Analyzing the behavior of cyclists at intersections to improve behavior variability within micro-simulation traffic models

by

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I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

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ABSTRACT

The purpose of this thesis can be separated into two components:

Component 1:

The purpose of this component was to update the input parameters for cyclists for application in mixed-traffic micro simulation models. This component used GPS data from cyclists to develop distributions of desired speed under variable road and facility conditions. Desired speed distributions as a function of road grade and the effect that road surface and facility type have on desired speed were analyzed.   The findings suggest that facility type (multi-use trail, bike lane, and no bike lane) had no significant effect on the desired speed of the cyclists in the study. A distribution of the desired speed of cyclists was developed and can be applied to improve variability within micro-simulation traffic models.

Component 2:

The purpose of this component was to observe and analyze the left turn behavior of cyclists at different types of signalized intersections in the City of Toronto with the intent of recommending what facilities are most effective at facilitating left turning movements under varying input conditions. From the observations, a database was created that includes turning behavior, approach conditions, and individual cyclist related variables for each cyclist.

By analyzing the behavior data base, conclusions were made regarding the effect that intersection type, facility type, and input conditions have on the rule compliance and facility compliance of the cyclists that were observed.   From these conclusions, recommendations have been made that are intended to suggest some facility interventions that will result in improved rule compliance and facility compliance, ultimately creating a more comfortable cycling environment and one that matches that natural tendencies of cyclists in the city.

The measurement of rule compliance in this report is based on the simple observation of whether the cyclists, when making a left turn at the intersection, complied with the rules of the road or broke the rules of the road as defined by the Ontario Highway Traffic Act.   The

measurement of facility compliance is based on whether the cyclist made a left turn using the facility as the design intends them to use it.

Cyclist behaviors at five different intersection configurations were observed in the study. This sample of intersection configurations is significant as they represent most of the generic intersection types that are located throughout Toronto's cycling network. The distribution of these behaviors for each intersection type can be considered in micro-simulation models when considering the stochastic nature of a cyclists and their decision process with regards to navigating a left turn through an intersection.

Facilities with more left turning options proved to promote rule compliance more so than the intersections with fewer options.

ACKNOWLEDGEMENTS

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1.0   CHAPTER 1: INTRODUCTION

The use of bicycles to accommodate the urban transportation needs of citizens is energy efficient, space efficient, generates no carbon emission, and it promotes a healthy and active life style for the user. The benefits of promoting cycling as a transportation mode choice are overwhelming, not just from an urban mobility perspective, but from an economic, social, and public health perspective as well (World Health Organization, 2003). In its simplest form, this thesis is focused on improving the cycling environment in cities by observing tendencies to gain a better understanding of cyclist behavior and to ultimately improve design to increase safety and convenience for existing and potential riders. The findings can also provide a better understanding of the stochastic nature of cyclists and provide a distribution of these behaviors that can be included in micro-simulation traffic models.

There is a clear trend that our world is becoming more urbanized and urban areas are becoming more densely populated.   In 2014, the United Nations reported that 54 percent of the world's human population is now living in cities and that the number is forecasted to increase to 66 percent by 2050 (United Nations , 2014). As this trend continues, maintaining and improving the mobility of urban citizens is a challenge of increasing complexity that requires more progressive and effective solutions than the approach planners, engineers and policy makers have taken over the past century. The traditional paradigm of urban growth in North America over the past century, which is predicated on sprawl and the development of new land made accessible by highways and arterial road networks, has proven to be unsustainable. As cities sprawl and cover more area, commute times are increasing due to greater commute distances and the transportation networks that make these commutes possible are operating beyond their capacity, leading to extreme congestion and network failure in some cases (Vuchic, 1999). This has a negative impact on air and water quality, economic efficiency, and quality of life.

It is recognized within contemporary research related to urban studies, planning, and urban transportation, that progressive solutions to mobility problems include an attempt to

balance transportation mode choice away from the private automobile and to favor more efficient and environmentally sustainable modes of transportation. The promotion of cycling as a mode of transportation is one such example. However, regardless of all the benefits associated with utilitarian cycling, encouraging citizens to consider leaving the familiar and comfortable confines of their personal automobile has significant challenges as the private automobile represents a major pillar of our society and our way of life. Attempting to invoke such a massive change is a challenge that needs to be approached in small increments and gradual improvements, and that draws from multiple lenses and avenues of expertise. One of these approaches is through design of transportation infrastructure or the retrofitting of the urban streetscape to better consider the needs of cyclists. By designing infrastructure that is better suited to cyclists, culture and change can occur gradually and the use of cycling as a mode of transportation will become more viable for the average citizen.

One of the tools that planners and engineers use when planning for new transportation projects is computer simulation modelling that model the effects and benefits that the proposed improvements will have on traffic flow and traffic safety. Traditionally, these models are used to simulate the flow of automobiles, with limited consideration given to other road users, such as cyclists or pedestrians. As well, attempts to analyze the behavior of cyclists are limited and therefore a more generic approach to designing cyclist infrastructure has become common practice. The purpose of this study is to improve upon these inadequacies through research of the behavior of cyclists to gain a better understanding of the following:

- how environmental variables, such as road grade, infrastructure type and gender, affect the desired speed of a cyclist;

- how different intersection treatments affect the behavior of cyclists at those intersections;

- the propensity for cyclists to comply to the defined rules of the road under varying conditions;

- the propensity for cyclists to behave as the road design intends; and

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- the desire lines of a left turning cyclist at various intersection configurations.

From this research, the following two deliverables will be made available:

1. More variable input parameters to improve the micro simulation models of cyclists

2. Recommendations for bicycle facility types under varying conditions with specific application to the context of the City of Toronto

By gaining a better understanding of the behavior of cyclists, we can improve our design to match the desires and needs of cyclists and therefore make the cycling environment safer and more inviting to existing and prospective riders.

This thesis report is structured as follows. First, the context for the research is set and the specific challenges and attributes of the context is identified. Secondly, a literature review covers various topics that provide further justification for this research and identify gaps in the existing research that need to be addressed. Furthermore, a detailed overview of the methods used to conduct this research is presented. Finally, the results of the research will be presented and recommendations will be made.

2.0   CHAPTER 2: CONTEXT

The data that are used to formulate this thesis are taken from two different cities within the planning region in Ontario, Canada known as the Greater Golden Horseshoe. The first component of the thesis, which relies on GPS data from cyclists in a study conducted in 2011, comes from cyclists in Waterloo Region. The second component of the thesis uses video observation to analyze the left turning movements of cyclists in the City of Toronto.   The purpose of this chapter is to summarize the contexts from which these data were collected and to identify the efforts that are being made to encourage residents to use more active modes of transportation. It is also important to note these contexts as they are not traditionally "cycling friendly" cities.

2.1   THE GREATER GOLDEN HORSESHOE

The Greater Golden Horseshoe is a geographic area in Ontario and is the most densely populated region in Canada. In 2006, a plan for the area was set in place by the Ministry of Infrastructure that was aimed at managing the growth of the region over the next 20 years (Ministry of Infrastructure, 2006)

The region had experienced substantial and continuous growth over the preceding decades and was expecting a similar level of growth going forward. The growth to date could be classified as urban sprawl, as the suburban communities of the Greater Toronto Area grew rapidly and outwardly, taking up new and previously undeveloped farm land and natural areas.

One of the key strategies to mitigate the sprawl and to manage the growth going forward, was to identify existing urban areas that host the majority of growth going forward through the process of intensification and urban revitalization. This strategy was a requirement that the identified centres for growth would aim to implement more efficient and sustainable modes of transportation to serve the prospective increase in urban densities.

2.2   WATERLOO REGION

The Region of Waterloo is now the 10th largest metropolitan area in Canada after significant growth over the past half century. The Region is anticipating further growth into the future as the Ontario Places to Grow Plan has identified areas within the urban centres of the Region to be host to growth and intensification.   The population of the region, based on 2011 census data, is 507,000 and is expected to grow to 729,000 by 2031 (Ministry of Infrastructure, 2006).

The Region is considered to be progressive with regards to transportation policy as it will become the smallest community in Canada to have light rail transit (LRT). The first phase of the LRT is under construction and is projected to be operational by 2017. This new investment in alternative transportation modes has been a catalyst for investment into all alternative modes. Part of the planning process surrounding the LRT includes accommodation of other alternative modes to help facilitate the movement of people to and along the LRT line.

Part of this attempt towards more sustainable modes of transportation has been a commitment to improving the condition for cyclists in the Region through mass implementation of on street bike lanes and the development of a strategic cycling network throughout the Region. The implementation of coloured bike boxes in downtown Kitchener has recently been completed as well as plans for a new off street multi use trail from east of Downtown Kitchener to Uptown Waterloo.

Although considerable effort has been made to improve the condition for cyclists in the Region, cycling numbers still remain low (2% mode split) as the sprawling urban landscape of the area has made cycling inconvenient and unsafe for the majority of potential riders (Region of Waterloo, 2011). A commitment to land use policy and a strategic approach to improving the bike network will only improve the condition for cyclists in the area.

Given the low cycling numbers in the Region, the data set that was collected in this context is made up of a group of experienced cyclists and does not represent the behavior beginner cyclists. Therefore, the conclusions that are based on the Waterloo Region data set

may only be applicable to micro-simulation models from similar contexts; where the cyclist population is made up of primarily experienced riders.

2.3 THE CITY OF TORONTO

The City of Toronto is the largest metropolitan area in Canada and the 4th most populous city in North America. Although the City has grown to its geographic boundaries, with neighboring municipalities encroaching in all directions, Toronto continues to grow steadily in population. Between the last two census periods, 2006 and 2011, the City of Toronto experienced population growth of approximately 110,000 new residents (Statistics Canada, 2011). This trend of growth is expected to continue and the City's 2013 population of 2.77 million is forecasted to grow to 3.64 million by 2041 (Ministry of Finance, 2014). Given the land constraints of the city, the only way for Toronto to host the demand for new housing is through intensification. Specifically, the Ontario Places to Grow plan has set the following density target for the city:

"*Under Places to Grow, Toronto was required to increase downtown resident/job density to a combined minimum of 400 per hectare by 2031. But city data suggest the downtown core is already at twice the prescribed density, with 708 jobs and residents per hectare. That ratio is expected to rise to 775 residents and jobs per hectare by 2022*."

(Scallan, 2012)

This level of growth and increase in density poses major challenges for mobility. The economic, social, and environmental costs of traffic congestion in the city are already staggering, and as population increases, this issue will become a more complex problem to solve. A report titled "Cost of Road Congestion in the Greater Toronto and Hamilton Area" estimated that the cost of congestion to commuters in the Greater Toronto and Hamilton Area was $3.3 Billion and a $2.7 billion cost to the economy (Metrolinx, 2008). The City and Province have developed robust policy initiatives, aimed at solving these issues using a more progressive

approach of planning land use and the transportation facilities needed to support it. The

following are excerpts from the City of Toronto's Official Plan that speak to the type of

development and the type of transportation facilities that will need to take on a higher level of

priority:

> *"Promote mixed use development to increase opportunities for living close to work and to encourage walking and cycling for local trips"*
>
> *"Support the use of existing public investment in transit and other municipal assets, and create strong pedestrian and cycling linkages to transit stations."*
>
> *"Walking and cycling will be encouraged by creating safer and more attractive conditions in employment districts"*
>
> *"In a mature city like Toronto, the emphasis has to be on using the available road space more efficiently to move people instead of vehicles and on looking at how the demand for vehicle travel can be reduced in the first place. Reducing car dependency means being creative and flexible about how we manage urban growth. We have to plan in "next generation" terms to make transit, cycling and walking increasingly attractive alternatives to using the car and to move towards a more sustainable transportation system."*
>
> (City of Toronto, 2002)

In many cities in North America, sprawl and long trip distances are the primary reason that cycling is considered by many to be infeasible by most residents. In Toronto however, many neighborhoods have a dense concentration of residents, employment, and amenities and cycling is a very viable mode choice for the residents. However, one of the other major deterrents for cycling in the city is the perceived safety of the mode; many citizens are resistant to cycling in the city because they do not feel safe doing so (City of Toronto, 2009).

The 2009 City of Toronto Cycling Study suggests that a concern for potential utility cyclists is related to safety. Further to that, the consensus amongst current riders and non-riders is that having more bike lanes and by improving facility design to separate cyclists from

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regular traffic, would have the greatest impact on making cycling safer and more viable in the city. This finding was and continues to be the primary catalyst in an effort to implement more effective cycling infrastructure around the city and to further develop the existing cycling network (City of Toronto, 2009).

Toronto has experienced increases in cycling numbers as well. As numbers increase, so too does the demand for more infrastructure, which provides further justification for the continuing improvement of the network. To be specific, cycling numbers in the City of Toronto have increased by 30% between 2001 and 2006 (Statistics Canada, 2006) and in high volume cycling areas in downtown, like the intersection of Spadina Avenue and College Street, the number of cyclists has increased by 74% in the past three years (Simcoe, 2015).

The development of a successful and robust cycling network will require the bridging of gaps between major cycling corridors. Turning left through a major intersections represent one of these network gaps. By gaining a better understanding of the stochastic nature of cyclists behavior at intersections, more accurate micro-simulation models can be developed that will help creating the most affective designs to encourage good behavior and to create a comfortable cycling environment.

The 2001 Cycling Strategy has set out a framework for identifying areas that require improvement going forward. There is also a new cycling plan that is currently in development that will help guide new cycling projects in the city going forward. In conjunction with these efforts, this thesis will help to identify which types of facilities are the most affective at promoting the natural tendencies of cyclists in an effort to help inform facility selection decisions going forward.

3.0   CHAPTER 3: LITERATRE REVIEW

This literature review summarizes the research that has been conducted related to cycling infrastructure in the context of this study. Specifically, this literature review focuses on studies that support the opinion that building proper bicycle infrastructure has positive impacts on a community. It also supports the opinion that modelling and observing cyclist behaviors are important components in the process of building a better cycling environment. This literature justifies the need for this research, identifies the research done to date, and identifies the gaps in that research that this thesis investigates.

3.1   THE BENEFITS OF PROMOTING UTILITY CYCLING

The benefits of promoting utility cycling in a city have been well documented across many disciplines, from public health, to urban planning, and economics. This chapter summarizes the findings from two reports by major organizations that identify the benefits of investing in cycling infrastructure.

The World Health Organization (WHO), in their 2003 report titled "Social Determinants of Health: The Solid Facts Second Edition," identifies the importance of transportation policy and mode choice on the health of society.   The report identifies four ways in which taking measures to promote cycling and the use of public transit can improve public health: increased social contact, improved air quality, reduction in fatal traffic accidents, exercise.

The report suggests that by creating policy that promotes active modes of transportation, individuals can make up for the lack of physical activity in other aspects of their life.   Other benefits of promoting active modes include the social interactive component of these modes. Where cars alienate and separate people for their fellow travelers, walking, transit and cycling can promote interaction within a community (World Health Organization, 2003).

Another aspect of improved public health that comes from promoting active modes and transit are that deaths from traffic accidents would decrease. As active and transit modes

increase, fewer accidents will occur from high speed car crashes (World Health Organization, 2003). It calls for well-designed urban environments that separate cyclists and pedestrians from car traffic to create an environment that is safer for users.

The WHO report above is a summary of findings across multiple disciplines and uses a broad contextual lens to identify the benefits of promoting cycling. The second report, which is summarized below, is more context specific to the United Kingdom (UK) and uses a quantified cost benefit approach.

The Department of Transportation (DOT) in the UK released a report that summarizes cost benefit ratios of several proposals for new bicycle infrastructure.   The DOT had a total £94 Million to allocate to bicycle infrastructure projects in cities and National Parks. The allocation of the funding was prioritized based on the various funding proposals. The cost benefit for each proposal was considered. (Department for Transport, 2014)

The majority of benefits came from improved health and the societal benefits that could be quantified from improved public health. The HEAT tool, designed by the WHO was used to generate monetary values associated with increased physical activity in society.

The second most common benefit was that of the benefit of reduced road congestion. Included in this benefit, were the economic gains from reduced congestion (time), reduction in traffic accidents, and also decreased GHG emissions and air pollution.

The cost benefit ratio results for each proposal ranged from 3:1 to 13:1. In all proposals, the B/C ratio was positive, and in some cases was extremely high. Overall, the investment of £94 Million was calculated to provide a benefit of 5.5:1. Meaning that for every £1 spent, the benefit would be £5.5 in social and environmental benefits (UK D.O.T., 2014).

This report is another example of the type of analysis that has been conducted to indicate the overwhelming benefits that come from investment in bicycle infrastructure.

3.2 PROMOTING CYCLING CULTURE THROUGH DESIGN

By designing urban areas to better accommodate cyclists, gradually, a bicycle culture can be created as more people see cycling as a viable and comfortable transportation choice. By introducing new cycling facilities, more cyclists will ride. The following two sources are some examples of the research that support the strategy of building better bicycle infrastructure as a way of promoting utility cycling in a city. The first is a report found in the Transportation Research Record that takes a scientific approach to quantify the variables, specifically the implementation of new cycling facilities, that affect the propensity to cycle in that city. The second report is a case study that summarizes the historical policy initiatives that helped the community of Davis California to become one of the best cycling communities in North America.

A study conducted by Jennifer Dill and Theresa Carr in 2003 set out to identify the variables that affect the propensity to cycle in a city. Several survey based, stated preference studies were conducted and from them, the stated preference among the respondents was that if better infrastructure was built, that they would be more likely to use it. This stated preference method has its limitations, and so this study used revealed preference using data from 43 cities and a multi-variate regression comparing different input variables to amount of people commuting by bike in the city. The study concludes that,

"Higher levels of bicycle infrastructure are positively and significantly correlated with higher rates of bicycle commuting." (Dill & Carr, 2003)

This is a significant study within the North American context that suggests that investment in bicycle infrastructure will yield higher splits of bicycle commuting (Dill & Carr, 2003). A simple conclusion might be that increased cyclist numbers in a given area are inevitable for other reasons, and when a city that notices this trend builds new infrastructure to support it. However, this study suggests a causal relationship; that building infrastructure has a direct impact on cycling numbers (Dill & Carr, 2003).

