An Empirical Study of Bicyclists' Turning Behaviour at Signalized Intersections

by

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Author's Declaration

I hereby declare that I am the sole author of this thesis. This is the true copy of the thesis including any required final revisions, as accepted by my examiners. I understand that this thesis may be made electronically available to the public.

Abstract

Efforts to increase cycling mode share have seen some success in North America, though challenges persist due to real and perceived safety issues. Of particular concern are left turns at signalized intersections. Left turns can be particularly challenging to traverse and often leave cyclists feeling unsafe, especially those who are less experienced. To reduce conflict and enhance safe left-turn maneuvering, the City of Philadelphia, Pennsylvania has initiated a pilot study for the installation of two-phase left turn bike boxes.

This thesis investigates how the installation of two-phase left turn bike boxes influence left-turning behaviour at signalized intersections. A literature review found few studies that demonstrate the benefits of two-phase left turn bike boxes, and generally few studies that document left turn behaviour in a North American context. Similarly, few studies differentiate between signal control infractions and road space infractions. The approach used a before and after video analysis of five unique left-turning scenarios of installation of two-phase left turn bike boxes. A novel method of defining a series of left turn maneuvers was applied to analyze how these turns are conducted in the before and after stages. The method considers road positioning in the approach and departure, as well as the manner in which the bicyclists maneuvered through the intersection.

The video footage also produced sufficient data to investigate general cyclist behaviour regarding road space positioning (using proper lanes, sidewalk riding, switching in between) and red light running behaviour for all travel directions of the 6,786 observed cyclists at the study signalized intersections. Through adapting classifications from literature, road space positioning was grouped into three categories: vehicular behaviour, opportunistic behaviour, and pedestrian conflict behaviour. For the red light running behaviour, mean gap times were captured for select travel directions.

The research found that red light running rates were highly correlated with mean gap time in cross traffic ($R^2 = 0.95$) and that left turns at signalized intersections produce the most unpredictable behaviour relative to through or right turn movements. The study also found that improved predictability in behaviour of left-turning cyclists is possible with two-phase left turn bike boxes, though understanding treatment context is necessary to see behavioural changes. Cyclists tend to favour directness and reduced delay over predictability and law compliance. Use of two-phase turn boxes occur when cyclists desire to follow road rules and prioritize reducing conflict with other road users over directness and minimizing delay.

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1.0 Introduction

As cities have grown in population and complexity, transportation engineers and city planning professionals have faced challenges with moving people and goods efficiently and effectively. Traffic congestion, urban sprawl and the related economic and health impacts play major roles in these challenges, and push contemporary practice to find meaningful solutions. One trend within this field is Transportation Demand Management (TDM). TDM is comprised of policies and strategies to reduce and redistribute travel demand over space and/or time (FHWA, 2017). It can achieve greater efficiency of transportation systems by affecting travel behaviour. Within TDM initiatives is the effort to achieve a more diverse mode share, where urban trips are less dominated by personal auto, and modes such as public transit, walking and bicycling share a more significant role of appropriate trips. This "balanced transportation" approach seeks to shift auto travelers to modes that require less capital investment, lower operating costs, reduce congestion, reduce parking demand, improve personal health and have less environmental impact. As one of the most efficient forms of human travel, bicycling for utilitarian purposes plays an important role in achieving this initiative, and is identified as a key goal for many countries, including Canada (Transportation Association of Canada, 2012).

To achieve greater cycling mode share, professionals have made efforts to better understand what influences the propensity to travel by bicycle. Existing research has built a consensus that bicycle facilities and infrastructure have a positive relationship with increased bicycle use and improved safety (Pucher, Dill & Handy, 2010). Facilities such as bike lanes and cycle tracks are favourable for their user perceptions and safety benefits, but can face challenges in terms of political support, costs and other externalities (Henderson, 2011). Cycle tracks differ from regular bike lanes by being physically separated in some form from motor traffic. When local governments and transportation agencies are faced with the opportunity to introduce bicycle facilities, having safety performance data of the alternatives is meaningful for resources to be allocated and used effectively. Moreover, solutions that provide safety benefits and do not require significant capital are inherently valuable and easier to implement.

For bicycle infrastructure treatment to mitigate the number of collisions, severity of collisions and general conflict between road users, treatment should address one or more of the following objectives (DiGioia et al. 2017):

- Increasing the separation of bicycles and motor vehicles in time and/or space
- Increasing the visibility and conspicuity of non-motorized users
- Improving lines of sight between the modes
- Reducing the number of interactions between modes
- Reducing motor-vehicle speeds

Though motor vehicles are not solely responsible for bicycle collisions, they are considered the main cause of cyclist injuries and deaths (National Highway Traffic Safety Administration, 2017). For this reason, bicyclist safety measures are largely focused on mitigating the risks posed by motor vehicle and bicycle interactions. Of critical significance are signalized intersections, where collisions between bicyclists and motorists more frequently occur due to errors made by both cyclists and drivers (Tomlinson, 1998; Government of Ontario, 2012; Isaksson-Hellman, 2012; City of Vancouver, 2015; City of Philadelphia, 2015, European Commission, 2015). Nonetheless, responsibility for cyclist safety lies in all road users, but also the operation and design of the intersections. Cyclists' behaviour is often a function of many factors such as their experience, confidence, risk aversion and perception of safety, producing an extensive range of behaviours. Safety, either real and perceived, can be influenced by understanding what type of operations and infrastructure create consistent behaviours of bicyclists and drivers.

Literature and contemporary studies have developed a strong base in understanding the performance of many bicycle infrastructure alternatives in achieving one or many of the objectives, though some gaps persist. One of the more challenging types of maneuvers at intersections are left turns, and understanding how to best facilitate this maneuver is still a subject of interest.

1.1 Nature of the issue

Bicycles are considered vehicles in Ontario (Highway Traffic Act, 1990) and in many other jurisdictions in North America, though bicycle behaviour is not always consistent with this mandate. As such, bicyclists are expected to behave as vehicles unless otherwise designed such as protected bike lanes. Bicyclists approaching multi-lane signalized intersections can have challenges traversing safely. In particular, traveling from a right side bike lane and merging safely to make left turns is often difficult for bicyclists, though this is one of the expected behaviours. The same is true in situations when bike lanes are on left shoulders (one way multi-lane roads, two-way bike lanes grouped on one shoulder). In most cases, bicyclists merge and navigate through traffic lanes with little guidance, which can be challenging and leave cyclists feeling unsafe – especially for less experienced bicyclists. This maneuver can cause conflict with vehicles and other road users when caution is not taken. In severe cases, collisions can occur.

Aside from a vehicular method, bicyclists have three other legal options for left turns, presented in Figure 1.

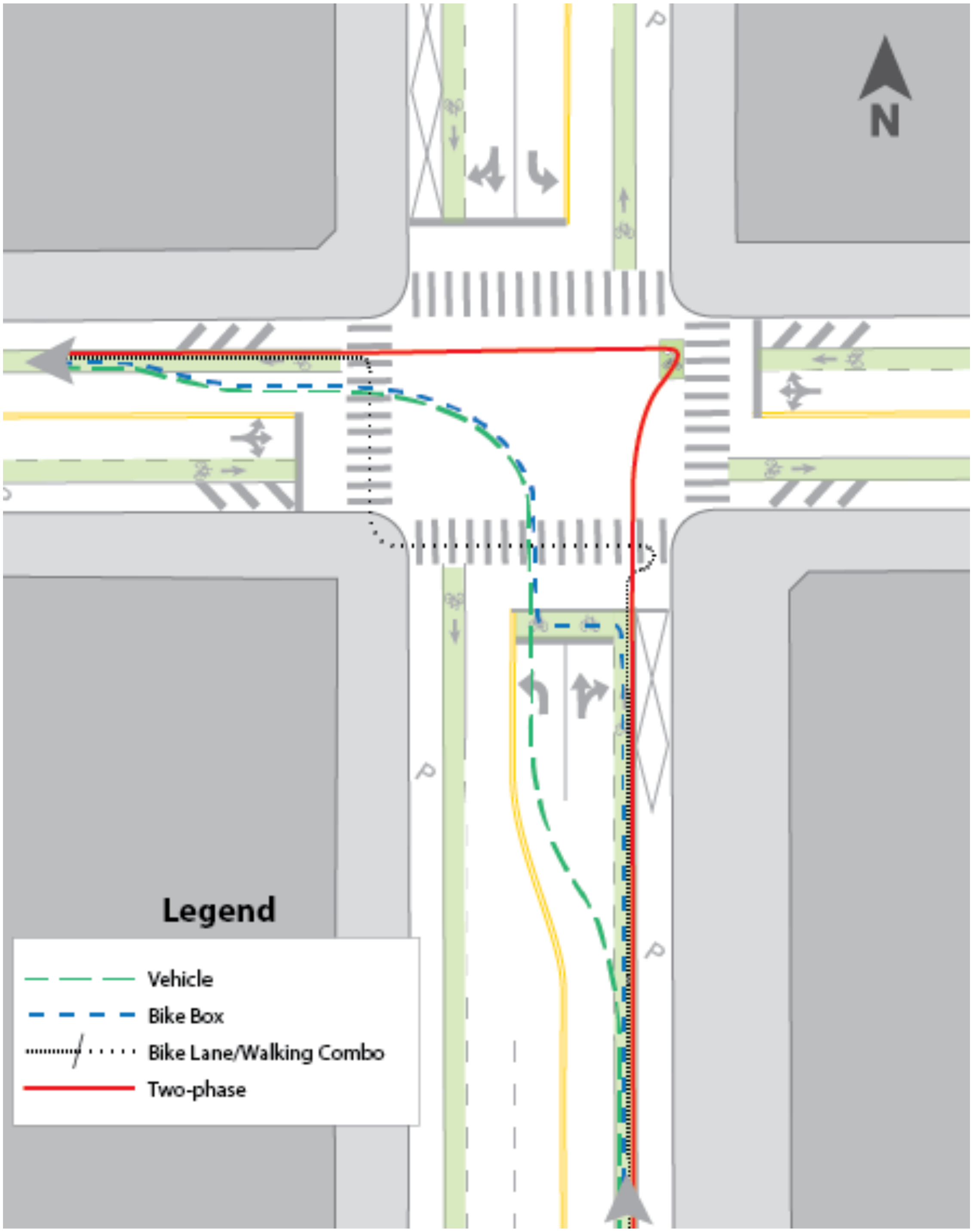


Figure 1: Main Legal Options for Left Turning Cyclists

The vehicle route depicted as a long dashed green line merging into the left turn lane is appropriate for approaching on a red or green signal phase. If no left turn lane is present, bicyclists are expected to merge into the vehicle lane. The bike box option (when a bike box is present) depicted as a medium dashed blue line is only for when a bicyclist approaches on a red signal phase. Here, bicyclists can stay in the bike lane up to the stop line, then move over into the front of the left turn queue lane and wait for the signal phase to turn green and proceed with the left turn. In both cases, bicyclists will at some point find a gap in oncoming traffic to turn left unless an advanced dedicated left turn phase is present. Being exposed to many moving vehicles on the edge or in the middle of the intersection is another element of a vehicle left turn that can produce a feeling of being unsafe. The bike lane/crosswalk walking option depicted in dense and spaced dots combination is also only for cyclists who approach on red signal phases. In this case, a bicyclist dismounts and walks their bike westbound over the crosswalk and waits for the signal phase to change to proceed north to the bike lane and then mounts their bike again to continue west in the bike lane.

The two-phase option depicted in solid red is most appropriate for bicyclists approaching on a green signal phase. Here, bicyclists proceed through the intersection as phase 1 to the front of the east-west traffic bike lane and out of the way of other northbound bicyclists. Once the signal phase changes, they can then proceed west and complete phase 2 of the maneuver.

Two-phase left-turns as an alternative to merging with traffic and otherwise performing potentially unsafe maneuvers are the focus of this study. This method of left turning removes bicyclists from the exposure of a vehicle left turn. The compromise is that bicyclist must wait for the signal phase to change (hence the name two phase) instead of turning like a vehicle and finding a gap in oncoming traffic within the same approaching green phase. This maneuver can be done with or without a formal coloured box, though bike boxes of other kinds at intersections have demonstrated value regarding visibility, predictability and perception of safety of bicyclists (Pucher, Dill & Handy, 2010).

Two-phase left turns are common in European intersection design and in some cases like Copenhagen, Denmark are the legal way to make left turns. Some cities have implemented two-phase left turn bike boxes in North America, though very little data exist to support the effectiveness of this type of infrastructure.

In some instances, bike lanes are positioned on the left shoulder of a roadway, either when it is a one-way road or when the bike lanes are grouped to make a wide two-way bike lane. In these situations, right turns for cyclists form a left-side bike lane can face similar challenges as left turns from a traditional right side bike lane. An intersection with this situation is studied in this research and will be further explained in Chapter 3.

1.2 Objectives & Scope of Work

This research examines intersection infrastructure best practices for bicyclists. This research is focused on the implementation of two-phase, or two-stage turn bike boxes to facilitate left turn maneuvers and unusual right turn maneuvers for bicyclists, and better understand how this infrastructure affects cyclist behaviour.

The main research question is: Does the installation of two-phase turn bike boxes at signalized intersections create greater consistency in behaviour (thus, greater safety) for left-turning and right turning cyclists? Other questions can be asked in relation to this question:

I. How do cyclists conduct left-turn maneuvers at signalized intersections?

II. How do cyclists conduct right turns from a left side protected bike lane at a multi-lane signalized intersection?

In relation to bicyclists' behaviour, this research can also uncover how bicyclist of all travel directions maneuver through signalized intersections and interact with signal phases. This research can also ask the following questions:

III. What are bicyclists' preferred routes of navigating intersections (*desire lines*)/ where are bicyclists riding? i.e. in bike lanes, on sidewalks, switching in between?
IV. Does the approaching signal phase influence where bicyclists ride?
V. How frequently and under what circumstances do bicyclists run red lights?

The objectives and outcomes of this research are to:

I. Provide a foundation of evidence for new intersection treatment – using evidence-based decision making regarding the use of two-phase turn boxes,
II. Better understand the behaviors and motivations of cyclists making left turn maneuvers, and right turn maneuvers from left side protected bike lanes.
III. Develop a better understanding of desire lines of bicyclists approaching signalized intersections and under what conditions preferred behaviour occurs in a North American context.

To accomplish this, a collaboration with the City of Philadelphia, Pennsylvania was formed through which four intersections with varying characteristics were identified and studied. The method used in the study relied on video cameras that were set up at the selected intersection to capture cyclist behaviour at two different periods.

1. The before period, wherein the two-phase bike boxes and associated signage are not installed;
2. The after wherein the two-phase bike boxes and associated signage have been in place and operational for 1 month after installation.

Video footage was reviewed and the travel behaviour of each bicyclist passing through the study intersections documented. The collection of bicyclist data was then organized and categorized to demonstrate the outcomes to accomplish the research question and other objectives. Continued studies of these intersections are intended to be conducted by the City of Philadelphia to enhance this research, including a propose one-year follow up.

1.4 Thesis outline

Chapter 1 introduced the nature of the issue, and establishes the specific research questions and objectives. Chapter 2 is a review of relevant literature and Chapter 3 covers the study context for the City of Philadelphia and research methods. Results in Chapter 4 are divided into two sections: section 1 is for results of the two-phase turn bike box study and observations on how bicyclists make left turns, and section 2 is for results of other bicycle behaviour at signalized intersections. The conclusion is in Chapter 5 along with limitations, and potential future research.

2.0 Literature Review

This Chapter provides a brief history of North American urban mobility and an overview of the benefits of bicycling for utilitarian purposes. Then, research regarding the propensity to bicycle, current intersection treatments for bicyclists, safety, and bicyclists' interactions with intersections is presented. Finally, a summary of findings and gaps in current literature are provided.

2.1 A Brief History of North American City Mobility

Prior to technological innovation in transportation, travel on land was done by human or animal power, predominantly walking and drawn carriages. City size was limited by a 30 to 45-minute travel range to access the central business district (CBD). Adams (1970) classified the evolution of cities and transportation into four eras that coincide with new transportation technologies (Figure 2). The electric streetcar era established greater mobility where public transit permitted residential land farther away from the CBD, though accessing transit service was still limited to human power and carriages creating a constricted radial form. Residential land expanded modestly once automobiles became available to consumers, however automobile production was limited and cost prohibitive except for the wealthy. Escaping the city was possible for those able to afford it, though the road infrastructure was not yet designed, nor needed, to support high demand.

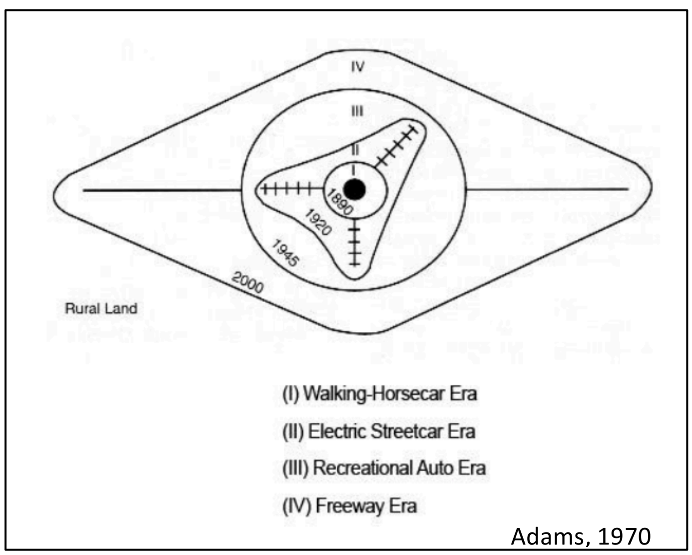


Figure 2: The Evolution of Transportation and City Growth

After World War II, the commodification of automobiles and sprawling road and residential development resulted in decentralization – where businesses and consumers no longer required a central location for their needs. Owning a vehicle shifted from recreational for the wealthy, to a necessity for work, shopping and socializing (Wilson, Papadopoulos & Whitt 2004). In the USA, local and regional automobile travel was further encouraged with the 1944 Federal Highways Act which was the beginning of the interstate limited access highway system

(Hayden & Wark, 2006). Likewise, high automobile ownership incurred equal demand for parking space and higher capacity collector roads.

As a result of the Freeway Era, cities evolved in varying forms depending on local conditions. Bertaud (2014) developed four models to demonstrate how spatial distribution of jobs and people exist in modern cities as a result of decades of development emboldening auto use, demonstrated in Figure 3.

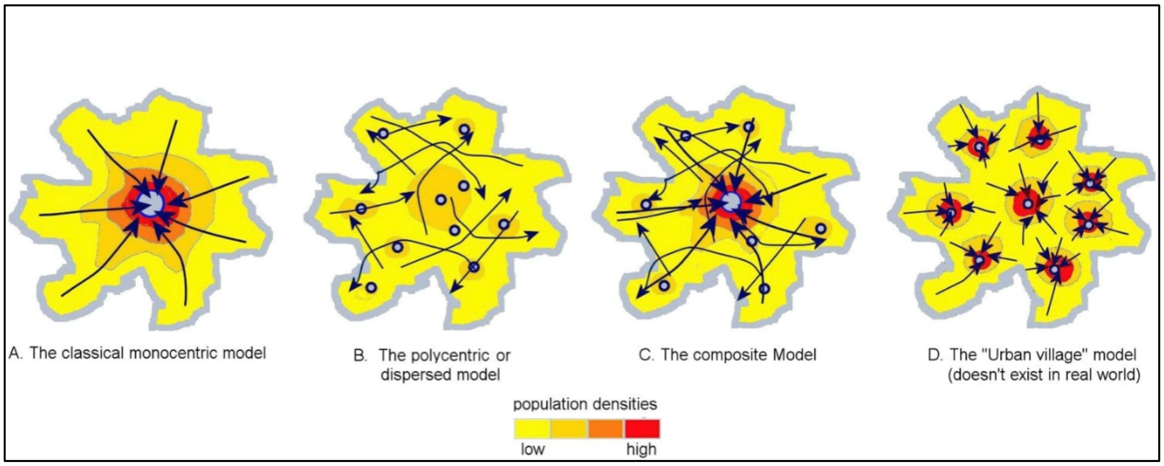


Figure 3: Spatial Distribution models of Jobs and Population

For the most part, cities that could once be represented by the classical monocentric model (A) have evolved into polycentric (B) or composite (C) models. There are a few exceptions to this shift such as Edmonton, Canada, which has managed to maintain a centralized business district. A polycentric example in North American is Phoenix, Arizona, where a city center exists but a significant portion of the city is decentralized and sprawling; Philadelphia has been studied as a polycentric city for which providing transit and sustainable modes remains a challenge (Casello, 2007). Toronto, Canada is an example of a composite model. Toronto has a strong CBD but also has hubs around the city that generate cross-city commuting patterns. As noted, the urban village model is not represented in the real world.

Presently, around 74% and over 76% of commuting is done by personal automobile in Canada and the USA respectively; cycle-commuting constitutes 0.6% mode share in both Canada and the USA (Statistics Canada, 2011; US Census Bureau, 2013). The persistent auto dominance has challenged cities to keep up with demand for infrastructure while suffering direct and indirect costs as a result. In response to these challenges Urban Planning and Transportation engineering solutions such as Transit Oriented Development (TOD) and Transportation Demand Management (TDM) have become widely adopted tools to reduce work-home commuting distances and travel time, reducing auto-reliance, and improving mobility efficiency (Handy, 2005; FHWA, 2017).

2.1.1 Bicycles for Transportation

Leading up to the end of the 19th century, bicycles were becoming a recognized form of transportation. As such, cyclists advocated for improved riding surfaces, considering that wheel technology was far more primitive compared to modern air-filled tubes in tires. From the turn of the century towards then end of World War II, bicycle popularity was linked to war era fuel rationing. Cycling was considered an attractive transportation alternative, especially as bicycles were increasingly affordable due to lowered production costs (Wilson, Papadopoulos & Whitt 2004). By that time, the bicycle and its many iterations were close to 80 years old and had experienced fluctuating enthusiasm. Nevertheless, bicycle prominence waned as the automobile freeway era flourished (Wilson, Papadopoulos & Whitt 2004)

Cities like Davis, California (Driven by the University of California – Davis Campus) evolved differently than many cities in United States, the freeway era and developed policy and infrastructure that favoured the bicycle instead, and bicycling flourished (City of Davis, 2017). Like Davis, some parts of North America had a cycling renaissance in the 1970s, as fuel prices skyrocketed, though the trend died out for most cities by the end of the decade. Despite token examples, auto-centric transportation continued in North America and many cities' land use patterns to this day reflect this legacy.

In European cities, cycling was popular through the end of the 19th and into the early 20th century, notably for countries such as The Netherlands and Germany. Like in North America, Europe also experienced the onset of auto-centric development post WWII, yet transportation policy and citizen advocacy for safer roads curbed impact. Notable alternatives to auto-centric development were present in The Netherlands, where child death rates caused by vehicle collisions and oil shortage in the early 70s triggered protest to develop safer and more bicycle friendly roads (BBC, 2013). These citizen led movements are credited for the Netherlands pro-cycling and pro-cycling infrastructure reputation known today.

Cycling in North America has demonstrated evidence of another renaissance. Between 1988 and 2009, Annual Federal funds toward cycling and walking in the USA changed dramatically from around $5 Million per year (88 – 90) to almost 1 Billion per year (06 – 09) (Pucher et al., 2011). From 2000 to 2013, major US cities have seen double or triple the percent of bicycle commuting (League of American Bicyclists, 2015). Similarly, Canadian cities Like Toronto, Vancouver and have had success in increased cycling mode share. Between 2006 and 2016, numerous Toronto neighbourhoods had over 20% increases in bicycle commuting (Statistics Canada, 2016). Between 2013 and 2016, The City of Vancouver went from 4% to 7% bicycle mode share (City of Vancouver, 2016)

Internationally, there are numerous examples of organizations, be it private or public, that have developed progressive policies and targets to increase active modes of transportation. The contemporary perspective is that cycling, as one component of active transportation, is an essential mode in mobility (European Union, 2015). The objectives are quite similar across the board: to increase cycling mode share, reduce auto-related congestion and pollution, increase physical activity, and improve the safety of pedestrians and cyclists. In developing countries, cycling is also seen as a component of rising out of extreme poverty by providing greater mobility (Sibilski, 2015).

2.2 Cycling benefits

Individuals with travel needs weigh the costs and benefits of different modes to decide which mode is most suitable for a given trip destination, path and purpose. Considerations such as travel time, cost, reliability and comfort are prioritized differently from person to person. Despite the uniqueness of travel decision-making, a common theme in the literature is that cycling presents multiple benefits to travelers and the environments in which cycling takes place. This section presents literature that demonstrates the benefits of cycling.

2.2.1 Health & Environment

Decreases in active modes of travel such as walking and cycling are partially a result of the increased convenience and dependence on motorized vehicles. The outcome of such a transition is a substantial increase in the overall time spent sedentary (González-Gross and Meléndez, 2013). Among many other first world countries, Canada and the USA face an obesity epidemic linked to reduced physical activity and dietary changes (Ng et al., 2014). In 2014, 40% and 70.7% of adults in Canada and the USA, respectively, are considered overweight or obese (Statistics Canada, 2014; CDC,2014). Those who are overweight or obese are at greater risk to diabetes, heart disease, high blood pressure, liver disease, osteoarthritis, certain types of cancer, stroke, mental illness and overall increased mortality (Pratt et al. 2014).

Bicycling for utilitarian or recreational purposes is one of many methods to achieve the exercise recommended for good physical and mental health. Indeed, the health benefits are well understood – yet shifting to a greater cycling mode share has more implications. A greater mode share means fewer automobiles are driven and air pollutants are reduced. Volatile Organic Compounds (VOC) from the exhaust of combustion engines have toxic carcinogenic properties and are linked to higher mortality rates, particularly for the young and elderly. Globally, 5.5 million people die prematurely due to air pollution (GBD, 2013). Transportation is one of largest sources of air pollution in Canada; in the US, transportation generates over one quarter of all greenhouse gas emissions, contributing to the various causes of climate change (Environment Canada, 2016; US Environmental Protection Agency, 2014).

Some have suggested that the health benefits of bicycling may be offset by exposure to road-related air pollution and being at greater risk and severity of collisions relative to other modes. These concerns are valid given cyclists, for example, rest at signalized intersections breathing adjacent to vehicle exhausts and are objectively more vulnerable road users. However, Mueller et al. (2015) reviewed existing literature of the net health impacts of active transportation and found that the benefit-risk ratio results range from 2:1 to 360:1 with a median of 9:1, suggesting even on the conservative end that the health benefits of cycling outweigh the risks.

2.2.2 Efficiency and Safety

Traditionally, road congestion and travel delays for automobiles are often overcome by providing greater capacity through road widenings. Over time, however, professionals have realized that interventions of this nature can have short-lived results. As capacity is increased, demand soon follows and, as a result, travel times are not reduced in the long term. This phenomenon is known as *induced demand* (Litman, 2017). At a time when mobility associated with automobiles was of upmost concern for transportation professionals, many cities developed high capacity multi-lane roads through CBDs. Generally, priorities have since shifted to balance the demands of vehicular traffic with other urban activity. Strategies such as road diets, traffic calming measures, intersection redesigns, street network redesigns and bicycle infrastructure have shown to increase safety of *all* road users (Marshall & Garrick, 2011).

Research suggests that the installation of bicycle infrastructure has a positive relationship with increased rates of bicycling (Dill & Carr, 2003; Pucher, Dill & Handy, 2010; Aziz et al., 2018). Intuitively, the shift in focus could result in a decrease in *throughput,* traditionally seen as the number of vehicles per hour per lane past a certain point. However, if throughput is viewed as persons per hour per lane, cycling can provide greater throughput relative to personal automobile. Figure 4 is a visual example to demonstrate the space needs of different common modes.

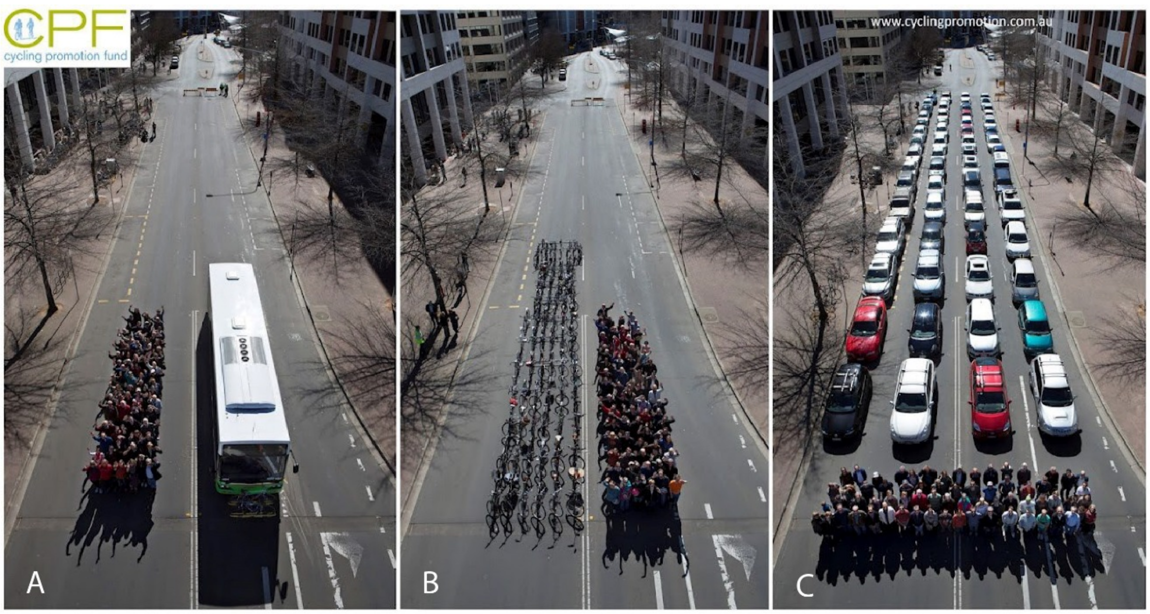


Figure 4: Road-space Comparison Between Bus, Bicycle, and Automobile (Australian Cycling Promotion Foundation, 2017)

Each image as part of Figure 4 has the same number of people, where A represents the space a group of people take up with a bus; B, for bicycles; and C, for personal automobiles. The throughput for private motor vehicles in urban areas ranges from 600 to 1,600 per hour and two way protected bikeway (requiring the same amount of space) can achieve 7,500 riders/hour (NACTO, 2014)

2.2.3 Economy

There exists a body of literature that suggests cycling has economic benefits. The health benefits of cycling can limit or reduce levels of poor health due to being overweight or obese which can reduce reliance on the healthcare system. Anis et al. (2010) calculated the direct cost of obesity and overweight Canadians at $6 billion dollars annually and an additional $5 billion in lost productivity. A more modest analysis suggests a burden of $5.3B for direct and indirect costs. The same study calculated that a 10% increase in physical activity of Canadians translates to a direct healthcare savings of $150 million (Katzmarzyk & Janssen, 2004).

