Coord(:,1),Coord(:,3),'lineColor','ffff0000','lineWidth',5,'polyColor','ff660033','altitude
Mode','relativeToGround');

% k5 = kml('Surface');
%
k5.plot3(classMatrix(:,2),classMatrix(:,1),classMatrix(:,3),'lineColor','ffff0000','lineWidth',5,'polyColor','ff6
60033','altitudeMode','relativeToGround');

myRoute.run;
% k2.run;
distance.run;
% k4.run;
% k5.run;

%END

```

#### **4. 4-Lane Road with Bicycle Lane (4LWB)**

```
%BEGIN

clear %Clear workspace. Delete all the variables
clc % Clear Command Window.

% Data import and preparation

logfile = fopen('LOG.TXT'); % Open the log file. Name of the file should be changed before each run.
gpsdata = fopen('GPS.csv','w'); % Make new file called GPS.csv to store GPS data.
sensordata = fopen('sensor.dat','w'); % Make new file called sensor.dat to store Sensor data.

tline = fgets(logfile); % Read first line of the logfile and -
lineLength = length (tline); % measure the length of the new line
while ischar(tline) % Check if the line is a character array (i.e. the line is not empty, or any other
array)
    if tline(1) == 'G' % If the fist character is 'G' -
        fprintf(gpsdata,tline); % Print the line in GPS.csv file -
    else % Otherwise -
        fprintf(sensordata,tline); % Print the line in sensor.dat file-
    end
    tline = fgets(logfile); % Read the next line and go back to the begining of this while statement.
end % End the while statement if there is no more line to be read.

fclose(logfile); % Close the logfile
fclose(gpsdata); % Close the gpsdata file
fclose(sensordata); % Close the sensordata file

header = 'Z_axis,usDistance'; % Make the header row for sensor.dat file.
outf3 = fopen('sensortemp.dat','w'); % create a new file called sensortemp.dat which will temporarily
store the data from sensor.dat
fwrite(outf3,header); % Write the prepared header in the sensortemp.dat file
fprintf(outf3,'\n');
fwrite(outf3,file_read('sensor.dat')); % Write all the data from the sensor.dat file to sensortemp.dat file.
fclose(outf3); % Close sensortemp.dat file
movefile('sensortemp.dat', 'sensor.dat'); % Replace sensor.dat file with sensortemp.dat file. The new file is
named sensor.dat which now has header row as well.

sensorData=importdata('sensor.dat'); % Store all the info in sensor.dat file to sensorData 2D array.

for i = 1:size(sensorData.colheaders, 2) % Make 1 dimensional vectors for each sensor type out of
sensorData array. Name of the vector is the header above it.
    assignin('base', genvarname(sensorData.colheaders{i}), sensorData.data(:,i));
end
```

```

% Sensor data processing

zaxis = Z_axis/10;          % Copy value of Z_axis in array zaxis before processing for later use in
classification.
% rowszaxis = size(zaxis,1);
% for i = i:rowszaxis
%   if zaxis(i) > 590.7 && zaxis(i) < 624.7
%     zaxis(i) = 607.7;
%   end
% end
% plot(zaxis)
Z_axis = (zaxis-507.15)/100.55; % The difference between 1g is 100.55. For Z axis the 0g value is 507.15,
1g is 607.7 and -1g is 406.6

maxDis = 4.0;              % Maximum measurement range is 4 m
minDis = 0.3;              % Minimum measurement range is 30 cm
usDistance = usDistance / 200; % usDistance * 5 will give measurements in mm and dividing it by
1000 will give results in meters.
usDistance(usDistance(:,1) > maxDis) = 0;
usDistance(usDistance(:,1) < minDis) = 0;
usDistance = maxDis - usDistance;

%GPS data processing

[num txt raw] = xlsread('GPS.csv');

rawGPS = cell2mat(raw(1:end,[4 6 8])); % rawGPS contains raw Latitude, Longitude and Speed data of
NMEA format
NLL=rawGPS(~any(isnan(rawGPS),2),:); % NLL (NMEA Latitude Longitude) contains coordinates in
NMEA format. They will be converted to Google Earth format.
rowsNLL = size(NLL,1);      % Find number of rows in NLL array

Coord = zeros(rowsNLL,3);
Coord(:,3) = NLL(:,3)*0.5144444; % Convert speed from knots to m/s
for j=1:rowsNLL             % Convert NMEA Latitude Longitude values to google earth supported
format
    numberx=NLL(j,1)/100;
    integx=floor(numberx);
    fractx=(numberx-integx)*1.66667;
    Coord(j,1) = integx+fractx;

    numbery=NLL(j,2)/100;
    integy=floor(numbery);
    fracty=(numbery-integy)*1.66667;
    Coord(j,2) = -1*(integy+fracty);

```



```

end

iCoord = zeros((rowsNLL-1)*10,4);           % iCoord array contains interpolated coordinates,
acceleration and speed
iCoord(:,4) = zaxis;                       % Copy Z axis values to 4th column of iCoord
iCoord(:,5) = abs(iCoord(:,4) - 607.7);
slope = cumsum(iCoord(:,5));

p=0;                                       % Interpolation of coordinates and speed
for n = 1:rowsNLL-1
    x1 = Coord(n,1);
    x2 = Coord(n+1,1);
    y1 = Coord(n,2);
    y2 = Coord(n+1,2);
    s1 = Coord(n,3);
    s2 = Coord(n+1,3);
    dx = x2-x1;
    if dx==0
        dx=0.000001;
    end
    ds = s2-s1;

    m = (y2-y1)/dx;
    b = y1-m*x1;
    for i=(p+1):(p+10)
        iCoord(i,1) = x1+(dx/10)*(i-p);
        iCoord(i,2) = y1+m*(iCoord(i,1)-x1);
        iCoord(i,3) = s1+(ds/10)*(i-p);
    end

    p=p+10;
end

rowsiCoord = size(iCoord,1);
classSeg = 2;                             % This is the specified segment length in meters by which the classification will be
made for the entire route
length = 0;                               % This is the calculated distance between two points. It will be compared with
classSeg
o = 1;                                     % Counter register for classMatrix array
m = 1;
length1=0;