The 2008 paper titled "50 years of bicycling policy in Davis, California (Buehler & Handy, 2008)" looks at the evolution of the community of Davis, California from a small farming community, to the "bicycle capital" of America. Although there are several variables, unrelated to policy and infrastructure, such as mild topography and weather that made this an ideal location for cycling, there were several public policy decisions that contributed to the development of Davis into a bicycle friendly community.

The first major policy decision was made at the local University. As the University was anticipating expansion in the 1940s, the president of the University instructed the planners to plan for a bicycle friendly campus and to encourage incoming students to bring their bicycle to campus. This level of leadership from an enthusiastic decision maker lead to the type of development that helped Davis become the bicycle friendly community that it is today (Buehler & Handy, 2008).

Like many other communities during the post war development boom that saw the rise of the personal automobile and a sprawling urban fabric, Davis was no exception. As car traffic grew in the community, the conflict between cars and bikes started becoming a problem of increasing prevalence. However, where other communities welcomed and planned for this new trend and alienated the bicycle and other modes in favour of the automobile, Davis maintained its priority of developing and promoting the bicycle as a utility transportation mode. As such, in 1963 the development plan for the university called for the elimination of cars from the campus core, the provision of several bicycle thoroughfares, and accommodation for bicycle parking throughout the campus.

The early 1960s in Davis was marked by the continuing angst between cyclists and automobiles, but the municipal election in 1966 was a major milestone as the elected council was pro-bicycle and recognized that more progressive solutions would be required to create a safe environment for all road users. The presence of the new leadership lead to the opening of the community's first bike lane in 1967 (Buehler & Handy, 2008).

Having leaders that recognized the benefits of cycling in the policy and decision making arena was crucial in the development of the cycling environment for Davis going forward.

Planners and engineers used best practice solutions and observations from the Netherlands to justify it and became pioneer in North America. The 1990s saw decline in bike use primarily as a result of declining investment and a discontinuation of programs focused on promoting the mode. This era also marked the retirement of the original bicycle advocacy group that was a major reason for early success.

The case of Davis California is a great example of the influence a few enthusiastic and competent leaders/champions can have on promoting the construction of bicycle facilities and the affect that those facilities can have on the use of the bicycle as a viable mode of transport.

3.3   TYPES OF BICYCLE FACILITIES

There are several types of bicycle facilities that have become common practice solutions for creating a safer and more comfortable environment for cyclists. Lane markings, infrastructure, and signage are all such examples. The focus of this research is on improving the condition for cyclists making a left turn through an intersection. Therefore, the following is an inventory of the facilities that have been implemented to improve the left turn in the City of Toronto.

The Bike Box

Bike boxes extend out from the bike lane, in front of the vehicle stop line at signal controlled intersections to allow cyclists to move to the front of the queue at an intersection. This positioning allows cyclists to take advantage of the advance green for left turns and to allow numerous cyclists to proceed straight through an intersection, ahead of motorists, once the green signal begins. (Ministry of Transportation of Ontario, 2013).

< Figure 1 is an example of a bike box at the south-west corner of Harbord Street and Spadina Aavenue in Toronto, Ontario. The initial design did not include the green coloured surface. The surface colour was added after to improve awareness of the facility's presence for both cyclists and motorists. This design allows for cyclists riding eastbound down the Harbord Street bike lane to jump to the head of the queue for all turning movements.

This diagram from the Ontario Traffic Manual for Bicycle Facilities illustrates the design of bike box on a two lane road. Like the photograph above, this bike box allows cyclists to travel from the bike lane to the front of the queue to perform left, through, and right turning movements.

(Ministry of Transportation of Ontario, 2013)

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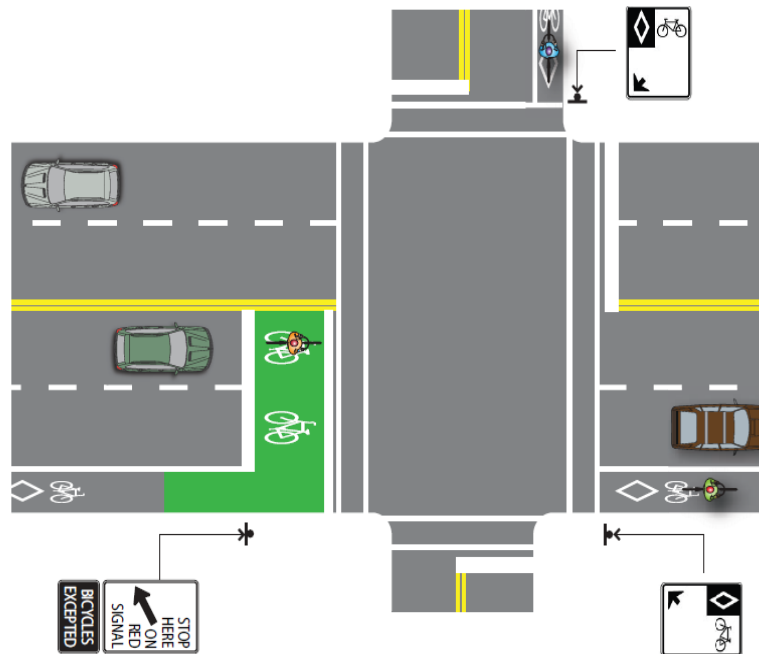
The Two-Phased Left Turn

Figure 2 - Two-phased left turn
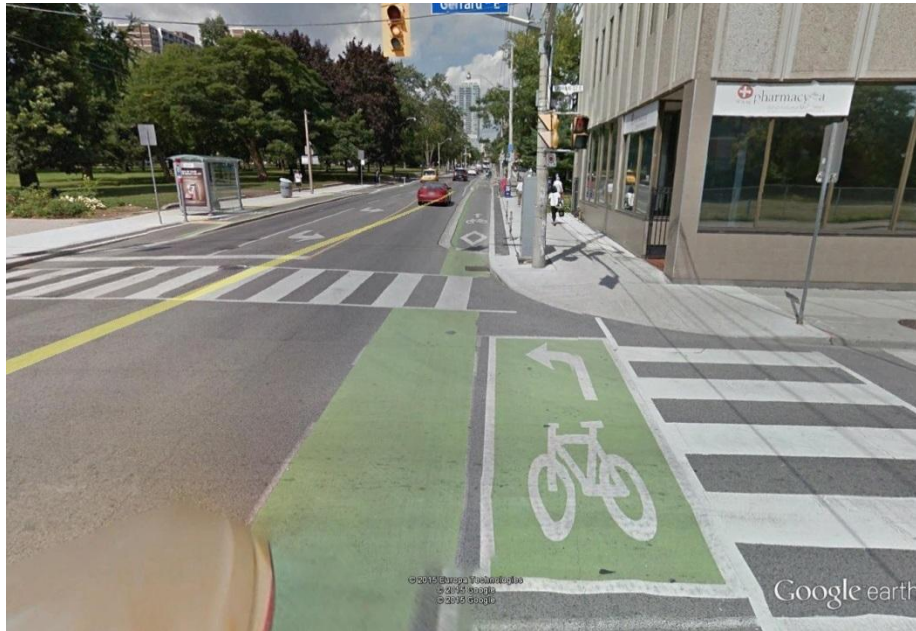
< Figure 2 is an image from Google Earth Street view. It is the two-phase turn box located on Sherbourne street in Toronto. These left turn facilities are located all along the Sherbourne Street cycling route to help facilitate the left turns of cyclists turning left off of Sherbourne Street.

Two-phase turn boxes allow cyclist a space to wait for the signal to turn green after they've crossed the intersection, in the middle of turning left through an intersection. This design can also be referred to as "the Copenhagen Left" due to its original implementation in Copenhagen and its prevalence in the Copenhagen cycling network. This facility is effectively used by left turning cyclists as they approach a signalized intersection during a green signal phase. The box is located between the cycle lane and the pedestrian crossing. This is an important feature to eliminate the impedance of pedestrians and cyclists moving straight through the intersection.

Left Turn Lanes

Although the left turn lane is built to accommodate left turning vehicle traffic, it can also better facilitate left turning cyclists. Cyclists that use the left turn lane to conduct a left turn through an intersection must cross the general purpose lanes between the bike lane and the left turn lane. As the amount of lanes and the density of automobile traffic increase, the gaps in traffic

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decrease and this maneuver becomes more challenging.   In the example illustrated in Figure 6, cyclists must wait for an appropriate gap in traffic to traverse the through lane to get to the left turn lane.

Figure 3 - Vehicle Left Turn Lane

< Figure 3 exemplifies an approach to an intersection that has a left turn lane, one through lane, and a bike lane. This is at the intersection of Annette St. and Runnymede Avenue in Toronto.

Cycle Tracks

Cycle tracks run parallel to the road way but are separated by a barrier. This barrier is usually in the form of bollards, a raised curb, a boulevard, or parking. This barrier helps to prevent the conflict between forward moving cyclists and automobiles.

Figure 4 - Cycle Track
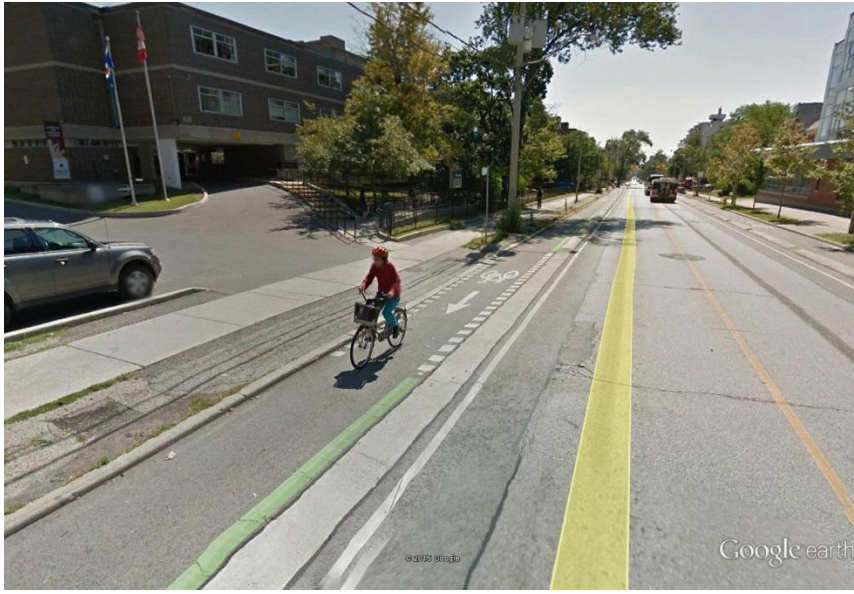
< Figure 4 is an example of a section of cycle track on Sherbourne Avenue in Toronto. This cycle track is separated from the automobile lanes by a raised curb.

Bike Lanes

Bike lanes are road markings that identify an area for cyclists, separate from automobile traffic. Bike lanes are usually 1-2 meters in width in urban areas and are delineated by a solid white line. In sections where crossing a bike lane is necessary for laneway and drive way access, dashed lines are used.

Figure 5 - Bike Lane

< Figure 5 is an example of a bike lane found on Harbord Street in Toronto. At this location, a dashed white line is used to indicate the entrance to the lane way.

3.4   PERCEIVED SAFETY

There are several variables that influence an individual's mode choice decision, including safety, cost, convenience, comfort, and reliability. When it comes to choosing cycling as a mode choice, safety is one of the most influential factors.

As indicated in the context chapter of this thesis, perception of safety plays a major part in promoting cycling as a mode of transportation. It is important to define the concept of "perceived safety" and how it differs from actual safety. Actual safety can be quantified by accident rates, fatalities, etc. Perceived safety, although partially a function of actual safety, is a more qualitative measure (opinion based) and is related to the perception of safety, or whether or not someone feels safe riding their bicycle to get from their origin to their destination.   The perception of safety of a given network, or of a given origin and destination (O-D) varies greatly across the population of current and potential cyclists. Current and

potential cyclists represent a wide range capabilities and confidence levels, their perception of safety differs accordingly, and it is a challenge to create a network that meets the needs of everyone. Ideally, a bicycle network should be made up of several options for any given O-D, each appealing to different levels of riders. For example, a single O-D might consists of 4 potential routes. One of these routes might have a segregated bike lane, one might be along a major arterial, with no bike facilities, and the other two might be along side streets. Depending on the safety of each of these route alternatives, riders with different confidence levels might choose a different option.

This type of O-D route decision process was modelled in a 2014 paper titled "Modelling Cyclists' Route Choice Based on GPS Data" (Casello & Usyukov, 2014). This paper assumes that there is a trade-off between directness of a given route and the safety of a given route in that a cyclist may choose the longer route if it is safer (Casello & Usyukov, 2014). With this, it is assumed that as the proportion of people that perceive a given cycling route to be safe increases, it is more likely that they will consider cycling as a viable mode choice and cyclist numbers will increase.

As cities build their network, since much of it might already cater to high level, comfortable cyclists, new facilities will help promote the use of cycling for current non-riders that use the lack of safety as their reason for not cycling.   The following section is a summary of the research relating to the perception of safety of cycling, and how this impacts the willingness of a population to cycle and how design can improve this perception. Rule compliance and the use of safety equipment are also explored as indicators for perception of safety and the quality of a cycling environment.

Perceived Safety and Propensity to Cycle

As identified in the context portion of this thesis, cycling numbers in Toronto are heavily influenced by the perceived safety of the mode. It has been concluded and incorporated into Toronto planning policy that improving the environment by building separated cycle lanes and

cycle tracks will improve the condition and therefor increase the number of people the cycle to work in the city. The 2009 City of Toronto Cycling Study suggests that 40% of recreational cyclists would consider biking to school or work, and that half of them would do so if it was safer to do so (City of Toronto, 2009).

Consensus amongst researchers is that the perception of cyclist safety in established cycling cities, such as Copenhagen, is much better than in up and coming cycling cities like Brisbane and Toronto (Chataway, Kaplan, Nielsen, & Prato, 2014). The need to share the road in networks that are incomplete, like most networks in North America and Australia, compared to more developed networks of Europe, proves to be a major cause for concern amongst potential riders as the road sharing experience is perceived to be highly stressful for cyclists in these contexts.

Safety Gear as an indicator of Perceived Safety

Several studies have investigated the link between the propensity to wear safety gear and the perception of safety. It is suggested, and as one might intuitively assume, the propensity to wear safety gear (i.e. higher helmet usage) is correlated with higher perception of risk (Chataway, Kaplan, Nielsen, & Prato, 2014). In this study, the percentage of cyclists wearing helmets was 63% (1041 of 1648 cyclists). In Denmark, counts from the Cycling Embassy of Denmark suggest that just 15% of Danish cyclists wear a helmet. This would be an indication of the difference in perceived safety between the two cities.

Rule Compliance as an indicator of the completeness and quality of a cycling environment.

In a study conducted by the Copenhagenize Design Co., left turning cyclists at a high volume intersection in Copenhagen were analyzed using revealed preference behavior through observation. The purpose of the study was to compare the desire lines of the cyclists to the design of the intersection to assess the effect of the design on promoting rule compliance and facility compliance. The design that was analyzed in the study was a two-phased left turn box, referred to as a "Copenhagen Left" in this study, to facilitate the left turn of cyclists trying to navigate the intersection. Results revealed that 86.5% of cyclists turned left using the facility and therefore conformed to the facility design, 2.2% used the same maneuver as a left turning automobile, and 11.3% performed a "snake" crossing, which entails crossing the near side pedestrian cross, to minimize wait times at the signal, then crossing over once the light changes to get to their desired direction of travel. Figure 6 shows the three types of left turns that were observed. 63% of these "snake turners" got off their bike to cross the pedestrian area, and the remaining 37% stayed on their bike (Copenhagenize Design Co., 2014).

Figure 6 - Three left turn behaviors
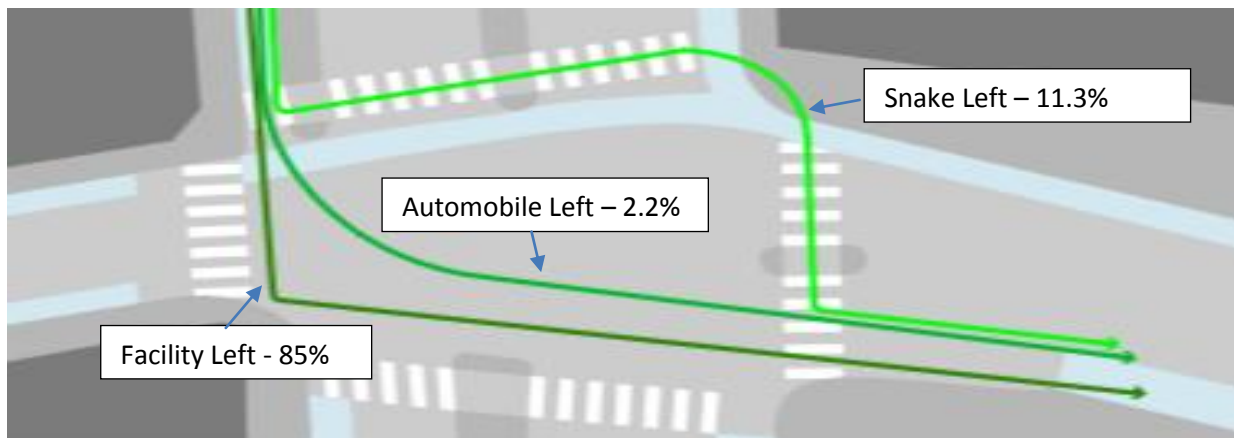
This high rule compliance is common across cities with highly developed cycling networks. In cases like Copenhagen, where the cycling domain is well defined and the network is complete, there is little incentive to break the rules for safety or convenience reasons, and doing so would result in high risk of collision and high ridicule from other road users.

3.5   TRAFFIC MODELLLING

In today's political arena, it can be a challenge to get leaders and policy makers to deviate from the status quo. Changing from the traditional paradigms of car centric improvements to improve traffic congestion could be viewed by the politician as "political suicide" and unconventional. Sound reason and scientific proof that is clearly communicated is imperative to the process of promoting the implementation of progressive and alternative transportation modes. However, generating these data and forming this argument in an easily communicable way is a challenge. Simple computer simulation models can be an effective way to communicate. By generating models that include active transportation, we can demonstrate, within the limits of the model, that bike infrastructure can be used to alleviate congestion, rather than relying on hypothetical arguments to promote such solutions.