A shift to greater mode share of cycling, walking and public transit can also reduce the economic costs of congestion. In 2006, the Greater Toronto Area (GTA) commuter congestion costs such as travel delays, environmental impact, increased vehicle costs because of delays and increased chance of vehicle collision was quantified to be $3.3 billion. Moreover, the cost of lost productive time because of congestion relative to Gross Domestic Product was $2.7 billion. These numbers are expected to rise to $7.8 billion and $7.2 billion respectively by 2031 year if trends continue (Metrolinx, 2008). Cycling, along with other active modes of transportation can mitigate these impacts.

Several other studies have looked at the total economic impact of investing in cycling infrastructure, inclusive of environment, health, productivity and other factors. Transport for London (2014), England quantified the benefit-cost ratios to be 5:1, meaning that for every $1 dollar spent on cycling infrastructure, society accrues $5 dollars in benefits. Similar results of 10-25:1 and 11:1 were found in studies from Britain and New Zeeland, respectively (Beale et al. 2012; Macmillan et al. 2014). In fact, a systematic review by Brown et al. (2016) revealed that 26 of the 32 benefit-costs analyses related to active transportation produced net positive returns. From a local business perspective, cyclists have been found in multiple studies to on average spend less per trip to urban centers but make more frequent trips, and over time spend just as much or more compared to those traveling by personal auto (OTREC, 2012; Popovich & Handy, 2014; Moos et al. 2015).

2.2.4 Benefits: Personal vs. Societal

Another method of considering the benefits of cycling is to characterize the benefits as personal or societal relative to other modes. For example, cycling provides an individual benefit of physical exercise and a societal benefit of no pollution relative to personal auto or bus transit. Cyclists will have different motivations that contribute to their choice to travel by bicycle over other modes. Some may be motivated by an economic and convenience advantage, while others may be more concerned of the environmental impacts of motorized modes. From a systems perspective, many cities and tiers of government have recognized the negative impacts of traffic congestion and have taken more significant efforts in promoting modes that are more efficient and carry fewer negative externalities. Table 1 provides a non-exhaustive list of intuitive or previously referenced cycling benefits and disadvantages relative to other modes such as walking, public transit and personal automobile.

Table 1:Individual vs. Societal Benefits of Bicycling

Recipient	Advantage:	Relative to:	Disadvantage:	Relative to:
Individual	Cost of purchase	auto	Weather	auto, bus
	Cost of maintenance & repair	auto	Seasonal changes	auto, bus
	Cost of parking (none)	auto	Travel speed	auto
	Reduced health risk	auto	Topographical variation	auto, bus
	Fuel cost (none)	auto	Theft risk	auto, but, walking
	Low space consumption	auto	Collision injury	auto, bus
	User Fees (none)	transit, auto		
	Increased heart rate and cardiovascular health	walking, transit, auto		
	Speeds	walking		
Societal	Reduced parking needs	auto		
	No contribution to congestion	auto		
	Increased happiness & wellbeing	auto		
	Increased social cohesion	auto		
	Consumer habits (Economic benefit)	auto		
	Less toll on healthcare system	auto		
	Increased safety for road users	auto		
	Zero use pollution	auto, transit		

The predominant comparison is to auto use since the benefits of walking and transit use are more comparable to cycling.

2.3 Factors influencing propensity to cycle

Individuals with travel needs weigh the costs and benefits of different modes to decide which mode is most suitable, and travel time is extremely important when considering transportation mode (Börjesson and Eliasson, 2012). In urban areas, bicycles are particularly competitive with motorized transportation within certain distance thresholds (Hunt and Abram, 2007). Despite this, North American urban areas still struggle with translating competitive travel times to greater proportions of bicycling (Sanders, 2015). To quantify and express travel cost, modelers have traditionally employed a linear weighted sum of travel factors through a generalized cost model. A common example is presented in Equation 1 (Casello, Nour & Hellinga, 2009):

$$GC_M = (a_0 AT + a_1 WT + a_2 IVT)VOT + OPC \quad (1)$$

where:

GC_M is the generalized cost of a trip my mode M($);
AT is the access time to travel mode (eg. bus stop, car in driveway, bicycle in garage) (minutes);
WT is the waiting time (minutes);
IVT is the in-vehicle time (minutes);
VOT is the value of time ($/minute);
OPC is the out of pocket cost ($);
a_i is the relative importance of that variable.

This model adequately quantifies costs under the condition that mode choice is solely a function of distance, time and value of time. However, there are other non-monetary 'costs' this model does not include that are critical to cycling propensity. This is likely why factors such as time and cost are found not to be as influential regarding bicycle use, suggesting other psycho-social or environmental considerations hold a more significant weight (Eriksson & Forward, 2011).

The Geelong Bikeplan (1978) was early research that introduced the concept of *bicycle stress level* to better describe the experience on roadways for bicyclists. The assumption with bicycle stress level is that routes are chosen to minimize effort and stress – where stress relates to conflict and interaction with motor vehicles. Stress was found to be influenced by curb lane width, traffic volumes, and vehicle speed. Many studies have evolved out of these assumptions, notably the adaptation of traffic level of service (LOS) models for bicycles, or bicycle level of service (BLOS) (NACTO, 2007) and the Bicycle Compatibility Index (BCI) (FHWA, 1998). The distinguishing features of BLOS and BCI relative to models design for motor vehicles is that they rely on perceived safety of road and environmental conditions. Though, they are not without limitations. The models have been found to be insensitive to bicycle-specific intersection treatments and generally require extensive information, making validation and implementation challenging (Huff & Liggett, 2014).

As with programs like Vision Zero (Vision Zero, 2018) cities have adopted initiatives to address real and perceived safety issues with bicyclist and pedestrians. The real safety measure are quantifiable – often rooted in collision data and reported in government documents. Perception of safety is far more complex. Though partially a function of real safety, perceived safety is made up factors such as skill, past experiences, confidence and expectations that vary greatly between individuals.

An oft-cited study by Dillon & Carr (2003) used a stated preference survey and a multi-variate regression analysis of data from 43 North American cities to identify the variables that affect bicycling propensity. The stated preference results suggested improved infrastructure would produce an increase in bicycling and the regression analysis demonstrated a positive correlation between presence of bicycle infrastructure and proportion of bicycle mode share. A study by Fernandez-Heredia et al. (2014) investigated perceptions influencing propensity to bicycle. The conceptual model developed in this study of factors affecting bicycle use is presented in Figure 5

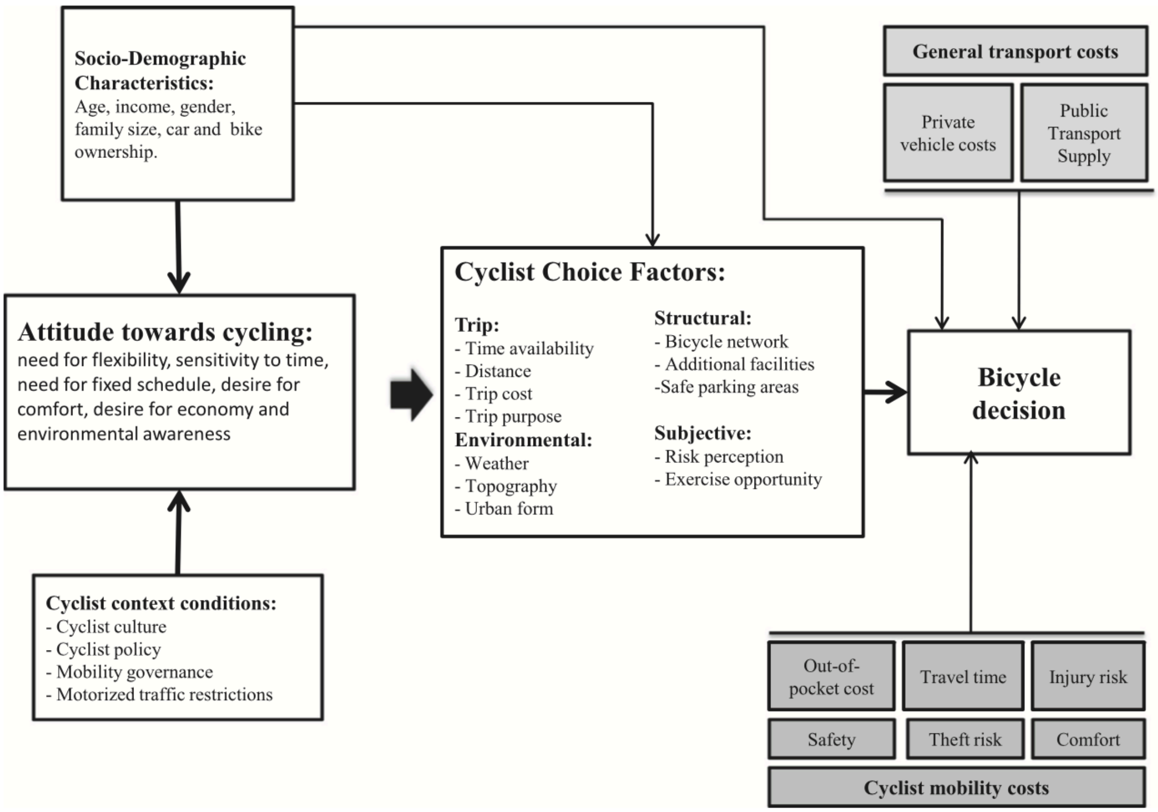


Figure 5: Conceptual Model of Factors Affecting Bicycle Use

This conceptual model has, among other factors, socio-demographic, policy, cultural context, and attitudes feeding an interpretation of bicyclist choice factors. This includes important environmental factors like weather, topography and urban form. The conceptual model was developed into fourteen key factors for a structural equation model to find relationships among the variables. There are two relevant results of this study. The first is that *external restrictions* - being danger (perceived risks), bicycle theft, vandalism, and auxiliary facilities like change rooms and showers at places of employment, are perceived as very important to users. The second relevant result is the desire for convenience (the perception of bicycling being a fun, healthy, fast, and cheap mode for medium-range distances) is crucial for convincing potential bicyclists. Casello et al. (2011) in Waterloo, Ontario used survey and GPS data to better understand motivations and obstacles to cycling and to develop a generalized cost model for cycling trips. Of significance, this study found that generalized costs comprising of only distance and travel time are insufficient in predicting cycling route choices. In the survey, the highest rated motivation to cycle was "convenience compared to other modes" and most significant obstacles were "feels unsafe" and "poor motorist behaviour". Also in Waterloo, Ontario, Casello et al. (2012) gathered socioeconomic and observed travel data to analyze how the built environment and roadway networks influence cyclists' path choices. The authors collected origin and destination data and then generated shortest paths and calculated excess travel distances. The results demonstrated that grid-like street patterns provide greater directness for cyclists, contrasting curvilinear/large retail and commercial developments; the latter was found to create excess travel. They found that trails can substantially reduce distances that cyclists are required to travel. The results also found that trips beginning or ending in zones with unfavourable cycling street patterns or unfriendly land uses experienced much more excess travel than other zones.

2.4 Bicyclists & Intersections

As stated in the introduction, intersections can pose challenges for cyclists. Literature related to cyclist interaction with intersections is presented below.

2.4.1 Collision Risk

Urban bicycle networks by necessity have junctions and crossings with other transportation infrastructure – roads, pedestrian paths and rail crossings. Conflict between motorized and non-motorized road users raises safety concerns; understanding the risks and potential solutions is crucial for reducing collisions. Both bicyclists and drivers are to blame for collisions, though drivers are more often at fault (Barclay, 2011). For both road users, the most significant cause of collisions is failure to yield to the right of way (Barclay, 2011). Numerous studies have found intersections, opposed to midblock or pathways to have the highest rate of bicycle collisions (Tomlinson, 1998; Isaksson-Hellman, 2012; City of Vancouver, 2015; City of Philadelphia, 2015, European Commission, 2015). A comparison was made in Vancouver and Toronto on the effects of infrastructure for intersections and non-intersections regarding bicyclist injury (Harris et al. 2013).The results demonstrated that intersecting route type and intersection design influenced safety. Intersections of two local streets had one-fifth the risk of intersections with more than two traffic lanes, and non-intersections with cycle tracks were very low-risk. One study using U.S. national databases of fatalities, police reports and emergency visits found that 33% of vehicle-bicycle collisions occur when a bicyclist is riding on the sidewalk. The same study found that bicyclists in crosswalks facing traffic were disproportionally represented in crash types, mainly caused by failure to yield by motorists. However, failure to yield was likely due to the unexpected positions and route choices of bicyclists (Schimek, 2014).

Other studies have found that intersections are the locations for a minority of cycling crashes that result in fatalities. The U.S. National Highway Traffic Safety Administration (2017) (NHTSA) statistics suggest only 28% of fatalities occur at intersection, 61% occur at non-intersections based on probability samples of police reports in 60 locations across the U.S. It is possible that higher rates of *fatalities* occur midblock because speeds are often greater midblock opposed to intersections. Nonetheless, variations in studies emphasize the challenges of reliability of cyclist collision data.

A persistent problem in research on cycling safety is underreporting of incidents. Shinar et al. (2018) found this phenomenon to be internationally common. On average, only 10% of all crashes are reported to police. Near-miss incidences are particularly challenging to obtain reliable statistics, though one ongoing project, bikemaps.org, uses crowd-source reporting of cyclist collisions and near misses and collects numerous attributes relating to incidences (Nelson et al., 2015). Near misses are found to be far more common than actual accidents, and these incidences heighten cyclists' awareness of risk (Sanders, 2015). Opportunities for infrastructure improvements may get overlooked for not having data to support the intervention if incidences go under or unreported. More comprehensive data can assist in the understanding of what and where interventions are needed on an intersection or network level.

2.4.2 Signalized Intersection treatments for bicyclists

Numerous intersection treatments have been studied and implemented in cities all over the world and their benefits are reasonably well understood. The National Association of City Transportation Officials (NACTO) developed the Urban Bikeway Design Guide, currently on their Second Edition (2014), that compiles bicycle infrastructure and design for bicyclists in a North American context. Readers are directed to this guide for a more comprehensive list of designs and infrastructure. The following text lists a non-exhaustive list of infrastructure specific to signalized intersections. Images of each item can be found in Appendix A.

Crossing Markings:

Crossing markings extend bike lane markings through intersections, often with colour, to remind other road users of the path cyclists take while traversing through intersections. It establishes an expected space in which bicyclists should be consistent with and drivers to be aware of.

Bike Box:

Bike boxes create safe and visible spaces ahead of queuing traffic at signalized intersections for bicyclists arriving during red signal phases. Bike boxes can extend into left turn lanes to facilitate bicyclists getting to the front of left-turn queues and have been implemented in countless cities around the world.

Two-Phase Left-Turn Bike Box

Also referred to as:

- Two-Stage Left-Turn Bike Box
- Twice-crossing left
- Copenhagen left

As described in the introduction, this facility is useful for left-turning bicyclist at intersections where left turns are challenging due to high traffic volume, multi-lane intersections or perceived safety concerns. The left turn is completed in two phases and is most useful for bicyclists arriving on a green signal phase. The first phase is completed by traversing straight through the intersection staying curbside to the box located near the far side right curb edge. Once arriving at the box, the bicyclist turns 90 degrees to the left. The first provided example demonstrates a bicyclist who has completed the first phase. The second phase is completed once the signal phase changes, and the bicyclist traverses through the intersection in the intended travel direction. The box is strategically located to not impede other bicyclist maneuvers.

Two-Phase Right-turn Bike Box

The intention and merits of this facility is the same as two-phase left-turn bike boxes, but for right-turning situations. These situations only exist under specific conditions. For example, an intersection in this study where a protected bike lane exists on the left shoulder of a one-way multi-lane street. Bicyclists approaching the intersection on a green signal wanting to turn right can proceed to the bike box and turn right 90 degrees and wait. Then once the signal phase changes, proceed through the intersection to complete the right turn.

Through Lanes

Some intersections will have dedicated right turn lanes for vehicles, creating conflict for bicyclists not intending to turn right. The bicycle through lane establishes space between the through lane and right turn lane to facilitate a smoother transition. Some intersections will be treated with markings for when bicyclists are to leave the curbside lane to join the through lane.

Cycle Track Intersection Approach

Midblock cycle tracks are favoured for the physical separation from drivers, though maintaining a cycle track through intersections can cause conflict. Transitions prior to intersection arrival that mitigate conflict and is often less expensive than providing dedicated bicycle signals.

Bicycle Signal heads

Where bicycle routes meet signalized intersections, bicycle signal heads can be provided to give dedicated or explicit signals for bicyclists to stop or cross.

Intersection Signage

Signage exists to distinguish bicycle routes and facilities, and to provide information and instruction to drivers. Signage at intersections is especially important to remind who has the right of way.

A recent review of current infrastructure treatment safety research by DiGioia et al. (2017) found evidence to support the safety benefits of core bicycle infrastructure such as bike lanes, though the author determines that many of the existing treatments still need more rigorous research – particularly for quantifying appropriate risk exposure methods. Benefits of bike boxes are significant to this current research because they are assumed to translate to two-phase turn bike boxes. The assumptions are that they both reduce conflict, and that a reduction in conflict improves safety and perception of safety. Also like bike boxes, two-phase turn bike boxes provide greater visibility of bicyclists at signalized intersections. DiGiota et al. (2017) at the time of publication found no existing research on two-phase turn bike boxes, though the stated benefits in NACTO's design guide presumably rely on anecdotal evidence or similarities to standard bike boxes.

There are other approaches to intersection design such as the 'Dutch Intersection'. Dutch intersection design priority is to have smooth cycle track transitions without sharp turns, seen in Figure 6.

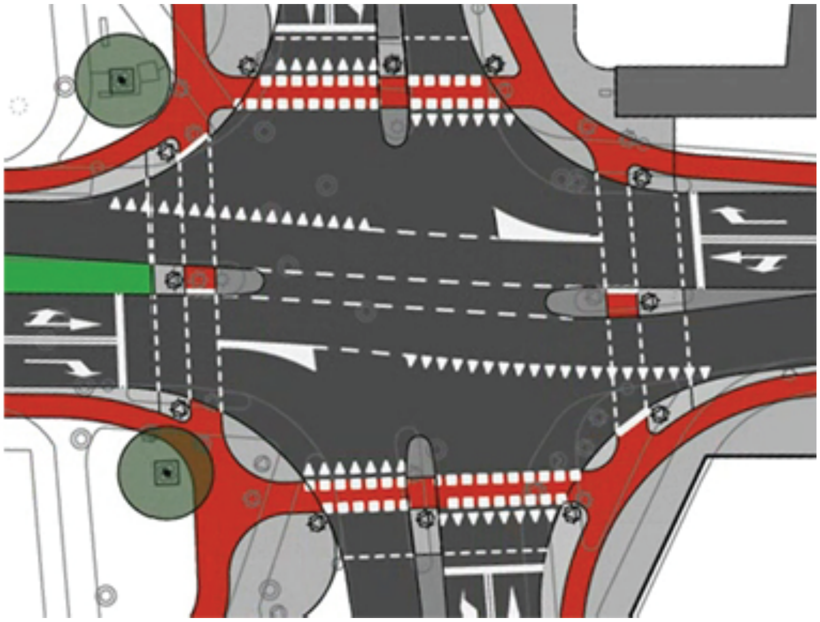


Figure 6: Dutch Intersection Design (Bicycle Dutch, 2011)

Right turns do not require stopping, and left turns are by default done in two crossing phases. Importantly, bicycles and pedestrians have dedicated crossings (known in North America as cross-rides) and are common in European design (Bicycle Dutch, 2011). There may be limited space for this type of design in a North American context and one-off applications of this, opposed to a network of Dutch-like intersections may not produce desired outcomes in behaviour of drivers and bicyclists.

2.4.3 Intersection Behaviour

Despite advancements in infrastructure and design favouring bicyclists, there are still challenges with addressing the extensive range of bicycle behaviour. Generally, safety is greater when cyclists and drivers have well established, common expectations. To further investigate these challenges, Copenhagenize Design Company (2014a) conducted a study titled "The Choreography of an Urban Intersection" in Copenhagen, Denmark. Video cameras were used to monitor bicyclist behaviour observing how riders travel though intersections revealed through desire lines. Bicyclists were documented and classified into three categories:

- *Conformists*: Riders that follow the rules.
- *Momentumists*: Riders that desire to continue rolling and making frequent adjustments. These riders turn right on red without stopping or carefully ride over pedestrian crossings
- *Recklists:* Riders that run red lights and turn left like cars (two phase left turn is the legal way to turn left in Copenhagen).

Out of all cyclists captured through video, 93% of users were classified as Conformists and the remaining and 6% and 1% made up Momentums and Recklists, respectively. Interestingly, 56% of all rule breaking between Momentumists and Reclkists was relatively benign – where cyclists crawled passed stop lines at red lights. The study also found that cyclist choices were influenced by other riders. The author describes this as “follow the leader”, where the first person in a red-light queue sets the precedent on where stopping occurs (before or after stop line) and crawling forward. The same study also looked at left-turning bicyclists tendencies, considering left turns are where a greater proportion of violations often take place. Bicyclist desire lines revealed that 85% used the design-intended two-phase left facility, 2.2% turned like vehicles and 11.3% performed “snake lefts”. Snake lefts are when bicyclists use the nearside pedestrian crosswalk to go left, and then another pedestrian crosswalk to end up in the desired direction and lane. Another example study by Armini, Twaddle & Leonhardt (2016) from Germany demonstrates few issues with incompliant bicycle behaviour. In this study, efforts were made to model left-turning bicycle behaviour also using video capture methods. Their findings omitted red-light running and bicyclists on sidewalks because neither occurred frequently enough to be statistically influential.

The studies by Copenhagenize Design Co inspired a first-of-its-kind North American study by Casello et al. (2017) in Toronto. Video capture methods were used to better understand what conditions left-turning bicyclist perform left turns legally and/or consistent with the intersection design. Five different intersection designs were selected to provide a variety of cycling conditions to asses including type of bicycle facility (bike lane, cycle track, bike box, two-phase left turn bike box), number of lanes, and presence of advanced left green signal phase. Results revealed that three designs had 100% compliance when bicyclists arrived on green signal phases, and the other two had compliance rates of 93% and 78%. Intersection design with a bike box extending to the left turn lane and an advanced green signal phase had the highest compliance rates. In this case, 90% of bicyclists were compliant with the law, and importantly, 80% of bicyclists arriving on a red signal phase were compliant. The intersection with a two-phase left turn bike box also had fairly high compliance rates, where 70% of bicyclists performed their left-turns legally, and 54% did so using the two-phase left turn bike box. This intersection did not demonstrate superior compliancy for bicyclists arriving on a red signal phase, however. The intersection with two through lanes between the left turn lane and bike lane had the poorest performance in facilitating left turning cyclists.

A recent study in China (Dong et al. 2017), also using video capture methods to model two-phase left-turning behaviour versus vehicular left behaviour found complementary results to Casello et al. (2017). The authors developed a cost analysis from incurred delay of drivers and bicyclists, and found that two-phase left maneuvers were more appropriate for larger multi-lane intersections or intersections with high vehicular volume. These results are consistent with expectations that bicyclists have safety concerns crossing multiple lanes of traffic. This research demonstrates specific types of intersection facilities for bicyclists can create greater compliance and therefore consistency in behaviour.

In comparing findings from both the European and North American cycling compliance studies, European cyclists are more likely to be rule abiding and to appropriately use cycling infrastructure. The North American case found greater inconsistent behaviour, especially with bicyclists approaching red signal phases. One of the supporting similarities is the positive influence of two-phase left turn movements.

2.5 Red Light Violations

Bicyclists violating red lights is often cited by drivers as the most irritating behaviour of a bicyclist and is perceived as a common occurrence (Fincham, 2006) The common perception of drivers is that bicyclists think traffic laws do not apply to them. Though collisions resulting from bicyclist red light running and rates of red light running have been found to vary greatly between countries and cultures (Fraboni et al., 2016), the behaviour is disruptive and carries risks. Often overlooked are the greater repercussions regarding perceptions and attitudes of drivers towards bicyclists.

Johnson et al. (2011) conducted a study in Melbourne, Australia to understand the characteristics, rate, and risk factors of commuting bicyclists running red lights. Cameras were set up to discreetly observe bicycle behaviour at ten sites along a high volume bicycle commuter route. A range of 3.9 to 13% non-compliance was observed depending on the intersection. A binary (compliant/non-compliant) logistic regression was conducted with multiple predictor variables. The direction of travel was found to have the highest impact on the likelihood of non-compliance. Specifically left turn cyclists (equivalent to right turns for right-side drive countries) were found to be 28.4 times more likely to violate a red light than through-bicyclists. Other statistically significant results suggest that intersections with dedicated left turn lanes with bike boxes only for the through lane are 2.6 times more likely to run a red light. Intuitively, running red lights was found most likely to occur when cross-traffic volume was low, and reduced as volume increased. A survey of bicyclists in a study in Australia, found that the main reasons for red light violations were: left turns (equivalent to right turns for right-side drive countries) (34%); loop detectors did not detect their presence (24.4%); and when no other road users were present (16.6%) (Johnson, 2013). A multinomial logistic regression found bicyclist red-light running behaviour is driven by the perception that doing so is perceived as safe, and that existing infrastructure hinders a willingness to be compliant.

A similar study by Larson et al. (2011) in Portland, Oregon monitored select intersections to compare red light violations between drivers and bicyclists. Findings were that 7% of drivers and 56% of bicyclist violated red lights. The study also notes that 70% bicyclists on cycle tracks ran red lights versus less than 40% on regular bike lanes.

Research on red light running in China identified three types of cyclists similar to, and predating studies done by Copenhagenize Design Co. The three types of cyclists are Law-obeying, risk-taking and opportunistic. The difference between risk-taking and opportunistic behaviour is that risk-takers ride through intersections without yielding, where opportunists yield but grow impatient with waiting and find a gap in cross traffic. This research also found 56% of bicyclists ran red lights (Wu, Yao & Zhang, 2012).

A study done by McKeil & Dill (2012) in the Washington D.C. area on compliance with signals found a relationship between crossing traffic and cyclist compliance with a red signal. Results found that rates of red light violations decreases with increasing number of conflicting vehicles, though the decision to violate a red light was also related to gaps in traffic and delay time of cyclists. Considering all study intersections, an average of 42% of cyclists arriving on a red signal violated the signal.

More permissive approaches to bicycle laws have developed in a few cities, though none are as established as the Idaho Stop law. Dating back to 1988, in its current form (Idaho Statute 49: Chapter 7 Pedestrians and Bicycles § 49-720) the Idaho Stop permits bicyclists to treat stop signs as yield signs and red lights as stop signs. Decades of this law in place has demonstrated no increase in conflicts and crashes - even some studies find it has resulted in decreased conflicts and crashes (Whyte, 2013). Another similar example surfaced in Paris in 2015. Traffic laws changed permitting bicyclists to turn right on red lights without stopping. However, no known results have been published since the law's introduction.

Literature for red light violations demonstrate mix results and rates of violation, supporting the notion that red-light violation rates are likely a function of characteristics unique to a city or country's bicycling culture and approach to infrastructure and permissiveness.

2.6 Literature Gaps

Cycling research is often conducted to inform practice, and the literature demonstrates the benefits of cycling and progress in research and safety that has been made in recent decades. The existing research also reveals numerous gaps and opportunities for further inquiry. A thorough review of bicycle infrastructure and bicyclist behaviour demonstrates how bicycling is important to cities, and getting design right makes a difference. In European design, two-phase left turns are common. In North America, two-phase left turn bike boxes have been implemented in some cities, yet no explicit research exists in a North American context of their influence on behaviour for left turning bicyclists. The closest case, providing motivation for this current study is the left-turn observational study by Casello et al. (2017). This research alludes to the benefit of two-phase left turn bike boxes, yet leaves some questions unanswered. Moreover, the critical review of bicycle infrastructure safety by Digiota et al. (2017) explicitly states that no study validating the benefits of two-phase left turn bike boxes exist. Studying two-phase left turn bike boxes can advance understanding of effective design and bicycle behaviour.

Many studies focus on the motivations behind cycling and what infrastructure is most appropriate for current and potential bicyclists. The literature demonstrates a great amount of variability in behaviour, and gaps exist in the stochastic nature of bicyclists in North America. The desire lines of *current* bicyclists in navigating intersections with or without infrastructure is not well understood. Drivers are known to complain when bicyclists switch behaviour from vehicle-like behaviour to pedestrian-like behaviour, yet very little data exist to describe what is happening. Some literature demonstrates behaviour can be grouped into three categories, though they do not differentiate between compliance of road space positioning with red light compliance. Desire lines, independent of signal compliance, especially ones switching between road spaces, are expected to be where conflict more frequently occurs because of the unpredictability of behaviour. Having a better understanding of this provides practitioners with existing perceptions through revealed behaviour and what types of conditions or situations result in greater or poorer predictability.