% classMatrix is an array that stores values for classifications based on
% accelerometer data.
% 1st column >> Latitude

```

```

% 2nd column >> Longitude
% 3rd column >> Class Number (Positive integers only)
% 4th column >> Mean speed
% 5th column >> Maximum acceleration (Z axis)
% 6th column >> Minimum acceleration (Z axis)
% 7th column >> Mean acceleration (Z axis)
% 8th column >> Variance in acceleration (Z axis)
while m < rowsiCoord-1
    n = m;
    while length < classSeg
        if n < rowsiCoord-1
            n = n+1;
            dx = (iCoord(n,1)-iCoord(m,1)) * 111106; % 111 km between two consecutive
latitude (always a constant)
            dy = (iCoord(n,2)-iCoord(m,2)) * (40075900/360) * cosd(iCoord(n,1)); % Distance between two
consecutive longitude changes according to the latitude
            length = sqrt((dx^2)+(dy^2));
        else
            break;
        end
    end
    classMatrix(o,1) = iCoord(m,1);
    classMatrix(o,2) = iCoord(m,2);
    classMatrix(o,4) = mean(iCoord(m:n,3));
    classMatrix(o,7) = mean(iCoord(m:n,4));
    sqdiff = 0; % Squared difference of segment mean and current value to calculate
variance over segment length
    absdiff = 0;
    for p = m:n
        sqdiff = sqdiff + (iCoord(p,4) - classMatrix(o,7))^2;
        absdiff = absdiff + abs(iCoord(p,4) - 607.7);
    end
    classMatrix(o,8) = sqdiff/(n-m);
    classMatrix(o,9) = absdiff;
    m = n;
    o = o + 1;
    length = 0;
end
classSlope = cumsum(classMatrix(:,9));

% length1
% rowsclassMatrix = size(classMatrix,1);
% for i = 1:rowsclassMatrix
%     if classMatrix(i,4) < 2.78 % If speed is less than 10 km/h (2.78 m/s)
%         if classMatrix(i,8) < 50 % Smooth-slow

```

```

%     classMatrix(i,3) = 5;
%     elseif classMatrix(i,8) > 200      % Sidewalk-slow
%         classMatrix(i,3) = 20;
%     else                                % Uneven-slow
%         classMatrix(i,3) = 35;
%     end
%     elseif classMatrix(i,4) > 5.56      % If speed is greater than or equal to 20 km/h (5.56 m/s)
%         if classMatrix(i,8) < 100      % Smooth-medium
%             classMatrix(i,3) = 10;
%         elseif classMatrix(i,8) > 525   % Uneven-medium
%             classMatrix(i,3) = 40;
%         else                            % Sidewalk-medium
%             classMatrix(i,3) = 25;
%         end
%     classMatrix(i,3) = 6;
%     else
%         classMatrix(i,3) = 11;
%     end
% end

% Generate KML files for Google Earth
% KML commands accept Longitude first and Latitude is followed..
% Z_axis = Z_axis + 5;          % Here 5 is added to all values but it is not necessary. This is just for
% better visibility in Google Earth.

myRoute = kml('Route');
myRoute.plot3(iCoord(:,2),iCoord(:,1),'lineColor','ff1400ff','lineWidth',2);
%
% k2 = kml('Z Axis');
%
k2.plot3(iCoord(:,2),iCoord(:,1),Z_axis,'lineColor','ff1400ff','lineWidth',5,'polyColor','ff660033','altitudeM
ode','relativeToGround');
%
distance = kml('Ultrasonic Distance');
distance.plot3(iCoord(:,2),iCoord(:,1),usDistance,'lineColor','ff33ff99','lineWidth',5,'polyColor','5833ff99','
altitudeMode','relativeToGround');
%
% k4 = kml('Velocity');
%
k4.plot3(Coord(:,2),Coord(:,1),Coord(:,3),'lineColor','ffff0000','lineWidth',5,'polyColor','ff660033','altitude
Mode','relativeToGround');

% k5 = kml('Surface');
```

```
%  
k5.plot3(classMatrix(:,2),classMatrix(:,1),classMatrix(:,3),'lineColor','ffff0000','lineWidth',5,'polyColor','ff6  
60033','altitudeMode','relativeToGround');  
  
myRoute.run;  
% k2.run;  
distance.run;  
% k4.run;  
% k5.run;  
  
%END
```

## Appendix G

This appendix presents the MATLAB codes for parsing the data obtained from the VISSIM models (section 6.1). These codes are developed using the MATLAB programming language. These codes estimate the probability of unsafe passings on 4-lane roads without bicycle lanes and estimate the number of unsafe passings per bike trip. Each of the following three codes is specific to one of three test cases (Case 1, Case 2 and Case 3) as explained in section 6.1.

### Case 1

```
% Case 1
% Uses the v/c vs. section length curves as input.

clear;
clc;
format compact;

%% CONSTANTS

% saturation = 1900; % Saturation flow rate in vh/hr/ln
% nlanes = 2; % Number of lanes
% gC = 0.5; % g/C ratio
% capacity = saturation * nlanes * gC; % Intersection capacity (vph)
critpd = 1000; % critical passing distance (mm). It should be in increments of 50 mm from 600 to 3150.

%% ESTIMATION
prctCritPassTable = [];
for rownum = 1:10 % row also correspond to the v/c ratio

    vc = rownum/10; % v/c ratio
    % demand = vc * capacity; % Demand at the intersection (vph)

    % In the table rows are v/c ratios from 0.1 to 1 in 0.1 increments.
    % and columns are section lengths (increments of 50m).