Caliper Corporation identifies the following benefits of modelling:

- "provides something real for stakeholders to react to, rather than arguing abstract hypotheticals."

- "helps to build understanding of the level-of-service impacts on communities of transportation projects"

- "asks and answers what if? Questions"

- Prioritizes funding and projects

- Base decision making on state-of-the-art analysis

- Engage the public through dynamic and compelling visualization

(Caliper Corporation, 2013)

Traditionally, there is a major gap between efforts in transportation modelling, which are usually headed and carried out by engineers and technical staff, and the more qualitative methods used by planners and urban designers. There is an opportunity to bridge the gap between these two approaches by using the conceptual and observation of desire lines and to incorporate these behavioral tendencies into simulation models.

By observing behavior, we can design an environment that is better suited to the natural and comfortable tendencies of the cyclists instead of trying to design within the confines of the road, which is designed primarily for the automobile.

By taking into account observed behavior, we can develop distributions of behavior and model those tendencies and the propensity for a cyclist to behave a certain way under varying conditions. As these get incorporated into traffic simulation models, instead of assuming that cyclists will follow the rules that are defined by the design of the roadway, a more realistic approach to modeling cyclist behavior can be developed.

Modelling Efforts to Date

Extensive amounts of literature and software development have gone into improving micro-simulation traffic models. Traditionally, these models are focused on the flow of motorized traffic, including freight movement, public transit, and automobiles, with significantly less consideration for bicycle traffic, and how bicycles interact with other road users. Traffic modelling, for both bicycles and automobiles, can be separated into three different categories:

1. How users of the system/mode interact to specific conditions of the road/surface

2. How users of the system/mode interact with traffic control systems and intersections

3. How users of the system/mode interact with other road users.

Each of these categories has variable distribution of behavior/interaction associated with it, but when it comes to cyclists, even more variability and unpredictability exists. Table 1 below outlines the input variables associated with each category for both automobiles and bicycles. The highlighted items in the table are the focus of this thesis. Component 1 is highlighted in green and component 2 is highlighted in orange.

Table 1 - Micro-Simulation Input Parameters

	Automobiles	Bicycles	
Road	Flow, speed and density variability across road hierarchy. - Arterial - Local Street - Controlled Access	Speed and acceleration variability across different facility/road type - No Bike facility - On street bike lane - Off Street bike path	Component 1
	Speed distribution as a function of road grade	Speed distribution as a function of road grade	
	Lateral movement within a lane	Lateral Movement within a lane	
Traffic Control	Distance between stopped vehicles.	Distance between stopped vehicles.	
	Lane Changing Gap acceptance – moving over to turning lanes	Lane Changing Gap acceptance – moving over to turning lanes	
	Acceleration from stop, away from intersection.	Acceleration from stop, away from intersection.	
	Deceleration approaching an intersection – Stopping Distance	Deceleration approaching an intersection – Stopping Distance	
Users	Distribution of driver types and erratic behavior probability distributions.	Distribution of left turn behaviors at intersections. Cyclists could act like pedestrians or they could act like cars. Behavior is much more erratic than motorist behavior at an intersection	Component 2
Other Vehicles	Lateral movement within a lane	Lateral movement within a lane	
	Following distances with other vehicles	Following distances with other vehicles	
	Passing conditions	Passing Conditions	

In 1999, A.Faghri and E.Egyhaziova developed the first computer simulation to include bicycles in a mixed traffic micro-simulation. At the time that this paper was published, very little research had been completed on the modelling parameters of cyclists. Where there were significant gaps in the data, this study collected new data (Faghri & Egyhaziova, 1999).

An acceleration rate for bicycles in this model uses a constant rate of acceleration for level grade and a linear equation to determine acceleration as a function of road grade but uses the same linear grade/acceleration function for bike acceleration as it does for other vehicles. The car following assumptions in this model also uses the same principles of behavior as automobiles, with slight adjustments for the differences in vehicle characteristics (deceleration, acceleration).

Desired speed for cyclists is either maximum speed on road link or maximum speed for cyclists. There are no distributions of speeds considered, rather just one generic speed for all cyclists.

As this was the first micro-simulation to include bicycles in mixed traffic, it represents a baseline to work off of. However, there are significant shortcomings that lead to the need for further development and research into the variability amongst different cyclists' physical (vehicle) characteristics, and behavioral (user) characteristics.

In 2013, Caliper Corporation recognized that previous mixed traffic micro-simulation models did not have proper inputs for cyclists and so they set out to investigate and improve these parameters. The justification for the research was based on the recognition that motorists and cyclists have significantly different behavior and that variability in behavior from one cyclist to the next is extensive, even more extensive than that between motorists.

Caliper Corporation generated inputs for speeds, following distances and acceleration, lane changing, gap acceptance, critical distance with some consideration for average behavior and distributions of behaviors amongst the mean. (Caliper Corporation, 2013)

This research has made considerable improvements to developing distributions of physical characteristics of bicycles for inclusion in mixed traffic micro-simulation models. It has

done so by analyzing the physical movement of cyclists and developed distributions of these movements. However, the extensive variability of behavior amongst cyclists is not considered here.

3.6   GAPS IN THE LITERATURE

This literature review provides a thorough review of why improving cycling infrastructure is an important part of making our cities better places to live. The literature also suggested that in order to make this happen, it is important to understand the behavior of cyclists on a more practical level so that proper infrastructure can be built; infrastructure that is designed to match the intuitive nature of cyclists.

The literature on modelling cyclists has gaps in addressing the stochastic nature of cyclist behaviors at intersections as well as how the desired speed of a cyclist is variable depending on input conditions such as path type or gender of the cyclist. In the models that have been reviewed in the literature, just one generic behavior is considered for a cyclist in a model. A huge amount of variability can occur at an intersection with regards to the desired path a cyclist takes and whether a cyclist complies with the rules of the road or the way the facility is designed.   This study observes the behavior of cyclists at an intersection and specifically identifies the various methods that a cyclist navigates the left turn through the intersection. By identifying the distribution of behaviors, we can improve the input parameters for modelling cyclists at various intersection types.

In addition to providing improved input parameters, analyzing cyclists' behavior can help to improve intersection design to satisfy the natural tendencies of cyclists (desire lines). By including design elements within a facility that matches the natural desire lines of a cyclist at a specific intersection, we can yield better results in terms of rule and facility compliance and overall make the design match the desire to improve safety and predictability of a cyclist.

4.0   CHAPTER 4: METHODS

4.1   COMPONENT 1 METHOD

The purpose of this component of the research was to investigate a set of cyclist GPS data and develop distributions of desired speed to provide a range of inputs for desired speed that can be adopted by the VISSIM micro-simulation models. VISSIM is commonly used micro-simulation software developed by PTV Group and will be the software that is referred to in this thesis.

In 2011, a student at the University of Waterloo conducted a study to gain information on the behavior and physical attributes of cyclists in Waterloo Region (Rewa, 2012). Participants of the study carried GPS units on them on their bike trips over the course of the study period. The GPS units were then returned to the researchers and the data were extracted and summarized into a database.

For the purpose of this analysis, data from 108 participants were analyzed. The number of trips from each participant varies, but the GPS units were configured to collect the following information:

- XY coordinates every 3 seconds

- Z (elevation) values every 3 seconds

- Velocity every 3 seconds

There was also a survey component to the study. For the purpose of this analysis, the gender and age information from the surveys were analyzed. Of the 108 participants, 75 provided age and gender information.

Desired Speeds and Cyclist Attributes

The desired speed of a cyclist refers to the speed at which the cyclist stops accelerating, and maintains a constant cruising speed. In the traffic modeling context, this refers to the speed a cyclists would accelerate towards.

Desired speed distributions are based on the 85th percentile speed of each study participant. By choosing the 85th percentile speed, the top speeds and outlier speeds of a participant can be considered above desirable as a result of various factors, such as significant downhill periods, miscalculation of the GPS device, or other unexplainable factors.

To determine the 85h percentile speed of a participant, all the data points from every trip was grouped into one worksheet, speeds of 0 km/h were filtered out, and the excel function (=PERCENTILE,.85) was applied to the speed column.

Once a value for desired speed was determined for each cyclist, the cyclists were separated into age and gender groups to determine if desired speed varied depending on age and gender characteristics.

To determine if there was a difference between the desired speeds of the female and male study participants, a two sample t-test of means was completed.

To determine if there was a difference between the desired speeds of each age group, an ANOVA test for equality was conducted on the sample means.

The results of these hypothesis tests are summarized in the results chapter of this thesis.

Desired Speeds on Gradients

A macro was developed to determine average speed over a "hill." A hill was defined by a succession of increasing or decreasing elevation values. When the elevation value switched from a negative to a positive value (or visa-versa), the hill ended and the average grade and speed for that hill was calculated.

The elevation data were collected during data collection. The accuracy of these data had been improved by deleting outliers to eliminate situations of extreme discrepancies from the altitudes of the study area.

For each participant, the 85th percentile speed was determined for each gradient. The gradients were separated into 1% intervals. A linear regression analysis was applied to determine how speed is a function of the change in road grade.

Facility Type and Speed

Using ArcGIS software, participant route shapefiles were created. Using a Region of Waterloo cycle network shapefile, each cyclist data point was assigned a facility type based on the facility type in the cycling network shapefile.   If the data point was not in proximity to a cycling facility, it was assumed that the point was not on a cycling facility.

Once the facility type was added to the data base files, analysis could be conducted.

A macro was created that determined the average speed for three different facility types:

1. Off Road Path

2. Bike Lane

3. No Facility

The macro can be found in: CalcGandV Macro (Appendix A)

To determine if there was a statistical difference between the speeds in each facility, an ANOVA multiple means test was conducted.

4.2   DATA LIMITATIONS AND RELIABILITY IN COMPONENT 1

Most of the cyclists in this study were considered experienced cyclists based on a participant survey and therefore the sample did not include a lot of variability in the types of cyclists with ranging competence and comfort. Also, since the cyclist knows they are being tracked, it can have an influence on their performance. When a cyclist is not aware that they are being observed, more candid behavior and performance might occur.

The desired speed as a function of road grade only considered road grade as a factor and did not consider the presence of traffic control or the gradient prior to and after the hill. The grades in the study area were also relatively flat as there are no major hills. The topography in the area is also extremely variable as the natural landscape is made up of shallow rolling hills. This makes it difficult to apply a constant speed to a hill because hills end before a desired speed can be reached.

4.3   COMPONENT 2 METHOD

The behavior of cyclists at different types of intersections was determined by collecting digital video footage at each intersection of study during peak hours.

For each intersection, two cameras were set up; one capturing footage along the E-W corridor and another capturing footage along the N-S corridor. Two cameras were required in order to capture the complete turning movements of the cyclists approaching from all directions as well as the traffic conditions upon approach of the intersection.

Two traffic conditions were observed on approach:

1. Signal phase on approach (Green or Red) – This refers to the signal phase that the cyclist bases their decision on.

2. Traffic volume on approach

This is an observational evaluation of the traffic volume. To equate it to an exact traffic volume value, further research would need to be conducted or applied to transfer the observational

volume in a specific instant to the traffic volume counts of the subject intersection. The following three volume conditions were considered. It should be noted that these are volumes based on the instant of observation and gap times were not calculated. For inclusion in micro-simulation models, further work would need to be conducted to determine gap size related to volume data and to categorize gap size into the low, medium, and high volume categories identified in this thesis.

a. Low volume refers to traffic flow that is sparse and provides no hindrance for cyclist to cross the general purpose traffic lane to get to the left turn lane. Further observation would need to be analyzed to determine which v/c ratio range might apply to the "low volume" category. As a speculative example, low volume might represent a v/c ratio of 0.3 or less.

b. Medium volume refers to traffic flow that has some traffic adjacent the bike lane but gaps are large enough to comfortably change lanes to get from the bike lane to the left turn lane. Further observation would need to be analyzed to determine which v/c ratio range might apply to the "medium volume" category. As a speculative example, low volume might represent a v/c ratio between 0.3 and 0.7.

c. High volume refers to heavy traffic flow with very few or no gaps to safely cross from the bike lane to the left turn lane. Further observation would need to be analyzed to determine which v/c ratio range might apply to the "high volume" category. As a speculative example, low volume might represent a v/c ratio of 0.7 or greater.

d.

The cameras were either fastened to a telephone poll (approx. 3 meters up) or on top of a high surface, such as a community notice board or bus shelter. This allowed for the viewing angle to be unobstructed by most passing vehicles.

The method of choosing the intersections of study was based on the following criteria:

1. The Intersection of two bicycle routes (defined by the presence of a bike lane, shared lane, or cycle track).

2. One through lane in each direction (with the exception of one subject intersection).

3. The presence of a vehicle left turn lane

4. A combination of different treatments of bicycles at intersections, including:
   a. No treatment
   b. Two-phased left turn (Sherbourne Avenue)
   c. Bike Box (St. George and College Street)

Six intersections were included in the study that represent five different types of intersections:

1. Annette Street and Runnymede Road, Toronto (vehicle left turn lane and bike lane only)

2. Sherbourne Street and Wellesley Street, Toronto (cycle track and two-phased left turn box)

3. Dundas Street and Jones Avenue, Toronto (vehicle left turn lane and bike lane only)

4. St. George Street and Hoskin Avenue, Toronto (bike lane and bike box)

5. St. George Street and College Street (bike lane and bike box and advanced green signal)

6. Harbord Street and Spadina Avenue (two through lanes, vehicle left lane).

Table 2 below indicates each of the intersection types, the facilities that are included in each, and the location of each of the intersection types. Figures 7-12 are schematics showing the camera set ups for each intersection of study.
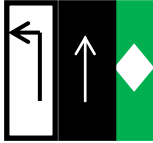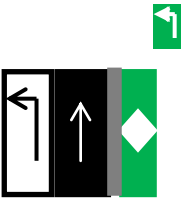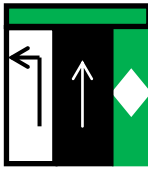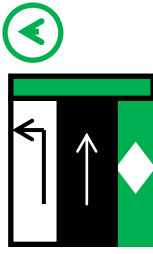
Table 2 - Intersection Types
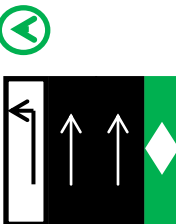
Intersection Type	Locations	Intersection Configuration	Description
1	Runnymede and Annette (all directions) Jones and Dundas (all directions)	BL, 1T, LTL 	The approach has an on street bike lane (BL), one through lane (1T) and a left turn lane (LTL)
2	Sherbourne and Wellesly (north and south bound approaches)	CT, 1T, LTL, PHASED LEFT BOX 	The approach has a cycle track (CT), one through lane (1T), a left turn lane (LTL), and a two-phase left turn box (PHASED LEFT BOX)
3	St. George and Hoskin (all directions)	BL, 1T, LTL, BIKE BOX 	The approach has an on-street bike lane (BL), one through lane (1T), a left turn lane (LTL) and a bike box (BIKE BOX)
4	St. George and College (South bound approach)	BL, 1T, LTL, BIKE BOX, AG 	The approach has an on-street bike lane (BL), one through lane (1T), a left turn lane (LTL), a bike box (BIKE BOX) and an advanced green left turn signal (AG).
5	Spadina and Harbord (north and south bound approaches)	BL, 2T, LTL, AG 	The approach has an on-street bike lane (BL), two through lanes (2T), a left turn lane (LTL) and an advanced green left turn signal (AG)

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Figure 7 - Camera set up - Annette Street and Runnymede Road