3.0 Context and Research Methods

This study was done in conjunction with an ongoing pilot project regarding two-phase turn bike boxes in the City of Philadelphia, Pennsylvania. Many contemporary cities in North America looking for new or alternative solutions for bicycle safety and intersection treatment may find the results of this study relevant to their needs. This chapter provides context to the study intersections, intersection characteristics, methods for observing and documenting bicyclist behaviour, and the data analysis approach.

3.1 The City of Philadelphia

The City of Philadelphia has a population of 1.57 Million (2015) and is the 10^{th} largest city in North America, ahead of Phoenix, Arizona and behind Ecatepec de Morelos, Mexico. At its population peak, Philadelphia had over 2 million inhabitants in the 1950s and 1960s but declined as the economy shifted away from its industrial roots. Philadelphia is the largest city in the state of Pennsylvania, located in Northeastern United States at the confluence of the Delaware and Schuylkill Rivers depicted in Figure 7.

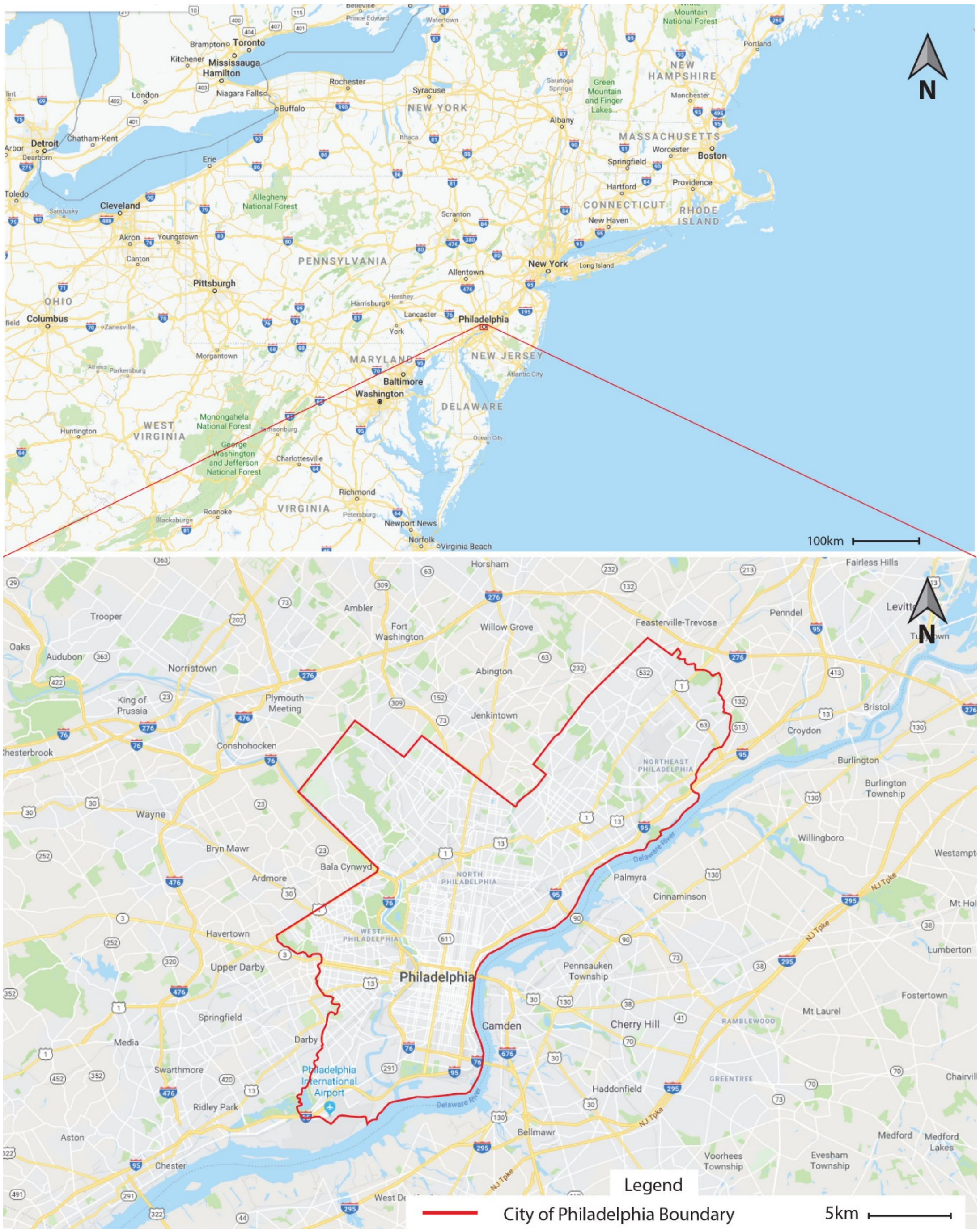


Figure 7: City of Philadelphia Context

The City of Philadelphia's bicycle mode share as of 2016 is 2.2%, an increase of 23% from 2011 and a 280% increase from 1990 (League of American Bicyclists, 2016). Interestingly, Philadelphia has the 11th highest bicycle mode share in the USA and the only city with a population over 1 million to exceed 2% mode share. (League of American Bicyclists, 2016).

The city's bicycle mode share is strongly (and negatively) influenced by many outlying neighbourhoods within city boundaries that have very low rates with many observations of no cycling. Considering the home to work distances for many of these neighbourhoods, commuting by bicycle simply is not a reasonable option. This relationship is visible when assessing mode share on a neighbourhood level. The Pedestrian and Bicycle Plan Progress Report (2015) by the City of Philadelphia estimates that the three planning districts this study covers – South Philadelphia, University Southwest, and River Wards – have bicycle mode shares of 6.5%, 6.2% and 2.9% respectively. These three districts are adjacent to the Center City district. Outlying districts such as Upper Far Northeast have 0% bicycle mode share (City of Philadelphia, 2015b).

Between 2009 and 2013, reported bicycle crashes remained relatively constant with the highest number of reported incidences of 573 in 2010. 46.4% of bicycle crashes were of riders aged 16 to 30 and 79% of crashes were male (City of Philadelphia, 2015a).

3.2 Vision Zero

Vision Zero began as a national policy in Sweden in 1997 to "*eliminate all traffic-related deaths and severe injuries, while increasing safety, health, and mobility for all*" (Vision Zero, 2018). After successfully reducing traffic-related deaths by 30%, other cities, including many in the US and Canada, began adopting Vision Zero. The City of Philadelphia officially released their Three-Year Action Plan in September of 2017 setting out the following fundamental principles to eliminate traffic-related deaths by 2030:

- "*Traffic deaths are preventable and unacceptable.*
- *Human life is our highest priority.*
    - *Preserving human life takes priority over convenience.*
    - *Philadelphia's transportation system should be safe for all of its users, in all neighborhoods.*
- *Human error is inevitable and unpredictable. Our transportation system should be designed to anticipate human error so that the consequence is not death or severe injury.*
- *Safe human behaviors, education, and enforcement are essential to a safe transportation system.*
- *People are inherently vulnerable and speed is a fundamental predictor of crash survival. Our transportation system should be designed for speeds that minimize risk to human life."*

City of Philadelphia, 2017, p. 5

Implementation of these principles is undertaken by six sub-committees covering evaluation & data, engineering, education & engagement, traffic safety enforcement, fleet management, and policy. This report presents a High Injury Network that includes only 12% of Philadelphia's roads but accounts for 50% of all traffic related deaths and severe injuries. Many of the strategies of Vision Zero are focused on vulnerable road users, namely pedestrians and bicyclists. In 2016, there were three fatal accidents involving a bicyclist and 12 major injuries (City of Philadelphia, 2017).

3.3 Research Methods - Intersection Selection

Staff with the City of Philadelphia put forward a request for experiment to the United States Federal Highway Administration (FHWA), as two-phase turn boxes are not yet approved for 4-leg multi-lane controlled intersections in the Manual on Uniform Traffic Control Devices (MUTCD). The MUTCD is a document that provides standards and guidance for traffic control. Traffic control devices (locations, messages, size, shape, and colours) reduce crashes and improve the efficiency of road transportation based on years of practical research informing the manual. Ongoing research ensures traffic control devices are "*visible, recognizable, understandable, and necessary*" (USFHA, 2017). The manual is designed to change with time to reflect evolving operational and safety issues (FHWA, 2017).

The City selected 11 locations where two-phase turning boxes could be effective based on staff's analysis of the existing bicycle network. Five of the 11 intersections were subsequently upgraded with two-phase boxes and signage prior to collaboration for this study. Two of the remaining 6 intersections were provided and one was agreed upon that was outside of the initial remaining 6 to create variety in intersection design to be studied. A late addition by the City requested a fourth intersection be included to study the impact of a two-phase right turn bike box.

No explicit rational for the selection of intersections to receive the two-phase turn boxes was provided, however the main intent of the two-phase turn box installations was to provide options for less experienced or risk averse cyclists that limit conflict with vehicles. It is assumed that the selected locations were popular junctions for left turns. Ideally, any upgrade in infrastructure is best where it has the greatest potential for impact. The study intersections were likely selected based on existing junctions of the bicycle network in high bicycle volume areas. Each of the intersections is described in detail in the following sections.

3.4 Research Methods – Video Data Collection

To capture and categorize bicyclist behaviour for this study, digital video footage was collected by the thesis author for each study intersection and manually reviewed through video playback to document and categorize bicyclist behaviour. This approach was chosen for two main reasons. First, most of the required video equipment was available with minor expenses to meet the documentation needs. Second, contemporary computer automated tracking methods require specific skills and have limitations that made a semi-manual approach a more practical approach.

Video Cameras were set up at four intersections to monitor five individual turning maneuvers. The location of each intersection relative to the greater Philadelphia area is denoted in Figure 7.

Figure 8: Locations of Study intersections in Philadelphia

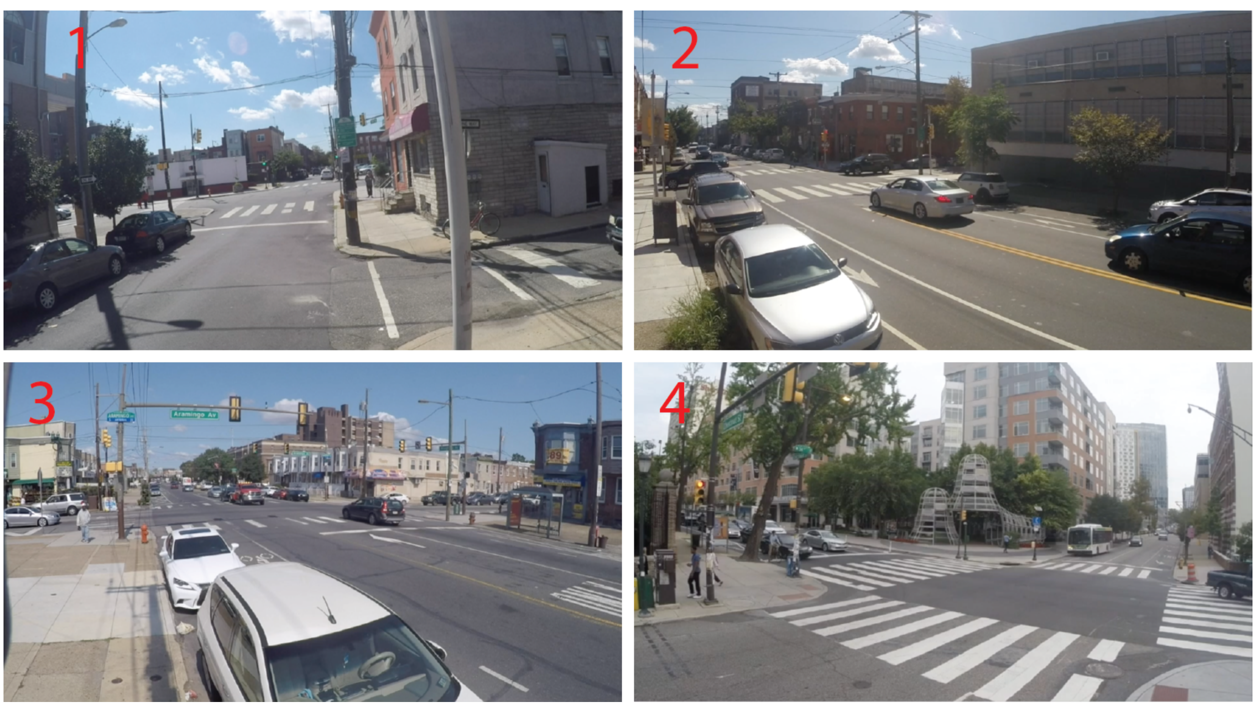
Intersection 1 and 2 are a few blocks apart in South Philadelphia. Intersection 3 is to the northeast of Center City and near large retail commercial land uses. Intersection 4 is abutting the University of Pennsylvania Campus and has high volumes of auto, pedestrians and bicyclists.

Two periods of video capture were conducted to create the longitudinal study. From September 7th to September 12th, the before stage took place to gather existing bicycle behaviour at the study intersections prior to any infrastructure changes.

Subsequent to the before data collection, two-phase turn boxes were installed for the five turning maneuvers in late September of 2017. To provide a break in period for bicyclists to potentially become more familiar with facilities, one month was given between installation of the new facilities and the second stage of video capturing. From October 25th to 28th, the 'after' period took place to document the identical intersections, this time with the facilities in place. A mixture of peak, off-peak and weekend times were documented in the before and after periods to capture behavioural variety relative to traffic conditions.

Three GoPro Hero 3's and One GoPro Hero 4 equipped with microSD cards and additional battery packs were used to collect the video footage. Mounts were discreetly attached to utility poles between 10 and 12 feet off the ground to be accessed by a ladder. The mounts made it possible for the cameras to be removed and reattached easily for replacing batteries, transferring data, and overnight removal to avoid the risk of theft. The mounts were attached to the utility poles using metal ring clamps and adhesive tape. This attachment method allowed for discrete removal and no permanent material left behind after the video collection was completed. The cameras were positioned to ensure all legs of the intersections were in frame. A sample screen shot from each camera is presented in Figure 9. The position of each camera, approximate view angles, turn directions of interest, and intersection configuration details are presented in Table 3.

Figure 9: Intersection Video Camera Views



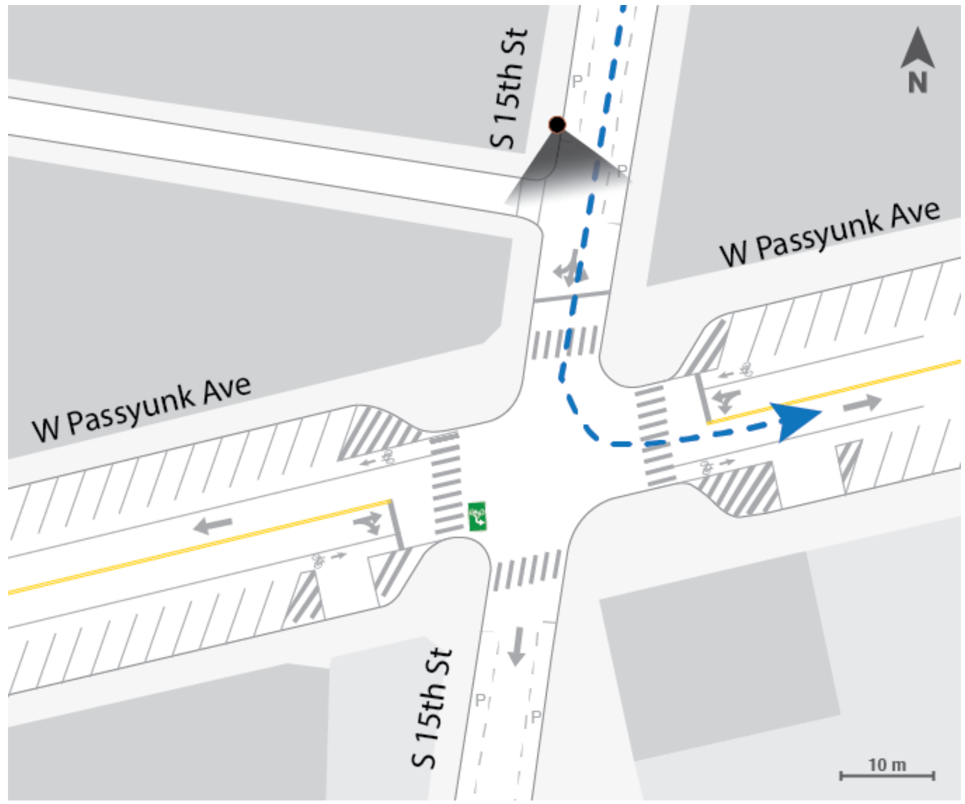
Intersection 1: S 15th St & W Passyunk Ave

Type of Turn: Left turn

Approach road configuration (S 15th St):
- Southbound one-way
- On-street parking, both shoulders
- No bike lane or sharrows
- No left-turn lane

Departing road configuration (W Passyunk Ave):
- Two-lane, two way traffic
- Bike lanes in both directions
- Angled on-street parking, both sides for 1 block east of intersection
- No turn lanes

Intersection Characteristics:
- No turning signal phases
- No detectors
- No pedestrian crossing actuators for any crossings
- Bulb-out curbs on all corners
- Speed limit: 25MPH



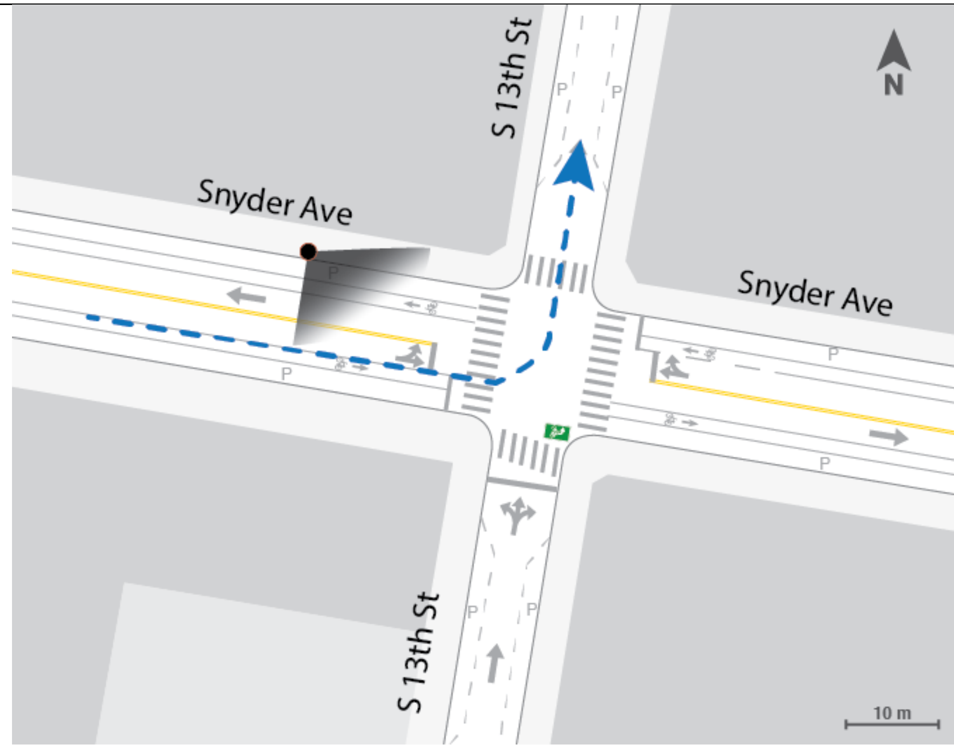
Intersection 2: S 13th St & Snyder Ave

Type of Turn: Left turn

Approach road configuration (Snyder Ave):
- Two-lane, two way traffic
- Bike lanes in both directions
- On-street parking, both shoudlers
- No left turn lane

Departing road configuration (S 13th St):
- Northbound one-way
- On-street parking, both shoulders
- No bike lane or sharrows
- No turn lanes

Intersection Characteristics:
- No turning signal phases
- No detectors
- No pedestrian crossing actuators for any crossings
- Speed limit: 25MPH



Intersection 3: E Allegheny Ave & Aramingo Ave

Type of Turns: Left turns

Approach road configuration (E Allegheny Ave. Same for both approaches)

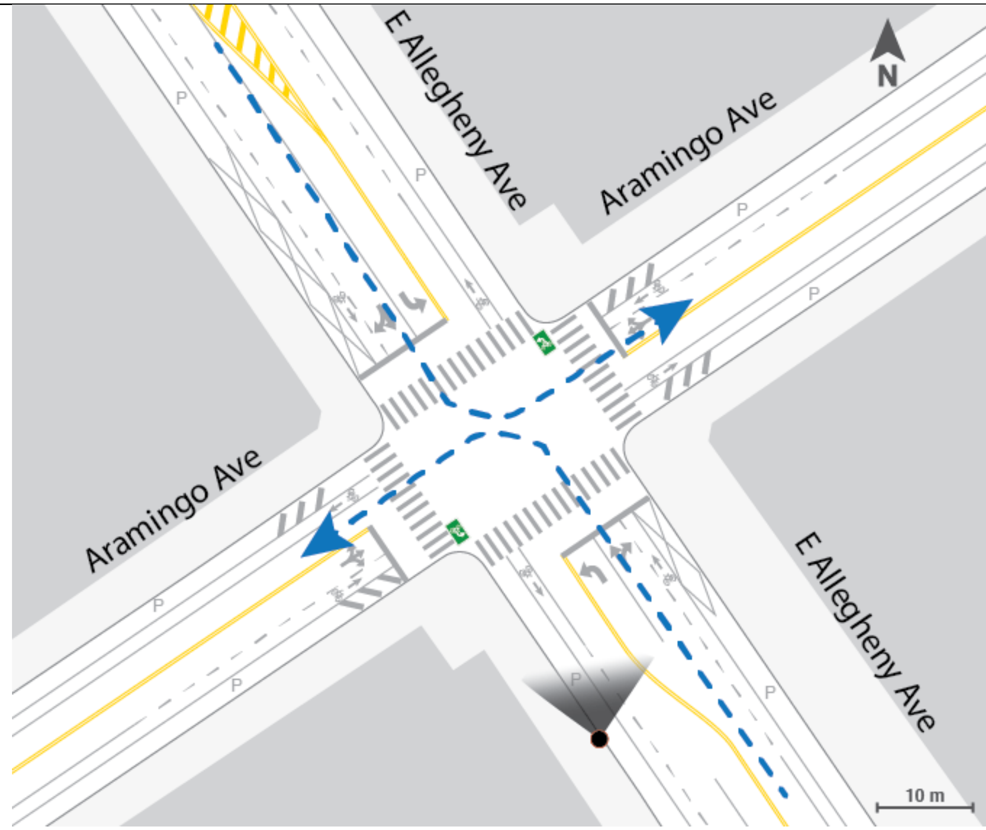
- Two-lane, two way traffic
- Bike lanes in both directions
- On-street parking, both shoudlers
- left turn lane

Departing road configuration (Aramingo Ave. Same for both departures)

- Two-lane two way traffic
- Bike lanes in both directions
- On-street parking, both shoulders
- No turn lanes

Intersection Characteristics:

- No turning signal phases
- No turning lane detectors
- Wide sidewalks along both roadways
- No pedestrian crossing actuators for any crossings
- Speed limit: 30MPH



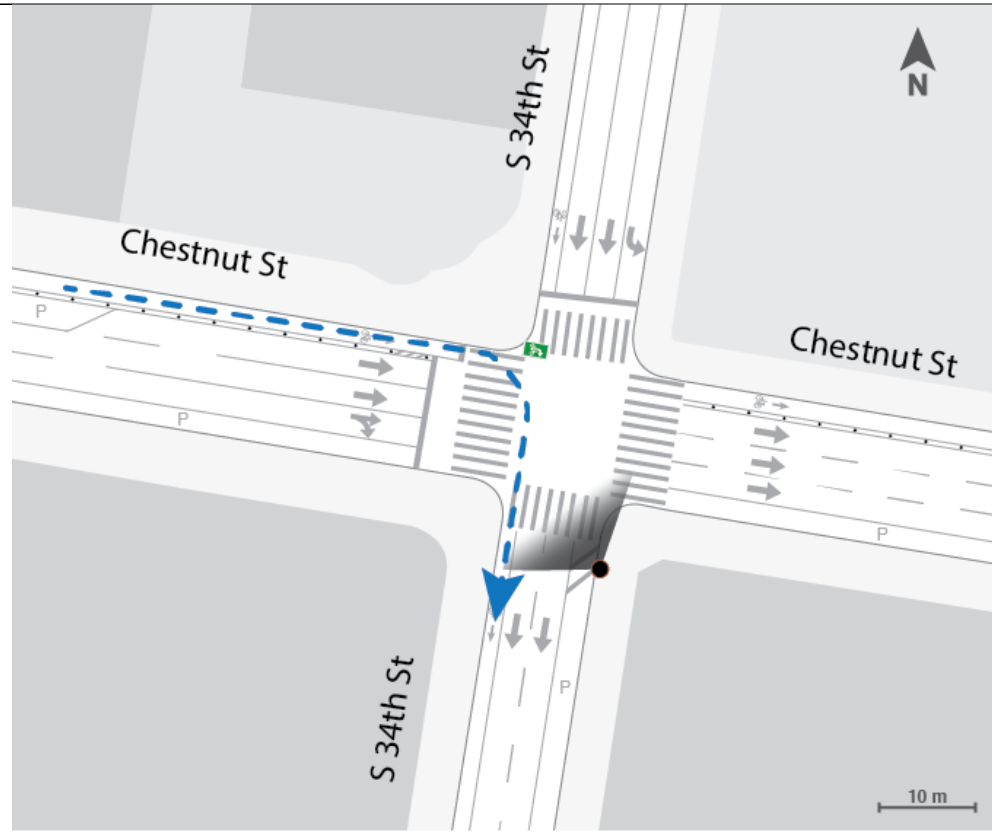
Intersection 4: S 34th St & Chestnut St	
Type of Turn: Right turn **Approach road configuration (Chestnut St):** - Eastbound one way - Protected bike lane eastbound on left shoulder - 3 total vehicle lanes: two through-lanes and one shared through lane and right turn lane - On-street parking southern shoulder, and northern shoulder mid-block but transitions to through lane approaching intersection **Departing road configuration (S 34th St):** - Southbound one-way - Bike lane on right shoulder - Two through-lanes - On-street parking, left shoulder **Intersection Characteristics:** - No turning signal phases - No detectors - High pedestrian crossing volumes - No pedestrian crossing actuators for any crossings - Speed limit: 30MPH	

Table 4 provides information regarding before and after period of data collection, intersection number, street crossing, date, and number of hours of video footage taken in each period.

Table 3: Video Capture Locations Dates and Hours of Footage

Period	Intersection number	Location	Dates	Hours of footage	Observed Cyclists
Before	1	S 15th St & Passyunk Ave	September 7-10, 2017	26:15:25	719
After	1	S 15th St & Passyunk Ave	October 25-28, 2017	31:20:22	799
Before	2	S 13th St & Snyder Ave	September 7-9, 2017	23:26:04	1127
After	2	S 13th St & Snyder Ave	October 25-28, 2017	41:32:52	1796
Before	3	E Allegheny Ave & Aramingo Ave	September 9-12, 2017	41:03:30	728
After	3	E Allegheny Ave & Aramingo Ave	October 26-28, 2017	35:30:40	473
Before	4	S 34th St & Chestnut St	September 12, 2017	6:49:18	535
After	4	S 34th St & Chestnut St	October 25, 28 2017	9:28:28	632

Intersection 4 was initially a request by the City for video footage independent of the two-phase left turn study, and was not intended to receive the same magnitude of footage as the other three study intersections. It is unique relative to the other intersections, though the design implications are similar, so it was decided to include Intersection 4 into the analysis.

3.5 Research Methods - Processing & Organization

All raw video footage was first processed to reduce the total file size. The GoPros used had a minimum megapixel rating that was more than necessary for this study, resulting in nearly 2 terabytes of raw video hard drive storage use for all footage. By using commercially available software, the video footage was reduced to a more manageable file size and allowed for time stamps to be included on the video for playback and documentation purposes.

Upon video playback, every bicyclist of any travel direction was documented. The documentation was collected and organized using the application Microsoft Excel. Collected details are presented in Table 5.

Table 4: Bicyclist data collection details

Item	Comments
Time Stamp	Time in the video clip the cyclist can be observed. Example: 01:25:14
15 Minute Interval	The real-time 15 minute interval the cyclist was observed. Example: 8:15AM to 8:30AM
Travel Direction	Example: southbound left, northbound through, westbound left - shortened to sbl, nbt, wbl, etc.
Arriving and departing road space behaviour • In bike lane/on roadway • In the wrong way bike lane • Pedestrian	*Pedestrian* is for right sidewalk use relative to travel direction *Pedestrian Contraflow* is for left sidewalk use relative to travel direction
Signal phase on arrival	Red or Green
Red light violation	Did the cyclist run a red light?
Notes	More detailed description of unusual behaviour or events.

A sample of bicyclist documentation and intersection signal timing sheets are available in Appendix B and C respectively. Collecting the arrival and departing road space positions allows for a better understanding of bicycle behaviour and the conditions in which certain choices are made. Similarly, automobile volumes were documented for one morning and evening peak period, and one weekend afternoon period to include as part of intersection characteristics. Automobile volumes were not adjusted to Passenger Car Units (PCU) to consider heavy vehicle presence because it is beyond the objectives of this study.

3.6 Data Analysis

Recall from Chapter 1 that the research questions addressed in this thesis include the following:

I. How do cyclists conduct left-turn maneuvers at signalized intersections?
II. How do cyclists conduct right turns from a left side protected bike lane at a multi-lane signalized intersection?
III. What are bicyclists' preferred routes of navigating intersections (*desire lines*)/ where are bicyclists riding? i.e. in bike lanes, on sidewalks, switching in between?
IV. Does the approaching signal phase influence where bicyclists ride?
V. How frequently and under what circumstances do bicyclists run red lights?

In this section, the methods employed to answer these questions are addressed. As noted above, extensive video footage has been gathered at four intersections, with different geometries, lane configurations, traffic and cyclists volumes. The data are analyzed to determine cyclists' behavior as they traverse the intersection as a function of both the intersection design, and other influencing variables, including signal phase.