    %nbikes = 20; % Number of rows (bikes) (20*50 = 1000 bikes)
    nlengths = 20; % Number of columns (section lengths) (20*50 = 1000m)

    % pdDistribution stores the values of all passing distances for the
    % current section length. It will reset for each section length.

    for lengthIncr = 1:nlengths
```

```

prctCritPass = []; % Stores the cum. rel. freq. of critical passing distance (e.g. 1000mm) for all
iterations
for iterations = 1:1 % do 10 iterations for prctCritPass a
    pdDistribution = [];
    % loc is the location of passing (increments between 0 and section length)
    % nloc is the number of location increments between 0 and current section length
    % increment
    loc = 0;
    %for nloc = 1:(lengthIncr*50)/0.01
    for nloc = 1:100000 % Number of 1 cm increments in the current section length
        %loc = nloc/100; %loc + (0.01 * nloc);
        loc = random('Uniform',0,lengthIncr * 50); % New location on the section to evaluate(m)
        % restriction = rate of restriction in lane changing
        if vc == 0.1
            restriction = (2e-7)*loc*loc - 0.0005*loc + 0.4443;
        elseif vc == 0.2
            restriction = (2e-7)*loc*loc - 0.0005*loc + 0.6120;
        elseif vc == 0.3
            restriction = (2e-7)*loc*loc - 0.0004*loc + 0.7103;
        elseif vc == 0.4
            restriction = (1e-7)*loc*loc - 0.0004*loc + 0.7734;
        elseif vc == 0.5
            restriction = (1e-7)*loc*loc - 0.0003*loc + 0.8243;
        elseif vc == 0.6
            restriction = (1e-7)*loc*loc - 0.0003*loc + 0.8666;
        elseif vc == 0.7
            restriction = (7e-8)*loc*loc - 0.0002*loc + 0.8991;
        elseif vc == 0.8
            restriction = (5e-8)*loc*loc - 0.0002*loc + 0.9324;
        elseif vc == 0.9
            restriction = (6e-8)*loc*loc - 0.0002*loc + 0.9503;
        elseif vc == 1.0
            restriction = (5e-8)*loc*loc - 0.0002*loc + 0.9698;
        end
        %rORnr is a binomial variable, decides stochastically if a
        %particular passing is restricted or not restricted. 1 = restricted
        %and 0 = not restricted
        rORnr = random('Binomial', 1, restriction); % 1 = Restricted, 2 = NOT Restricted
        if rORnr == 1 % If the lane changing is restricted
            x1 = random('Uniform',0,1.012176);
            pdDistribution(end+1,1) = -57068 * x1^6 + 170857 * x1^5 - 195078 * x1^4 + 110580 * x1^3 -
31742 * x1^2 + 4879.7 * x1 + 606.91; %ok<*SAGROW>
        else % If the lane changing is NOT restricted-
            x1 = random('Uniform',0.005553,0.980365);
            if x1 <= 0.022049287

```

```

        pdDistribution(end+1,1) = 155714 * x1^2 + 8216.7 * x1 + 549.57;
    else
        pdDistribution(end+1,1) = 362.44 * x1^2 + 2172.5 * x1 + 722.48;
    end
end
    bins = 600:50:3150; % Bins to count frequency of passing distances.
end
    histog = histc(pdDistribution,bins); % Find counts of passing distance in bins specified above.
    cumHistog = cumsum(histog); % Finds cumulative frequencies (counts).
    prctHistog = cumHistog/cumHistog(end); % Finds cumulative relative frequency (percentiles).
    critBin = (round((critpd - 600)/50)+1); % Bin number representing the critical passing distance.
    prctCritPass(end+1,1) = prctHistog(critBin); % The cumulative relative frequency for the critical
    passing distance for the current length and v/c ratio in current iteration.
end
    prctCritPassTable(rownum,lengthIncre) = mean(prctCritPass,1)
    cellName = 'ABCDEFGHJKLMNOPQRST';
    xlsCell = [cellName(lengthIncre),num2str(rownum)];
    xlswrite('prctCritCase1Table.xlsx',prctCritPassTable(rownum,lengthIncre),1,xlCell);
end

end
beep
% THIS FILE HAS PASSING % Critical Passing (critical passing distance = 1000 mm) BUILT IN.
% It first calculates the total number of near lane passing using v/c ratio,
% g/C ratio, green time and number of bikes. After that it estimates the
% number of critical passing.
clc;
clear;
format compact;

%% Constants

nLanes = 2; % Number of lanes in one direction. For 4-lane roads, nLanes = 2, for 2-lane roads nLanes = 1
saturation = 1900; % saturation flow rate = 1900 (veh/hr/ln)
greenTime = 30; % Green time in seconds
cycleTime = 60; % Cycle time in seconds
g_C = greenTime/cycleTime; % g/c ratio
capacity = saturation * nLanes * g_C; % Capacity at the intersection (veh/hr)

speedBike = 4.72222; % Bike speed in m/s (17 km/h)
speedVehicle = 13.88889; % Vehicle speed in m/s (50 km/h)

% Table of percentage critical passing (of only NL passing) for case 1.
% The values are probability of passing distance less than 1000 mm for a
% specified v/c ratio and section lengths.

```