Figure 8 - Camera set up - College Street and Beverley Street
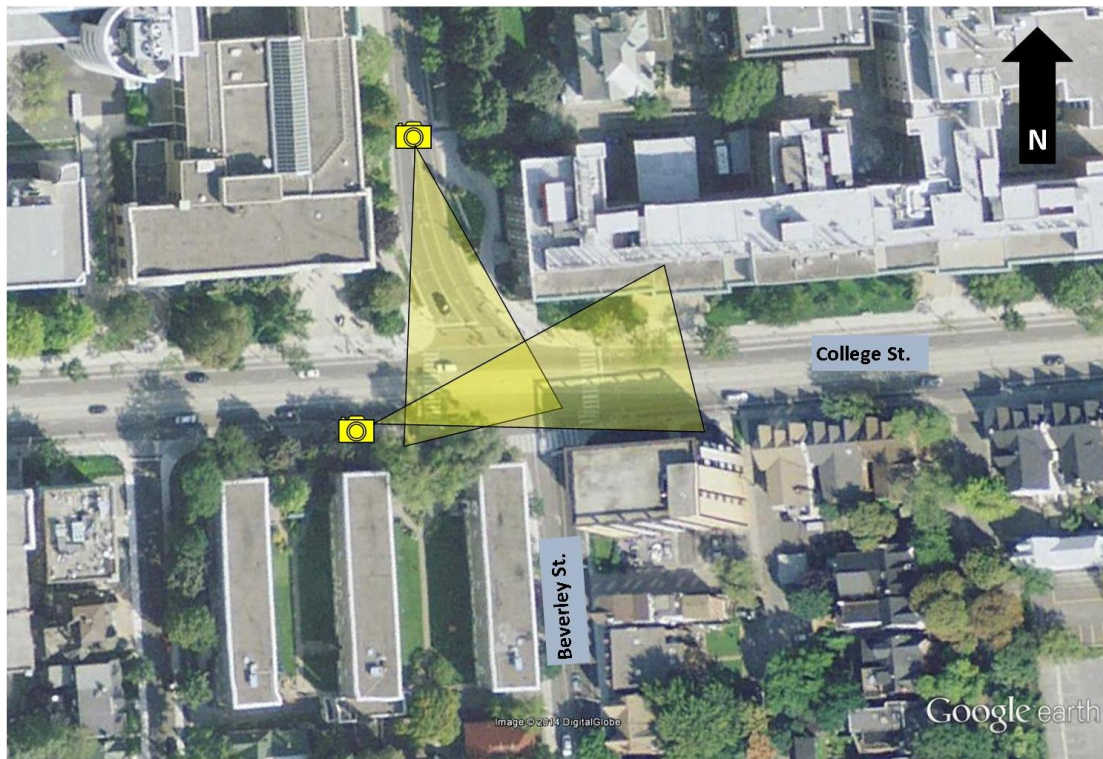
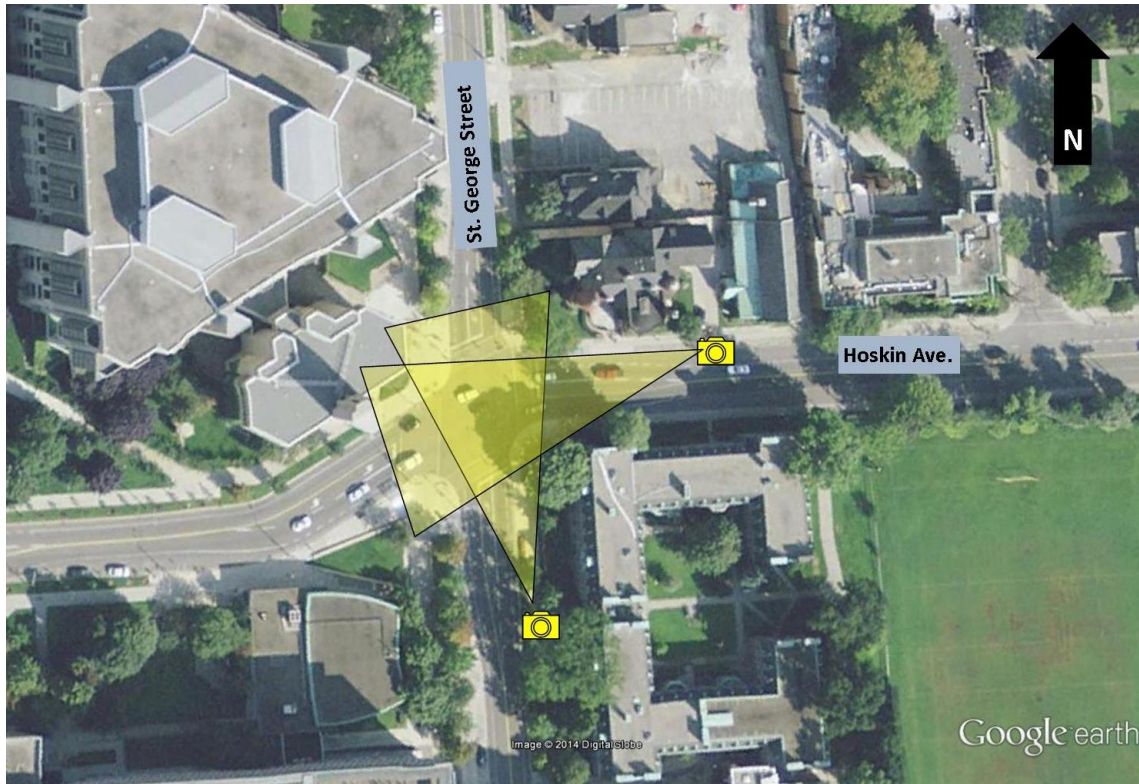**Figure 9 - Camera set up - Hoskin Avenue and St. George Street**

Figure 10 - Camera set up - Dundas Street and Jones Avenue

Figure 11 - Camera set up - Sherbourne Street and Wellesley Street
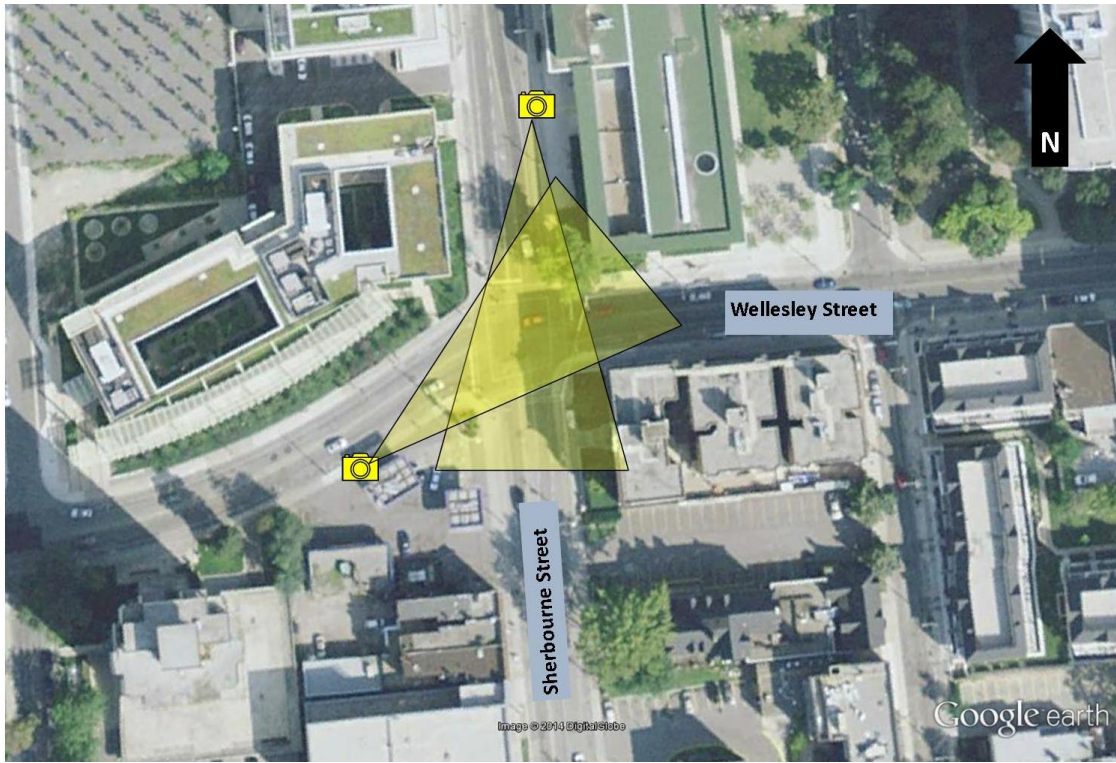

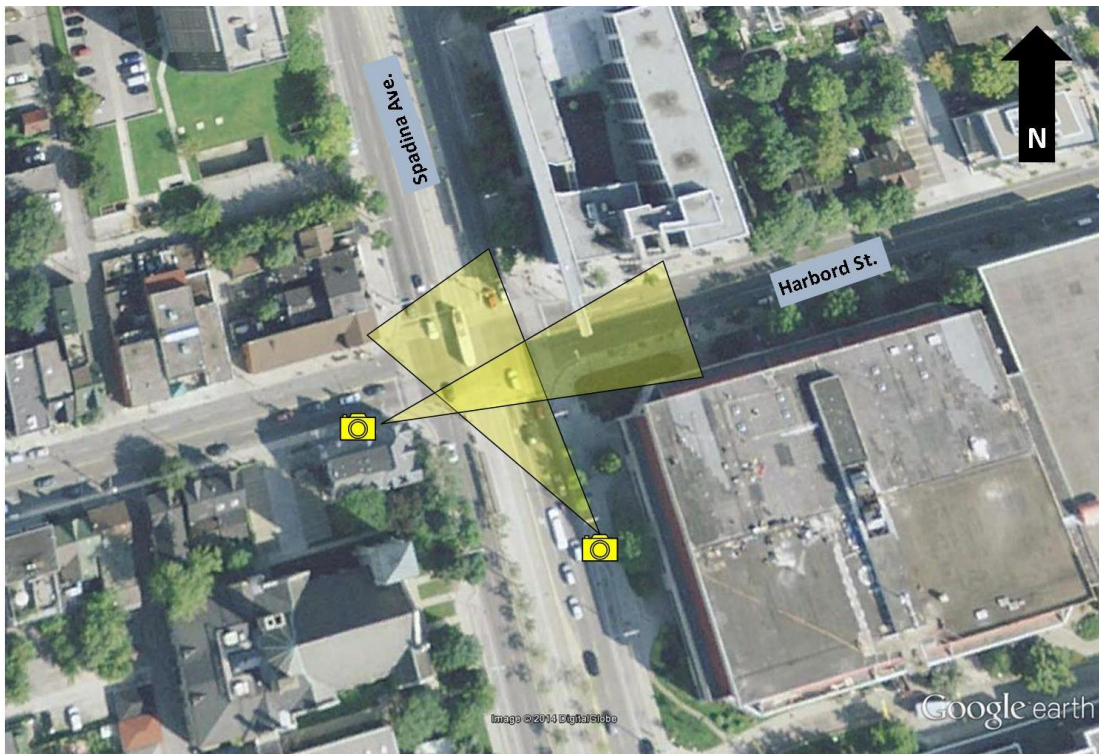**Figure 12 - Camera set up - Harbord Street and Spadina Avenue**

Table 3 provides a detailed summary of the data collection details at each intersection

of study.

Table 3: Data Collection Details

Location	Date and Time	Equipment	Data Collector	Characteristics
Runnymede Road and Annette Street in Toronto, Ontario	9/23/2014 3:23 pm – 5:00 pm	2 Sony Handycam Video Cameras: 1 on top of a community notice board and one strapped to a telephone pole		
Dundas Street and Jones Street	9/24/20142014 3:12 pm to 5:03 pm	2 Sony Handycam Video Cameras: both strapped to telephone poles		
Sherbourne Street and Wellesley Street	10/9/2014 9:11 am to 10:40 am	2 Sony Handycam Video Cameras: One strapped to a telephone pole and one sitting on top of a community notice board	Alex Mereu (thesis author)	Digital Video Data of Cyclists navigating the intersection. From this video data, the thesis author created a database of cyclist behaviors.
Harbord Street and Spadina Street	10/27/2014 4:00 pm to 6:00 pm	2 Sony Handycam Video Cameras: one sitting on top of a community notice board and one on top of a bus shelter		
St. George Street and College Street	10/8/2014 9:00 am to 10:30 am	2 Sony Handycam Video Cameras: one sitting on a bus shelter and one sitting on a garden stone		
St. George Street and Harbord Street	9/25/2014 3:43 pm to 5:30 pm	2 Sony Handycam Video Cameras: 1 on top of a community notice board and one strapped to a telephone pole		

4.4   Data Limitations and Reliability

The behavior and other descriptive variables of 1650 cyclists were recorded in this

study. However, of those 1650, just 322 of them were navigating a left turn direction. In some

of the low volume intersections studied, the sample of left turning cyclists was quite small.

Since each intersection had a similar amount of recorded time, the sample of left turning cyclists at the low volume intersections is lower than that of the left turning cyclists at the high volume intersections. If further studies are to be conducted using this methodology, more filming time at low volume intersections would be required, compared to that of the high volume intersections to ensure similar sample sizes across intersections and to ensure the sample of left turning cyclists is large enough at the low volume intersections.

It would be valuable to compare the rule compliance results of each intersection with the collisions at each intersection. However, collisions occurring at the intersections of study are very few over the last 5 years, and some of the intersection designs have been modified over the same time period. Also, collisions that are reported are believed to only represent 10% of collisions as a whole. Trying to draw comparisons or correlation between collisions at each intersection and the rule compliance at each intersection is therefore not reliable at this scale. If an inventory of all the intersections could be made and the rule compliance at each of those, that would be a worthwhile study moving forward. Since only 6 intersections were observed in this research, no reliable conclusions could be made between these two variables.

5.0   CHAPTER 5: RESULTS

5.1   Component 1 Results

The results of component 1 are intended help to improve the input parameters for cyclists within existing micro-simulation traffic models. The distributions of desired speeds for cyclists, as well as the affect grade and facility type have on desired speed are included in these results.

The Data

The database is comprised of data points, recorded every 3 seconds of a participants trip using a GPS unit. Each participant has a separate database that consists of several trips. For each study participant and each cycling trip, the GPS unit records the start time, coordinates,

altitude, and cyclists speed every 3 seconds. Table 4 contains an example of the outputs of the information in the form of an excel database. Further details regarding data collection can be found in the previously referenced study by (Rewa, 2012).

Table 4: Example Data Points

Track #	Date	Start Time	Lat		Long		Alt m	Speed km/hr
1	8/26/2010	18:16:22	43.44563	N	80.46718	W	301.9268	5
1	8/26/2010	18:16:27	43.44561	N	80.46721	W	297.532	6
1	8/26/2010	18:16:32	43.44559	N	80.46719	W	291.3782	8

From this information, the conclusions from this thesis were developed.   For example, the speed over the course of one participant's trip is show in Figure 13. The 85th percentile speed of the cyclist was calculated based on the 85th percentile speed across all trips and was included in the distribution of desired speeds across all cyclists is shown in Figure 14. As an example, the desired speed for cyclist in Figure 13 was 16 km/hr.

Figure 13: 1 Participant's Journey - Speed over time
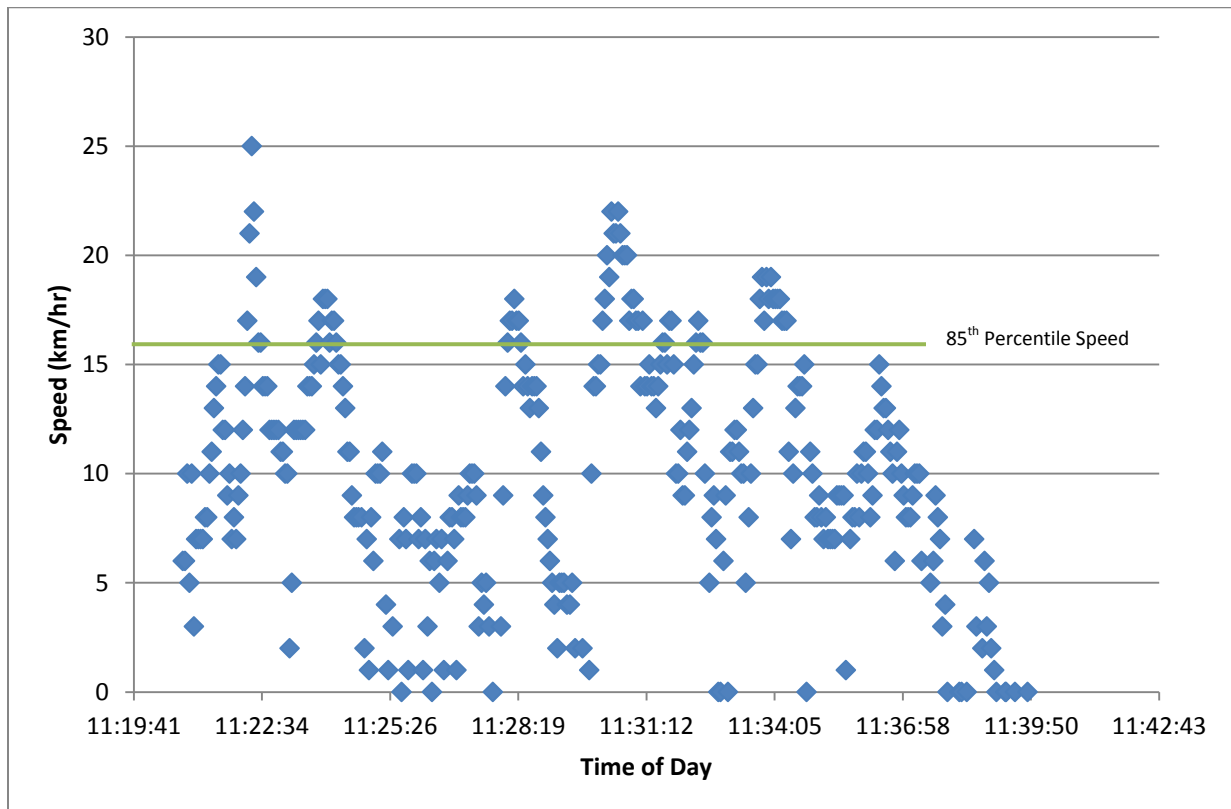
Desired Speeds

A hypothesis test of the difference in means between cyclists within different attribute groups was conducted. The results suggest that there are no differences in the desired speeds between different attribute groups. A two-sample t test was used to develop this conclusion and the results are explained below.

Firstly, the two sample t-test to determine the difference in means between male and female participants yielded the results that are summarized in Table 5.

Table 5: t-Test: Two-Sample Assuming Unequal Variances

t-Test: Two-Sample Assuming Unequal Variances		
	Females	*Males*
Desired Speed (km/hr)	22.57	22.5
Variance	20.47	26.56
Observations	28	46
Hypothesized Mean Difference	0	
df	63	
t Stat	0.06243535	
P(T<=t) one-tail	0.475206905	
t Critical one-tail	1.669402222	
P(T<=t) two-tail	0.95041381	
t Critical two-tail	1.998340522	

The results show that the t-Stat is significantly smaller than the t-critical value. This would suggest that the probability of yielding the sample result is very high if the means of the two data sets are assumed to be equal. We would therefore accept the null hypothesis that the means are equal and that gender has no (or very little) effect on speed. This has important implications for their application to modeling within the context of VISSIM.

The second test was conducted to determine if differences exist between different age groups. In this case, an ANOVA test for equality was conducted. The age group classifications were determined in the previous study as part of the survey component of the research. The participants had to choose from one of 4 age categories. The results are summarized in Table 4.

Anova: Single Factor						
Age Groups	Count	Sum	Average Desired Speed (km/hr)	Variance		
19 -30	20	441	22.05	25.94474		
31-50	29	725	25	122.7143		
51-60	15	349	23.26667	13.78095		
60+	10	222	22.2	30.84444		
ANOVA						
Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	124.9626	3	41.6542	0.662758	0.577727	2.735541
Within Groups	4399.483	70	62.84976			
Total	4524.446	73				

Once again, we can accept the null hypothesis that the means are the same. With a high p-value and low F statistic, the test would suggest that age has no effect on speed and therefore separating into groups within VISSIM is not suggested to be a requirement.