Ideally, cyclists would demonstrate very consistent behaviours. This is not always the case in North American contexts, where cyclists are known to switch between road user types to minimize delay. Through initial review of the footage, a wide range of behaviour was found with many combinations of approaching and departing maneuver preferences. From this initial review, a series of movements were defined to classify behaviours. The method of classification and analysis is shown conceptually in Figure 10. For each intersection, a cyclist's travel direction, desired path (through, right or left), and arrival signal phase are recorded. The cyclist's arrival position –in the bike lane/roadway (BLRW), using the wrong way bike lane (WWBL), or pedestrian conflict (PC) – is also documented. Next, the departing path (using the same categories) is recorded. For example, in the case of left turns, Figure 11 and 12 demonstrate the opportunistic and pedestrian conflict behaviour respectively. Legal and expected behaviour was previously demonstrated in Chapter 1.

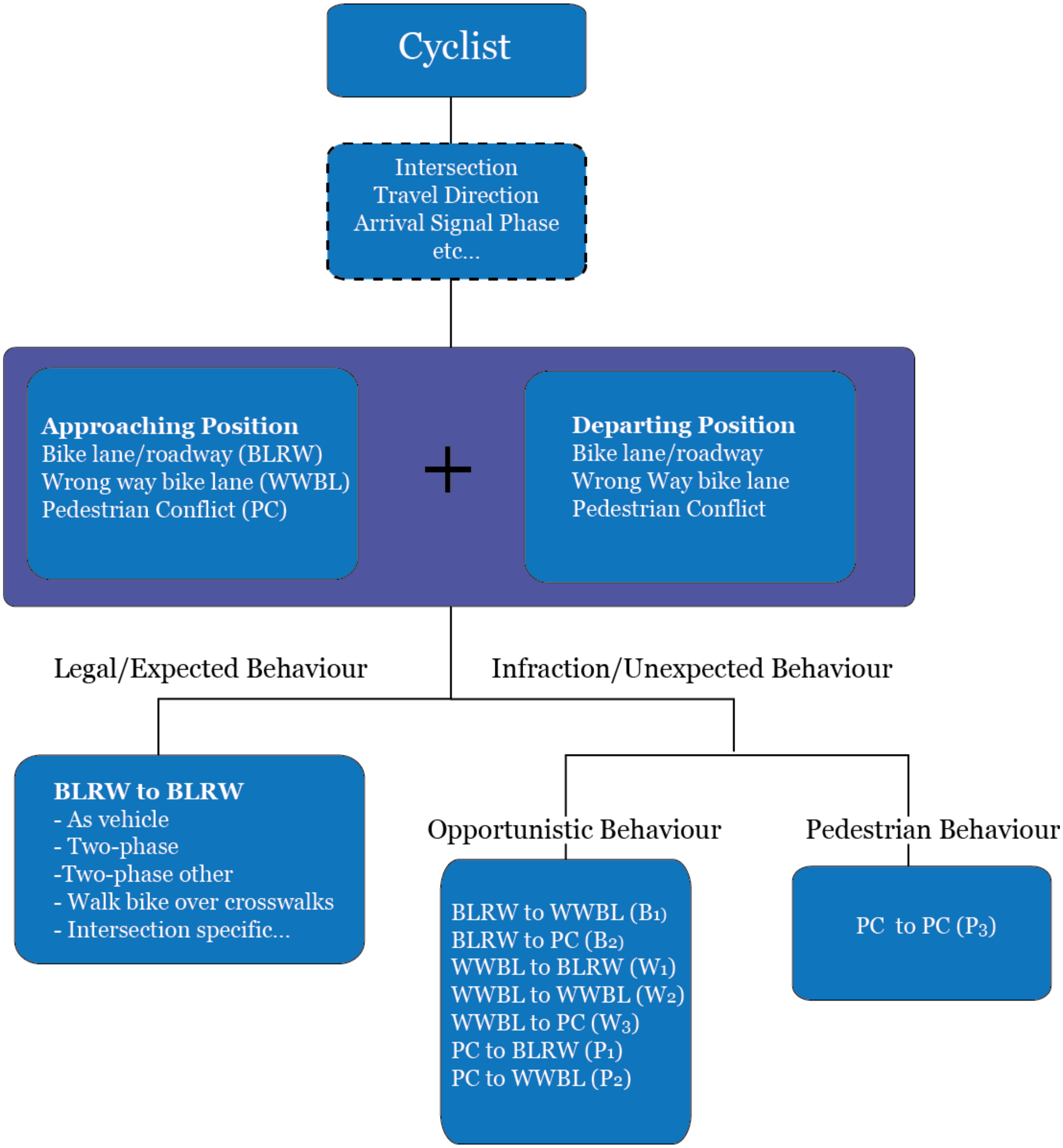


Figure 10 Conceptual Mapping of Cyclist behaviour at Signalized Intersections

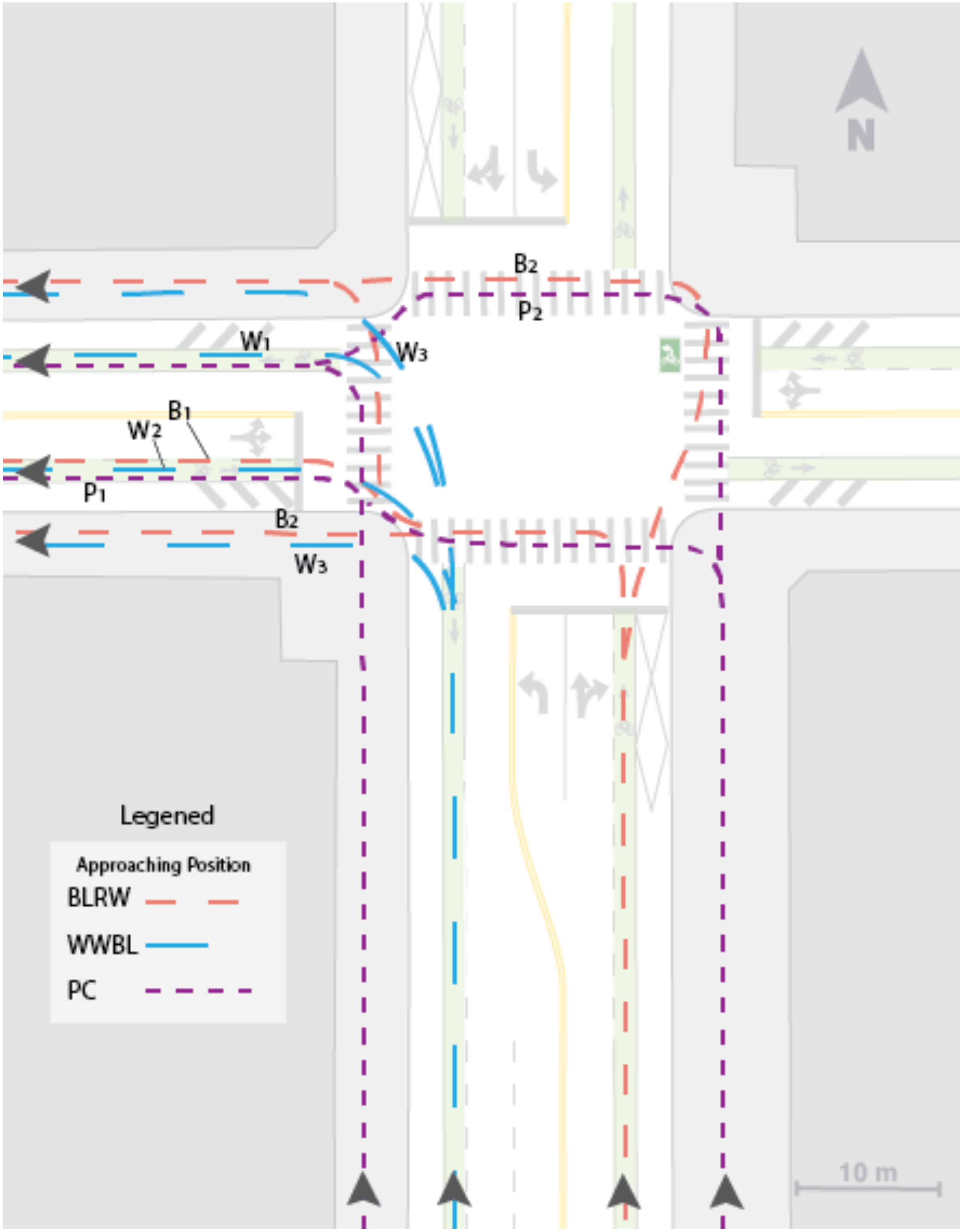


Figure 11: Sample Opportunistic Behaviour Left-Turn routes

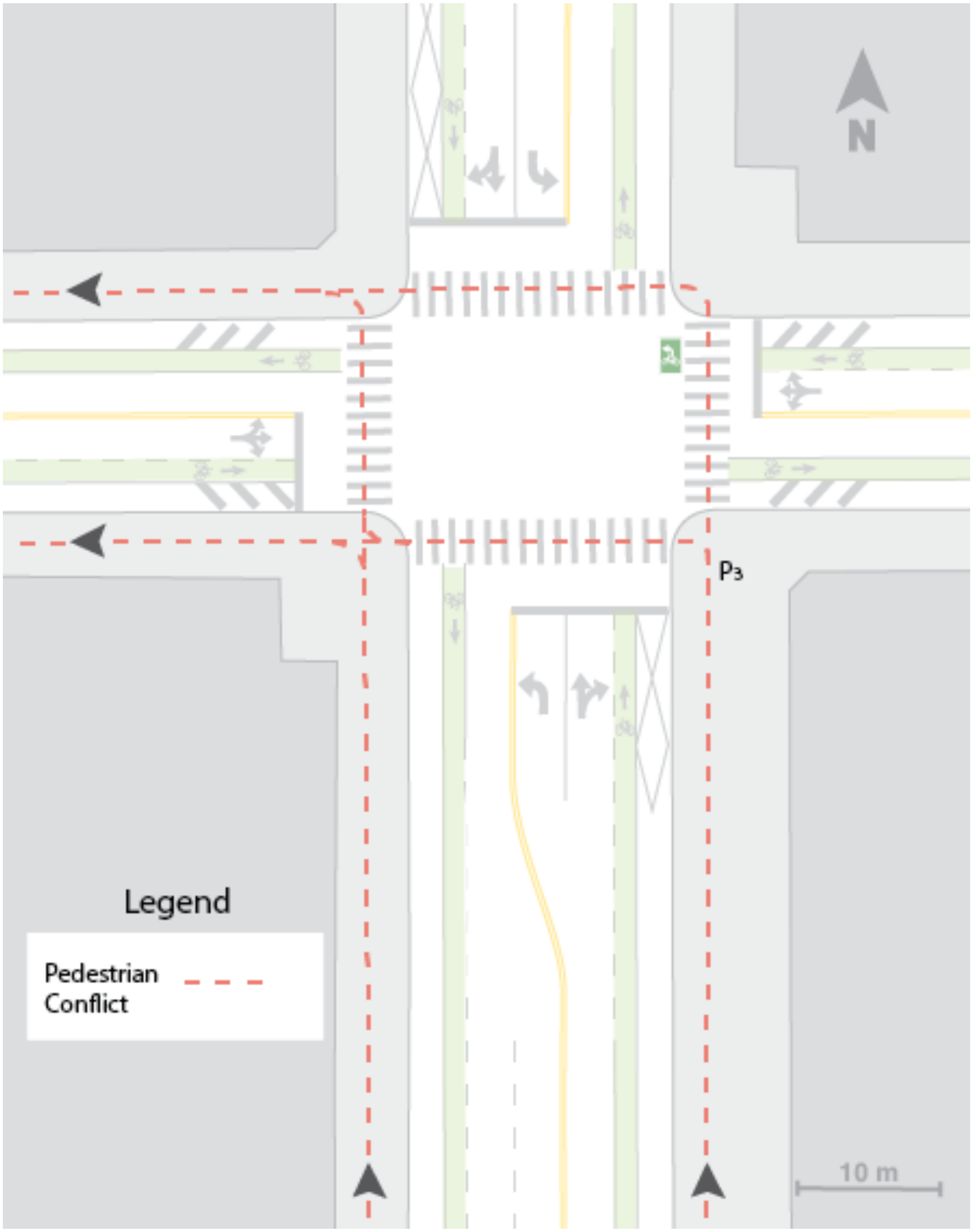


Figure 12: Sample Pedestrian Conflict Left-Turn Behaviour

Opportunistic behaviour demonstrated in Figure 11 can occur by either switching between road-space or simply being in an area of conflict such as in the wrong way bike lane. Other road users – especially drivers – may not be actively looking for cyclists riding in positions that are not permitted such as movements that are counter-flow to traffic. Examples of this in Figure 11 are northbound cyclists on the west sidewalk under pedestrian conflict, or cyclists in the wrong way bike lane crossing through and turning left into the bike lane or north side sidewalk westbound. Drivers are trained to be aware of pedestrians, though because cyclists often move at a higher rate of speed relative to pedestrians, a driver may check for a safe opportunity to traverse an intersection, but o*nly* check for other road users behaving appropriately. For these reasons, it is likely that cyclists at signalized intersections such as in Figure 10 face greater conflict with drivers under maneuvering conditions flowing through the south-west corner of the intersection. More generally, conflict is also likely to occur when switching from one road-space to another, such as P_1 & P_2. In the case of P_1 or P_2, for example, a northbound driver intending to turn right may look for potential crossing pedestrian and proceed when clear, though may not be aware or prepared for a relatively faster moving cyclist. The same is possible for eastbound right-turning drivers, or westbound left-turning drivers.

Similar to conflict scenario described for Figure 11, cyclists riding on the sidewalk and over the crosswalks depicted in Figure 12, especially at higher rates of speed, do not behave in a manner that is predictable or provide awareness to other road users.

The combination of these data allows for different levels of analysis, presented here in three sections.

Section 1:

As described in Chapter 2, cyclists often perceive interactions with motorists to be a significant safety concern, and infrastructure to reduce conflict can improve safety and cycling ridership. It has also been demonstrated in previous research that traffic volume, lane configuration, geometry and presence of bicycle facilities affect cycling behaviour. To help understand the relationships between bicycle behaviour and intersection geometry, Section 1 of the results presents a scale comparison of intersections size, as well as vehicle and bicycle volumes. The expectation is that larger (in area) intersections, with higher volumes, and more (and more complex) movements will generate a wider range of cyclist behaviour.

Section 2:

In Section 2, the behaviour of all cyclists is analyzed and compared between study intersections. To do this, observed behaviours are classified into the three categories discussed earlier in this chapter, informed extensively by Wu, Yao & Zhang, (2012) and Copenhagenize Design Co. (2014). The classifications are defined as:

1. **Vehicular behaviour:** Bicyclists that behave as vehicles on the road or proper use of bicycle facilities. This behaviour represents what is legal and assumed to be the most predictable and expected type of behaviour. The exception here is when cyclists conduct vehicular behaviour but dismount and walk their bicycles over the crosswalks to traverse signalized intersections. This mode is legal and safe.
2. **Opportunistic Behaviour:** Switching from, to, or between sidewalk, bike lane, and wrong way bike lane while traversing the intersection. Or, bicyclists traversing completely in the wrong way of a bike lane. This behaviour represents a series of

maneuvers made by cyclists that disregard traffic laws and are challenging to predict by other road users. These cyclists prioritize momentum and directness over predictability.

3. **Pedestrian Conflict Behaviour:** Behaviour consistent with what a pedestrian would do, but done riding a bicycle. Pedestrian conflict behaviour of cyclists is prohibited in most jurisdictions and is generally challenging for drivers to be aware of their presence at intersections and dangerous for pedestrians.

For each of these three behaviour types, observations are made based on signal phase experienced by cyclists on arrival, and by the cyclist's desired path through the intersection – continuing straight, turning right, or turning left. It is expected that arrival signal phase will have minimal impact on distribution of these three behavioural types and that left turns will produce the greatest opportunistic behaviour relative to other turns because vehicular lefts face the greatest level of potential conflict.

The objective with the data is to better understand the conditions under which bicyclists behave as expected, opportunistically, or as pedestrians regarding their desire lines while traversing intersections. Normally, a bicyclist running a red light would not be considered expected behaviour, however because the categorization is for desire lines (where bicyclists choose to ride - red light running rates **<u>are not</u>** included in the classification. This separation will allow for a clear distinction between where bicyclists ride, and whether or not a bicyclist runs a red light. If this is not done, for example, a bicyclist that runs a red light but is otherwise compliant is classified the same as a bicyclist riding in the wrong way bike lane (opportunistic behaviour). Red light running rates will be presented separately by intersection and turn direction.

Based on previous research outlined in Chapter 2, it is expected that right turning cyclists will be the most frequent red light running turning movement because there are few conflicts to require stopping for right turns. Under that same principle, it is expected that left turns will have the lowest rates of red light running because they inherently have the greatest level of potential conflict.

Another variable that is expected to influence cyclists' behaviours is the presence (or absence) of opportunities to traverse the intersection safely even when arriving on a red signal. Often, cyclists will approach intersections on red, evaluate the traffic that presents conflicts, and if no traffic (and therefore no conflict) exists, the cyclist will proceed on red. One measure of the presence of a conflict is Gap Time, the time between the rear bumper of a car and the front bumper of a different car passing a certain point. When gap times are long, few conflicts exist. When gap times are short, the potential for conflict and unsafe conditions is much higher.

To quantify the impacts of gap times on cyclists' behaviours, gap times were measured for one hour of footage at each intersection: from 5pm to 6pm for intersections 1, 2 and 3 and from 8AM to 9AM for intersection 4 (because pm peak video was not taken). Mean gap times are compared to red light running rates for through cyclists. It is expected that intersections with more frequent and longer gaps in cross-traffic will have greater incidences of red light running.

Section 3:

In Section 3, results are presented intersection by intersection to detail how left turn maneuvers were conducted before and after the installation of two-phase turn boxes at the most detailed level of analysis, looking at the specific desire lines of each cyclist to discover trends. For each intersection, graphics will visually demonstrate the desire lines of each left turning cyclists in the before and after periods. A sample of these graphics is presented in Figure 13.

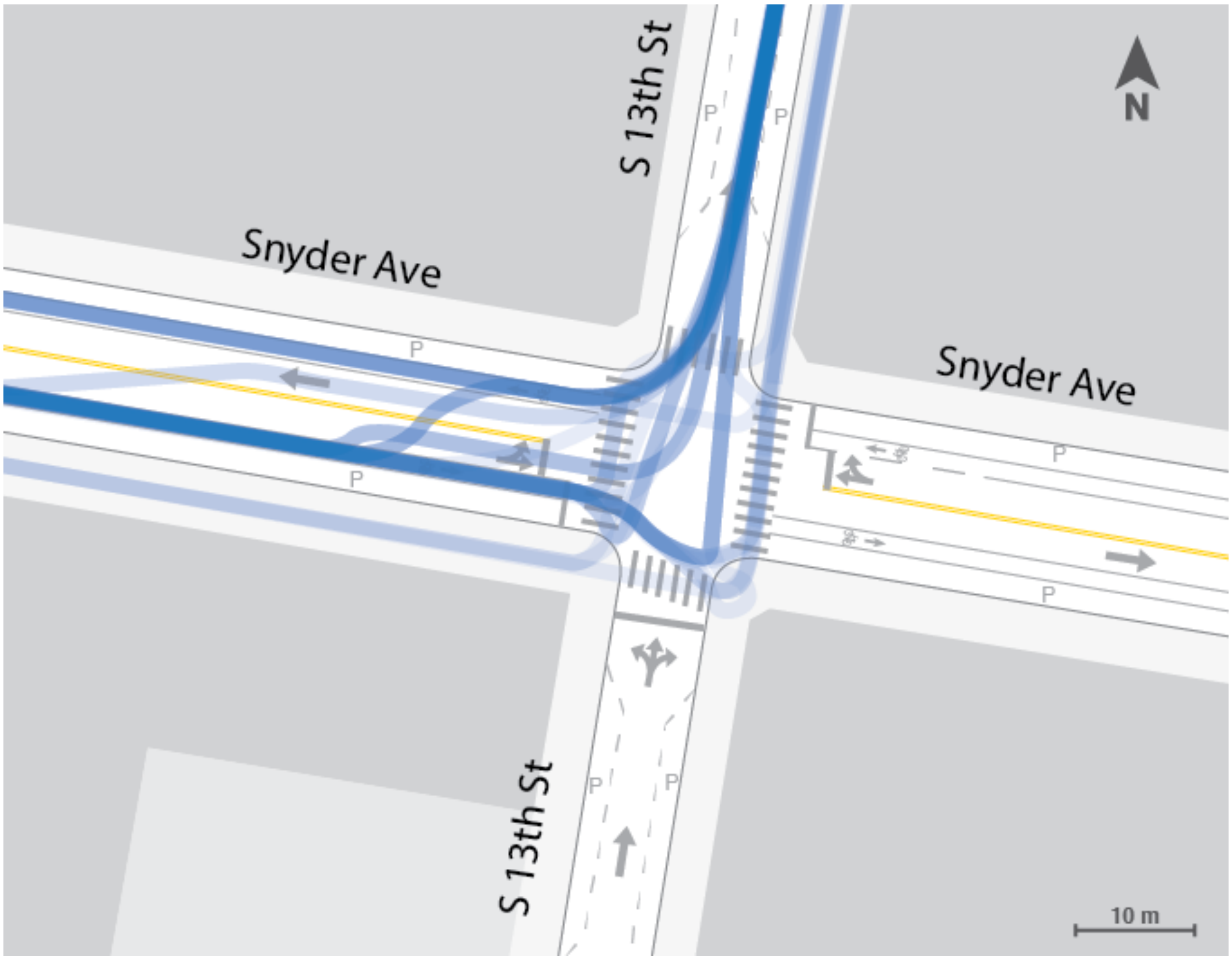


Figure 13: Sample of Intersection 2, Graphic of Cyclist Left-Turn Desire Lines

In these graphics, cyclists' desire lines are denoted by highly transparent blue lines. Where common desire lines exist, the blue colour becomes more prominent. Accompanying these figures when appropriate will be tables with counts and percentages of defined methods of turn maneuvers. From the detailed analysis chi-squared tests for independence are done to see if the changes observed are statistically significant.

To uncover potential differences in behaviour on green and red arrival signal phases for left turns, data are combined from before and after, and presented in a tabular format demonstrating the proportions of approaching and departing road spaces.

It is expected that cyclist desire lines will reflect the practice of maintaining momentum and avoiding conflict. Signal phase is expected to have modest impact on behaviour, though demonstrate a tendency for cyclists to switch to the wrong way bike lane or sidewalk when arriving on a red signal phase.

4.0 Results

This chapter presents results in three sections. The first section provides figure-ground diagrams for each intersection with collected volumes of vehicle traffic and bicycle traffic. The second section present results of behaviour of all video footage, classified by expected, opportunistic and pedestrian conflict behaviour. The second section also includes results of red light running rates. The third section answers the primary research question which assesses the results of the before and after study of two-phase turn box installations. The primary and secondary research questions are presented in reverse because the secondary research questions provide bigger picture context for results addressing the primary research questions.

4.1 Results Section 1: Vehicle and Bicycle Volumes

To best demonstrate the similarities and difference between the study intersections, intersection characteristics from chapter 3.4 have been visually summarized to scale in Figure 12 using a figure-ground approach. In Figure 14 the black colour space represents buildings or private area, the dark grey represents sidewalk space, the light grey represents angled on-street parking (intersection 1 only) and the white is road space that includes vehicle lanes, bike lanes and parallel on-street parking. Subsequently, Table 6 presents results of vehicle volumes for sample peak hours. Table 6 also presents bicycle volumes as an average of all video footage per hour, and the foremost unique characteristics.

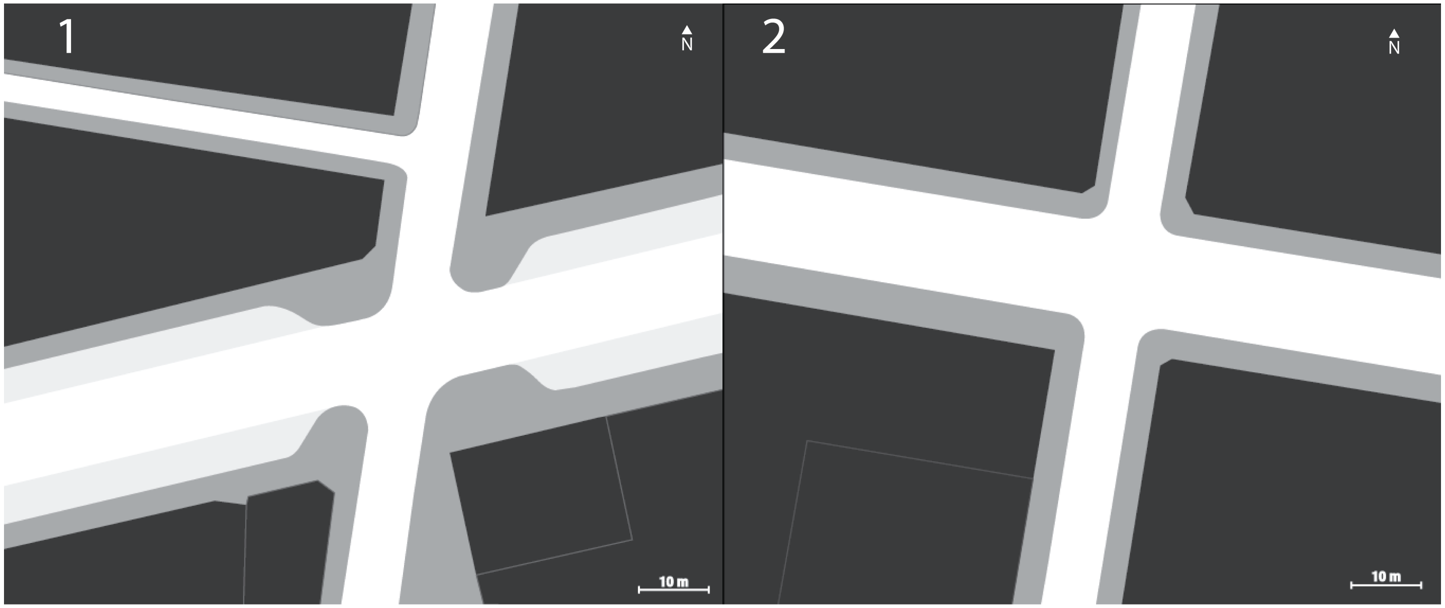


Figure 14: Figure-Ground Diagram, Intersections 1-4

Table 5: Vehicle & Bicycle Volumes, Intersections 1-4 and Identifiable Features

Intersection 1

Vehicle volume: ~250-300 vph/l (low)

Bicycle Volume: 25 bph all directions (medium)

Identifying feature(s):

- Angled junction
- Sidewalk bulb-outs on corners
- One way n/s

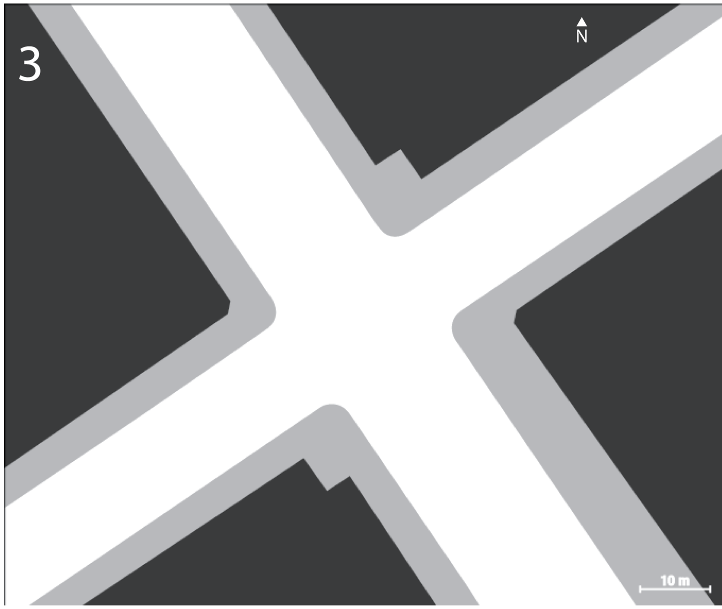
Intersection 2

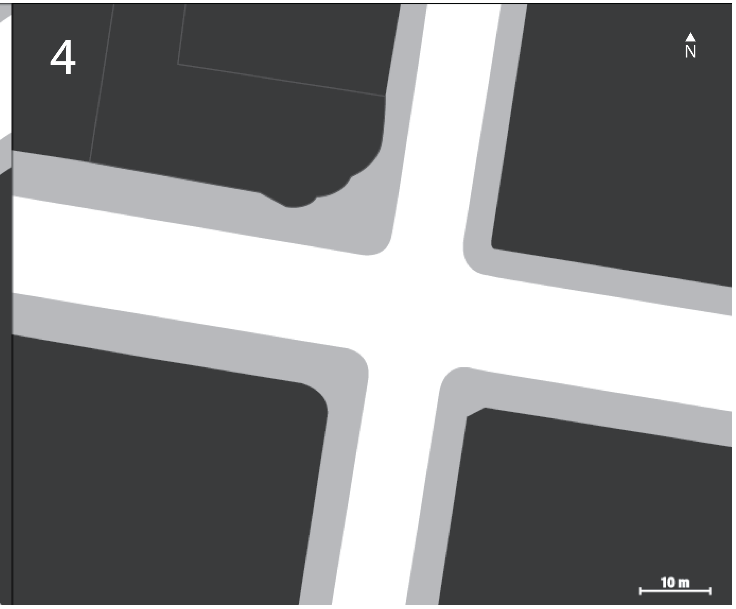
Vehicle volume: ~250 – 330 vph/l (low)

Bicycle Volume: 45 blh all directions (medium-high)

Identifying feature(s):

- On popular bike route
- High school on southwest corner
- One way n/s





Intersection 3

Vehicle volume: ~550 – 690 vph/l (high)

Bicycle Volume: 15 bph all directions (low)

Identifying feature(s):

- Large intersection
- Left turn lanes for nb and sb traffic
- Wide sidewalks

Intersection 4

Vehicle volume: ~300 - 430 vph/l (medium)

Bicycle Volume: ~65 – 80 bph all directions (high)

Identifying feature(s):

- Multi-lane one way eb intersects multi-lane one way sb
- On University of Pennsylvania campus
- Protected bike lane on north side of eastbound road

Referring to Figure 12 and Table 6, Intersection 1 and 2 have very similar vehicle volumes, thought intersection 2 is on a more popular bike route and has greater cycling volumes. Intersection 3 is the largest and most complex intersection of all study locations. With the highest vehicle volumes relative to the other intersections, the low relative cyclist volumes are expected. Intersection 3 generally has wider sidewalks than the other intersections, but comparable to sections of sidewalk at intersection 1 and 4. Intersection 4 has moderate vehicle volume, though significantly more cycling volume than all other intersections. Wider streets suggest faster vehicle speeds and higher vehicle volumes. Similarly, wider sidewalks provide greater potential space for cyclists preferring to not ride on the roadway. Turning movement diagrams and sample weekday and weekend 15-minute interval bicycle volumes can be found in Appendix D and E respectively.