```

% The columns represent section length from 50 to 1000 m in 50 m
% increments
% The rows represent v/c ratio from 0.1 to 1.0 in 0.1 increments

prctCritPass = [0.12170  0.12070 0.11970 0.11870 0.11770 0.11670 0.11570 0.11470 0.11370 0.11270
                0.11170 0.11070 0.10970 0.10870 0.10770 0.10670 0.10570 0.10470 0.10370 0.10270
0.13940 0.13840 0.13740 0.13640 0.13540 0.13440 0.13340 0.13240 0.13140 0.13040 0.12940 0.12840
                0.12740 0.12640 0.12540 0.12440 0.12340 0.12240 0.12140 0.12040
0.15020 0.14970 0.14920 0.14870 0.14820 0.14770 0.14720 0.14670 0.14620 0.14570 0.14520 0.14470
                0.14420 0.14370 0.14320 0.14270 0.14220 0.14170 0.14120 0.14070
0.15740 0.15640 0.15540 0.15440 0.15340 0.15240 0.15140 0.15040 0.14940 0.14840 0.14740 0.14640
                0.14540 0.14440 0.14340 0.14240 0.14140 0.14040 0.13940 0.13840
0.16280 0.16230 0.16180 0.16130 0.16080 0.16030 0.15980 0.15930 0.15880 0.15830 0.15780 0.15730
                0.15680 0.15630 0.15580 0.15530 0.15480 0.15430 0.15380 0.15330
0.16770 0.16720 0.16670 0.16620 0.16570 0.16520 0.16470 0.16420 0.16370 0.16320 0.16270 0.16220
                0.16170 0.16120 0.16070 0.16020 0.15970 0.15920 0.15870 0.15820
0.17075 0.17040 0.17005 0.16970 0.16935 0.16900 0.16865 0.16830 0.16795 0.16760 0.16725 0.16690
                0.16655 0.16620 0.16585 0.16550 0.16515 0.16480 0.16445 0.16410
0.17450 0.17410 0.17370 0.17330 0.17290 0.17250 0.17210 0.17170 0.17130 0.17090 0.17050 0.17010
                0.16970 0.16930 0.16890 0.16850 0.16810 0.16770 0.16730 0.16690
0.17675 0.17630 0.17585 0.17540 0.17495 0.17450 0.17405 0.17360 0.17315 0.17270 0.17225 0.17180
                0.17135 0.17090 0.17045 0.17000 0.16955 0.16910 0.16865 0.16820
0.17885 0.17840 0.17795 0.17750 0.17705 0.17660 0.17615 0.17570 0.17525 0.17480 0.17435 0.17390
                0.17345 0.17300 0.17255 0.17210 0.17165 0.17120 0.17075 0.17030];

%% Calculations

% OUTPUT FORMAT - Number of bikes in columns (from 50 to 500 bph in 50 increments)
%           Section Length in rows (from 50 to 1000m in 50m increments)
%           v/c ratios in individual pages. (from 0.1 to 1 in 0.1 increments.)
%           Each page is for an individual v/c ratio
%
% First for a given v/c ratio find total number of near lane passing for a
% given number of bikes. Than multiply with prctCritPass to find number of
% critical passing.

output = zeros(10,20);

% rowNum is the page number index for the output table and is an indicator
% of the number of the v/c ratio. It corresponds to the rows in the
% prcrCritPass table.

for rowNum = 1:10

```



```

% colNum is the column number index for the output table and is an indicator
% of the section length. It corresponds to the columns in the
% prctCritPass table.
for colNum = 1:20

    sectLength = colNum * 50; % Section length in m
    volume = capacity * rowNum / 10; % Flow rate discharge at the intersection in vph
    tb = sectLength / speedBike; % Time a bike takes to travel the entire section (s)
    tv = sectLength / speedVehicle; % Time a vehicle takes to travel the entire section (s)
    hv = 3600 / (volume/2); % Time headway between vehicles in just one lane (s)
    nlPPB = (tb - tv) / hv; % Number of near lane passing per bike
    output(rowNum,colNum) = nlPPB * prctCritPass(rowNum,colNum) * 2;

end

end

pass = [];
pass = output;
rowsPass = size(pass,1);
colsPass = size(pass,2);

figure1 = figure;

axes1 = axes('Parent',figure1,'Layer','top');
xlim(axes1,[1 20]);
ylim(axes1,[1 10]);
box(axes1,'on');
hold(axes1,'all');

pmin = min(pass(:,1));
pmax = max(pass(:,colsPass));
if pmax - pmin < 1
    inc = 0.03125;
elseif pmax - pmin >= 1 && pmax - pmin < 2
    inc = 0.06250;
elseif pmax - pmin >= 2 && pmax - pmin < 4
    inc = 0.1250;
elseif pmax - pmin >= 4 && pmax - pmin < 8
    inc = 0.250;
elseif pmax - pmin >= 8 && pmax - pmin < 16
    inc = 0.5;
else
    inc = 1;
end
end

```

```

zmin = ceil(pmin/inc)*inc;
zmax = floor(pmax/inc)*inc;
zinc = inc;
zlevs = zmin:zinc:zmax;
contour(pass,zlevs,'ShowText','on');
grid on;

xlabel({'Section Length (m)'});
ylabel({'AADT'});
title('Critical Passings per Bike Trip (g/C = 0.5, g = 30 sec, C = 60 sec)','FontSize',12);
xlabels = 100:100:1000;
ylabels = 3800:3800:38000;
set(gca, 'XTickLabel', xlabels); % Change x-axis ticks labels.
set(gca, 'YTickLabel', ylabels); % Change x-axis ticks labels
print(figure1, '-dpng', '-r600', 'Case 1 Section Length vs. v_c Ratio.png');

```

## **Case 2**

```

% Case 2
% Uses the v/c vs. section length curves as input.

clear;
clc;
format compact;

%% CONSTANTS

saturation = 1900; % Saturation flow rate in vh/hr/ln
nlanes = 2; % Number of lanes
gC = 0.5; % g/C ratio
capacity = saturation * nlanes * gC; % Intersection capacity (vph)
critpd = 1000; % critical passing distance (mm). It should be in increments of 50 mm from 600 to 3150.