Although differences may exist between different attributes, this study has found that the differences are minor. Within the context of traffic modelling, especially modeling something as unpredictable as cyclists, it is reasonable to apply one probability density function to all cyclists within the model. The desired speed distribution, which can be classified as a normal distribution is shown in Figure 13. The classification of the data as a normal distribution was determined by comparing the mean, median and mode, which are 22.8, 22, and 21 respectively. Another indication of the distributions normality is comparison between the

expected z-scores (if this distribution were normal), and the actual z scores of the distribution. If the residuals are minor, one can conclude a normal distribution. In the case of this distribution, the residuals are small and the r-squared value of the trendline of this plot is 0.93. The plot is illustrated below in Figure 14.
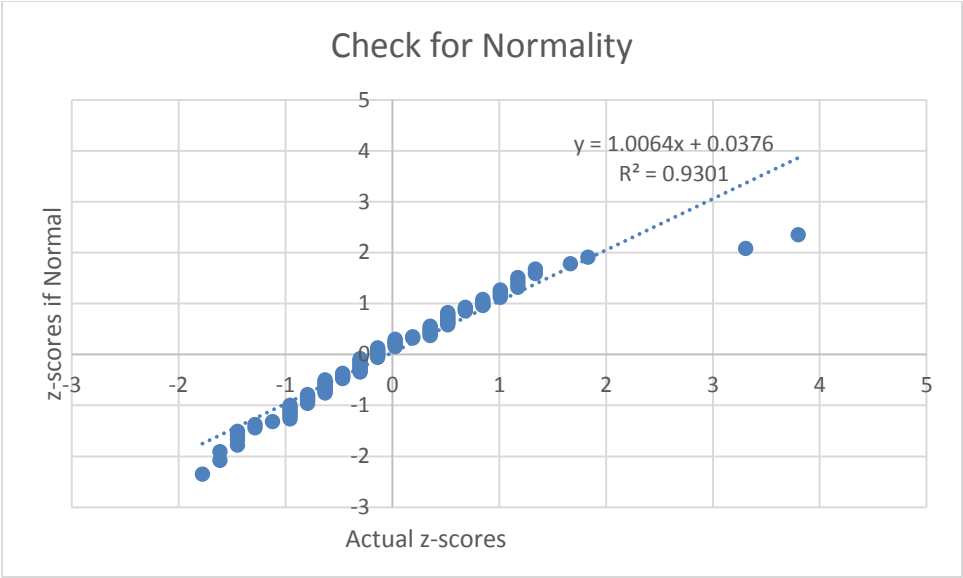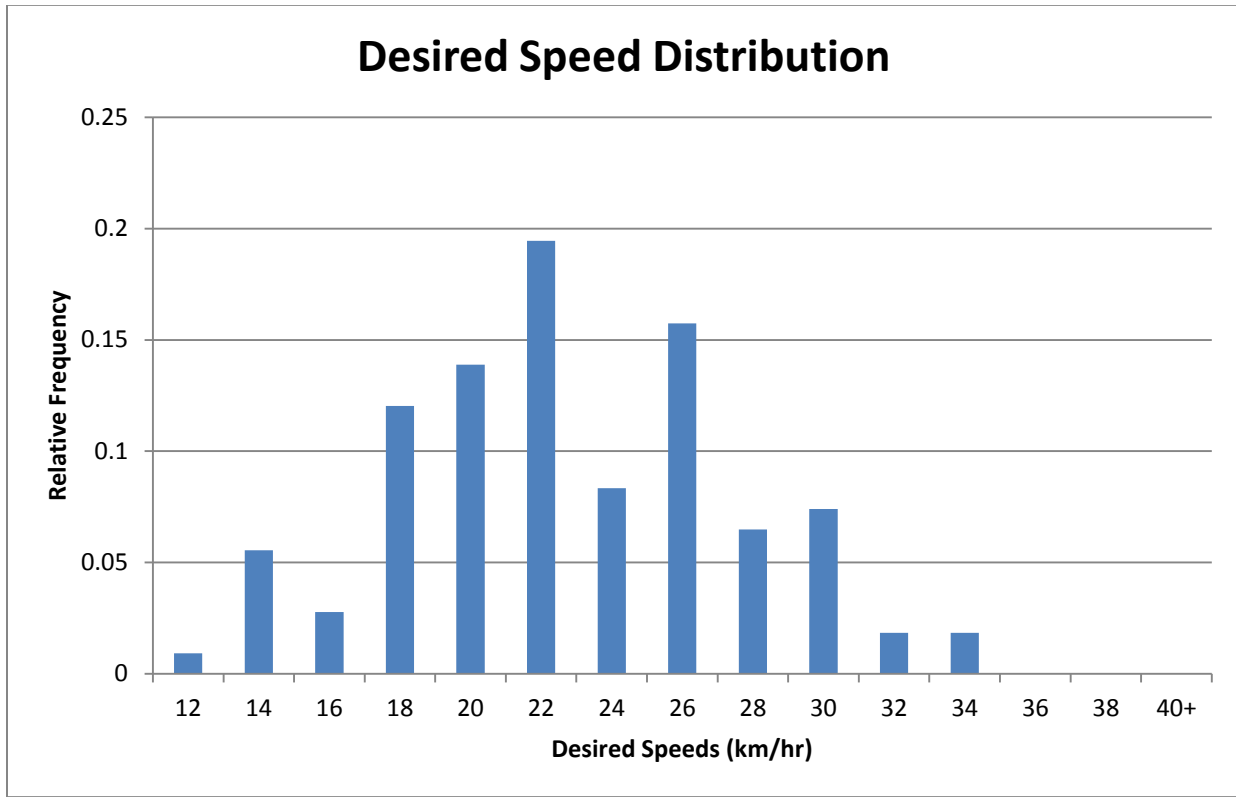
Figure 14: Check for Normality

Figure 15 - Desired Speed Distribution

Grade

Once the desired speeds were separated into grade bins, they were averaged and plotted on the graph below. This graph would suggest that, as the grade approaches 0, the desired speed of the cyclist increases. Intuitively, one might hypothesize that speeds would increase for downhill or flat surfaces and decrease on uphill grades. The later portion of this hypothesis is verified by these data, as speed decreases as grade increases uphill. Counter to that intuition, is the relationship between speed and downhill grades in this data. This data suggests that as a downhill grade increases, speed also decreases. Figure 14 plots the relationship between grade and desired speed.

Percent Grade and Desired Speed
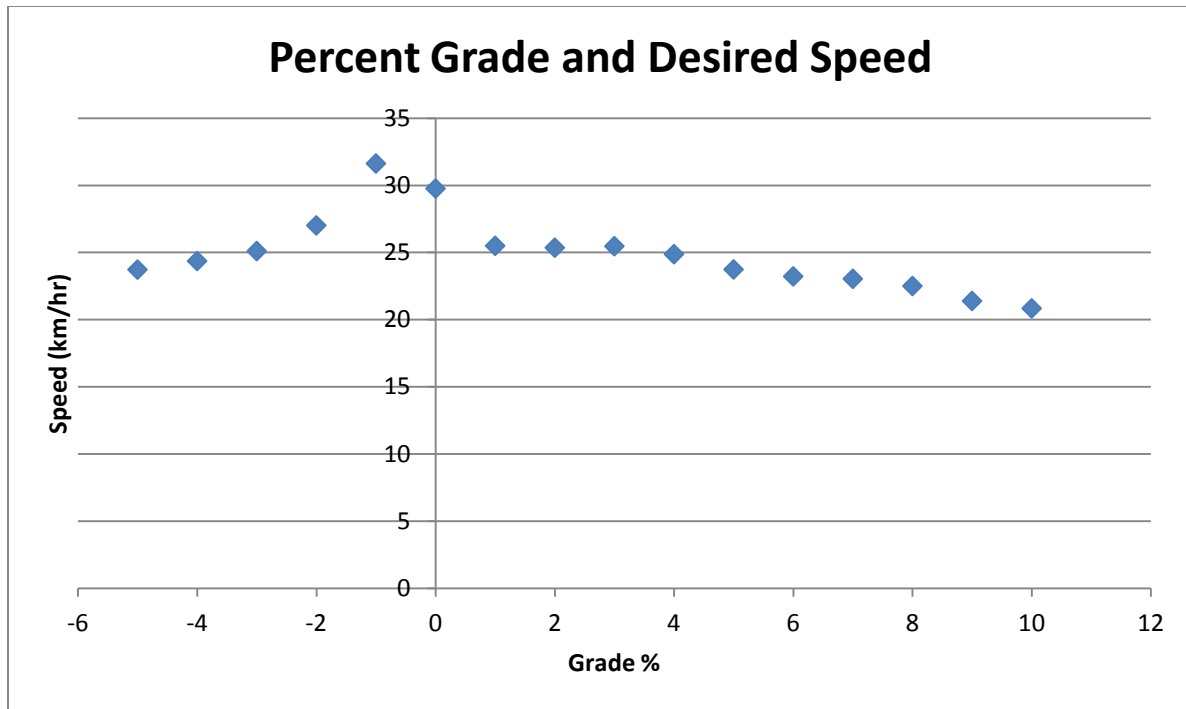
To explain these phenomena, logical reasoning is as follows: It may be that, when a cyclist is on a downhill, they take advantage of an opportunity to produce less work while using the grade to generate speed for them. This, then, transfers into riding at a slower speed than they would if they were doing work on a flat surface.

When the data are separated into two groups: downhill grades, and uphill grades, a strong linear relationship can be realized. With relatively high R-squared values, the regression equations found below can be applied to determine desired speed at various grades. The two graphs below (Figure 15 and Figure 16) show this linear relationship. The speed/grade function equation is also included.

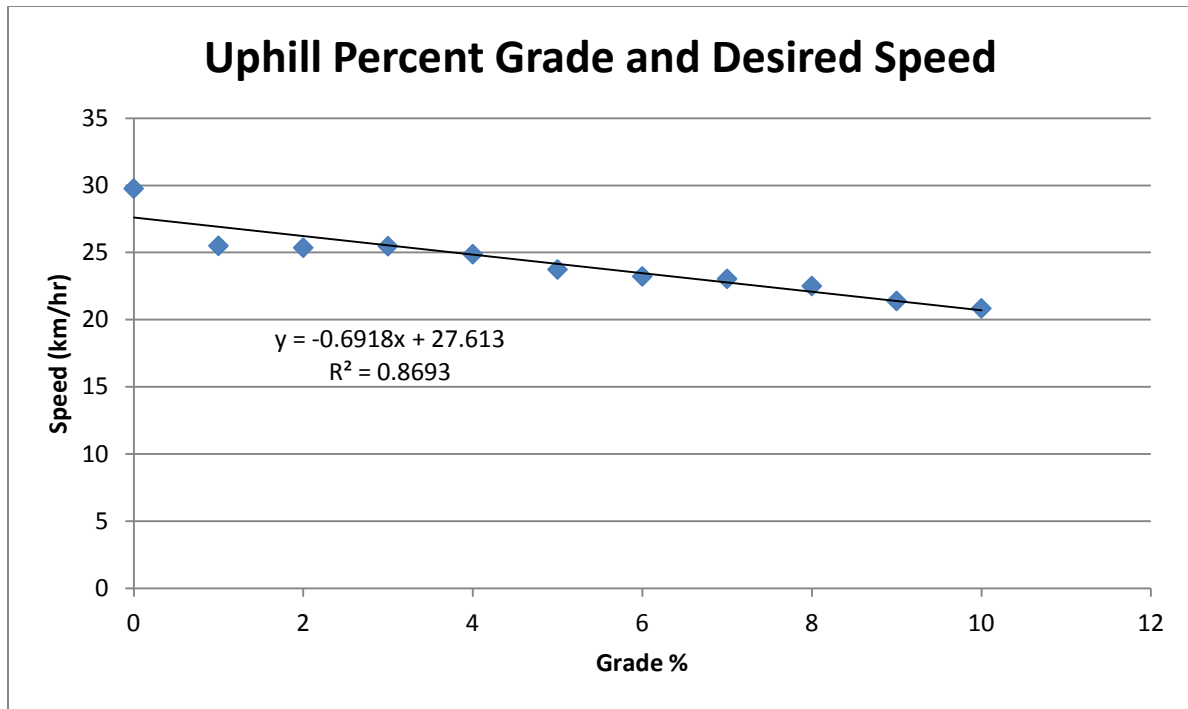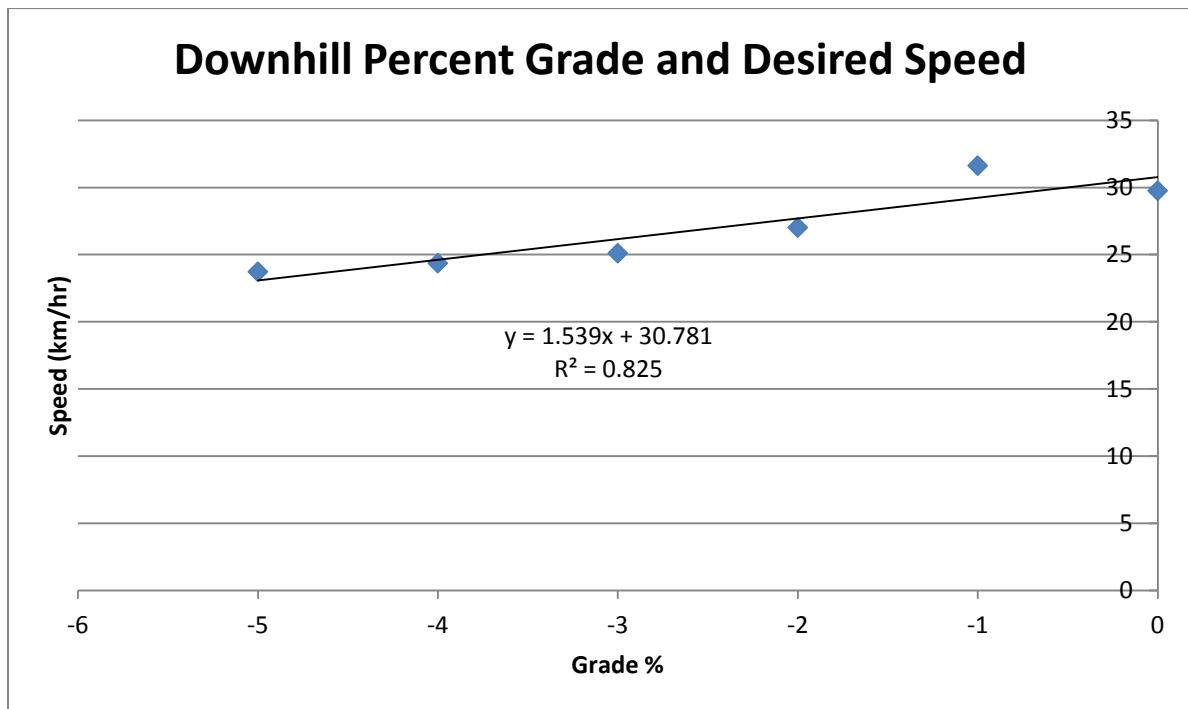Figure 17: Uphill Grade and Desired Speed

Uphill Percent Grade and Desired Speed

$y = -0.6918x + 27.613$
$R^2 = 0.8693$

Figure 18: Downhill Grade and Desired Speed

Downhill Percent Grade and Desired Speed

$y = 1.539x + 30.781$
$R^2 = 0.825$

Facility Type

The results of the ANOVA multiple means test suggest that there is little difference between the mean speeds in each facility type. This little difference in means and a p value of .07, mean we can reject the hypothesis (at the .05 significance level) that facility type has an effect on the speed of cyclists

The results from the testing can be found in the file: FacilityType_Speed_June2014.xlsx

Within the VISSIM context, if a network includes facility type, the desired speed should not be affected by the variable facility type. The results of the ANOVA multiple means test is summarized in Table 5.

Table 7: ANOVA results for facility type and desired speed

ANOVA						
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	142,020	2,000	71,010	2,666	0,071	3,029
Within Groups	7190,264	270,000	26,631			
Total	7332,284	272,000				
Anova: Single Factor						
SUMMARY						
Groups	*Count*	*Sum*	*Average*	*Variance*		
No Facility Avg. Speed (km/h)	91	1621,6	17,820	26,950		
Bike Lane Avg. Speed (km/h)	91	1754,9	19,285	28,368		
Off-Road Path Avg. Speed (km/h)	91	1610,4	17,697	24,574		
ANOVA						
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	142,020	2,000	71,010	2,666	0,071	4,685
Within Groups	7190,264	270,000	26,631			
Total	7332,284	272,000				

Although these results suggest that the speed of a cyclist does not change based on facility type, it should not be concluded that facility type has no influence on the behavior of cyclists. For example, where there is an off street cycle track, cyclists may be more inclined to pass a slower moving cyclist ahead of them, while they might not if they are on an on street bike lane because of adjacent automobile traffic. Further research could be conducted to improve the understanding of how infrastructure affects cycling behavior.

5.2   Component 2 Results

The results of this component are based on tallying the observed behavior of left turning cyclists at each of the subject intersections. The propensity to follow the rules (rule compliance) and the propensity to follow the facility design (facility compliance) are considered under different signal approach and traffic flow conditions. Each of the sub-sections in these results is based on observations and conclusions for each of the intersection configuration types. The charts in this chapter classify the intersection configurations using the acronyms that are described in Table 2.