4.2 Results Section 2: Bicycle Behaviour and Red Light Running

In Section 2 of the results, behaviour of all travel directions of each intersection and red light running rates are analyzed.

4.2.1 Vehicular, Opportunistic & Pedestrian Conflict Behaviour

As described in Section 3.6, Section 2 of the results presents observations of bicycle behaviour of all video footage, travel directions, and turning movements. The objective with the data is to better understand the conditions under which bicyclists behave as expected, opportunistically, or as pedestrians regarding their desire lines while traversing intersections. Normally, a bicyclist running a red light would not be considered expected behaviour, however because the categorization is for desire lines – where bicyclists choose to ride - red light running rates **<u>are not</u>** included in the classification. Not conflating road position and red light running will allow for a clear distinction between where bicyclists ride in the carriageway, and whether or not a bicyclist runs a red light. If this is not done, for example, a bicyclist that runs a red light but is otherwise compliant is classified the same as a bicyclist riding in the wrong way bike lane (opportunistic behaviour). Red light running rates will be presented separately.

For reference, the three classifications modified from literature are:

1. **Vehicular behaviour:** Bicyclists that behave as vehicles on the road or proper use of bicycle facilities. This behaviour represents what is legal and assumed to be the most predictable and expected type of behaviour. The exception here is when cyclists conduct vehicular behaviour but dismount and walk their bicycles over the crosswalks to traverse signalized intersections. This mode is legal and safe.
2. **Opportunistic Behaviour:** Switching from, to or between sidewalk, bike lane, and wrong way bike lane while traversing the intersection. Or, bicyclists traversing completely in the wrong way of a bike lane. This behaviour represents a series of maneuvers made by cyclists that disregard traffic laws and are challenging to predict by other road users. These cyclists prioritize momentum and directness over predictability.
3. **Pedestrian Conflict Behaviour:** Behaviour consistent with what a pedestrian would do, but done riding a bicycle. Pedestrian conflict behaviour of cyclists is prohibited in most

jurisdictions and is generally challenging for drivers to be aware of their presence at intersections and dangerous for pedestrians.

The total documented bicyclists for each intersection is presented in Table 7

Table 6: Total Number of Bicyclists Documented by Intersection

Intersection	Number of bicyclists	Cyclists/Hour
1	1,506	26.
2	2,901	45
3	1,191	16
4	1,188	72
Total	6,786	

Overall, 75% of bicyclists had expected behaviour in terms of their riding position, meaning on the road and in the proper lanes and travel directions. where they rode. Opportunistic behaviour and pedestrian conflict behaviour represent 12.93% and 11.18% respectively. These rates separated by intersection and arrival phase are presented in Figure 15.

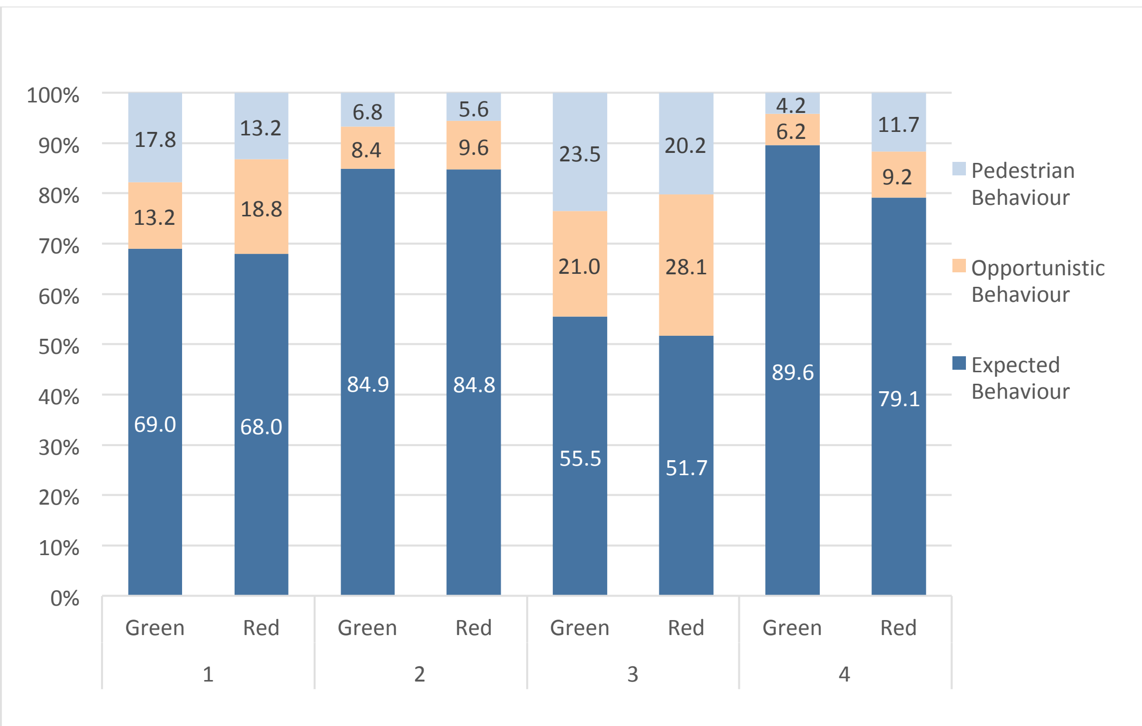


Figure 15: Total Expected, Opportunistic, and Pedestrian Conflict Behaviour by Intersection and Signal Phase Approach Colour.

Intersection 2 and Intersection 4 are the best performing intersections. Here, cyclists most often behave as expected, presumably increasing safety. These results are consistent with expectations because the intersection characteristics and results from Section 1 demonstrated similar findings of behaviour. Opportunistic and pedestrian conflict behaviours occur more frequently at Intersections 1 and 3. This may be the case because it is generally easier to move between roadway and sidewalk when the sidewalks are wide and do not create significant conflict.

Comparing within each intersection demonstrates very little difference in behaviour between arrival signal phases. However, intersection 4 has more significant variation between green and red arrival phases because two one-way roads meeting limits the available travel directions of bicyclists. The observed pedestrian or opportunistic behaviour of bicyclists was often against the flow of traffic for at least a portion of the bicyclist's maneuver through the intersection. Otherwise, these results suggest bicyclists that behave as expected are unlikely to change their riding patterns based on the approaching signal phase. Indeed, all forms of behaviour seem mostly independent of the approaching signal phase. In other words, cyclists' desired behaviour does not change significantly relative to the signal phase. The more significant determinants are the characteristics of the intersection, demonstrated by the variations between each intersection. Though, modest exchange between opportunistic behaviour and pedestrian conflict behaviour is present between approaching on green versus approaching on red. However, these results disproportionally represent through-traffic since they represented over 78% of all movements of documented cyclists.

To better understand behaviour based on turning movement, Figure 16 presents each intersection by turning direction and their relative behavioral distribution.

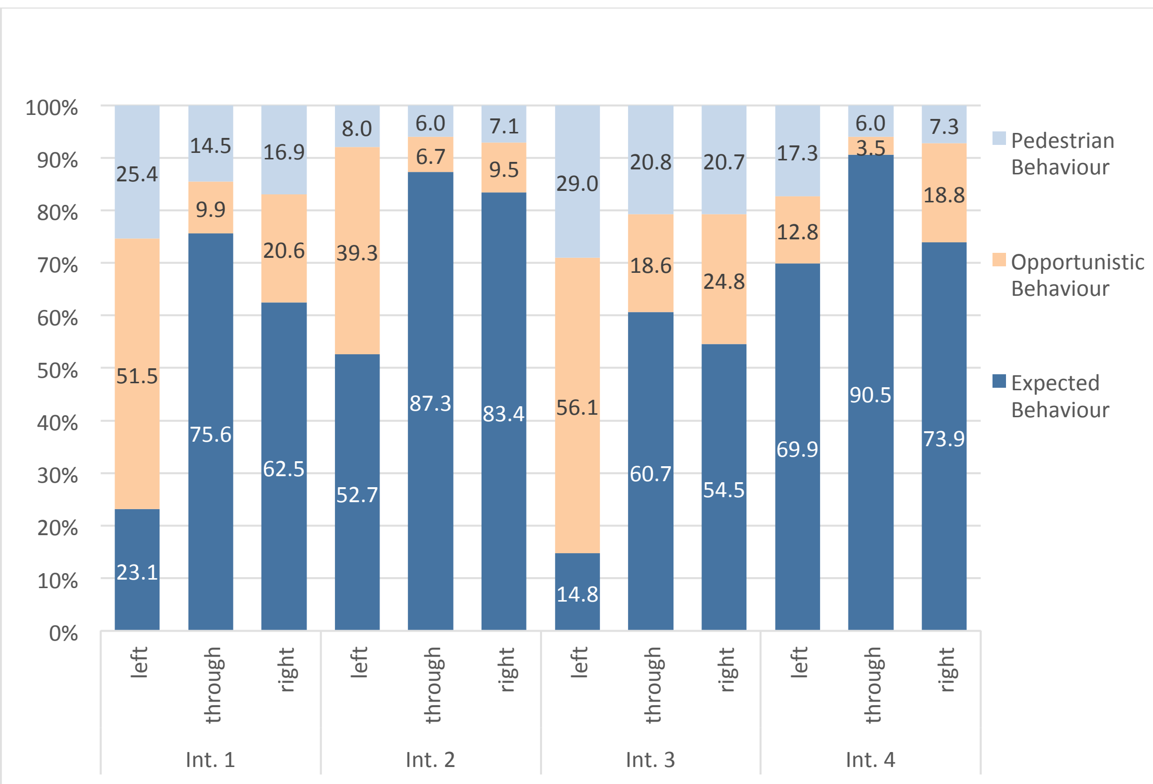


Figure 16: Total Expected, Opportunistic, and Pedestrian Conflict Behaviour by Intersection and Turn

As anticipated, left turns have the lowest expected behaviour, especially at Intersection 1 and 3 (23.1% and 14.8% respectively). Left turns at intersection 2 have greater expected behaviour over intersections 1 and 3 likely due to their differing intersection characteristics and conditions through the available left turns.

Left turns at Intersections 1 and 3 are dominated by opportunistic behaviour (51.5% and 56.1% respectively) and make up a large minority of behaviour in intersection 2 (39.3%). This is consistent with expectations, that bicyclists will make tactical decisions more often at left turns because of the inherent conflict with the maneuver. Specific to Intersection 1, the behaviour of switching from the roadway to sidewalk or vice versa commonly occurred to take advantage of the wide sidewalks abutting the east and westbound carriageway and use the curb bulb-outs. This behaviour is expanded on in Section 4.3.

In every intersection, through traffic has the greatest levels of expected behaviour which meets expectations. Bicyclists' only conflict is crossing through the intersection; there are no cases where merging lanes or crossing over opposing traffic occurs. However, some cases not included in this study are where dedicated right turns exist for vehicles, and may have different results. Intersection 4 has the highest rate of expected behaviour for through traffic on green, 90.5%; intersection 2 is similar at 87.3%. Intersection 3 has the lowest expected behaviour and highest pedestrian conflict behaviour for through movements. This is likely because this intersection has wide sidewalks paired with high volume traffic and more significant heavy vehicle presence. A subjective observation of this intersection is that driving behaviour seemed more aggressive relative to the other intersections, something that is challenging to quantify but can be easily felt when present.

It was anticipated that right turning bicycles would have similar expected behaviour relative to through behaviour considering right turns have few conflicts in terms of crossing paths with other road users. The results demonstrate this not to be true. This may simply be because right turns provide an opportunity for bicyclists to switch from the roadway to sidewalk with a curb cut, or occur because a bicyclist feels unsafe on the road onto which they are turning. Alternatively, destinations may be more accessible by switching to the sidewalk.

A closer comparison can be made between Intersection 1 and Intersection 2. In both cases, there is a one-way road intersecting with a two-way road with bike lanes in both directions and parking on both sides of the street. Also, both intersections have very comparable vehicle volumes during peak hours. Bicycle volumes are higher at Intersection 2, though the proportions of travel directions are very similar. Despite the similarities, Intersection 1 has poorer rates of expected behaviour and greater pedestrian conflict behaviour for all turning directions relative to Intersection 2. The defining characteristics are that Intersection 1 has wide sidewalks on W Passyunk Ave, bulb-outs on all corners and the intersection is at an unusual angle. One or many of these characteristics may explain the variations between Intersection 1 and 2.

4.2.2 Red light behaviour

As stated in the previous section, cyclist riding desire lines between expected, opportunistic and pedestrian revealed that three-quarters of bicyclists behave as expected. In short, they ride on the road or in the provided bike lane. However, red light running rates do not share the same patterns. Red light running rates, defined as a cyclists traversing an intersection despite arriving on a red signal in the direction of travel, are presented by intersection in Table 25.

Table 7: Red Light Running Rates by Intersection

Intersection	Arrival on red count	Red light run count	Red light run percent (%)
1	670	515	76.9
2	1420	1101	77.5
3	602	234	38.9
4	436	292	67.0
Total	3128	2142	68.5

Among all documented bicyclists arriving on a red signal phase, 68.5% ran the red. Intersections 1 and 2 have very similar red light running rates, likely because of their comparable intersection sizes and proximity. Intersection 3 has the lowest overall rate likely for having higher relative vehicle volumes and being the most complex intersection studied. Intersection 4, though multi-lane, only has one travel direction of conflicting traffic for red-light running cyclists to watch for. The red light running rates by intersection and turn type is demonstrated in Figure 17.

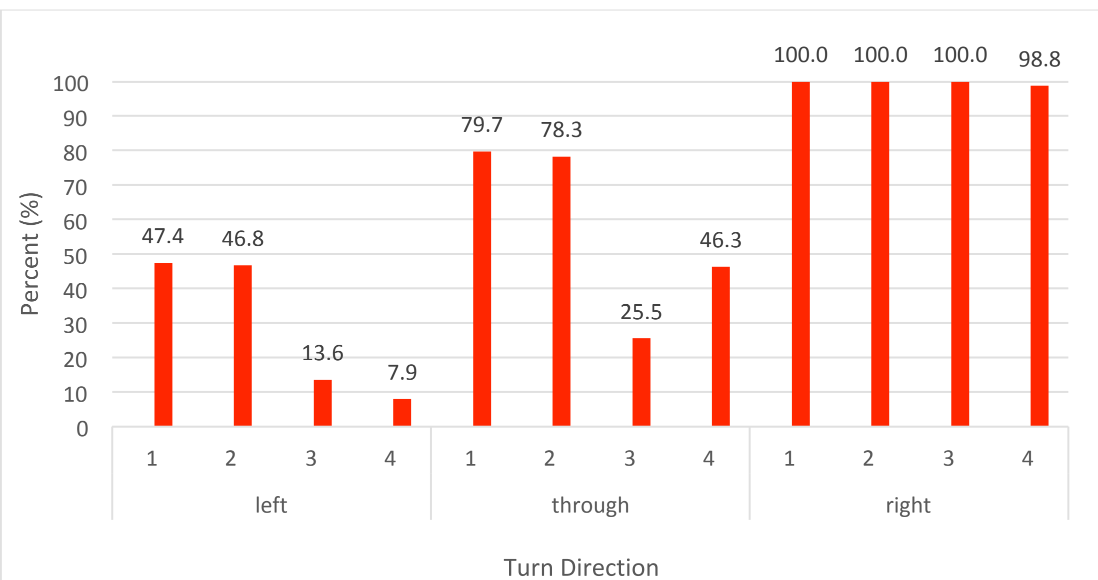


Figure 17: Total Red Light Running Rates by Turn and Intersection

Interestingly, the arrangement of left, through, and right turns coincide with the order in which these turns face conflict. Left turning bicyclists must cross multiple lanes of traffic of both approaching road and destination road. Through cyclists only need to navigate cross traffic, and right turning bicyclists do not necessarily need to merge or cross any lanes (except for intersection 4's left shoulder protected bike lane). This same order may explain the rates of red light running.

Intersection 1 and 2 have few lanes, relatively small intersections, so the distance and time required for gap acceptance at a red light is minimal. Paired with the relatively low vehicular volume levels, many gaps in traffic are available and used. For through traffic, 79.7% and 78.3% of bicycles arriving on a red signal phase violate the light for intersection 1 and 2 respectively. The rates are lower for intersection 3 (25.5%) and 4 (46.3%) because these intersections are physically larger and with more vehicular volume to compete with.

Every bicyclist arriving on a red signal phase to make a right did not stop at the stop line while completing their right turn, except for one bicyclists at intersection 4. Some maneuvered right cautiously while maintaining some momentum, and others made efforts to maximize momentum through the turn.

To demonstrate the relationship between cross traffic volumes and red light running rates, gap times for one hour of peak volume vehicle cross traffic were quantified for least one through travel direction per intersection, presented in Figure 18. Gap times of two seconds or greater were considered.

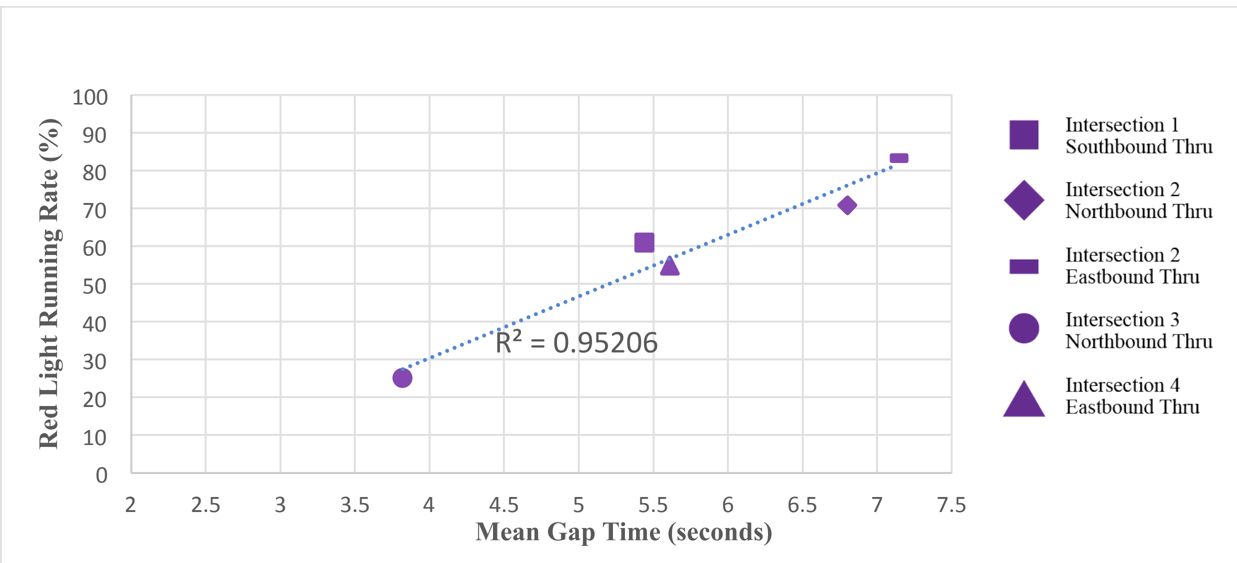


Figure 18: Mean Gap Time <2 Seconds vs Red Light Running Rates of Main Through Movements

The R^2 value of 0.95 using sample through movements tells us is that intersections with longer gaps in cross-traffic are strongly correlated with red light running. Two movements from intersection 2 were included to see if crossing distance would reveal itself to be a potential factor in addition to gaps time. Intersection 2 eastbound has the highest red light running rate, the highest mean gap time, as well as the shorter crossing distance relative to Intersection 2 northbound. If both directions of these through movements had very similar mean gap times, crossing distance could be considered an explanation for the difference, though the data demonstrate inconclusive results. A study specifically on gap distance could reveal more information, though it is theorized that gap distance does play factor on red light running rates or minimum gap time for crossing simply because crossing larger distances takes more time.

In a more practical sense, these results mean cyclists are very likely to cross the intersection on a red light when an opportunity is presented, similar to how stop signs or yield signs operate at non-signal controlled intersections. Similarly, these results suggest compliance with a red light is more significantly a function of not finding an appropriate gap than interest in compliance with traffic laws.

These results are consistent with existing literature, though these results show a stronger relationship than what was found in McKeil & Dill (2012).

4.3 Results Section 3: Before and After Two-Phase Turn Box Installation Study Results

In Section 3, results of the before and after study of two phase turn box installations are presented. Each intersection is presented independently.

4.3.1 Intersection 1: S 15th St & W Passyunk Ave

The left-turn being studied is of southbound bicyclists on S 15th St. turning left to travel eastbound on W Passyunk Ave. The video period, count, and signal phase of all southbound left-turning bicyclists are presented in Table 9.

Table 8: Intersection 1 Left-turn Counts

Video Period	Green	Red	Total
Before	8	17	25
After	10	16	26

A greater proportion of bicyclists arrived on a red signal phase because the signal timing prioritizes W Passyunk Ave as the higher capacity and higher volume road. As mentioned in chapter 1, cyclists approaching a red signal phase is not a favourable condition for studying the impact of two-phase left turn bike boxes since it is very unlikely for a bicyclist to use the facility if approaching on a red signal phase.

Neither in the before or after stage was a two-phase left turn maneuver observed. Despite this, observations of how cyclists maneuver left at this intersection is possible. Figure 19 and Figure 20 visually demonstrate the before and after periods respectively, of left-turning cyclist arriving at green and red signal phases. The more prominent blue lines represent more frequently traveled areas.

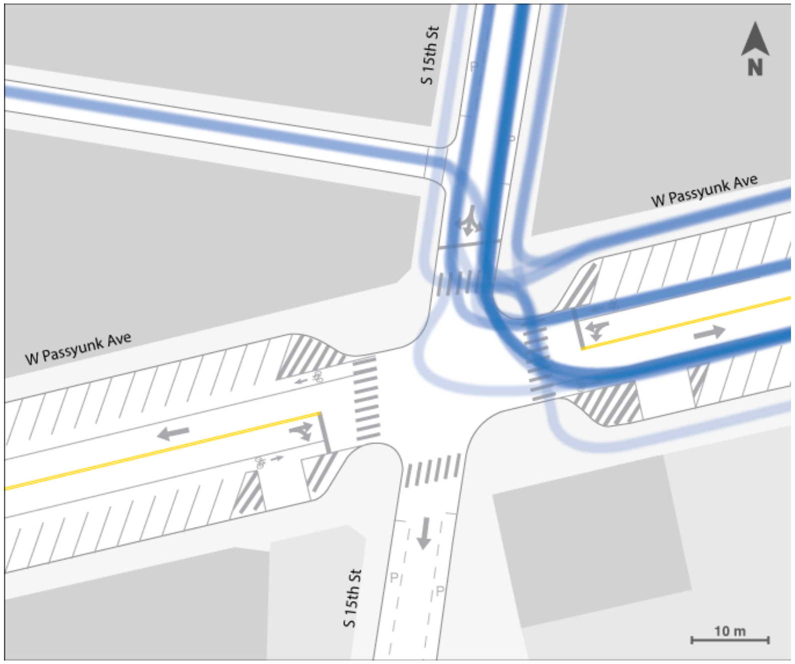


Figure 19: Intersection 1 'Before' Desire Lines of Southbound Left-turning Bicycles Arriving on Red and Green Signal Phases

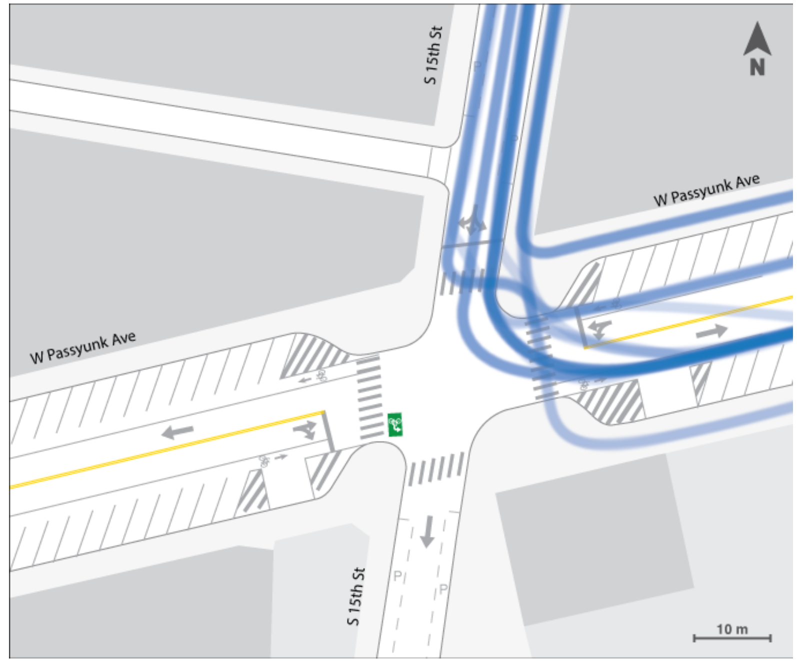


Figure 20: Intersection 1 'After' Desire Lines of Southbound Left-turning Bicycles Arriving on Red and Green Signal Phase

The two-phase left turn bike box has no direct measurable impact on left turn behaviour at this intersection. Including before and after 43% of left-turns were conducted by bicyclists approaching the intersection in the left side of the southbound lane. Cyclists would either wait by the north-east curb edge or follow through depending on the signal phase or impeding traffic. Other desire lines for left turn maneuvers favour bicycling on the north-most crossing zebra, bicycling on the sidewalk bulb-out on the north-east corner, and bicycling eastbound in the wrong way bike lane.

Similar to the motivations of bicyclists not wanting to incur delay from signalized intersections, it is likely that using a two-phase left maneuver is simply inconvenient given this particular intersection characteristics. The southbound single lane is one-way so riding on the left shoulder is permitted. Moreover, with lower relative speeds and volumes on a narrow one-way road, changing from the right shoulder to the left shoulder in preparation for a left turn is likely not perceived as a significant risk for bicyclists. Second, the unusual intersection dimensions create a sharp southbound left turn, thus making ‘short cuts’ easier. In other words, bicycling as an automobile into the intersection, then turning, incurs a longer travel distance which can be perceived as unnecessary for bicyclists. The travel distance has an even greater increase when looking at the path a bicyclist must take to use the two-phase left turn box in Figure 16. Thirdly, bicyclists’ desire lines may be motivated by limiting exposure to the middle of intersections where perceived exposure and risk to collision exists.

The two-phase left turn bike box was not used in the after stage, and data from the before and after stages can be combined to make observations on behaviour differences between arrival on greed phases and arrival on red phases. The arrival road space and departing road space of cyclists arriving on a green signal phase and red signal phase are presented in Table 10 and Table 11 respectively.

Table 9: Intersection 1 Before and After Combined Southbound Left-turning Cyclists Arriving on Green Signal Phase, Approach and Destination Road Space

	Went to Bike Lane	*Went to Wrong Way Bike Lane*	*Went to Pedestrian (either side)*	*Total*
Approached as Vehicle	0.44	0.11	0.11	0.67
Approached as Pedestrian	0.06	0.06	0.22	0.33
Total	0.50	0.17	0.33	1.00

n= 18

Table 10: Intersection 1 Before and After Combined Eastbound Left-turning Cyclists Arriving on Red Signal Phase, Approach and Destination Road Space

	Went to bike lane	*Went to wrong way bike lane*	*Went to Pedestrian (either side)*	*Total*
Approached as Vehicle	0.42	0.27	0.15	0.85
Approached as Pedestrian	0.06	0.00	0.09	0.15
Total	0.48	0.27	0.24	1.00

n=33

Interestingly, cyclists approaching the intersection using the sidewalk was more common for arrival on green phases (33.3%) than the red phases (15.2%). This is counterintuitive, since green phases do not incur delay or create additional motivation to behave inconsistently with traffic laws. Another observation is that in both arrival on green and red, half of bicyclists went to the proper bike lane through traversing the intersection. Of the other departing road spaces, red signal phase arrival is more associated with cyclists maneuvering to the wrong way bike lane. Pedestrian departure represents one third of behaviour when arriving on green and almost one half when arriving on red. However, the overall sample size is low for left-turning cyclists, so any conclusions have significant reliability issues.

4.3.2 Intersection 2: S 13th St & Snyder Ave

The left-turn being studied is of eastbound bicyclists on Snyder Ave turning left to travel northbound on S 13th St. The video period, count, and signal phase approach of all eastbound left-turning bicyclists is presented in Table 12.

Table 11: Intersection 2 Left-turn Counts of Bicyclists

Video Period	Green	Red	Total
Before	22	21	43
After	26	7	33

In the before stage, almost the same number of bicyclists were documented approaching on a green signal phase as on a red signal phase. The after stage shows a slight increase of left-turning bicyclists approach on a green signal phase, and a significant decrease in left-turning bicyclists approach on a red signal phase. Aside from the installation of the two-phase left turn box, no other design or operational changes were made to the intersection.