%% ESTIMATION
prctCritPassTable = [];
%iterationValues=[]; %*****
for rownum = 1:10 % row also correspond to the v/c ratio
    %rownum
    vc = rownum/10; % v/c ratio
    demand = vc * capacity; % Demand at the intersection (vph)

    % In the table rows are v/c ratios from 0.1 to 1 in 0.1 increments.
    % and columns are section lengths (increments of 50m).

```

```

%nbikes = 20; % Number of rows (bikes) (20*50 = 1000 bikes)
nlengths = 20; % Number of columns (section lengths) (20*50 = 1000m)

% pdDistribution stores the values of all passing distances for the
% current section length. It will reset for each section length.

for lengthIncr = 1:nlengths % Current section length is lengthIncr * 50 m
    prctCritPass = []; % Stores the cum. rel. freq. of critical passing distance (e.g. 1000mm) for all
iterations
    for iterations = 1:4 % do 10 iterations for prctCritPass
        pdDistribution = [];
        % loc is the location of passing (increments between 0 and section length)
        % nloc is the number of location increments between 0 and current section length
        % increment
        loc = 0;
        %for nloc = 1:(lengthIncr*50)/0.01 % Number of 2 cm increments in the current section
length*****
        for nloc = 1:100000 % Number of 1 cm increments in the current section length*****
            %loc = nloc/100; % New location on the section to evaluate(m)*****
            loc = random('Uniform',0,lengthIncr * 50); % New location on the section to
evaluate(m)*****
            % restriction = rate of restriction in lane changing
            if vc == 0.1
                restriction = (2e-7)*loc*loc - 0.0004*loc + 0.4779;
            elseif vc == 0.2
                restriction = (1e-7)*loc*loc - 0.0003*loc + 0.6406;
            elseif vc == 0.3
                restriction = (5e-8)*loc*loc - 0.0002*loc + 0.7098;
            elseif vc == 0.4
                restriction = (9e-8)*loc*loc - 0.0003*loc + 0.7854;
            elseif vc == 0.5
                restriction = (5e-8)*loc*loc - 0.0002*loc + 0.8263;
            elseif vc == 0.6
                restriction = (7e-8)*loc*loc - 0.0002*loc + 0.8665;
            elseif vc == 0.7
                restriction = (6e-8)*loc*loc - 0.0002*loc + 0.8946;
            elseif vc == 0.8
                restriction = (2e-8)*loc*loc - 0.0001*loc + 0.9176;
            elseif vc == 0.9
                restriction = (6e-9)*loc*loc - (9e-5)*loc + 0.9435;
            elseif vc == 1.0
                restriction = (4e-9)*loc*loc - (6e-5)*loc + 0.9567;
            end
            %rORnr is a binomial variable, decides stochastically if a
            %particular passing is restricted or not restricted. 1 = restricted

```

```

%and 0 = not restricted
rORnr = random('Binomial', 1, restriction); % 1 = Restricted, 2 = NOT Restricted
if rORnr == 1 % If the lane changing is restricted
    x1 = random('Uniform',0,1.012176);
    pdDistribution(end+1,1) = -57068 * x1^6 + 170857 * x1^5 - 195078 * x1^4 + 110580 * x1^3 -
31742 * x1^2 + 4879.7 * x1 + 606.91; %#ok<*SAGROW>
else % If the lane changing is NOT restricted-
    x1 = random('Uniform',0,0.005553,0.980365);
    if x1 <= 0.022049287
        pdDistribution(end+1,1) = 155714 * x1^2 + 8216.7 * x1 + 549.57;
    else
        pdDistribution(end+1,1) = 2552.1 * x1 + 648.01;
    end
end
end
bins = 600:50:3150; % Bins to count frequency of passing distances.
end
histog = histc(pdDistribution,bins); % Find counts of passing distance in bins specified above.
cumHistog = cumsum(histog); % Finds cumulative frequencies (counts).
prctHistog = cumHistog/cumHistog(end); % Finds cumulative relative frequency (percentiles).
critBin = (round((critpd - 600)/50)+1); % Bin number representing the critical passing distance.
prctCritPass(end+1,1) = prctHistog(critBin); % The cumulative relative frequency for the critical
passing distance for the current length and v/c ratio in current iteration.
%iterationValues(end+1,1) = prctHistog(critBin) % *****
end
prctCritPassTable(rownum,lengthIncr) = mean(prctCritPass,1);
cellName = 'ABCDEFGHJKLMNOPQRST';
xlcell = [cellName(lengthIncr),num2str(rownum)];
xlswrite('prctCritCase2Table.xlsx',prctCritPassTable(rownum,lengthIncr),1,xlcell);
end

end
beep
% THIS FILE HAS PASSING % Critical Passing (critical passing distance = 1000 mm) BUILT IN.
% It first calculates the total number of near lane passing using v/c ratio,
% g/C ratio, green time and number of bikes. After that it estimates the
% number of critical passing.
clc;
clear;
format compact;

%% Constants

nLanes = 2; % Number of lanes in one direction. For 4-lane roads, nLanes = 2, for 2-lane roads nLanes = 1
saturation = 1900; % saturation flow rate = 1900 (veh/hr/ln)
greenTime = 60; % Green time in seconds

```

```

cycleTime = 120; % Cycle time in seconds
g_C = greenTime/cycleTime; % g/c ratio
capacity = saturation * nLanes * g_C; % Capacity at the intersection (veh/hr)

```

```

speedBike = 4.72222; % Bike speed in m/s (17 km/h)
speedVehicle = 13.88889; % Vehicle speed in m/s (50 km/h)

```

```

% Table of percentage critical passing for case 3.
% The values are probability of passing distance less than 1000 mm for a
% specified v/c ratio and section lengths.
% The columns represent section length from 50 to 1000 m in 50 m
% increments
% The rows represent v/c ratio from 0.1 to 1.0 in 0.1 increments

```