Intersection Type 1

Figure 19 – Intersection Type 1 Layout
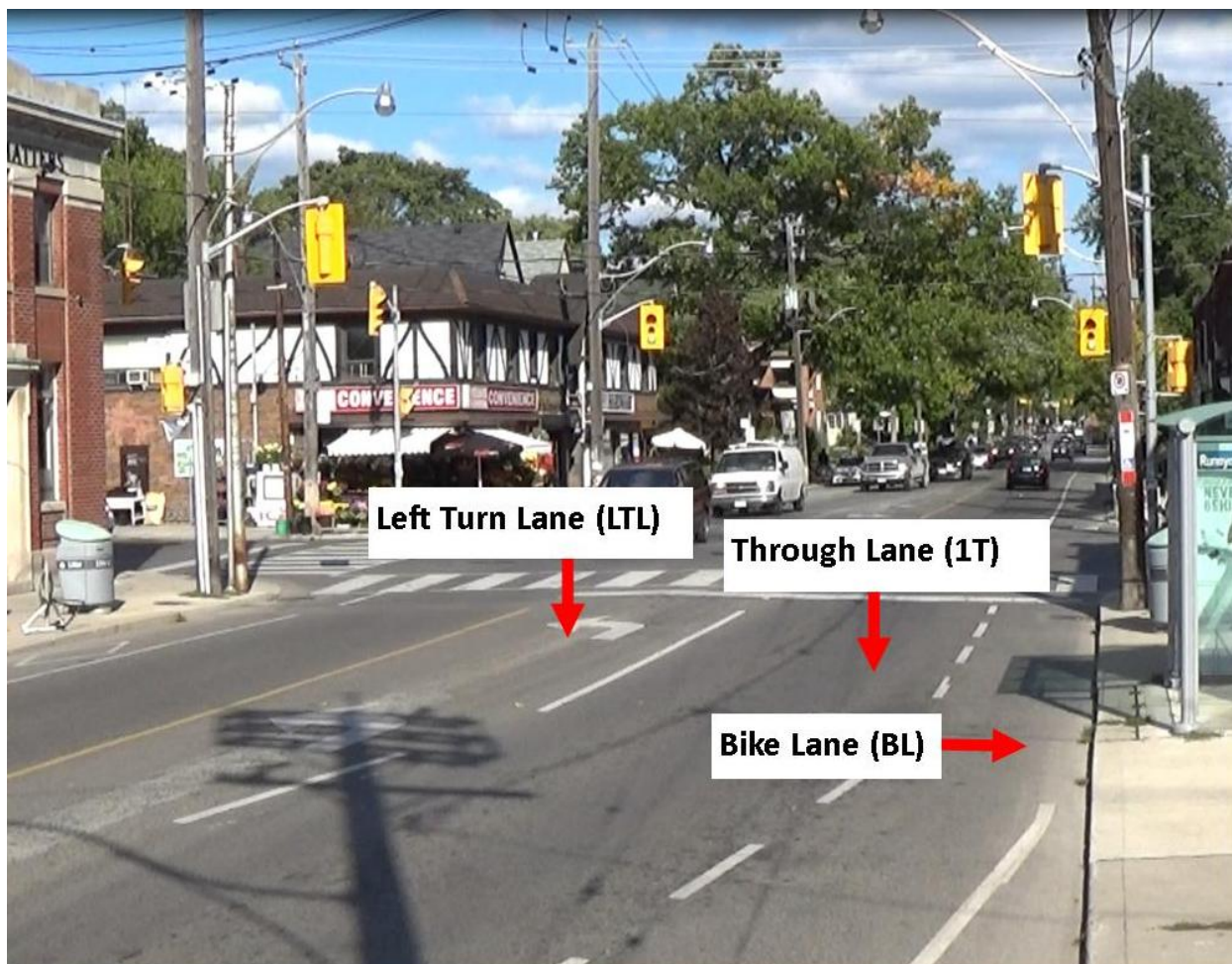
Intersection Type 1 (Figure 17) has an overall rule compliance of 52% and an overall facility compliance of 28%. Cyclists breached rules in one of two ways at this intersection; the cyclist crossed the intersection by riding his/her bike in the pedestrian crossing zone, or the cyclists rode on the sidewalk on approach of the intersection.

Figure 18 below provides a further breakdown of the rule and facility compliance under certain variable conditions. Rule compliance is the highest when the signal phase is green on the cyclists approach, compared to a very low compliance rate when the cyclist approaches a red signal. This can be attributed to that when a signal is green on approach, the cyclist is more inclined to do a 2-phase left turn, since he/she will only have to wait for one signal phase, whereas when the approach is a red signal, the cyclist will be more inclined to do a near side cross of the intersection by riding across the pedestrian crossing area.

Figure 20 – Intersection Type 1 Compliance

Sample size = 30 Using a 90% confidence interval, rule compliance is 52% +/-15% and facility compliance is 28% +/- 14%.
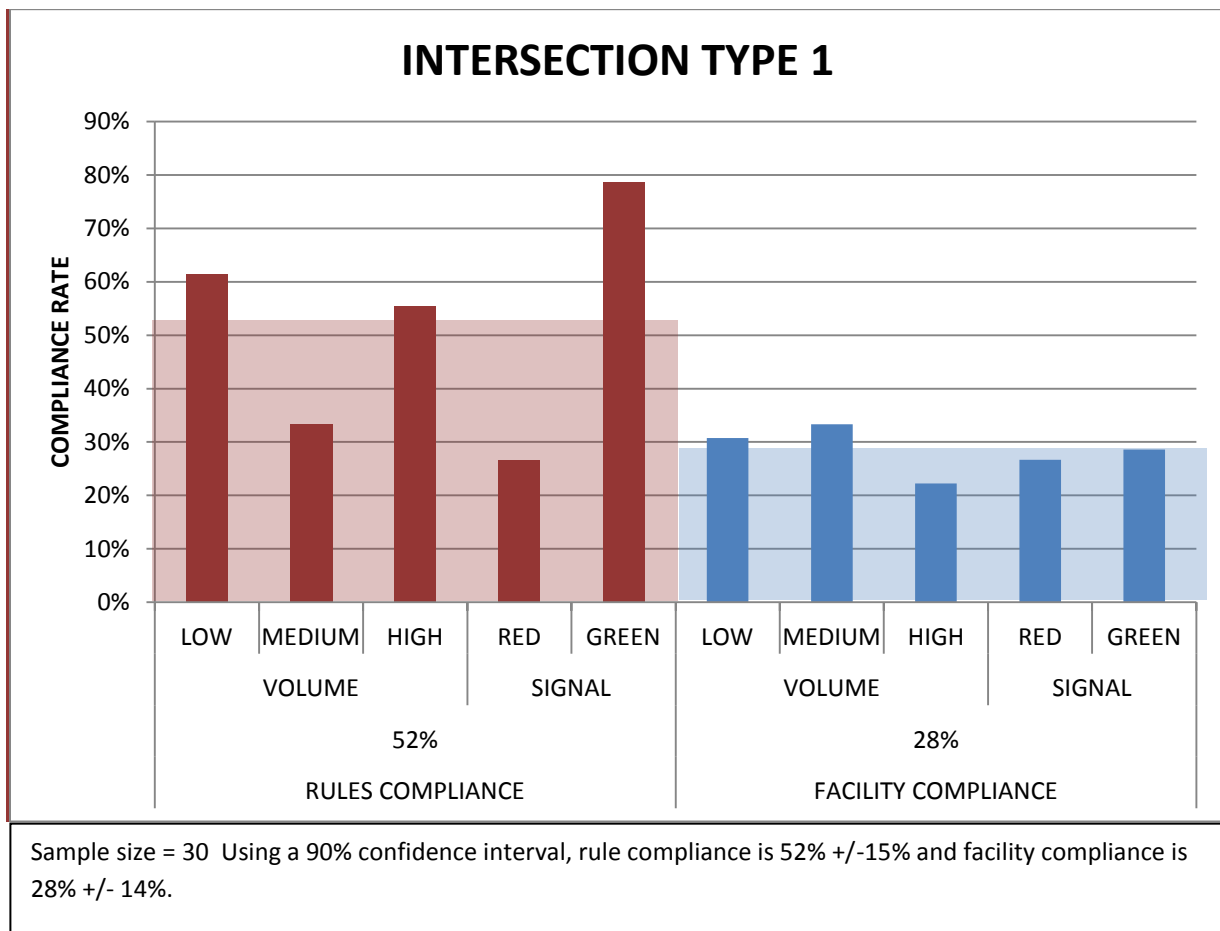
Traffic volume has very little to do with the decision of the cyclists in this context. Although there is variation between medium volume situation and low and high situations, the sample size of medium volume condition is too small to indicate a significant difference.

Facility compliance is relatively low across all input conditions. Facility compliance in this case would be using the left turn lane and making the vehicle left turn. Since this is the only official way that this intersection facilitates the left turn of cyclists, compliance is low. There is no signage or special markings to help cyclists facilitate a left turn that is any different than the method used by the vehicles at this intersection type.

The propensity to use the two-phased left in this case happened 28% of the time. All but one of these cases occurred when the cyclist had a green approach signal.

Intersection Type 2

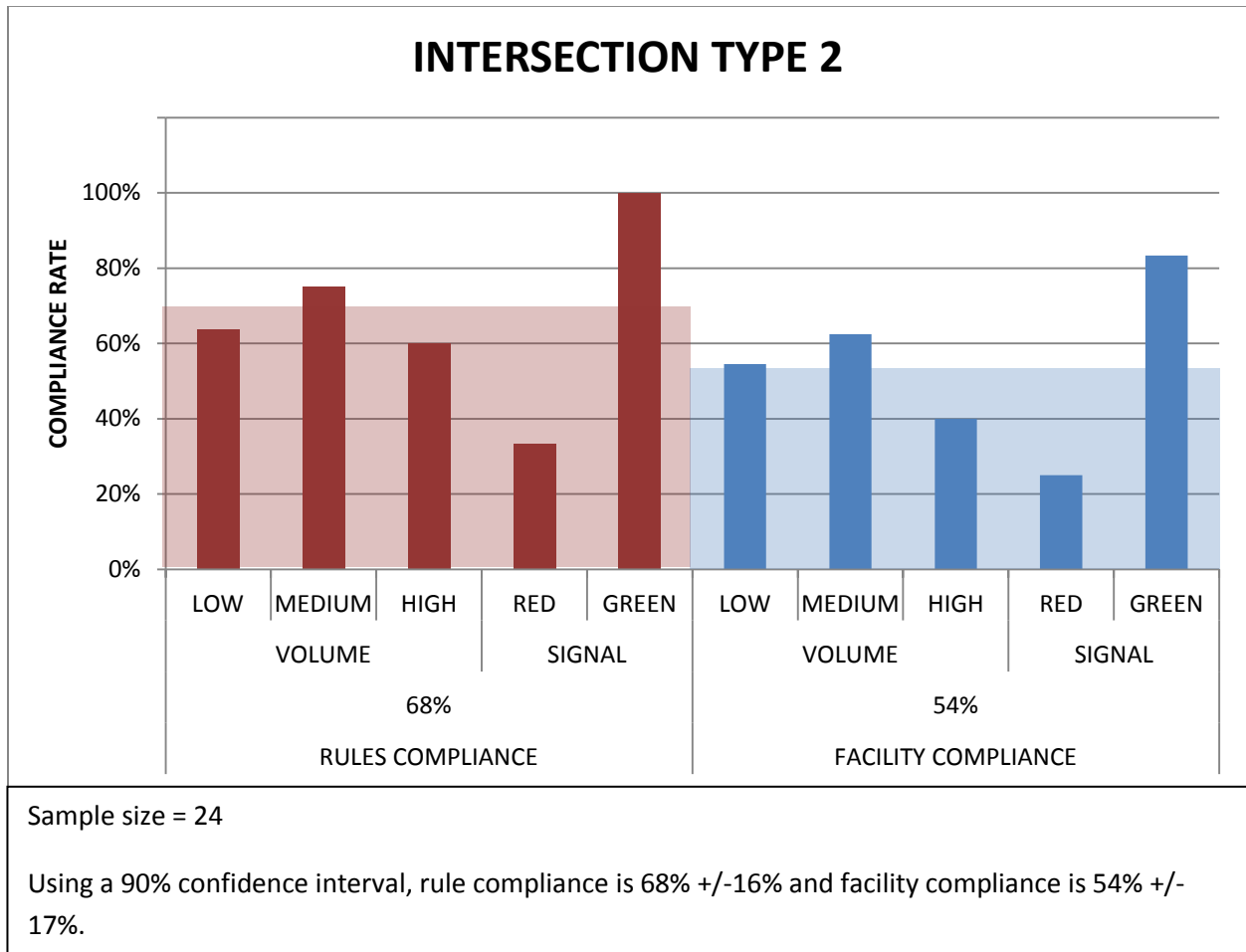Figure 21 – Intersection Type 2 Layout
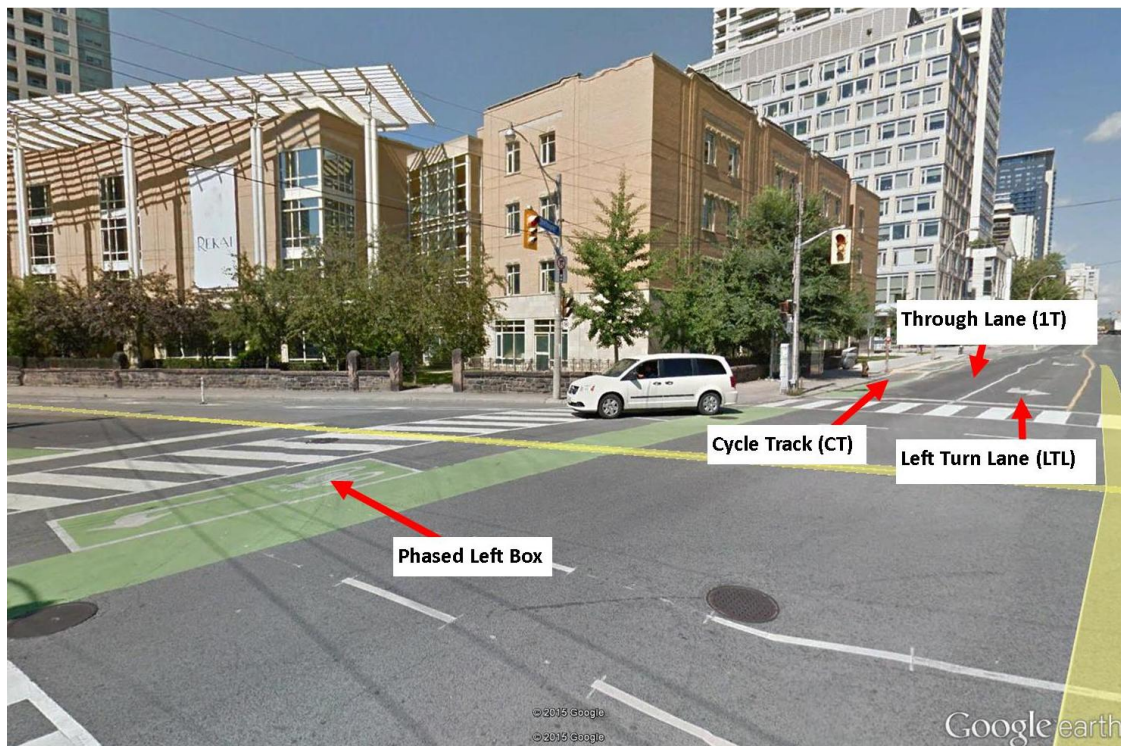
Intersection Type 2, which is illustrated in Figure 19, has an overall rule compliance rate of 68% and an overall facility compliance rate of 54%. Figure 20 provides a further breakdown of the rule and facility compliance under certain variable conditions.

There is a major contrast between the rule compliance rates of cyclists that are approaching during a green signal and those that are approaching during a red signal; 100% rule compliance during green approach and just 33% during a red approach. The breaking of the rules came primarily in the form of riding across the pedestrian cross walk at the intersection.

An important point of observation for this intersection type is the high facility compliance rate compared to some of the other intersections. Cyclists approaching on a green signal have an 83% compliance rate in this type. Facility compliance at this intersection refers to the proper use of the two-phased left hand turn, and does not include cyclists that use the vehicle left turn lane. This suggests that the facility is considered convenient when the cyclist approaches on a green signal, but is not convenient on approach of a red signal. Cyclists that approach on a red signal, prefer to either use the vehicle left turn, or cross the near side pedestrian crossing to limit the wait time for the signal by waiting for just a maximum of one phase instead of waiting for at least one phase or as many as two.

Figure 22 – Intersection Type 2 Compliance

INTERSECTION TYPE 2

Sample size = 24

Using a 90% confidence interval, rule compliance is 68% +/-16% and facility compliance is 54% +/-17%.