Though this decrease in left-turning bicyclists approaching on a red signal phase may be related to the two-phase bike box installment, insufficient data exist to make that conclusion. A chi-squared test for independence results in p=0.155, meaning the changes found between the before and after periods are not statistically significant since the result is above 0.05, or 95% confidence. If the two-phase bike box had an impact on bicyclists arrival phase, a possible explanation would be that upon approach, some eastbound bicyclists slow down or speed up to appropriately arrive on a green signal phase with the intention of using the two-phase bike box. Adjusting speed based on signal phase is not uncommon for road users, though not captured in this method of observation.

In the before period, 59% of left-turning bicyclists approaching on green began their maneuver from the bike lane as designed and completed their maneuver in the roadway northbound as designed. However, between the approach and completion is where behaviour varies greatly. The variation of maneuvers of bicycles approaching on green and red signal phases is illustrated in Figure 21 and listed in Table 13.

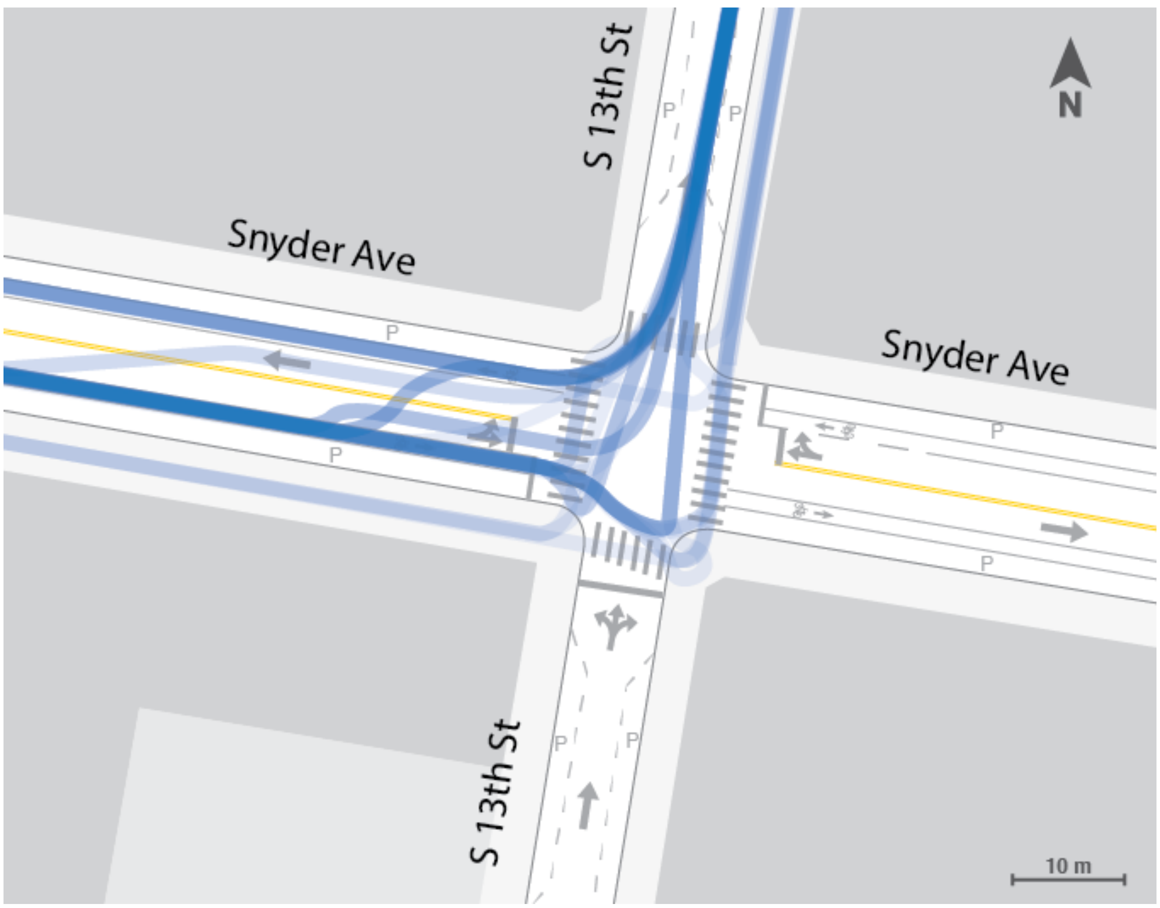


Figure 21: Intersection 2 'Before' Desire Lines of Southbound Left-turning Bicycles Arriving, Green Signal Phases

Table 12: Intersection 2 'Before' Left-turn Bicycle Behaviour Classifications

Left-turn Classification	Before Count: Green	Before Count: Red
Two phase (where future landing will go)	4	3
Two phase other[1]	3	1
As vehicle	1	3
Left from bike lane at stop line	1	3
Wrong way bike lane to vehicle	6	9
Pedestrian to vehicle	1	1
Vehicle to pedestrian	4	1
Wrong way bike lane to pedestrian	1	0
Pedestrian to pedestrian	1	0
Total	22	21

[1] term is defined in the text below this table

The most common method for left turns is for bicyclists to either enter the camera frame already in the wrong way bike lane or switch over to it from the proper bike lane before the intersection, then turn left onto S 13th St. Both types of maneuvers are not legal, and more importantly are unexpected behaviours for other road users to interact with. Performing left turns the same way a vehicle does, a formal method for performing a left turn, was only documented four times, suggesting bicyclists prefer other methods over traditional expectations of bicyclists. Overall, 8 of the 22 (36.3%) observed left turning bicyclists did so in a legal and expected manor in terms of road space on green arrival, and 7 of the 22 (33.3%) on red arrival.

The most frequent maneuvers on green arrival are two-phase left turns, though that includes the standard and unusual (other) two-phase methods. Three of those are unusual (and classified as 'other') in that the bicyclists stopping locations are inconsistent with traditional a two-phase maneuver stopping location such as on the southwest corner or the southeast corner up on the sidewalk. Two of the three chose to stop and prepare for the second phase on the left curb shoulder of S 13th St and one stopped on the southeast sidewalk corner. All three of the standard two-phase left turns observed during a red signal approach ran the initial red light and seemingly used the two-phase bike box to minimize how many travel directions they would conflict with at one time,

Observing some cyclists conducting two-phase left turns without a box present at this intersection was expected. The City of Philadelphia has previously installed two-phase left turn bike boxes in a few nearby locations in the city. Bicyclists may already be familiar with the method and choose it even when no two-phase bike box is present.

In the after period, 69% of left-turning bicyclists approaching on green began their maneuver from the bike lane as designed and completed their maneuver in the roadway northbound as designed. The transition between the approach and completion of the left turn are where a reduction in turning method variation is noticeable compared to the before stage. The variation of maneuvers of bicycles approaching on green and red signal phases after installation are illustrated in Figure 20 and listed in Table 14, followed by a total of before and after left turns in Table 15. A side-by side comparison of the before and after periods can be found in Appendix F.

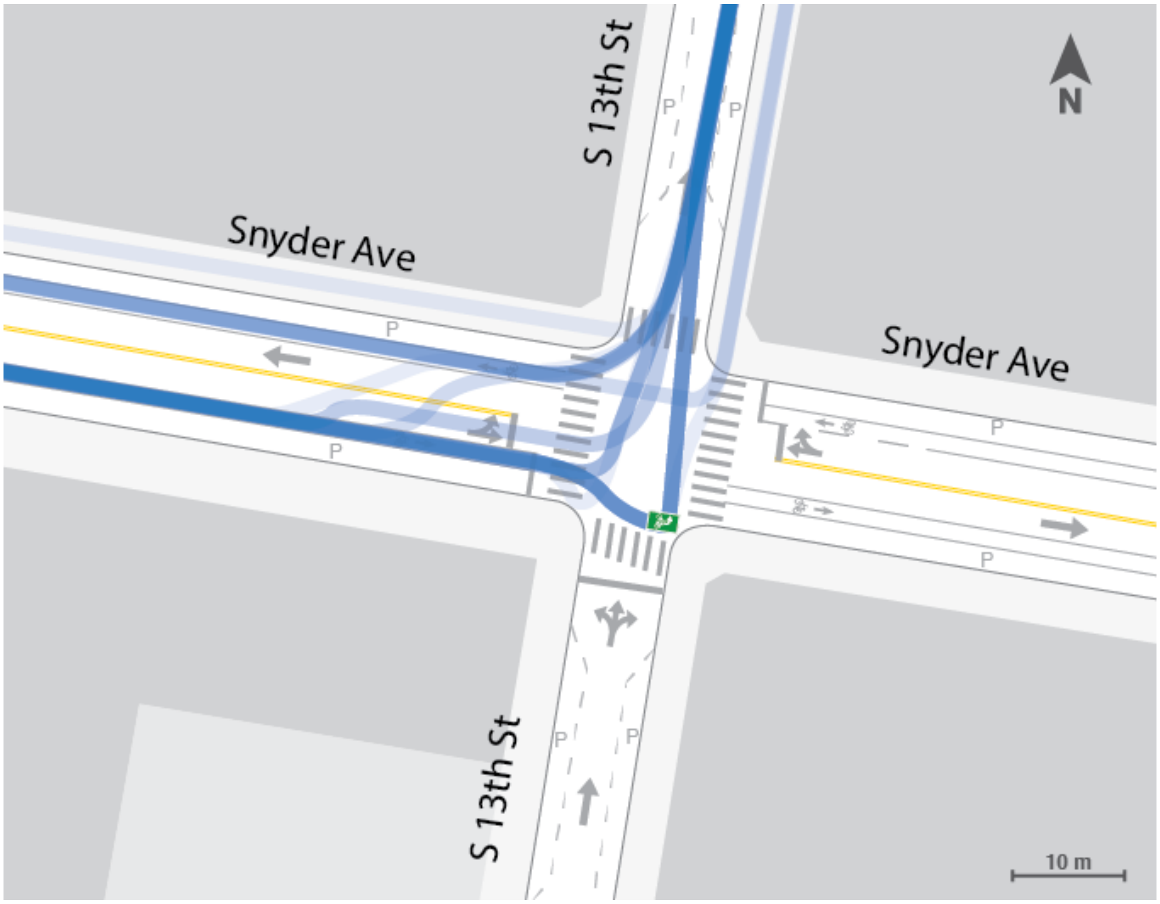


Figure 22: Intersection 2 'After' Desire Lines of Southbound Left-turning Bicycles Arriving on Green Signal Phases

Table 13: Intersection 2 'After' Comparison of Left-turn on Green & Red Bicycle Behaviour Classifications

Left-turn Classification	After Count: Green	After Count: Red
Two phase	11	0
Two phase other	1	0
As vehicle	4	2
Left from bike lane at stop line	5	1
Wrong way bike lane to vehicle	1	4
Pedestrian to vehicle	1	0
Vehicle to pedestrian	2	0
Wrong way bike lane to pedestrian	0	0
Pedestrian to pedestrian	1	0
Total	26	7

Table 14: Intersection 2 'Before' and 'After' Comparison of Left-turn on Green Bicycle Behaviour Classifications

Left-turn Classification	Before Count	Before Percent	After Count	After Percent
Two phase	7	16.3%	11	33.3%
Two phase other	4	9.3%	1	3.0%
As vehicle	4	9.3%	3	9.1%
Left from bike lane at stopping line	4	9.3%	5	15.2%
Wrong way bike lane to vehicle	15	34.9%	9	27.3%
Pedestrian to vehicle	2	4.7%	1	3.0%
Vehicle to pedestrian	5	11.6%	1	3.0%
Wrong way bike lane to pedestrian	1	2.3%	2	6.1%
pedestrian	1	2.3%	0	0.0%
Total	43	100	33	100

Left turns using the new two-phase facility in the after period increased by 17% when considering both arrivals on green and red signal phases. When isolating for just cyclists arriving on a green phase (when the facility is most appropriately used) proper two-phase left turn box use represented 11 of the 26 documented bicycles arriving on green, an increase of 24.1% from the before stage.

There is a decrease of 9.17% of "wrong way bike lane to wrong way bike lane" maneuvers, and decreases in bicyclists switching to pedestrian from vehicle through their maneuver. Bicyclists traveling the wrong way in the westbound bike lane persists, and an increase in left turns from the bike lane at the stop line is observed. Left turns from the bike lane face more potential conflict as the bicyclist must cut across the entire vehicle lane to complete the left turn. In doing so, the bicyclist must shoulder check if a vehicle is conflicting. Shoulder checking is when a cyclist looks over their shoulder for oncoming vehicles behind them, similar to how a driver checks a blind spot. If the shoulder check is done poorly or if the bicyclist makes a last second judgment call to take the turn, conflict may occur. Merging into the vehicle lane earlier provides time to establish intention and remove one degree of conflict prior to the turning maneuver. Doing so prevents any vehicles approaching from impeding the completion of the left turn.

Organizing the before and after periods into categories of expected behaviour and unexpected behaviour results in Table 16.

Table 15: Intersection 2 'Before' and 'After' Results Organized by Expected and Unexpected Behaviour

Observation	Before	After
Expected behaviour	15 (34.9%)	15 (45.5%)
Unexpected expected	28 (65.1%)	18 (54.5%)
Total	43	33

Overall, an increase of 10.6% of expected behaviour was found after the two-phase left turn bike box was installed. A chi-squared statistics test for independence between the before and after stage results in a value of p=0.35. This value is higher than the 0.05 or 95% confidence requirement, and therefore does not demonstrate a statistically significant change. A change in behaviour is observed despite the low counts from both before and after stages not statistically validating the impact of two phase left turn bike boxes at this intersection. With modest counts, the chi-square results are highly volatile and do not validate, nor dismiss the impact of installing the two-phase left turn bike box.

Low counts of observed left turning bicycles at this intersection do not meet expectations. The selection of this intersection for receiving installation of a two-phase left turn box was done by the City of Philadelphia and was assumed to have more significant left turn volumes. This assumption may have been unfounded considering objectives of the city. The objective may have been simply to upgrade intersections for cyclists at bike route junctions instead of a deeper analysis of where left turns occur most frequently. This is not to say a two-phase bike box at this intersection is unfounded; it is still useful for bicyclists who prefer or feel safer with a two-phase maneuver.

Combining the before and after data allows for a general comparison of how bicyclists maneuver left when approaching green and red phases, Table 14 and Table 15 demonstrate arrival on green and red respectively by arrival and departure road space.

Table 16: Intersection 2. Before and After Combined Eastbound Left-turning Cyclists Arriving on Green Signal Phase, Approach and Destination Road Space

	Went to Road	*Went to Pedestrian (Either Side)*	*Total*
Approached as Vehicle/Proper Bike Lane	0.58	0.06	0.65
Approached as Pedestrian	0.04	0.02	0.06
Approached in Wrong Way Bike Lane	0.23	0.03	0.29
Total	0.85	0.15	1.00

n=48

Table 17: Intersection 2. Before and After Combined Eastbound Left-turning Cyclists Arriving on Red Signal Phase, Approach and Destination Road Space

	Went to Road	*Went to Pedestrian (Either Side)*	*Total*
Approached as Vehicle/Proper Bike Lane	0.46	0.04	0.50
Approached as Pedestrian	0.04	0.00	0.04
Approached in Wrong Way Bike Lane	0.46	0.00	0.46
Total	0.96	0.04	1.00

n=28

Interestingly, Intersection 2 demonstrates that eastbound cyclists arriving at a green light are almost twice as likely to do so in the wrong way bike lane compared to arriving at a red light. Likely because the departing road is a one way, a significant majority of cyclists (95% on green and 85% on red) turn to the roadway, though 9% more cyclists divert to pedestrian activity on red signal phases. 15% more cyclists stay as a vehicle/in the proper bike lane while arriving on red because they can turn left from the stop line onto S 13th St. Doing so on a red light is technically a red light infraction, but it is easy to understand why cyclists may see this as a white lie of infractions. S 13th St is a narrow one way street and cyclists do not need to cross over to the right side of the road; They can stay on the left shoulder while S 13th St has the green light and merge from the left.

4.3.3 Intersection 3: E Allegheny Ave & Aramingo Ave

There are two left-turning maneuvers documented at this intersection. The first left turn is of northbound bicyclists on E Allegheny Ave turning left onto Aramingo Ave westbound. The second left turn is of southbound bicyclists on E Allegheny Ave turning left onto Aramingo Ave eastbound. The turning direction, video period, count, and signal phase of all documented left-turning bicyclists are presented in Table 19.

Table 18: Intersection 3. Left-turn Counts of Bicyclists

Direction of travel and video stage	Green	Red	Total
Northbound left Before	13	13	26
Northbound left After	12	12	24
Southbound left Before	13	22	35
Southbound left After	11	18	29

Both observed turns in the before and after periods did not produce a substantial count of left turning bicyclists. The signal timing for this intersection is evenly distributed between the travel directions so the greater number of bicyclists approaching on a red signal phase for southbound traffic is likely coincidental.

The before or after stages for both observed directions documented two left turn maneuvers using a two-phase approach on the bicycle facilities as designed. One northbound bicyclist conducted a two-phase left in the before stage without the presence of the new facility and one southbound bicyclist was documented using the new facility in the after stage. Figure 23 and Figure 24 demonstrate the before and after desire paths of all northbound left turns respectively. The more prominent blue lines represent more frequently traveled areas.

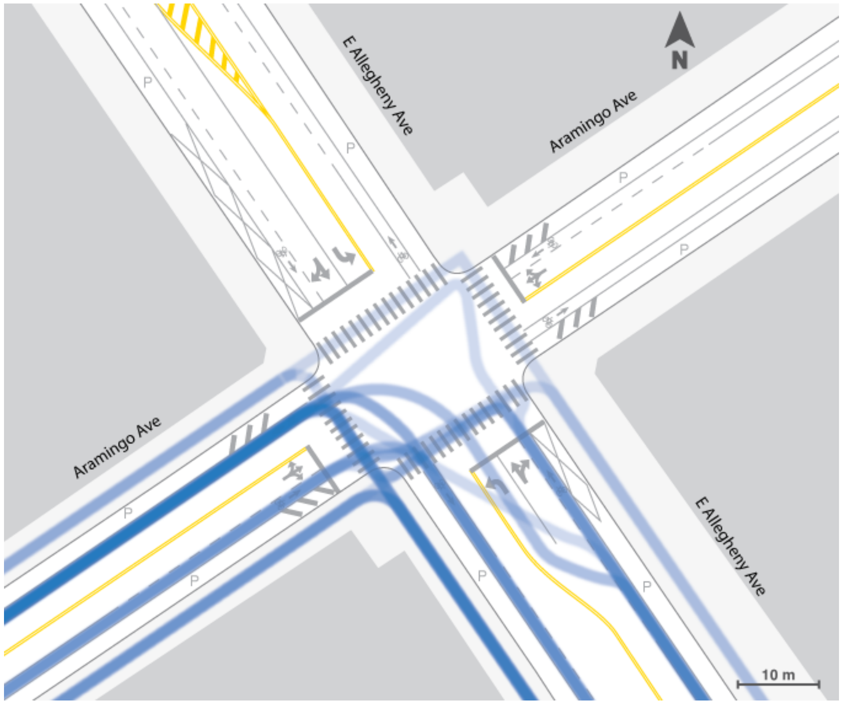


Figure 1: Intersection 3 'Before' Desire Lines of Northbound Left-turning Bicycles Arriving on Green and Red Signal Phases

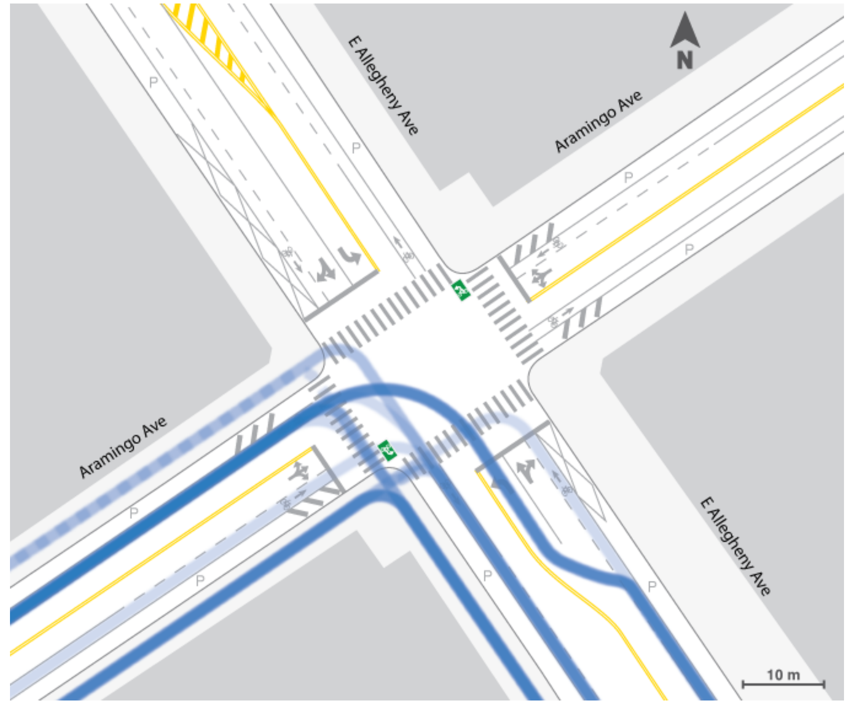


Figure 2: Intersection 3 'After' Desire Lines of Northbound Left-turning Bicycles Arriving on Green and Red Signal Phases

Though there appears to be a visual decrease in variation of left-turn maneuvers between the before and after stage, most are not expected behaviour. Only 2 out of the documented 26 bicyclists, or 7.7% conducted their left turn in an expected, legal way in the before stage, and 6 of the 24, or 25% in the after stage. The increase in expected and legal behaviour is likely independent of the installation of the two-phase left turn bike box considering the after stage only documented one bicyclists' use of the two-phase left turn bike box.

The most prominent approaches of northbound left-turning bicyclists for both observation periods are use of the vehicle left turn lane, from the wrong way bike lane, and use of the southwest sidewalk. Bicyclists using the turn lane as one of the legal options seem to have a consistent follow through (they turn to the proper bike lane westbound). Bicyclists approaching in the proper bike lane and not using the left turn lane and bicyclists approaching in wrong way bike lane are far less predictable. The desire lines for these bicyclists show opportunistic behaviour of choosing the path of least resistance to favour continued movement toward the destination, regardless of potential safety issues, bicycle etiquette or road rules. There is a tenancy for bicyclists to end up in the proper bike lane westbound, though the desire lines are not known once bicyclists travel out of the camera frame. Considering numerous bicyclists were captured switching to and from proper and apposing bike lanes, a portion of the documented left turning bicyclists that did not initially turn to the proper bike lane, likely switched over to the proper bike lane midblock. Not to say this tendency justifies the observed behavior, if anything, it demonstrates the fluidity and opportunistic tendencies of bicyclists.

Figure 25 and Figure 26 demonstrate the before and after stages of southbound left turns respectively. The more prominent blue lines represent more frequently traveled areas.

Figure 1: Intersection 3 'Before' Desire Lines of Southbound Left-turning Bicycles Arriving on Green and Red Signal Phases

Figure 2: Intersection 3 'After' Desire Lines of Southbound Left-turning Bicycles Arriving on Green and Red Signal Phases

The left- turning behaviour for southbound bicyclists is similar to northbound bicyclists, with one major difference. There is a greater tendency for left-turning southbound bicyclists to reach the intersection in the wrong way bike lane, and turn to either continue in the wrong way bike lane or turn to the north side sidewalk. There are a few possible explanations for this. The first possibility is that a greater proportion of left-turning southbound bicyclists were documented approaching on a red signal phase, and the path of least resistance is to continue using the wrong way bike lane eastbound or switch to the sidewalk eastbound. The second possibility is that there may be a popular or common set of destinations or other route options that are easier to access on the north side of Aramingo Ave, and staying on the north side is decidedly easier for bicyclists than using the proper bike lane and navigating back to the north side at a later point.

Both northbound and southbound left-turn approaches are nearly identical in terms of road characteristics and results can be combined as one t*ype* of intersection for analysis. Because the two-phase left turn bike boxes were not used in the after stage except for one bicyclist, data from the before and after stages can also be combined to make observations on behaviour differences between arrival on greed phases and arrival on red phases. The arrival road space and departing road space of cyclists arriving on a green signal phase and red signal phase are presented in Table 20 and 21 respectively.

Table 19: Intersection 3. Before and After Combined Northbound and Southbound Left-turning Cyclists Arriving on Green Signal Phase, Approach and Destination Road Space

	Went to Bike Lane	*Went to Wrong Way Bike Lane*	*Went to Pedestrian (either side)*	*Total*
Approached as Vehicle/Proper Bike Lane	0.22	0.02	0.02	0.27
Approached as Pedestrian	0.16	0.12	0.06	0.35
Approached in Wrong Way Bike Lane	0.12	0.00	0.27	0.39
Total	0.51	0.14	0.35	1.00

n=49

Table 20 Intersection 3. Before and After Combined Northbound and Southbound Left-turning Cyclists Arriving on Red Signal Phase, Approach and Destination Road Space

	Went to Bike Lane	*Went to Wrong Way Bike Lane*	*Went to Pedestrian (either side)*	*Total*
Approached as Vehicle/Proper Bike Lane	0.15	0.05	0.09	0.29
Approached as Pedestrian	0.08	0.22	0.11	0.40
Approached in Wrong Way Bike Lane	0.05	0.02	0.25	0.31
Total	0.28	0.28	0.45	1.00

n=65

Comparing between arrival on green signal phases and red signal phases, there is slight variation in approaching road space, notably an increase of 8% for cyclists approaching in the wrong way bike lane on green compared to red signal phase arrivals. More significant are the changes in destination road spaces. The percent of cyclists that went to the proper bike lane dropped from 51% to 27.7% between arrival on green and arrival on red. Intuitively, increases in wrong way bike lane and pedestrian departing road spaces occur. On green arrivals, only 14.3% went to the wrong way bike lane – this number increases to 27.7% for cyclists arriving on a red signal phase. In both green and red arrivals, switching to and from pedestrian space and wrong way bike lane space is common. 42.9% of the 114 cyclists switched either to or from these spaces.

4.3.4 Intersection 4: S 34th St & Chestnut St

The protected bike lane described along Chestnut St was completed on August 29th, 2017, just over one week before the before footage was captured at this intersection. This is Philadelphia's first protected bike lane and lead to some complications. One challenge is facilitating right turns for bicyclists traveling in the eastbound protected lane to the southbound bike lane. Normally, bike lanes are on the right shoulder of a given carriageway, and right turns inherently do not require crossing lanes of traffic. In this case, bicyclists must navigate across Chestnut St, preferably to the bike lane southbound on S 34th St. The city decided to install a two-phase right turn bike box– an unusual but location-specific solution. The two-phase right turn box is used similarly to a two-phase left turn bike box, however the sequence is slightly different. A bicyclist approaching on a green signal phase in the protected bike lane is to traverse over the near-side sidewalk and stop, in this case on the north-west corner at the front of the queue of the southbound bike lane as phase one. Once the traffic signal changes, continue southbound through the intersection as phase two and completing the right turn.

The cyclists are not impeded when arriving on a red signal phase and have no use for the two-phase right turn box. Only the cyclists arriving on a green signal phase are included in this analysis.

The video captured in the before stage is focused on seeing how bicyclists prepared and maneuvered right turns with the new protected bike and no right-turn facility. As a result of the infrastructure newness, bicyclist may be looking, and more willing, to adapt behaviour to new facilities or suggestions on safe intersection navigation.

In the before stage where the two-phase bike right turn bike box had not been installed, the predominant method of right turns when approaching on green was to stop before the pedestrian crosswalk. Once the signal phase changed, bicyclists would proceed diagonally across the pedestrian crosswalk to link up with the southbound bike lane, depicted as the darkest continuous blue line in Figure 27. The complete list of right turn maneuvers for arrival on green is presented in Table 22.