```

prctCritPass = [0.12610  0.12560 0.12510 0.12460 0.12410 0.12360 0.12310 0.12260 0.12210 0.12160
                0.12110 0.12060 0.12010 0.11960 0.11910 0.11860 0.11810 0.11760 0.11710 0.11660
0.14380 0.14330 0.14280 0.14230 0.14180 0.14130 0.14080 0.14030 0.13980 0.13930 0.13880 0.13830
                0.13780 0.13730 0.13680 0.13630 0.13580 0.13530 0.13480 0.13430
0.15155 0.15110 0.15065 0.15020 0.14975 0.14930 0.14885 0.14840 0.14795 0.14750 0.14705 0.14660
                0.14615 0.14570 0.14525 0.14480 0.14435 0.14390 0.14345 0.14300
0.15940 0.15890 0.15840 0.15790 0.15740 0.15690 0.15640 0.15590 0.15540 0.15490 0.15440 0.15390
                0.15340 0.15290 0.15240 0.15190 0.15140 0.15090 0.15040 0.14990
0.16395 0.16350 0.16305 0.16260 0.16215 0.16170 0.16125 0.16080 0.16035 0.15990 0.15945 0.15900
                0.15855 0.15810 0.15765 0.15720 0.15675 0.15630 0.15585 0.15540
0.16745 0.16710 0.16675 0.16640 0.16605 0.16570 0.16535 0.16500 0.16465 0.16430 0.16395 0.16360
                0.16325 0.16290 0.16255 0.16220 0.16185 0.16150 0.16115 0.16080
0.17120 0.17070 0.17020 0.16970 0.16920 0.16870 0.16820 0.16770 0.16720 0.16670 0.16620 0.16570
                0.16520 0.16470 0.16420 0.16370 0.16320 0.16270 0.16220 0.16170
0.17350 0.17320 0.17290 0.17260 0.17230 0.17200 0.17170 0.17140 0.17110 0.17080 0.17050 0.17020
                0.16990 0.16960 0.16930 0.16900 0.16870 0.16840 0.16810 0.16780
0.17685 0.17660 0.17635 0.17610 0.17585 0.17560 0.17535 0.17510 0.17485 0.17460 0.17435 0.17410
                0.17385 0.17360 0.17335 0.17310 0.17285 0.17260 0.17235 0.17210
0.17830 0.17810 0.17790 0.17770 0.17750 0.17730 0.17710 0.17690 0.17670 0.17650 0.17630 0.17610
                0.17590 0.17570 0.17550 0.17530 0.17510 0.17490 0.17470 0.17450];

```

```

%% Calculations

```

```

% OUTPUT FORMAT - Number of bikes in columns (from 50 to 500 bph in 50 increments)
%           Section Length in rows (from 50 to 1000m in 50m increments)
%           v/c ratios in individual pages. (from 0.1 to 1 in 0.1 increments.)
%           Each page is for an individual v/c ratio
%
% First for a given v/c ratio find total number of near lane passing for a
% given number of bikes. Than multiply with prctCritPass to find number of

```

```

% critical passing.

output = zeros(10,20);

% rowNum is the page number index for the output table and is an indicator
% of the number of the v/c ratio. It corresponds to the rows in the
% prcrCritPass table.

for rowNum = 1:10

    % colNum is the column number index for the output table and is an indicator
    % of the section length. It corresponds to the columns in the
    % prcrCritPass table.
    for colNum = 1:20

        sectLength = colNum * 50; % Section length in m
        volume = capacity * rowNum / 10; % Flow rate discharge at the intersection in vph
        tb = sectLength / speedBike; % Time a bike takes to travel the entire section (s)
        tv = sectLength / speedVehicle; % Time a vehicle takes to travel the entire section (s)
        hv = 3600 / (volume/2); % Time headway between vehicles in just one lane (s)
        nlPPB = (tb - tv) / hv; % Number of near lane passing per bike
        output(rowNum,colNum) = nlPPB * prcrCritPass(rowNum,colNum) * 2;

    end

end

pass = [];
pass = output;
rowsPass = size(pass,1);
colsPass = size(pass,2);

figure1 = figure;

axes1 = axes('Parent',figure1,'Layer','top');
xlim(axes1,[1 20]);
ylim(axes1,[1 10]);
box(axes1,'on');
hold(axes1,'all');

pmin = min(pass(:,1));
pmax = max(pass(:,colsPass));
if pmax - pmin < 1
    inc = 0.03125;
elseif pmax - pmin >= 1 && pmax - pmin < 2

```

```

    inc = 0.06250;
elseif pmax - pmin >= 2 && pmax - pmin < 4
    inc = 0.1250;
elseif pmax - pmin >= 4 && pmax - pmin < 8
    inc = 0.250;
elseif pmax - pmin >= 8 && pmax - pmin < 16
    inc = 0.5;
else
    inc = 1;
end

zmin = ceil(pmin/inc)*inc;
zmax = floor(pmax/inc)*inc;
zinc = inc;
zlevs = zmin:zinc:zmax;
contour(pass,zlevs,'ShowText','on');
grid on;

xlabel({'Section Length (m)'});
ylabel({'AADT'});
title('Critical Passings per Bike Trip (g/C = 0.5, g = 60 sec, C = 120 sec)','FontSize',12);
xlabel = 100:100:1000;
ylabel = 3800:3800:38000;
set(gca, 'XTickLabel', xlabel); % Change x-axis ticks labels.
set(gca, 'YTickLabel', ylabel); % Change x-axis ticks labels
print(figure1,'-dpng','-r600','Case 2 Section Length vs. v_c Ratio.png');

```

### **Case 3**

```

% Case 3
% Uses the v/c vs. section length curves as input.

clear;
clc;
format compact;

%% CONSTANTS

saturation = 1900; % Saturation flow rate in vh/hr/ln
nlanes = 2; % Number of lanes
gC = 0.5; % g/C ratio
capacity = saturation * nlanes * gC; % Intersection capacity (vph)
critpd = 1000; % critical passing distance (mm). It should be in increments of 50 mm from 600 to 3150.