Intersection Type 3
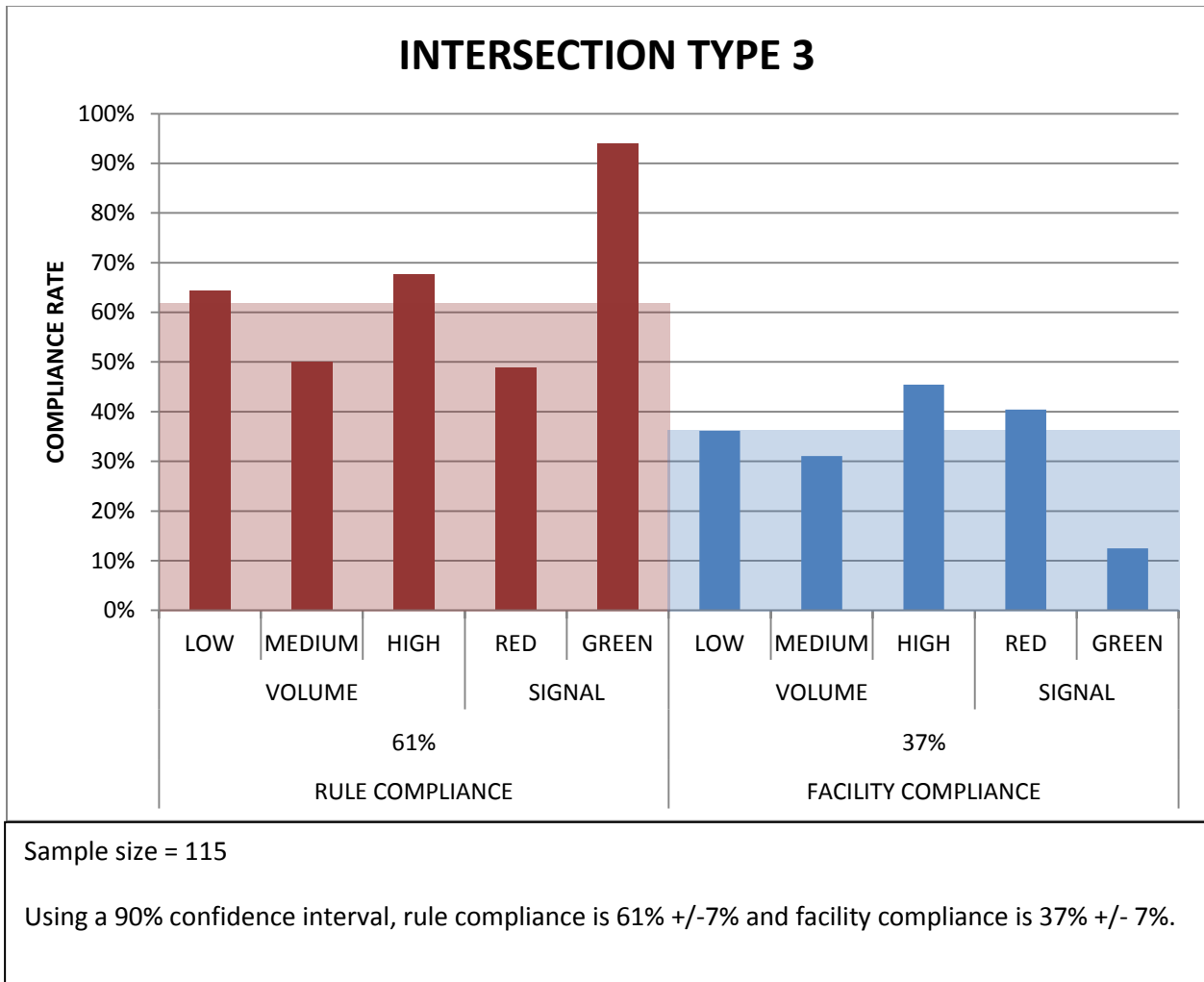
Figure 24 – Intersection Type 3

Figure 23 – Intersection Type 3

Intersection Type 3, which is illustrated in Figure 21 and Figure 22 has an overall rule compliance rate of 61%. There is a significant difference between rule compliance for cyclists with a green approach (97%) than there are cyclists that approach on a red signal (49%). This is explained by the propensity for cyclists to ride across the pedestrian crossing if the signal is red on their approach. This type of movement is not seen when the signal approach is green and alternatively, cyclists on a green approach either use the vehicle left turn lane, or they do a two phased left turn. The presence of the bike box is intended to help facilitate the left turning of cyclists that approach on a red signal, however given that less than 50% of cyclists comply with this; it is only somewhat effective at encouraging compliance to the rules.   Figure 23 summarizes the results of intersection Type 3.
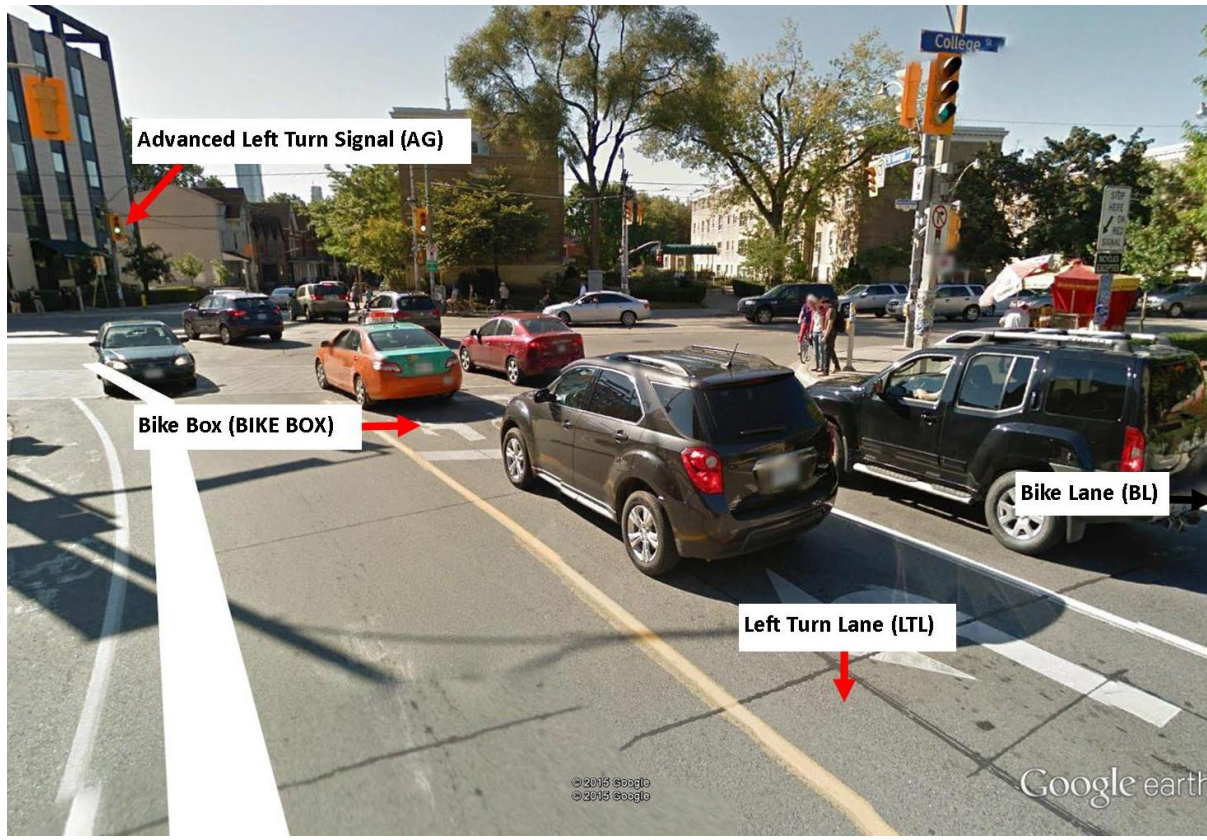
Figure 25 – Intersection Type 3 Compliance

INTERSECTION TYPE 3

Sample size = 115

Using a 90% confidence interval, rule compliance is 61% +/-7% and facility compliance is 37% +/- 7%.

This intersection type has an overall facility compliance of 37%. Since this facility does not have a 2 phase left turn box, those who used the 2-phased left on a green approach, did not comply to the design of the intersection.   The higher facility compliance during a red approach than the green approach, 40% and 13% respectively shows that the facility is more likely to be used by cyclists that approach when the signal is red than when the signal is green.

Intersection Type 4

Intersection type 4 (Figure 24) had the highest rule compliance rate for all the traffic volume conditions. Such a high compliance rate can partly be attributed to the presence of a bike box and an advanced green signal. Cyclists recognize that they will be in front of the left turn queue and that they will be able to make the left turn without having to get off to wait for oncoming through traffic. Other cases where a bike box is present but there is no advanced left turn signal, also has a relatively high compliance rate compared to some other configurations, but is significantly lower than the configuration with an advanced left turn. This would suggest that where a bike box is present to facilitate left turns that the addition of an advanced left turn signal can further add to the effectiveness of the facility. The comparison between the facility with an advanced signal and without can be seen in Table 6.

Figure 27 – Intersection Type 4 Compliance

INTERSECTION TYPE 4

Sample size = 111

Using a 90% confidence interval, rule compliance is 90% +/-5% and facility compliance is 37% +/- 7%.
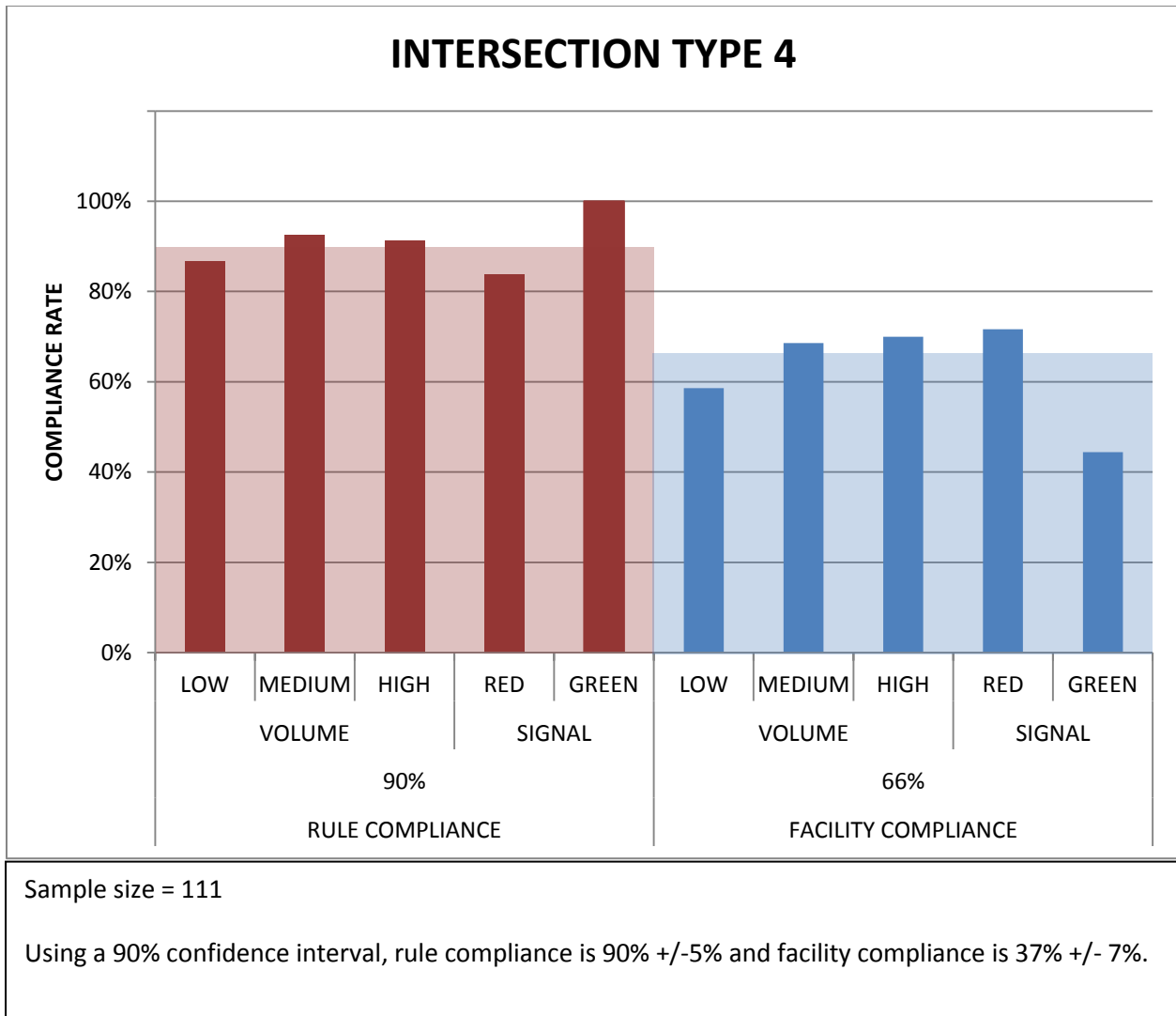
Table 6 compares the rule compliance of the two intersections with bike boxes, but the intersection with the advanced green shows considerably more rule compliance than the intersection without an advanced green signal.

Table 8 – Comparing bike box with advanced green and without advanced green

	Low Volume Approach	Medium Volume Approach	High Volume Approach
With Advanced Green	87% Compliance	93% Compliance	91% Compliance
No Advanced Green	64% Compliance	50% Compliance	68% Compliance

Intersection Type 5

The very low facility compliance in intersection type 5 (Figure 26) can be attributed to the 2 lanes of through traffic that cyclists would have to weave through to get to the left turn lane. The low rule compliance on a red approach suggests the high propensity to ride across the pedestrian crossing at the intersection. The width of the intersection (because of the presence of a through lane and the separated street car lane might be more of a reason for

cyclists to ride across the intersection rather than walking their bike. The high rule compliance during a green approach is because cyclists perform the 2 phased left. Since there is no two-phased left box, however, this behavior is not considered facility compliance in this case.

The rule compliance and facility compliance under varying conditions can be seen in Figure 27.

Sample size = 37

Using a 90% confidence interval, rule compliance is 50% +/-14% and facility compliance is 9% +/-8%.
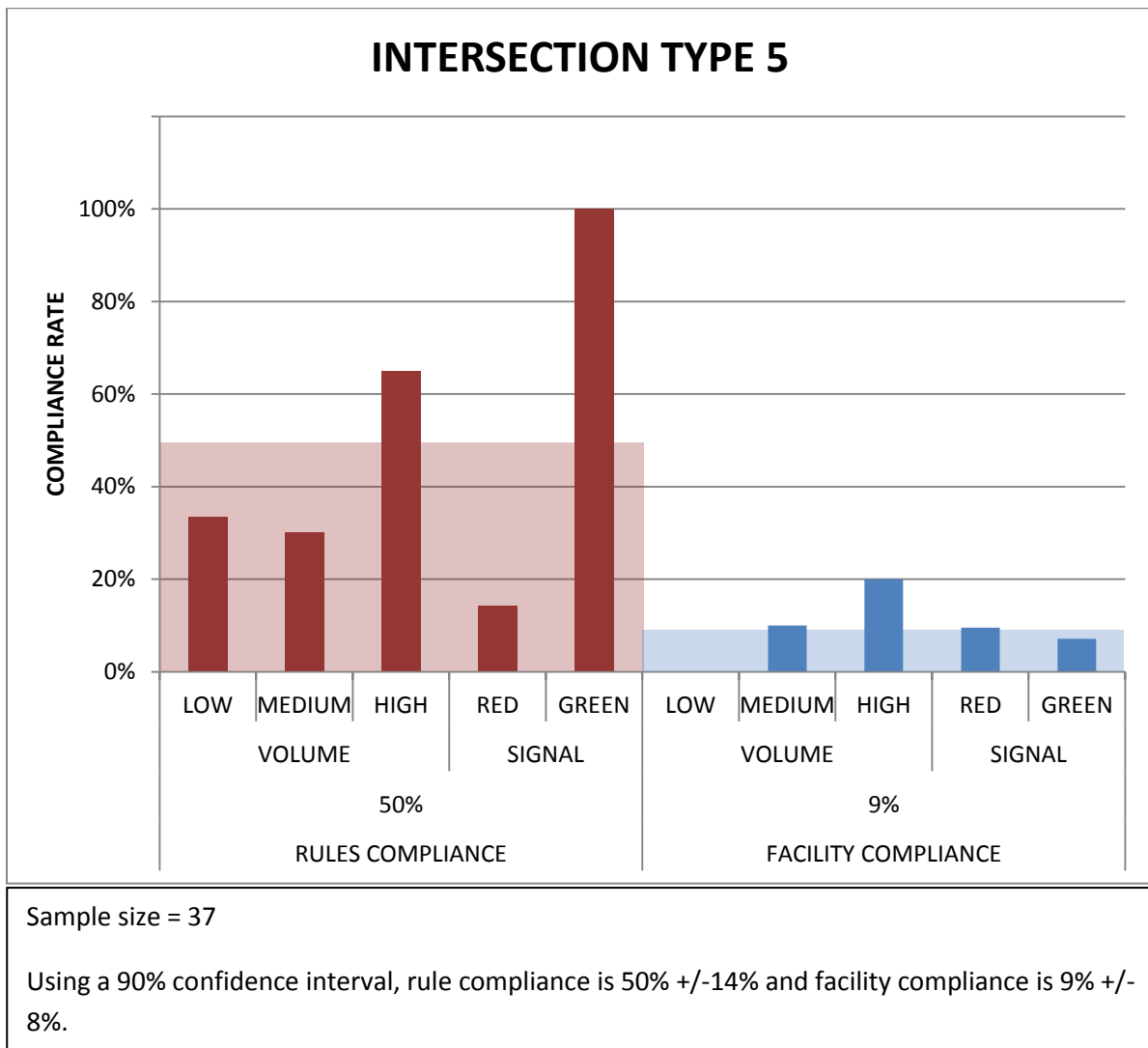
Comparing the Intersection Types

The intersection with the greatest overall rule compliance is Intersection Type 4. As illustrated in Figure 28, the overall rule compliance at this intersection is significantly higher than its counterparts.   The major difference in design between Type 4 and Type 3 is the presence of the left turn signal. Both have similar conditions otherwise, with a bike box and 1 through lane. The differences in rule compliance of these two intersections can be seen Figure 28 below and in Table 6.
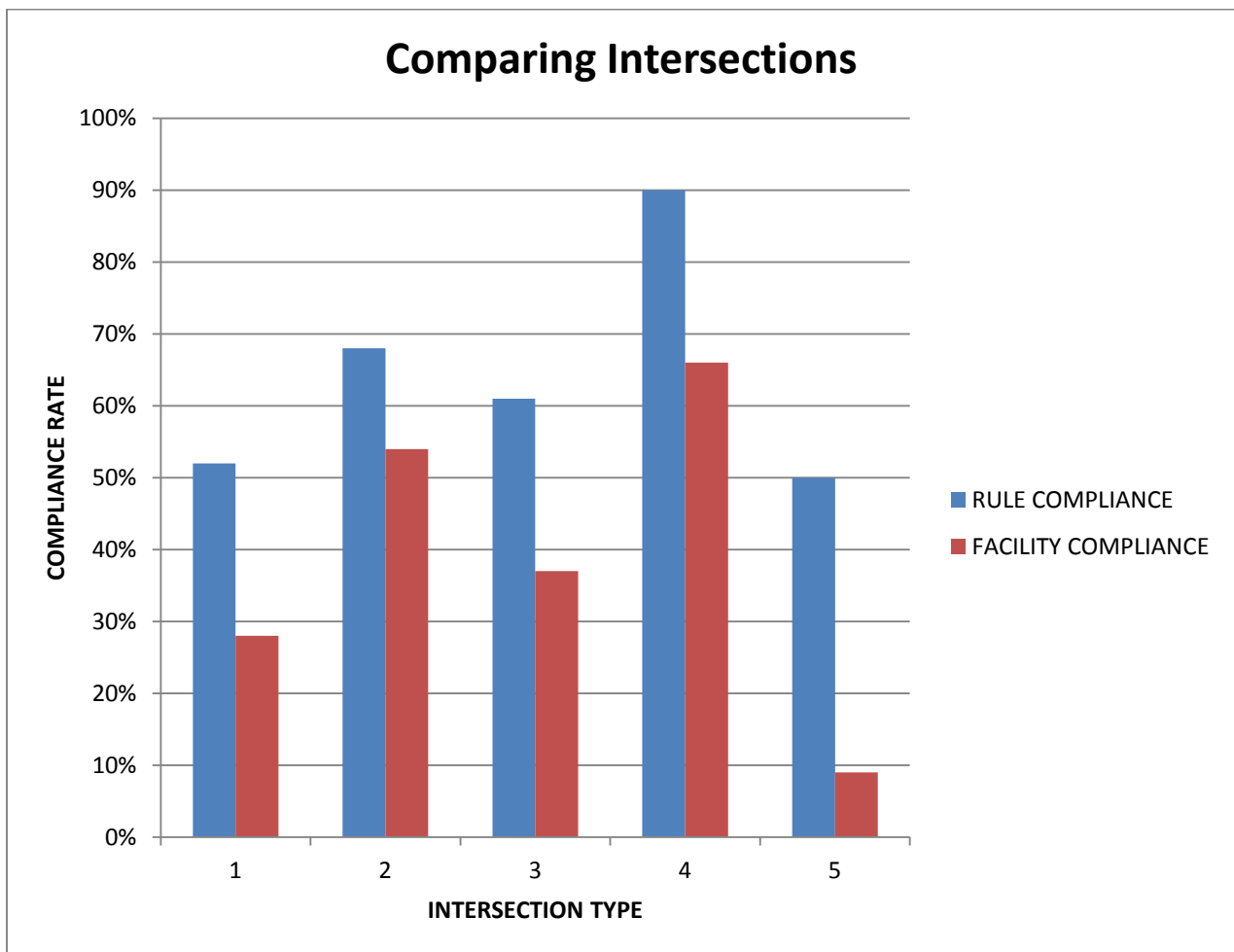
The two intersections with the lowest overall rule compliance are intersection Type 1 and Intersection Type 5. Both of these intersections have no special facilities that are designed to help facilitate the left turn of a cyclists other than the left turn lane, which is designed for

automobiles to turn left.   These intersections also have the lowest facility compliance, indicating that the vehicle left turn lane is ineffective at promoting a left turn for cyclists. Out of the two, intersection 5 has the lower of both rule and facility compliance, and this can partially be attributed to the presence of two through lanes instead of just one, which further deters cyclists from using the vehicle left turn lane, since two lanes of through traffic would have to be navigated to get from the road side cycle lane to the left turn lane.   Additionally, Type 5 is a much larger intersection that Type 1, making the vehicle left turn even more undesirable for cyclists.