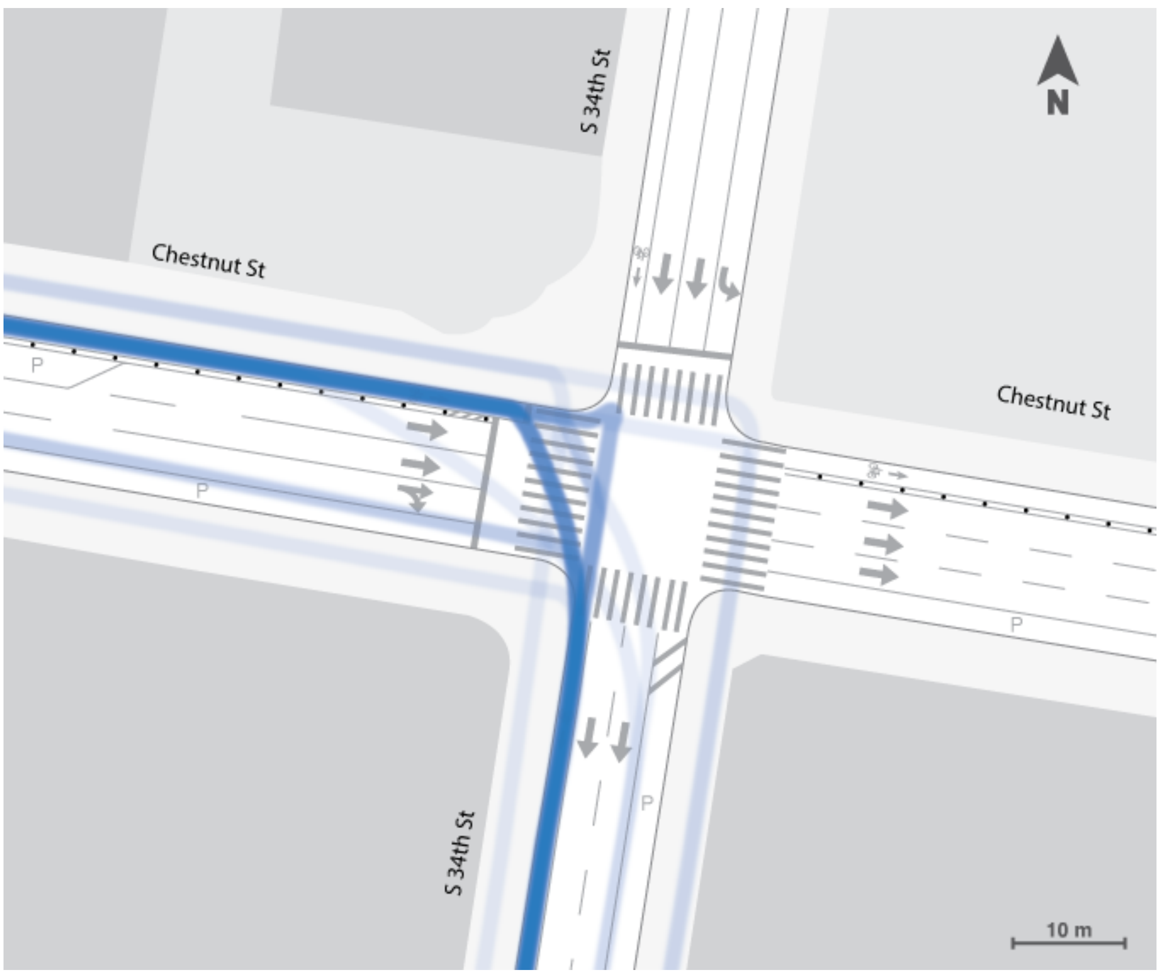


Figure 27: Intersection 4. 'Before' Desire Lines of Eastbound Right-turning Bicycles Arriving on Green Signal Phases

Table 21: Intersection 4. 'Before' Bicycle Behaviour Classification

Type of right:	Before Count	Before %
Two phase, stop before or on crosswalk	16	53.3
Two phase, stopping after crosswalk	5	16.7
Right shoulder to bike lane	2	6.7
Pedestrian to pedestrian	2	6.7
Pedestrian to roadway	1	3.3
Bike lane to pedestrian	1	3.3
Bike lane to left shoulder	1	3.3
Right shoulder to left shoulder	1	3.3
Other	1	3.3
Total	30	100

The issue faced with most bicyclist performing this maneuver is that there are often many pedestrians initiating their southbound and northbound crossing at the same time as the bicyclist is traversing diagonally over the crosswalk. As a result, the bicyclists weave through pedestrians to emerge on the other side, or wait until the pedestrians cross, then proceed to the southbound bike lane. From a bicyclist perspective, the delay and awkwardness resulting from this interaction with crossing pedestrians is unfavourable. This interaction was only found to occur at low speeds, though does not preclude the chance of a pedestrian being struck and/or a bicyclist falling. From a pedestrian perspective, the interaction could be perceived only as a minor nuisance, or taken more seriously as barrier to crossing safely.

Bicyclists stopping after the crosswalk in the area intended for the new facility did not face conflict with pedestrians and were free to proceed southbound unencumbered. This is not to say stopping before or after differ in a legal sense, except for cases where cyclists use the zebra crossing after stopping before the stop line. There are numerous ways to safely and legally traverse this intersection, and some of which are considered safer or more efficient.

Use of the protected bike lane for right turning bicyclists is favoured over use of the right shoulder. Because of the high volume of automobile traffic, it is likely that switching from one shoulder to another midblock is not perceived as a safe option.

The installation of the two-phase right turn bike box resulted in more bicyclist stopping to wait after the crosswalk on the provided facility, thus fewer bicyclists interacting and being impeded by pedestrians. Figure 28 demonstrates the desire lines and Table 23 presents all arrivals on green of right turn maneuvers in the before and after stages to compare. The more prominent blue lines in Figure 26 represent more frequently traveled routes. A side-by side comparison is available in Appendix G.

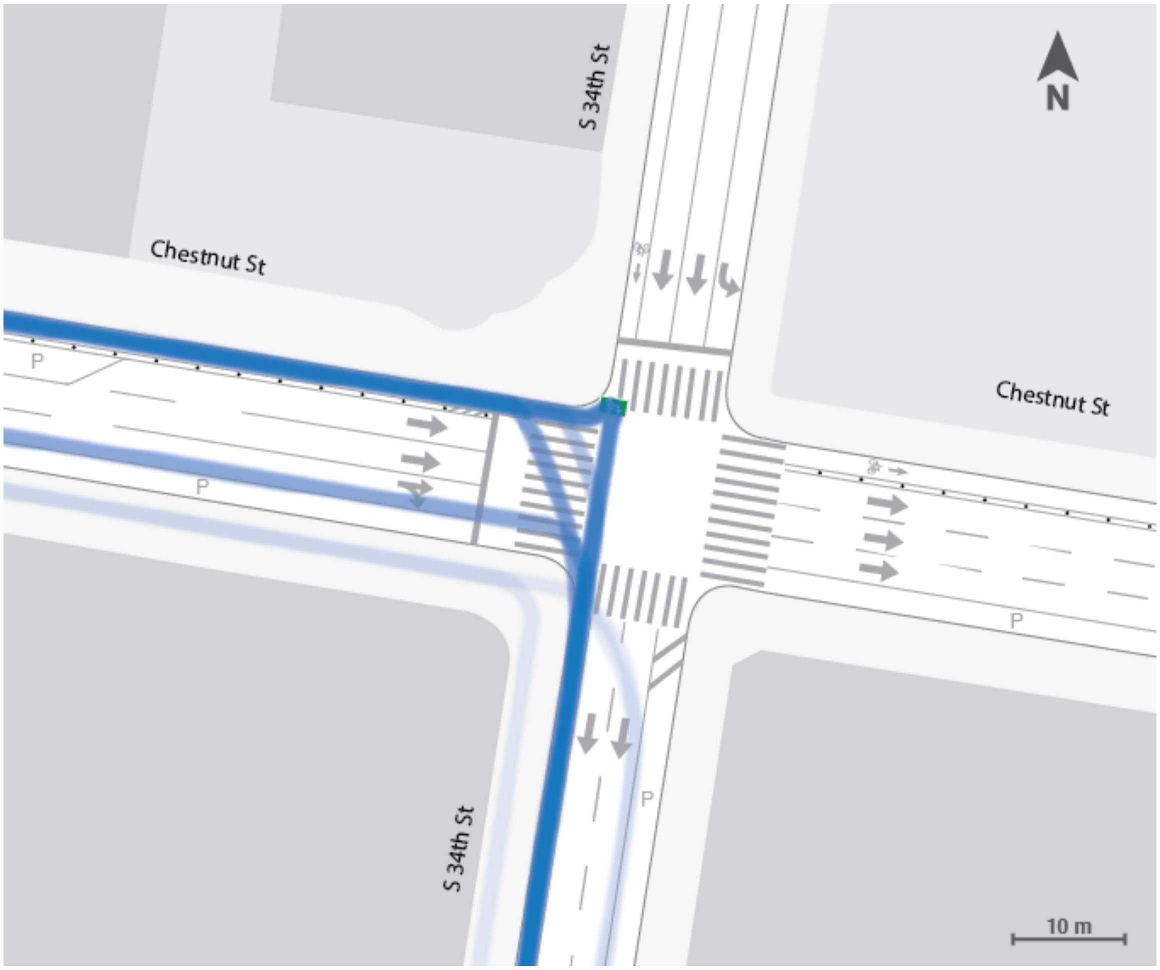


Figure 28: Intersection 4. 'After' Desire Lines of Eastbound Right-turning Bicycles Arriving on Green Signal Phases

Table 22: Intersection 4. 'Before' and 'After Comparison of Bicycle Behaviour Classification

Type of right:	Before Count	Before %	After Count	After %
Two phase, stop before/on crosswalk	16	53.3	12	30.8
Two phase, stopping after	5	16.7	17	43.6
Right shoulder to vehicle	2	6.7	6	15.4
Pedestrian to pedestrian	2	6.7	1	2.6
Pedestrian to roadway	1	3.3	1	2.6
Bike lane to pedestrian	1	3.3	0	0.0
Bike lane to left shoulder	1	3.3	0	0.0
Right shoulder to left shoulder	1	3.3	1	2.6
Other	1	3.3	1	2.6
Total	30	100	39	100

Two-phase right turns with bicyclists stopping before or on the crosswalk dropped from 53.3% to 30.8% - a decrease of 22.5%. More critically, two-phase rights after the crosswalk where the facility was put in place shows an increase from 16.7% to 43.3% - an increase of 26.9%. However, more bicyclists were documented arriving on the right shoulder prior to a right turn – an increase of 8.7%. Other types of less common maneuvers were not documented at all in the after stage such as bicyclists switching from the protected bike lane to pedestrian.

Organizing the before and after stages strictly looking at the exchange between bicyclist stopping before or on the crosswalk, and after the crosswalk results in Table 24.

Table 23: Intersection 4. 'Before' and 'After' Results of Right-turn Behaviour Simplified

Type of right turn	Before	After
Two phase before crosswalk	16	12
Two phase after crosswalk	5	17
Other	9	10
Total	30	39

A Chi-squared test for independence between the two observational periods produces the value p= 0.047, slightly exceeding the 0.05 –or 95% confidence – requirement for statistical significance. This suggests the installation of the two-phase right turn box results in statistically significant changes in right turn behaviour. Similar to the other documented intersections, the sample size of turning cyclists is low, but in this case the hours of footage was the limiting factor, not the popularity of cyclists turning right or cycling through the intersection in general.

Observing how cyclists maneuver right on green signal phase arrival revealed that a two-phase right turn box installation was more useful to reduce conflict and create greater consistency between cyclists and pedestrians, instead of between cyclists and vehicles seen in the other 3 study intersections. Nonetheless, reducing conflict between any groups of road users with significant speed differentials is beneficial at signalized intersections.

Combining the before and after data allows for a general comparison of how bicyclists maneuver right when approaching green and red phases. Table 22 and Table 23 demonstrate arrival on green and red respectively by arrival and departure road space.

Table 24: Intersection 4. Combined Before and After Eastbound Right-turning Cyclists Arriving on Green Signal Phase, Approach and Destination Road Space

	To Bike Lane	*To Pedestrian*	*To Left Shoulder*	*Total*
Approached in Protected Bike Lane	0.74	0.01	0.01	0.77
Approached From Right Shoulder	0.12	0.00	0.03	0.14
Approaches as Pedestrian	0.03	0.04	0.01	0.09
Total	0.88	0.06	0.06	1.00

n=69

Table 25: Intersection 4. Combined Before and After Eastbound Right-turning Cyclists Arriving on Red Signal Phase, Approach and Destination Road Space

	To Bike Lane	*To Pedestrian*	*To Left Shoulder*	*Total*
Approached in Protected Bike Lane	0.73	0.06	0.03	0.82
Approached From Right Shoulder	0.13	0.00	0.00	0.13
Approaches as Pedestrian	0.03	0.02	0.00	0.05
Total	0.89	0.08	0.03	1.00

n=62

Comparing right turns on green and red signal phase arrival, behaviour is very consistent. 90% of bicyclists approaching on green and 89% approaching on red did so with expected road space behaviour.

4.4 Chapter Summary

Video footage documented bicycle behaviour at four signalize intersections.

Apart from red light running, expected road space behaviour was found to be largely independent of arrival signal phase, though results demonstrate some exchange between opportunistic and pedestrian conflict behaviour. Intersections 1, 2 and 3 demonstrate that left-turning cyclists have the lowest rates of expected road space behaviour which is consistent with expectations based on existing literature. Highest rates of expected road space behaviour was found at Intersection 4 with the protected bike lane and the highest bph rate of all intersections.

Relative to each intersection's red light rates, left turns had the lowest red light running rates, followed by through movements, then right turns. 99.8% of all red lights for right turns were violated. A high correlation was found between red light running rates for through movements and mean gap time of cross traffic, suggesting cyclists treat signalized intersections like stop signs or yield signs. Combining the road space behaviour with red light running results, it seems left turning cyclists are most likely to ride inconsistently with expected road space behaviour, but least likely to run a red light relative to other turning movements.

The video footage was collected in two periods to create a before and after study for the installation of two-phase turn bike boxes. Three intersections had two-phase left turn bike boxes installed and one intersection had a two-phase right turn bike box installed. A period of one month was given between the facility installations and the after phase of video collection.

The three intersections that received two-phase left turn bike boxes provided mixed results. Intersection 1 did not have any cyclists use the two-phase left turn box likely because the intersection angle made use of the facility superfluous. Bicyclists preferred to position themselves on the left side of the approaching one-way street in preparation for a left-turn – something not as feasible in two-way traffic. Also, it was discovered that the main difference between left-turning cyclists arriving on green versus red signal phases is that cyclists are around twice as likely to depart the intersection in the wrong way bike lane when arriving on a red signal phase. Intersection 2 was the only intersection to demonstrate use of the two-phase left turn bike box. At Intersection 2, a 24.1% increase in two-phase left behaviour was documented for cyclists arriving on a green signal phase and an overall increase in expected behaviour, though neither are statistically significant results. Intersection 3 had two-phase left turn bike boxes installed for two different travel directions and only one bicyclist was documented using either facility after the facility installation. Cyclists preference for approach is in the wrong way bike lane, and as pedestrians and the percent of cyclists that went to the proper bike lane dropped from 51% to 27.7% between arrival on green and arrival on red.

Intersection 4 that received a two-phase right turn box proved to have the most promising results, though the turning maneuver was not the original intent of this study. It was initially discovered at Intersection 4 that right-turning cyclists from the protected bike lane were often facing conflict with crossing pedestrians. The installation of the two-phase right turn box demonstrated statistically significant changes in bicycle behaviour. The two-phase right turn bike box supported cyclists approaching on a green phase to wait for a signal change on the designated sport past the crosswalk and out of conflict with pedestrians

5.0 Conclusions

The focus of current cycling-related research is to determine how to improve cycling mode share and improve cycling safety – both of which require an understanding of cyclists motivations and behaviour. A review of the literature demonstrated that two-phase left turns are being encouraged in certain cities, but not well understood in a North American context. Furthermore, few studies were found that include two-phase turn bike box impacts on behaviour. The city of Philadelphia has made proactive efforts to improve its cycling network by experimenting with inadequately studied cycling network treatments. Results of this study can be useful for other cities to compare to and build from to better understand bicycle behaviour.

To better understand the impact in left-turning behaviour with the installation of two-phase turn boxes, this longitudinal study was undertake to answer the following research questions related to Section 1 of the results:

I. How do cyclists conduct left-turn maneuvers?

Cyclists demonstrated through desire lines that directness and avoidance of entering exposed parts of intersections is the preferred behaviour, and the majority of cyclists did so in ways inconsistent with expected behaviour. Riding in the wrong way bike lane was a common occurrence at all left-turn study intersections.

II. Does the installation of two-phase left turn bike boxes increase predictability (and therefore safety) of left-turning cyclists?

Based on the results of the before and after study, increased predictability in behaviour of left-turning cyclists is possible with two-phase left turn bike boxes, though understanding treatment context is necessary to see behavioural changes. The ways cyclists tended to turn left avoid delays, and two-phase left turn boxes do not offer that as a benefit. Use of two-phase bike boxes must therefore be by bicyclists more inclined to follow road rules, or perceive reducing conflict with other road users as a greater priority than directness and reduced delay. Literature found that two-phase lefts are more appropriate for larger intersections, though this study found no impact on the largest study intersection (Intersection 3). It is possible that the sheer size of Intersection 3 and existing turning habits prevent cyclists from seeing the two-phase left turn bike box on approach, and may take more time and repeated intersection use to see any change in behaviour. In this case, signage prior to the intersection is crucial.

III. How do cyclists conduct right turns from a left side protected bike lane when at a multi-lane signalized intersection?

Intersection 4 was used to answer this research question. Right turning cyclists in this condition were found to have expected road space behaviour for 90% of cyclists on green arrival and 89% of cyclists on red arrival. Cyclists approaching on a green signal phase often found conflict with pedestrians when the cyclists waited in front of the crosswalk. Few cyclists were documented using the right shoulder for a right turn. This behaviour is legal, though not consistent with the intended road design.

IV. How does the installation of a two-phase right turn bike box affect right-turn behaviour?

Based on the results from Intersection 4, the installation of a two-phase right turn box caused a statistically significant change in behaviour. Cyclists approaching on a green signal phase were convinced to maneuver over the pedestrian crosswalk to the two-phase box and avoid conflict with pedestrians upon signal phase change. Use of the two-phase right turn box area increased by 26.9% between the before and after stages. This intersection was found to have few behavioural inconsistencies, however, simple changes such as the observed impact of the two-phase right turn box remove conflict and delay between cyclists and pedestrians.

Relating to Section 2 of the results for all types of cyclist intersection maneuvers, this research can address the secondary research questions:

I. What are bicyclists desire lines/ where are bicyclists riding? i.e. in bike lanes, on sidewalks, switching in between?

As expected, desire lines varied significantly between study intersections. Of all cyclists, about three quarters demonstrated expected behaviours excluding red light running. Opportunistic and pedestrian conflict behaviour combined ranged from 47.3% to 85.1%. However, when the data is arranged by turning direction, left turns at all intersections demonstrated the lowest rates of expected behaviour ranging from 14.8% to 54.5% excluding red light running.

II. Does the approaching signal phase influence cyclist desire lines/ where cyclists ride?

Section 3 revealed that left turning cyclists arriving on red signal phases were more likely to depart intersections in the wrong way bike lane for intersections 1 and 3, and left turning cyclists were more likely to use the wrong way bike lane when arriving on a green signal phase for intersection 2 and 3. However, Section 2 for all movements (predominantly through movements) were not significantly impacted by arrival signal phase. More analysis is needed to understand signal arrival on right turning movements, though based on the red light running frequency, it is suspected that intersection phase has minimal impact on cyclists right turn desire lines.

III. **How frequently and under what circumstances do bicyclists run red lights in Philadelphia?**

At the study intersections in Philadelphia, 68.5% of cyclists arriving on red signal phases rand the red light. This rate is higher than the rates found through the literature review. A correlation with an R^2 value of 0.95 was found between sample through movements and mean gap times of cross traffic. This means cyclists reliably treat signalized intersections like stop signs or yield signs. Amidst the efforts to implement road diets to slow traffic and reduce crossing distances for pedestrians, a possible unintended consequence may arise. Lower traffic volume and shorter crossing distances through road diets may result in more frequent red light running. This is not to say that safety issues are increased, considering literature showed mixed consensus on the dangers and perceptions of red light violations. Increases in cyclist red light running after road diets is a possibility that municipal bodies must consider within their objectives and permissiveness in cyclist behaviour.

5.1 Result Limitations

The behaviour and descriptive variables of 6,786 bicyclists were recorded in this study in the before and after periods. The desired left-turning (or right turning in the case of Intersection 4) of bicyclists represented 373 of the 6,786 total bicyclist. The nature of two-phase turn box portion of this study benefits cyclists arriving at the study intersections on green signal phases far greater than arrival on red signal phases. In this case, just 160 of the 6,786, or 2.3% of documented bicyclists arrived on green signal phases to study the specific turning behaviour. Cyclists arriving on red signal phase were included in the results but are were not ideal data points. The low sample size reduces the reliably of the results significantly. As stated in the methods limitations, these results do not demonstrate stated preference for the two-phase turn box treatments. A survey of cyclists would provide greater information of cyclists. perceptions.

5.2 Future Research

The research in this study focused on four intersections in the City of Philadelphia. Future research would benefit from a greater scope involving more cities with different cycling expectations and behaviours. For research purposes, intersections should have a variety of design and operational characteristics. Variation allows for a greater understanding of what intersection operations and design conditions influence cyclist behaviour. Table 26 highlights characteristics that can be observed across different intersections and the units of measure for these attributes.

Table 26: Design and Operational Characteristics of Intersections

Design and Operational Characteristics	Units
Vehicular volume	Vehicles/hour/lane
Vehicular speeds	Km/h or Miles/h
Road Capacity	Vehicles/hour/lane
Bicycle volume	Bicycles per hour (bph)
Type and distribution of bicyclists: confident, cautious, novice, etc.	n/a
Presence of bicycle facilities: e.g. bike box, sharrows, bike lanes, cycle tracks	n/a
Presence of intersecting bike routs	n/a
Transition between facility types: e.g. park trail to bike lanes.	n/a
Intersection size/number of lanes	Number of lanes, carriageway width (meters or feet)
Presence of turning lanes	n/a

Presence of advanced green signal phase (left or right)	n/a
Signal timing, detectors, pedestrian actuators	Seconds

Follow-up observations should be conducted to improve on the one month post-installation, such as a six month or one year follow-up. This way, cyclists are given more time to potentially experiment with the new facilities. More promising results may come with more time for cyclists to adopt new infrastructure. Most importantly, conduct a beta test to ensure any study intersection will provide sufficient sample sizes so results can produce greater statistical rigor.

5.3 Recommendations

The results demonstrate a positive relationship with cycling predictability and the presence of two-phase bike boxes. More research is necessary to understand their impacts, though practitioners are suggested to consider two-phase turn boxes, particularly when signalized intersections are challenging for cyclists because of their size, operating speeds, or complexity. Guidance of their use and additional supporting components such as signage are well defined in the National Association of City Transportation Officials Urban Bikeway Design Guideline (2014).

This research supports past studies regarding cyclist red light running. It is recommended that more research be conducted in the interest of considering policy revisions that legally permit cyclists to in some ways behave differently than motor vehicles in a safe manor. Policies of this nature could impact the uptake of cycling culture and mode share.

In a future where cycling mode share is more substantial, it is important that road users are prepared to safely assess their surroundings. Beyond design and infrastructure changes that facilitate awareness and safe behaviour, road users are ultimately responsible for their own vehicle operations, be it a motor vehicle or bicycle. Though this study did not reveal any collisions or significant conflict, the possibility of such cases would have only needed a minor error in judgment by a cyclist or vehicle while traversing an intersection. Proper training is effective, and is highly recommended for drivers through driver training with contemporary content (such as two-phase left turn boxes) that reflect the emerging cycling infrastructure in North American cities. Likewise, bicycle training and educational programs are recommended to equip new and established cyclists with information to make sound choices.

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APPENDIX A: Cycling Infrastructure and Facilities for Signalized Intersections

Crossing Markings	
Bike Box	
Two-Phase Left-Turn Bike Box	

	
Two-Phase Right-turn Bike Box	
Through Lanes .	

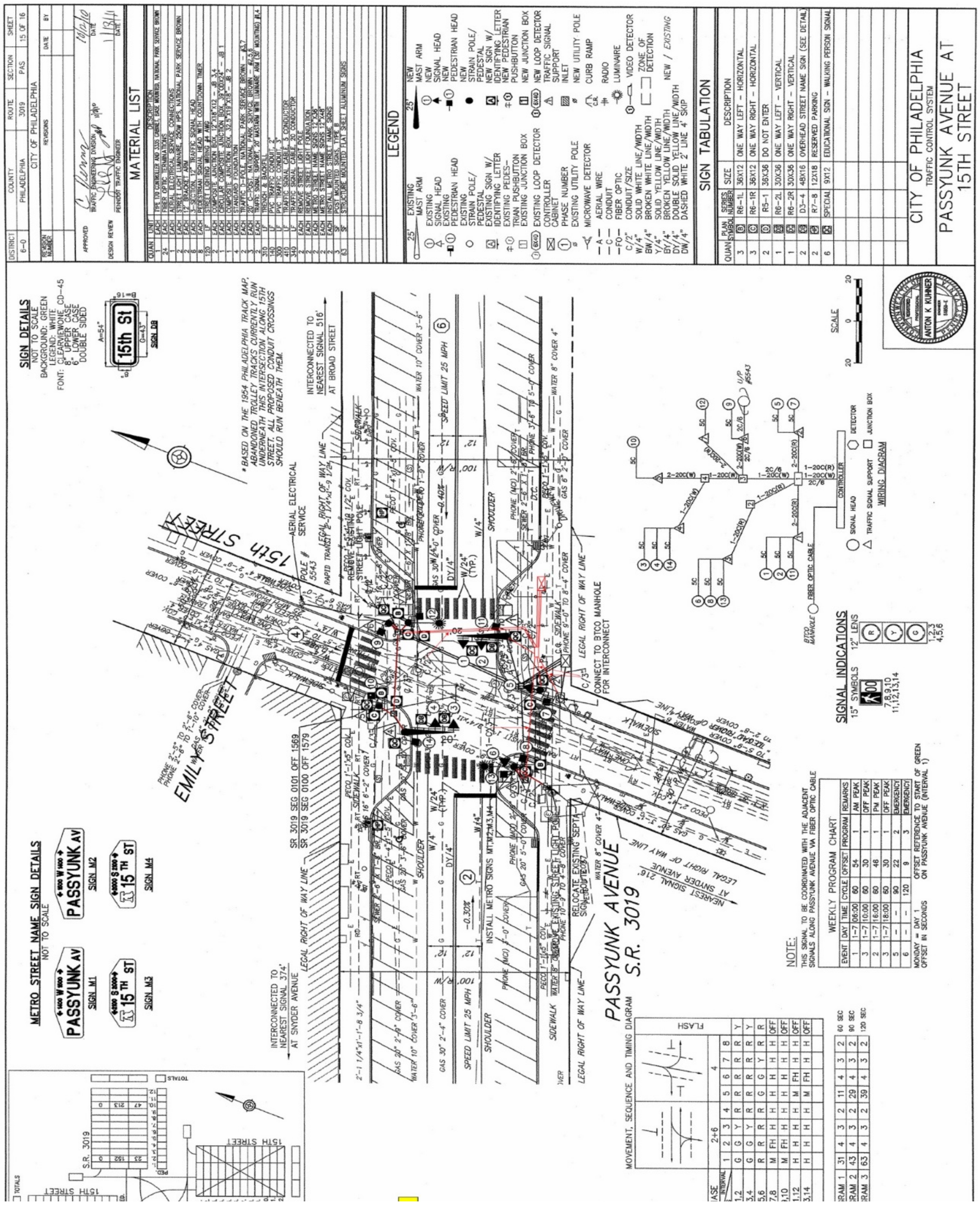
Cycle Track Intersection Approach	
Bicycle Signal heads	
Intersection Signage	

APPENDIX B: Sample of Microsoft Excel Cyclist Documentation Spreadsheet

C	D	E	F	G	H	I	J	K	L	M	N
)17											
r											
ur	15 minute interval	direction	As vehicle/bike lane	vehicle shoulde	As pedestri	As Pedestrian Contrafl	Wrong way in bike la	Red light run	clearance interval r	arrival colour	notes
	15	wbt	x							g	
	15	ebt	x							g	
	30	ebt	x							r	
	30	wbt	x							g	
	30	wbt	x					x		r	
	30	nbt		x				x		r	used box while waiting
	30	wbt	x							g	
	30	ebl	x(to)				x(from)			g	wrong way bike lane, lef to roadway nb
	30	wbt	x(to)		x(from)					g	switches through crossing
	30	ebt	x					x		r	
	30	wbt	x							g	
	30	nbt		x						g	
	30	wbt	x							g	
	30	ebt	x							r	
	30	wbt	x							g	
	45	ebt	x							g	
	45	nbl	x							g	
	45	nbr	x(to)		x(from)					g	switches through turn
	45	ebt	x							g	
	45	wbt	x					x		r	
	45	ebt	x					x	x	r	
	45	nbl	x							g	
	45	ebt	x							g	
	45	nbt		x						g	
	45	wbt	x							g	
	45	wbt	x					x		r	
	45	nbt		x(left)				x	x	r	
	45	ebt	x							g	
	45	ebt	x							g	
	45	ebt	x							g	
	45	ebt	x							g	
	0	nbt		x						r	used box while waiting
	0	wbt	x							g	
	0	nbt		x						g	
	0	ebt	x					x		r	
	0	ebt				x				g	
	0	ebt	x					x	x	r	
	0	wbt	x							r	
	0	wbr	x							g	
	0	ebt	x							g	
	0	nbt			x					g	walking bike. Switches from left side to right using crosswalks
	0	ebt	x							g	

APPENDIX C: Technical Drawing and Signal Timings

Intersection 1: S 15th St. & W Passyunk Ave.



Intersection 2: S 13th St & Snyder Ave.

WORK ORDER S11546

SIGNAL

Prepared by McCormick Taylor, Inc.