%% ESTIMATION

```

```

prctCritPassTable = [];
%iterationValues=[]; %*****
for rownum = 1:10 % row also correspond to the v/c ratio % CHANGE THIS LINE CHANGE THIS
LINE CHANGE THIS LINE
    %rownum
    vc = rownum/10; % v/c ratio % CHANGE THIS LINE CHANGE THIS LINE CHANGE THIS LINE
    demand = vc * capacity; % Demand at the intersection (vph)

    % In the table rows are v/c ratios from 0.1 to 1 in 0.1 increments.
    % and columns are section lengths (increments of 50m).

    %nbikes = 20; % Number of rows (bikes) (20*50 = 1000 bikes)
    nlengths = 20; % Number of columns (section lengths) (20*50 = 1000m)

    % pdDistribution stores the values of all passing distances for the
    % current section length. It will reset for each section length.

    for lengthIncr = 1:nlengths % Current section length is lengthIncr * 50 m
        prctCritPass = []; % Stores the cum. rel. freq. of critical passing distance (e.g. 1000mm) for all
iterations
        for iterations = 1:5 % do 10 iterations for prctCritPass
            pdDistribution = [];
            % loc is the location of passing (increments between 0 and section length)
            % nloc is the number of location increments between 0 and current section length
            % increment
            loc = 0;
            for nloc = 1:(lengthIncr*50)/0.01 % Number of 1 cm increments in the current section length
                loc = nloc/100; % New location on the section to evaluate(m)
                % restriction = rate of restriction in lane changing
                if vc == 0.1
                    restriction = (4e-7)*loc*loc - 0.0006*loc + 0.4951;
                elseif vc == 0.2
                    restriction = (3e-7)*loc*loc - 0.0007*loc + 0.7074;
                elseif vc == 0.3
                    restriction = (2e-7)*loc*loc - 0.0006*loc + 0.7725;
                elseif vc == 0.4
                    restriction = (2e-7)*loc*loc - 0.0005*loc + 0.8192;
                elseif vc == 0.5
                    restriction = (2e-7)*loc*loc - 0.0005*loc + 0.8701;
                elseif vc == 0.6
                    restriction = (1e-7)*loc*loc - 0.0004*loc + 0.8921;
                elseif vc == 0.7
                    restriction = (1e-7)*loc*loc - 0.0004*loc + 0.9246;
                elseif vc == 0.8
                    restriction = (6e-8)*loc*loc - 0.0003*loc + 0.9467;

```



```

elseif vc == 0.9
    restriction = (8e-8)*loc*loc - 0.0003*loc + 0.9629;
elseif vc == 1.0
    restriction = (4e-8)*loc*loc - 0.0003*loc + 0.9766;
end
    %rORnr is a binomial variable, decides stochastically if a
    %particular passing is restricted or not restricted. 1 = restricted
    %and 0 = not restricted
rORnr = random('Binomial', 1, restriction); % 1 = Restricted, 2 = NOT Restricted
if rORnr == 1 % If the lane changing is restricted
    x1 = random('Uniform',0,1.012176);
    pdDistribution(end+1,1) = -57068 * x1^6 + 170857 * x1^5 - 195078 * x1^4 + 110580 * x1^3 -
31742 * x1^2 + 4879.7 * x1 + 606.91; %ok<*SAGROW>
else % If the lane changing is NOT restricted-
    x1 = random('Uniform',0.005553,0.980365);
    if x1 <= 0.022049287
        pdDistribution(end+1,1) = 155714 * x1^2 + 8216.7 * x1 + 549.57;
    else
        pdDistribution(end+1,1) = 2552.1 * x1 + 648.01;
    end
end
    bins = 600:50:3150; % Bins to count frequency of passing distances.
end
histog = histc(pdDistribution,bins); % Find counts of passing distance in bins specified above.
cumHistog = cumsum(histog); % Finds cumulative frequencies (counts).
prctHistog = cumHistog/cumHistog(end); % Finds cumulative relative frequency (percentiles).
critBin = (round((critpd - 600)/50)+1); % Bin number representing the critical passing distance.
prctCritPass(end+1,1) = prctHistog(critBin); % The cumulative relative frequency for the critical
passing distance for the current length and v/c ratio in current iteration.
    %iterationValues(end+1,1) = prctHistog(critBin) % *****
end
prctCritPassTable(rownum,lengthIncre) = mean(prctCritPass,1)
cellName = 'ABCDEFGHJKLMNOPQRST';
xlcell = [cellName(lengthIncre),num2str(rownum)];
xlswrite('prctCritTableCASE3.xlsx',prctCritPassTable(rownum,lengthIncre),1,xlcell);
end

end
beep
% THIS FILE HAS PASSING % Critical Passing (critical passing distance = 1000 mm) BUILT IN.
% It first calculates the total number of near lane passing using v/c ratio,
% g/C ratio, green time and number of bikes. After that it estimates the
% number of critical passing.
clc;
clear;
format compact;

```

%% Constants

nLanes = 2; % Number of lanes in one direction. For 4-lane roads, nLanes = 2, for 2-lane roads nLanes = 1  
saturation = 1900; % saturation flow rate = 1900 (veh/hr/ln)

greenTime = 18; % Green time in seconds

cycleTime = 60; % Cycle time in seconds

g\_C = greenTime/cycleTime; % g/c ratio

capacity = saturation \* nLanes \* g\_C; % Capacity at the intersection (veh/hr)

speedBike = 4.72222; % Bike speed in m/s (17 km/h)

speedVehicle = 13.88889; % Vehicle speed in m/s (50 km/h)

% Table of percentage critical passing for case 3.

% The values are probability of passing distance less than 1000 mm for a

% specified v/c ratio and section lengths.

% The columns represent section length from 50 to 1000 m in 50 m

% increments

% The rows represent v/c ratio from 0.1 to 1.0 in 0.1 increments