When considering the variable of the signal phase, different trends appear. In all cases, the rule compliance of the intersections are much higher, and in 3/5 cases are 100% when a cyclist approaches during the green signal phase. What does stick out in this comparison is how all the intersections faired when a cyclist approached during a red signal phase. Intersection Type 4, once again, proves to promote the greatest compliance under this condition.   This suggests, that, even when a cyclist approaches during a red signal, the rules of the road are still followed, as cyclists choose not to use the "snake" turn in this condition. As intersection type 3, is the second most effective at promoting rule compliance when a cyclist approaches on a red signal, we can conclude that the presence of a bike box is helpful in promoting rule compliance when a cyclist approaches on a red signal. This comparison is summarized in Figure 29.

Figure 31 - Comparing Rule Compliance during red and green signal phases

61
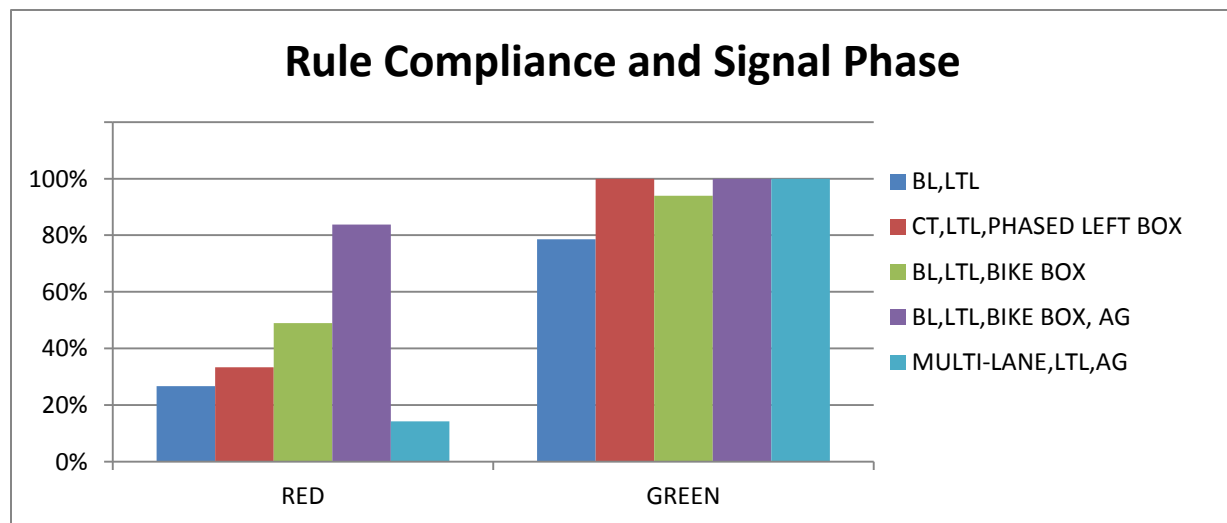
When comparing facility compliance during different signal phases, we see a similar trend to that of rule compliance comparison when a cyclist approaches on a red signal, but there are some major differences across the different intersections when a cyclist approaches during the green phase. The only intersection that has high facility compliance during the green approach is intersection type 2, which is the only intersection that has the two-phases left turn box. This suggests that the two-phase left turn box is very effective at promoting facility compliance when a cyclist approaches during a green signal compared to the other facilities. This comparison is summarized in Figure 30.

Figure 32 - Comparing facility compliance during red and green signal phases
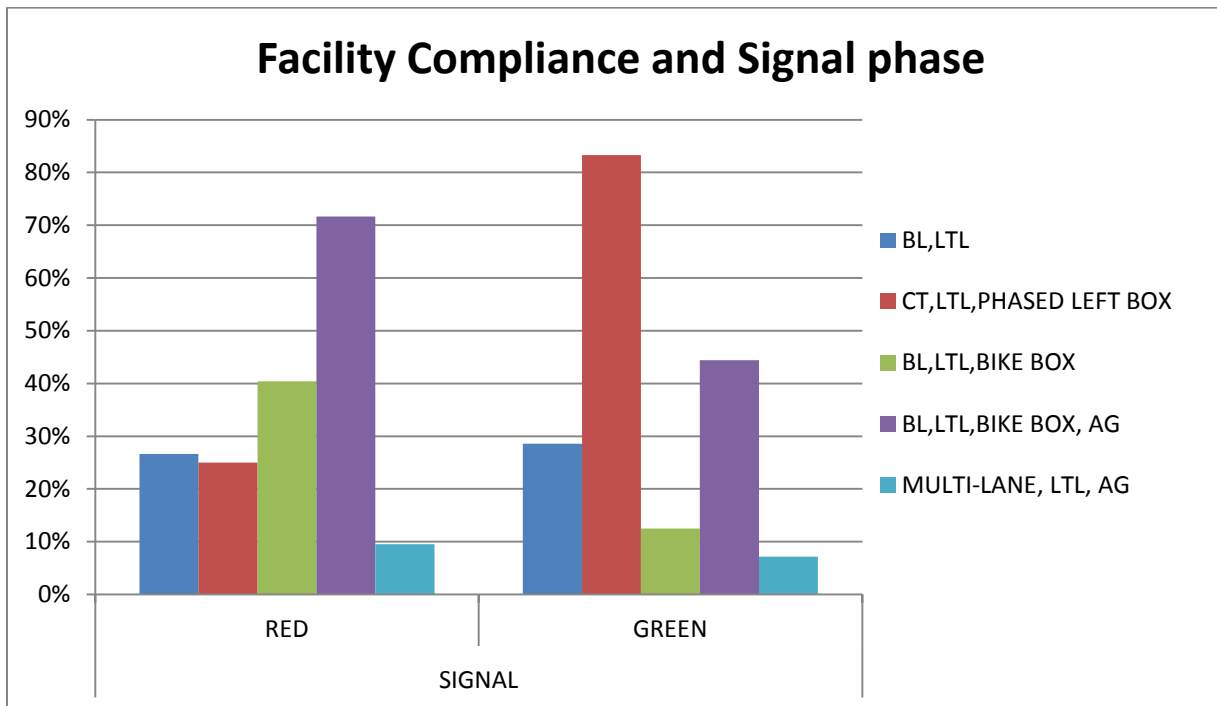
Additional Findings

Some additional findings worth noting, that could have implications on inputs for behavioral models are seen below. The first of the three contingency tables in Table 9 below compares helmet wearing to rule compliance. Based on the results from this study, these two variables are strongly dependent. For example, if someone is wearing a helmet, the probability that they will follow the rules is .96 where as the probability of following the rules overall is just .70. This supports the notion that people that wear helmets are more risk averse and therefore more likely to follow the rules.

Table 10 compares helmet use and gender. These variables are also dependent, as females are more likely (.72) to wear a helmet than males (.56). This also supports the notion that males are more likely to take risks.

Table 11 compares gender and rule compliance. These variables, although significantly less dependent, still show some dependence as the probability for a male to break the rules is .3 and the probability for females to break the rules is .26. This too supports the notion that males are more likely to take risks.

Table 9: Rule Compliance and Helmet Use

		Rule Compliance		
		Y	N	Total
Helmet	Y	244	10	254
	N	27	104	131
	Total	271	114	385

Table 10: Gender and Helmet Use

		Helmet		
		Y	N	Total
Gender	M	487	377	864
	F	454	174	628
	Total	941	551	1492

Table 11: Rule Compliance and Gender

		Rule Compliance		
		Y	N	Total
Gender	M	154	66	220
	F	110	40	150
	Total	264	106	370

As indicated in the literature review, in Denmark, fewer people wear a helmet, and also, fewer people break rules. This supports the notion that if a cycling environment is well defined, and separated from the domain of the automobiles, that the perception of safety is much greater and people do not feel the need to wear safety equipment.

6.0   CHAPTER 6: RECOMMENDATIONS

6.1   Recommendations from Component 1

Component 1 provides a distribution of desired speeds for cyclists in varying conditions. Although this sample is representative of a more experienced cyclist group, the range and distribution of speeds is something worth noting and considering for incorporation into the input variables of micro-simulation models. Since other variables that influence desired speed were not considered, this desired speed can only be applied to models that apply one single desired speed to their cyclists. Given that the models that are being used today do not consider other variables when applying desired speed, this distribution is an improvement on the existing practice. It is not recommended that the speed as a function of grade findings be used since the results are counter intuitive for the uphill grades; as uphill grade increases, so does speed.

6.2   Recommendations from Component 2

Implications for Micro-Simulation Modelling

Distributions of rule compliance and facility compliance under variable approach conditions can be incorporated into the behavior models of cyclists within mixed traffic micro simulation models. Since traffic volume in this study was determined at the exact instant that a

cyclist behavior was observed, it will be a challenge to assign gap data (categorized by low, medium and high volume in this study) to a specific intersection if only hourly traffic volumes are provided. It is there for recommended, that the volume of an intersection, within the interface of VISSIM platform, be categorized by low, medium, or high volume. High being an intersection operating at and volume capacity ratio close to 1, medium being between .5 and 1, and low being less than .5. Further research, or discretion by the model user in a specific situation may be applied to determine the categorization of traffic volumes in different situations.

Design Recommendations

Where the intersections could experience the greatest improvement in rule and facility compliance is the compliance when a cyclists approaches during a red signal. Since the preferred behavior in this condition is to ride across the near side pedestrian crossing, implementing a facility or markings that allow this behavior, rather than classifying it as illegal, would be a way to encourage and make safer, the natural path of the cyclists.

Allowing for a space beside the pedestrian cross walk, where cyclists can ride across the near side of the intersection when they approach on a red signal, would allow for the cyclists to continue using the method that they are comfortable with, but by defining a separate space from the pedestrians, would create a more seamless crossing for both cyclists and pedestrians. Such a facility can be referenced in the Ontario Traffic Manual, Book 18. One of the two following crossing markings (Figure 31 and Figure 32) could be implemented in such a situation:
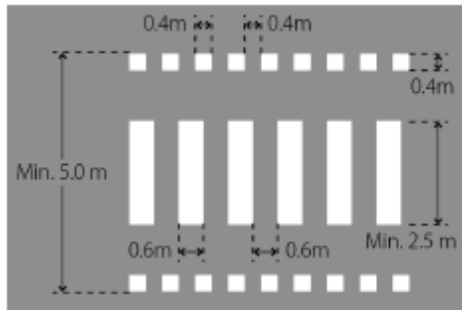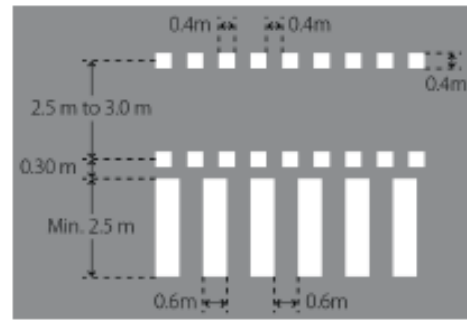
Figure 34 - Combined Crossride

Figure 34 - Combined Crossride

Figure 33 - Separate Crossride

7.0   CHAPTER 7: GOING FORWARD

Collisions occurring at the intersections of study are very few since the implementation of the existing facilities at each intersection. Also, collisions that are reported are believed to only represent 10% of collisions as a whole. Trying to draw comparisons or correlation between collisions at each intersection and the rule compliance at each intersection is therefore not reliable at this scale. If an inventory of rule compliance could be made at a larger sample of intersections, a more reliable connection could be made between rule compliance of an intersection and the accident rate at that intersection. Collision data is available on this scale, but rule compliance is not.   If we assumed rule compliance to be the same across all intersections of the same type, this could also be possible. The limitation is that the implementation of bicycle facilities at each intersection happened at varying times, and to correlate the intersection as it is today, with rule compliance as it is today, could leave with limiting data.

With more data, one could create a behavior model for inclusion in the micro simulation framework. The model could suggest the probability distribution of different behaviors or rule compliance based on inputs of traffic flow, approach signal, facility type, and gender.

Using this data set, or by adding to it with additional observation, one could generate a behavior distribution model for varying facility and approach conditions to be incorporated into the micro simulation model platform.

```
Loop Until lasttrack
'----------------------------------------------
'determine average grade and speed on each hill
'initiate values
   hillrise = 0
   hillrun = 0
   hillspeed = 0
   pt = 0
   avgspeed = 0
   avggrade = 0

'initiate speed values
  aspdMUP = 0
  spdMUP = 0
  iMUP = 0
  aspdBL = 0
  spdBL = 0
  iBL = 0
  aspdNF = 0
  spdNF = 0
  iNF = 0

  If Worksheets(k).Cells(2, 21).Value = "Off" Then
   offroad = True
   bikelane = False
  ElseIf Worksheets(k).Cells(2, 21).Value = "On" And
Worksheets(k).Cells(r, 16) = "Bike Lane" Then
   offroad = False

   bikelane = True
  Else 'no facility
  offroad = False
  bikelane = False
  End If

  If offroad = True And ptspeed > 0 Then
   spdMUP = spdMUP + ptspeed
   iMUP = iMUP + 1
  ElseIf bikelane = True And ptspeed > 0 Then
   spdBL = spdBL + ptspeed
   iBL = iBL + 1
  ElseIf bikelane = False And offroad = False And ptspeed > 0 Then
   spdNF = spdNF + ptspeed
   iNF = iNF + 1
  Else
   'skip zero speed
  End If

'loop to determine avg speed / grade on hill and average speed on
facility
r = 3 'start on second row after header
Do

   'read current values
   currtrack = Worksheets(k).Cells(r, 3).Value
   nexttrack = Worksheets(k).Cells(r + 1, 3).Value
   ptspeed = Worksheets(k).Cells(r, 13).Value 'read speed at point
   dElev = Worksheets(k).Cells(r, 37).Value 'read change in elevation at
point
   dDist = Worksheets(k).Cells(r, 38).Value 'read change in distance at
point
   nextelev = Worksheets(k).Cells(r + 1, 37) 'read next change in
elevation
```

```
  If currtrack <> nexttrack Then 'end of current trip/track
    endHill = True

  ElseIf currtrack = nexttrack And dElev >= 0.01 And nextelev < -0.01
Then
    endHill = True
  ElseIf currtrack = nexttrack And dElev < -0.01 And nextelev >= 0.01
Then
    endHill = True
  Else
    endHill = False
  End If

  If nexttrack = Empty Then 'end of sheet
    lasttrack = True
  Else
    lasttrack = False
  End If
 If endHill = True Or lasttrack = True Then

  hillrise = hillrise + dElev
  hillrun = hillrun + dDist
  hillspeed = hillspeed + ptspeed
  pt = pt + 1

  avgspeed = hillspeed / pt
  avggrade = (hillrise / hillrun) * 100

  Worksheets(k).Cells(r, 39).Value = avggrade
  Worksheets(k).Cells(r, 40).Value = avgspeed

  hillrise = 0
  hillrun = 0
  hillspeed = 0
  pt = 0
  avgspeed = 0
  avggrade = 0

  Else
    hillrise = hillrise + dElev
   hillrun = hillrun + dDist
   hillspeed = hillspeed + ptspeed
   pt = pt + 1

  End If
  r = r + 1

Loop Until lasttrack
'--------------------------------
'calculate average and print to first sheet
aspdMUP = spdMUP / iMUP
aspdBL = spdBL / iBL
aspdNF = spdNF / iNF

Worksheets(1).Cells(k, 1) = Worksheets(k).Name
Worksheets(1).Cells(k, 2) = aspdNF
Worksheets(1).Cells(k, 3) = aspdBL
Worksheets(1).Cells(k, 4) = aspdMUP

  Next k

End Sub
```

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