```
prctCritPass = [0.12610 0.12510 0.12410 0.12310 0.12210 0.12110 0.12010 0.11910 0.11810 0.11710
0.11610 0.11510 0.11410 0.11310 0.11210 0.11110 0.11010 0.10910 0.10810 0.10710
0.14830 0.14680 0.14530 0.14380 0.14230 0.14080 0.13930 0.13780 0.13630 0.13480 0.13330 0.13180
0.13030 0.12880 0.12730 0.12580 0.12430 0.12280 0.12130 0.11980
0.15710 0.15610 0.15510 0.15410 0.15310 0.15210 0.15110 0.15010 0.14910 0.14810 0.14710 0.14610
0.14510 0.14410 0.14310 0.14210 0.14110 0.14010 0.13910 0.13810
0.16140 0.16040 0.15940 0.15840 0.15740 0.15640 0.15540 0.15440 0.15340 0.15240 0.15140 0.15040
0.14940 0.14840 0.14740 0.14640 0.14540 0.14440 0.14340 0.14240
0.16550 0.16450 0.16350 0.16250 0.16150 0.16050 0.15950 0.15850 0.15750 0.15650 0.15550 0.15450
0.15350 0.15250 0.15150 0.15050 0.14950 0.14850 0.14750 0.14650
0.16930 0.16830 0.16730 0.16630 0.16530 0.16430 0.16330 0.16230 0.16130 0.16030 0.15930 0.15830
0.15730 0.15630 0.15530 0.15430 0.15330 0.15230 0.15130 0.15030
0.17360 0.17260 0.17160 0.17060 0.16960 0.16860 0.16760 0.16660 0.16560 0.16460 0.16360 0.16260
0.16160 0.16060 0.15960 0.15860 0.15760 0.15660 0.15560 0.15460
0.17580 0.17530 0.17480 0.17430 0.17380 0.17330 0.17280 0.17230 0.17180 0.17130 0.17080 0.17030
0.16980 0.16930 0.16880 0.16830 0.16780 0.16730 0.16680 0.16630
0.17760 0.17710 0.17660 0.17610 0.17560 0.17510 0.17460 0.17410 0.17360 0.17310 0.17260 0.17210
0.17160 0.17110 0.17060 0.17010 0.16960 0.16910 0.16860 0.16810
0.17900 0.17850 0.17800 0.17750 0.17700 0.17650 0.17600 0.17550 0.17500 0.17450 0.17400 0.17350
0.17300 0.17250 0.17200 0.17150 0.17100 0.17050 0.17000 0.16950];
```

%% Calculations

% OUTPUT FORMAT - Number of bikes in columns (from 50 to 500 bph in 50 increments)

```

%           Section Length in rows (from 50 to 1000m in 50m increments)
%           v/c ratios in individual pages. (from 0.1 to 1 in 0.1 increments.)
%           Each page is for an individual v/c ratio
%
% First for a given v/c ratio find total number of near lane passing for a
% given number of bikes. Then multiply with prctCritPass to find number of
% critical passing.

output = zeros(10,20);

% rowNum is the page number index for the output table and is an indicator
% of the number of the v/c ratio. It corresponds to the rows in the
% prcrCritPass table.

for rowNum = 1:10

    % colNum is the column number index for the output table and is an indicator
    % of the section length. It corresponds to the columns in the
    % prctCritPass table.
    for colNum = 1:20

        sectLength = colNum * 50; % Section length in m
        volume = capacity * rowNum / 10; % Flow rate discharge at the intersection in vph
        tb = sectLength / speedBike; % Time a bike takes to travel the entire section (s)
        tv = sectLength / speedVehicle; % Time a vehicle takes to travel the entire section (s)
        hv = 3600 / (volume/2); % Time headway between vehicles in just one lane (s)
        nlPPB = (tb - tv) / hv; % Number of near lane passing per bike
        output(rowNum,colNum) = nlPPB * prctCritPass(rowNum,colNum) * 2;

    end

end

pass = [];
pass = output;
rowsPass = size(pass,1);
colsPass = size(pass,2);

figure1 = figure;

axes1 = axes('Parent',figure1,'Layer','top');
xlim(axes1,[1 20]);
ylim(axes1,[1 10]);
box(axes1,'on');
hold(axes1,'all');

```

```

pmin = min(pass(:,1));
pmax = max(pass(:,colsPass));
if pmax - pmin < 1
    inc = 0.03125;
elseif pmax - pmin >= 1 && pmax - pmin < 2
    inc = 0.06250;
elseif pmax - pmin >= 2 && pmax - pmin < 4
    inc = 0.1250;
elseif pmax - pmin >= 4 && pmax - pmin < 8
    inc = 0.250;
elseif pmax - pmin >= 8 && pmax - pmin < 16
    inc = 0.5;
else
    inc = 1;
end

zmin = ceil(pmin/inc)*inc;
zmax = floor(pmax/inc)*inc;
zinc = inc;
zlevs = zmin:zinc:zmax;
contour(pass,zlevs,'ShowText','on');
grid on;

xlabel({'Section Length (m)'});
ylabel({'AADT'});
title('Critical Passings per Bike Trip (g/C = 0.3, g = 18 sec, C = 60 sec)','FontSize',12);
xlabel = 100:100:1000;
ylabel = 2280:2280:22800;
set(gca, 'XTickLabel', xlabel); % Change x-axis ticks labels.
set(gca, 'YTickLabel', ylabel); % Change x-axis ticks labels
print(figure1,'-dpng','-r600','Case 3 Section Length vs. v_c Ratio.png');

```