Approved by

12th Street & Snyder Avenue

Date 6/26/2015

Date 8/7/15

Work Completed By

Inspected By

Date 10-21-15

Date

Traffic Engineering District #1

Release date

CMAQ

#	Phase Movements	1	2	3	4	5	6	Flash
		4+8 Snyder Avenue			6 12th Street			
2								
5								
6	SB 12th Street	R	R	R	G	Y	R	R
1								
4	EB Snyder Avenue	G	Y	R	R	R	R	Y
7								
8	WB Snyder Avenue	G	Y	R	R	R	R	Y
3								
P2								
P6								
P4								
P8								
	Program 1	27.6	3.6	1.8	21	3.6	2.4	
	Percent	46%	6%	3%	35%	6%	4%	
	Dial Settings	46	52	55	90	96	0	
	Offset (%)	R1 = 98%						

Intervals

Minimums: G M FH

Extension

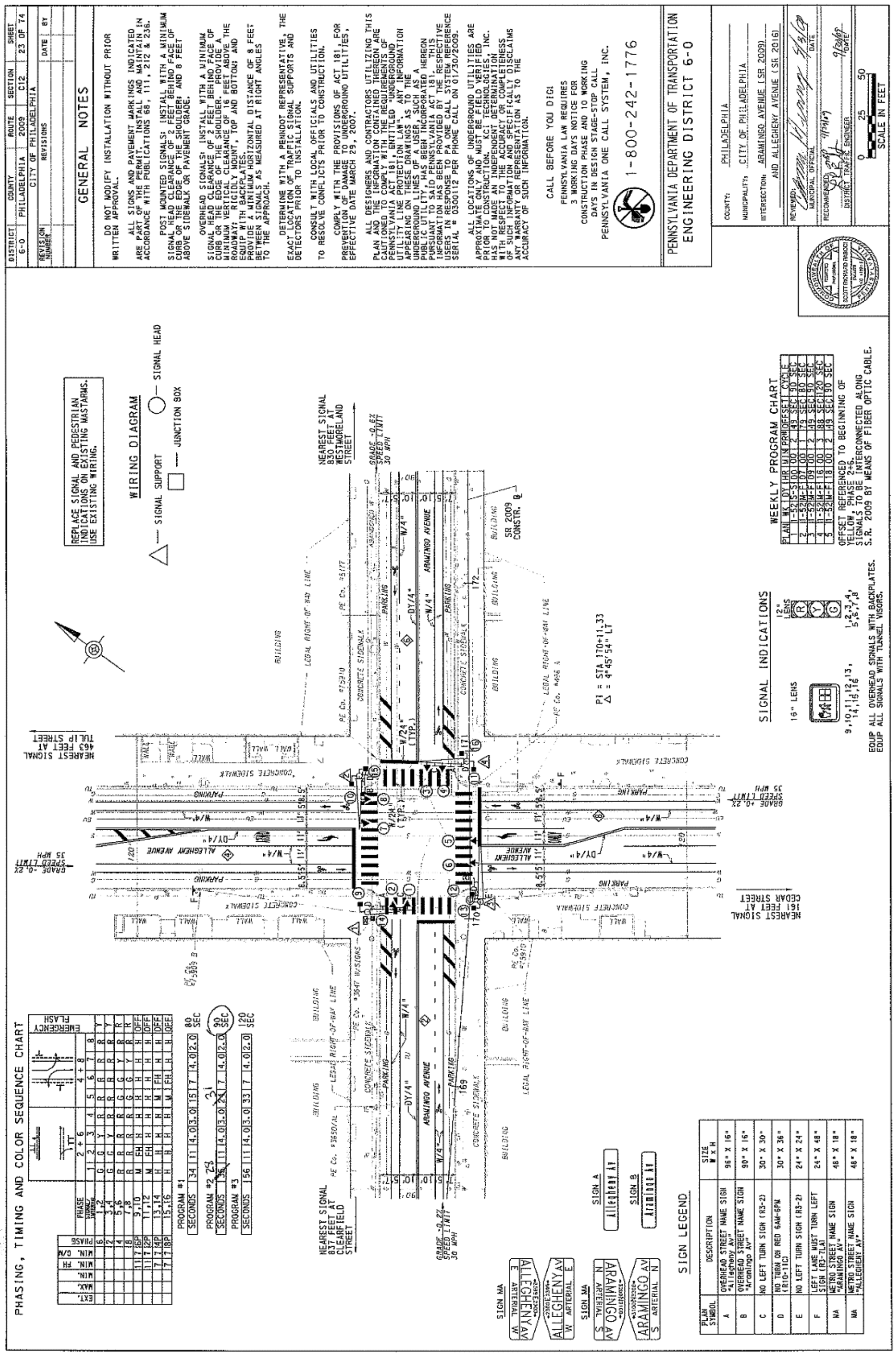
Maximums: G M FH

60 secs

100 %

Instructions: Install timings. Offset referenced to beginning of green, phase 4 + 8

Intersection 3: E Allegheny Ave & Aramingo Ave



Intersection 4: S 34th St and Chestnut St

ER

34th ST & CHESTNUT ST

Traffice Engineering District #3

Prepared by David Dlugosz

Approved by

Date 7/17/17

WORK COMPLED by

INSPECTED by

Date 8-4-17

Date

Release date

4 Chestnut — 6 34th

ʼhase vements	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	Flash	Minimums G	Minimums M	Minimums FH	Extension	Maximums G	Maximums M	Maximums FH
4th Street	R		R	R	R	G	G	Y	R								R							
stnut Street	G		Y	R	R	R	R	R	R								Y							
Chestnut	H		H	H	M	M	FH	H	H								OFF							
GRAM 2 n seconds)	47		4.2	1.8	3	20	8	3.6	2.4				90	second cycle										

Time of Day Plan

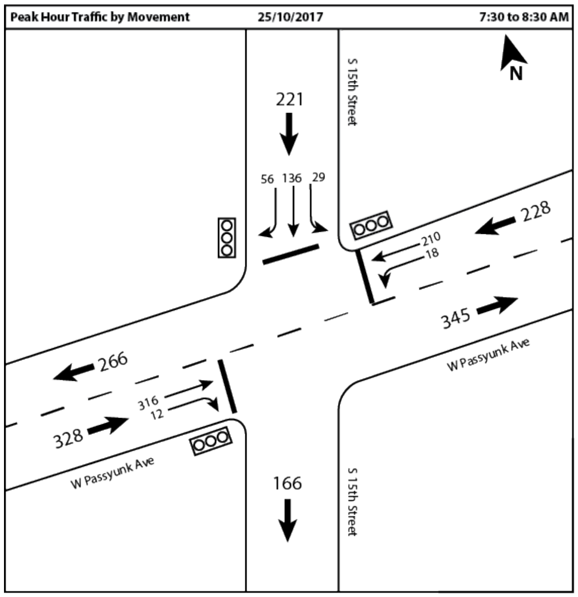
Time	Plan	Offse	Day
0:00	2	79	1-7

ructions: Change timings. Maintain LPI.
The coordinated phase is the end of the yellow interval of phase 4

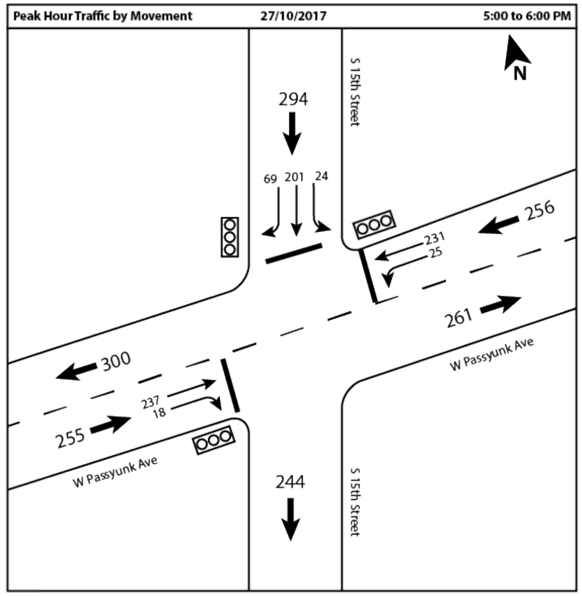
APPENDIX D: Turning Movement Diagrams

Intersection 1:

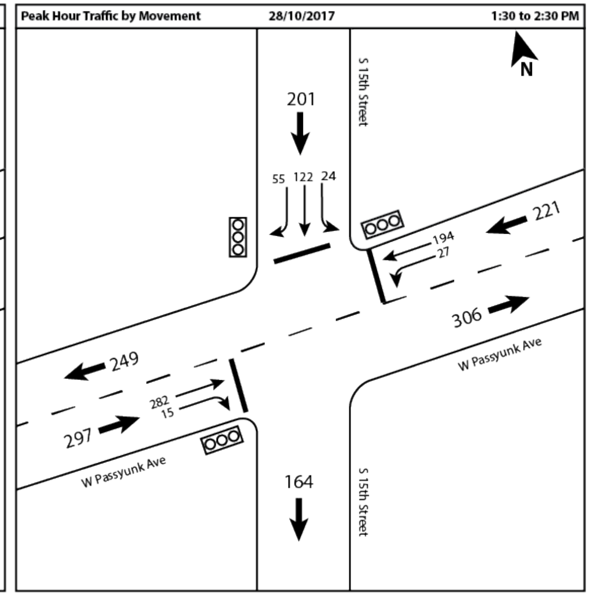
Weekday Morning Turning Movement Diagram



Weekday Evening Turning Movement Diagram

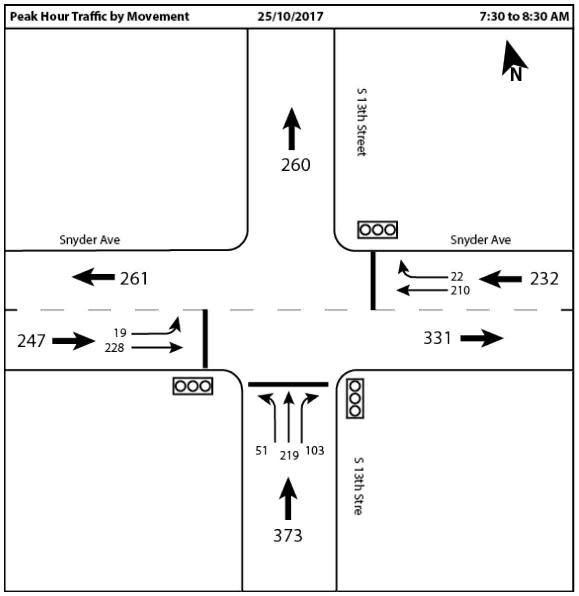


Weekend Afternoon Turning Movement Diagram

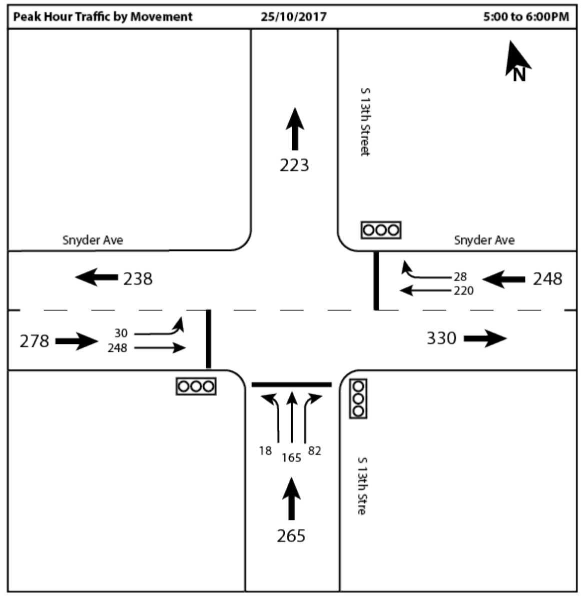


Intersection 2:

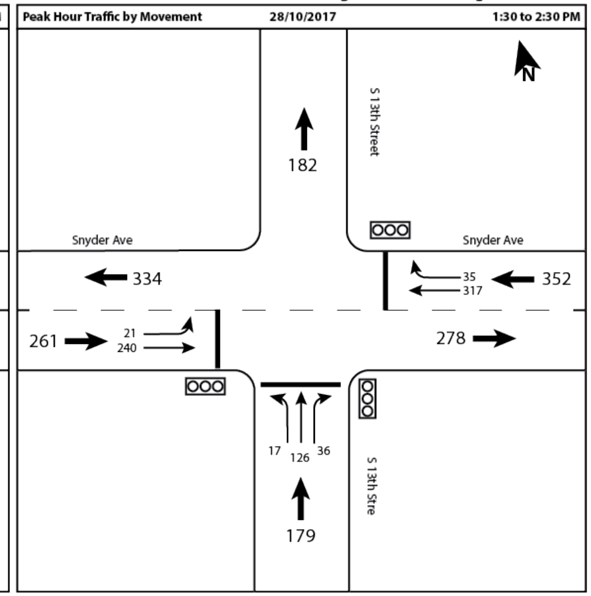
Weekday Morning Turning Movement Diagram



Weekday Evening Turning Movement Diagram

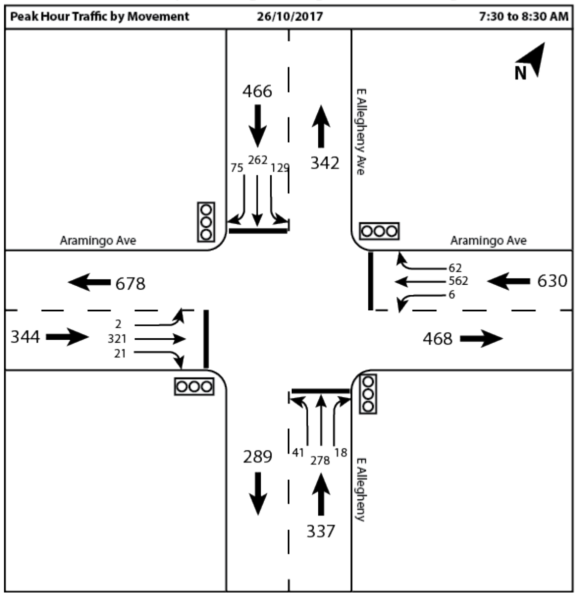


Weekend Afternoon Turning Movement Diagram

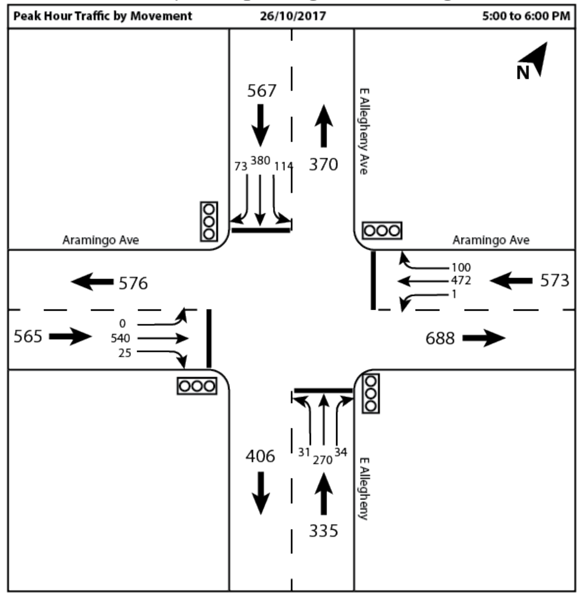


Intersection 3:

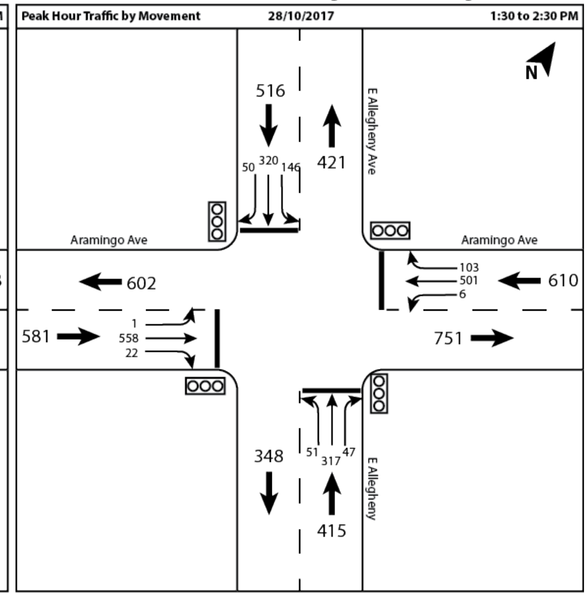
Weekday Morning Turning Movement Diagram



Weekday Evening Turning Movement Diagram

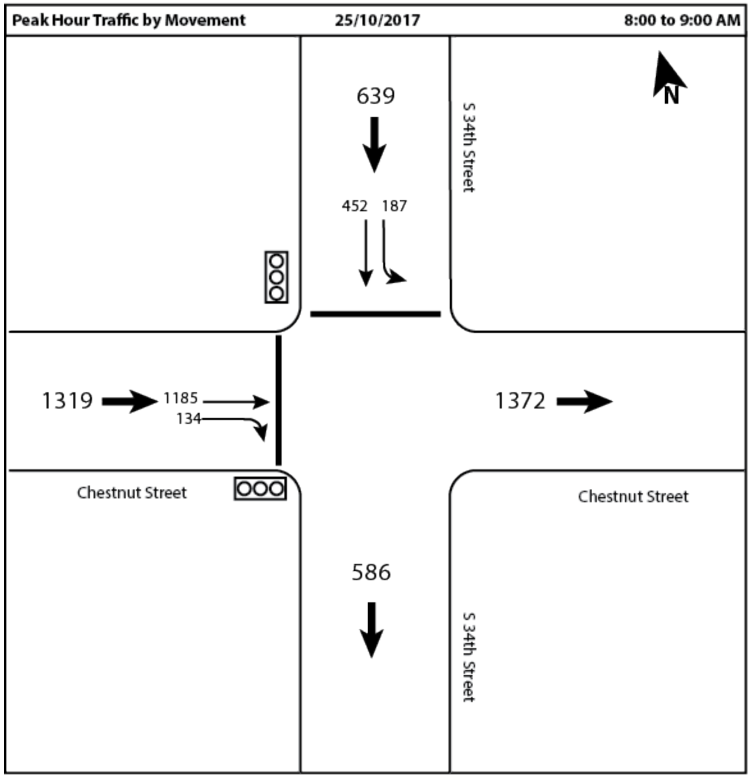


Weekend Afteroon Turning Movement Diagram

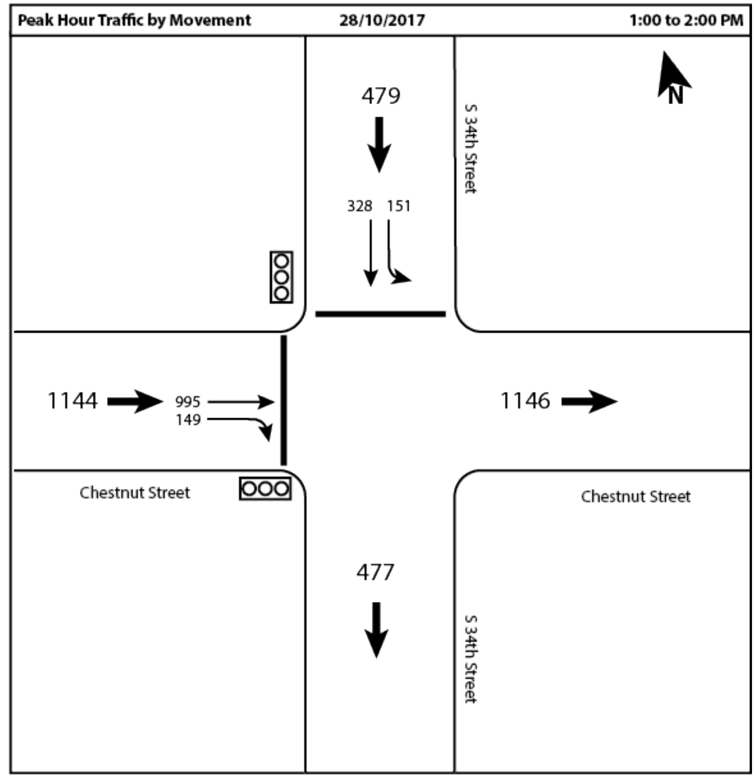


Intersection 4:

Weeday Morning Turning Movement Diagram

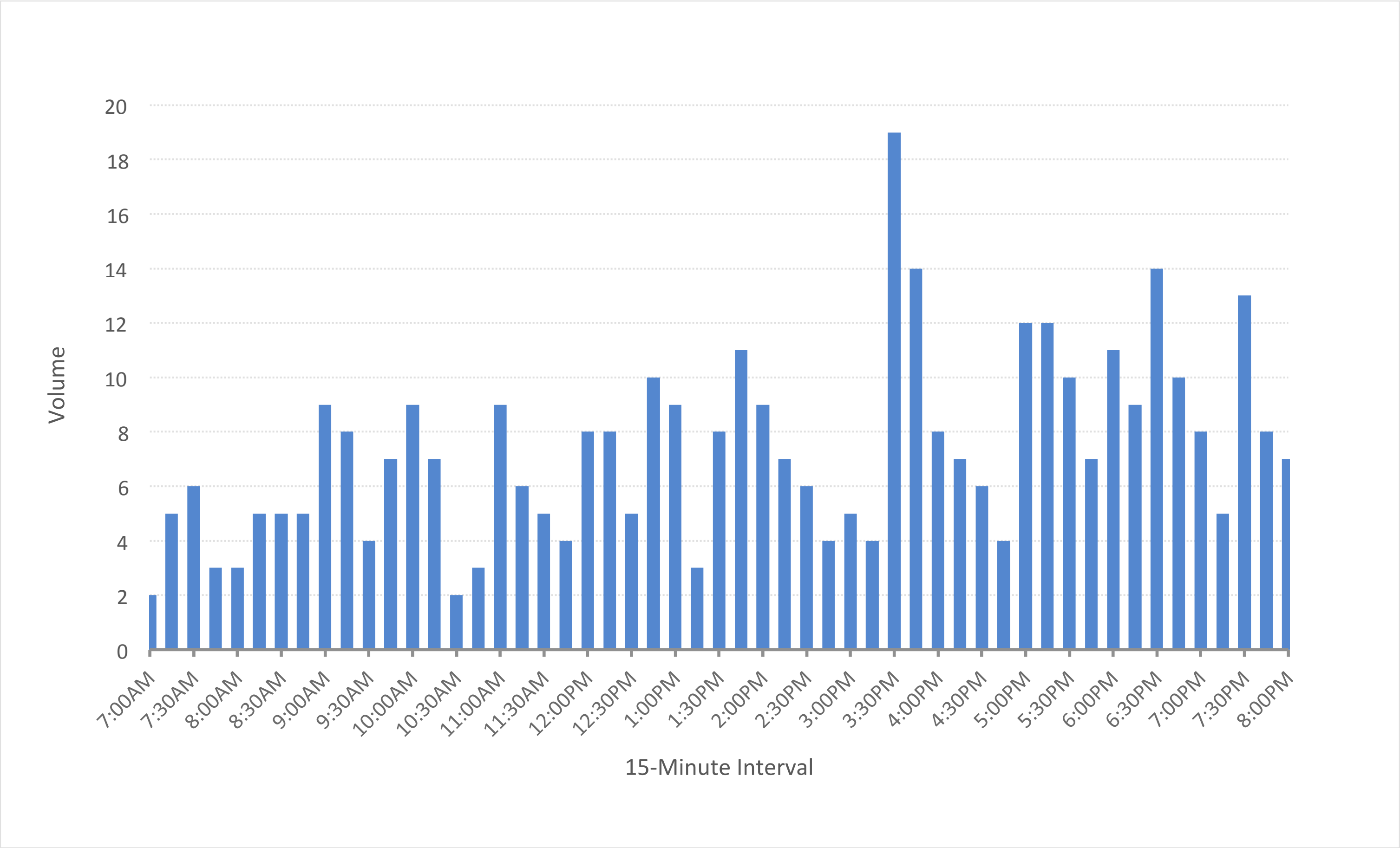


Weekend Afternoon Turning Movement Diagram

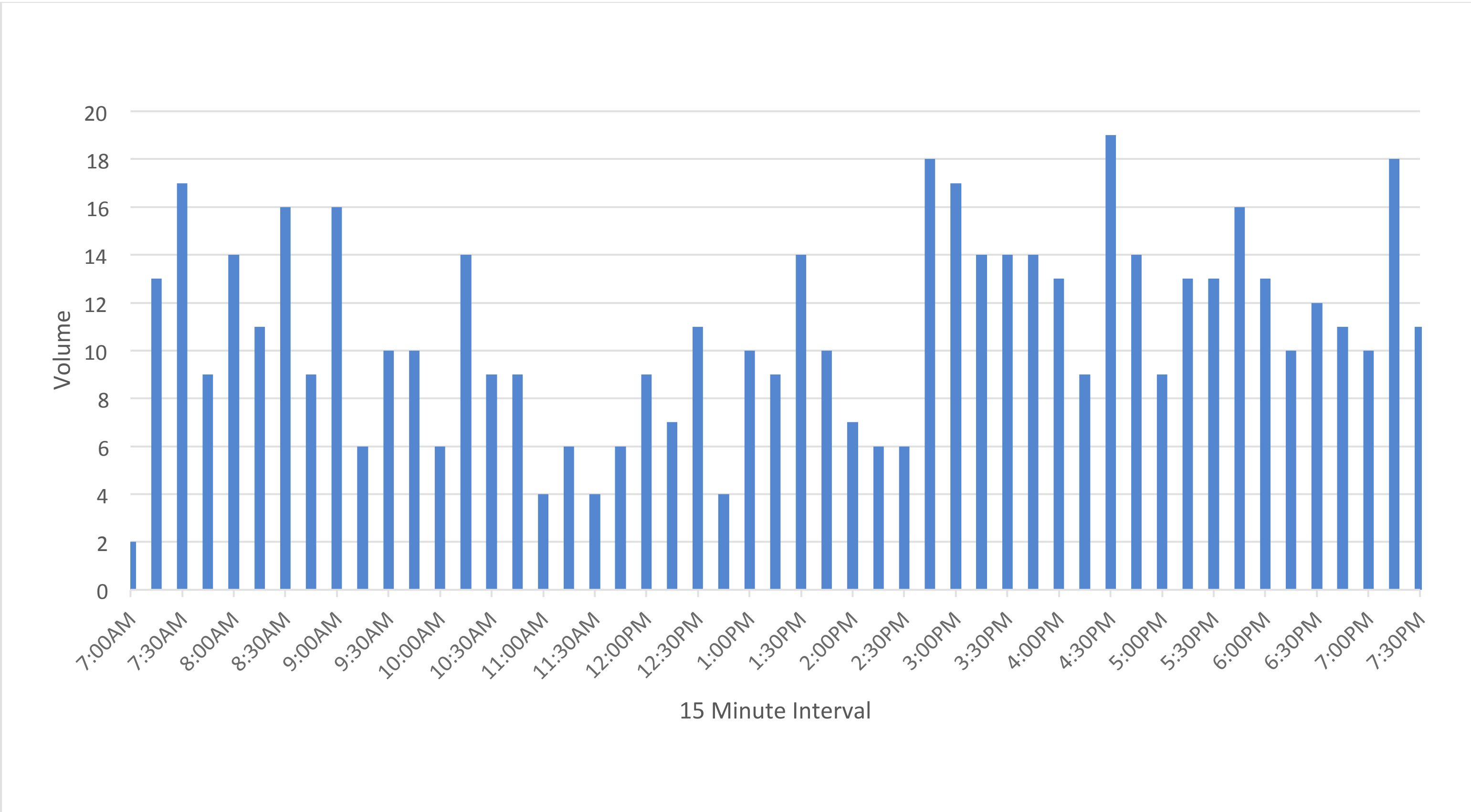


APPENDIX E: Sample Bicycle Volumes

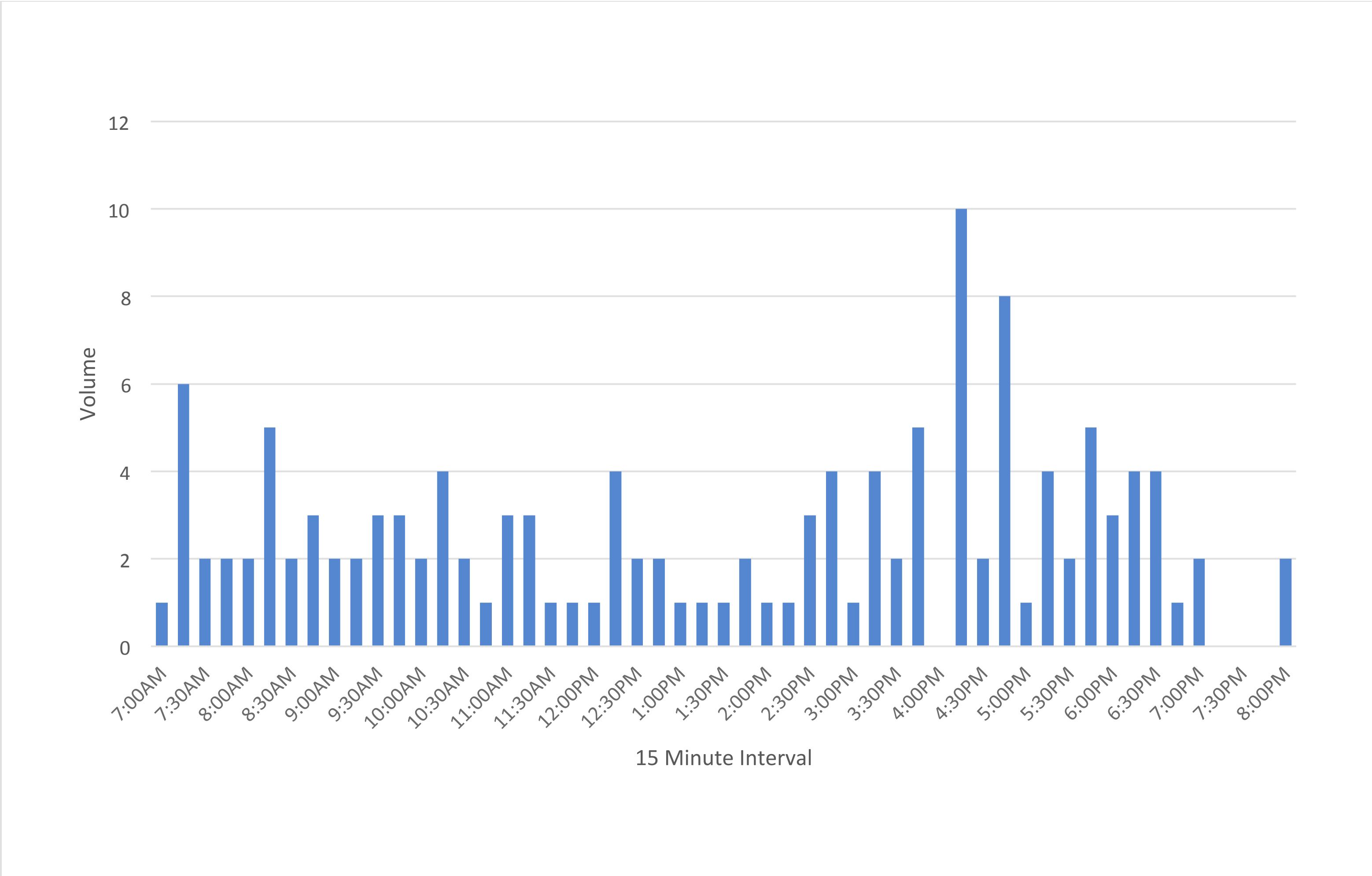
Intersection 1: Weekday Sample Bicycle Volume (All Directions)



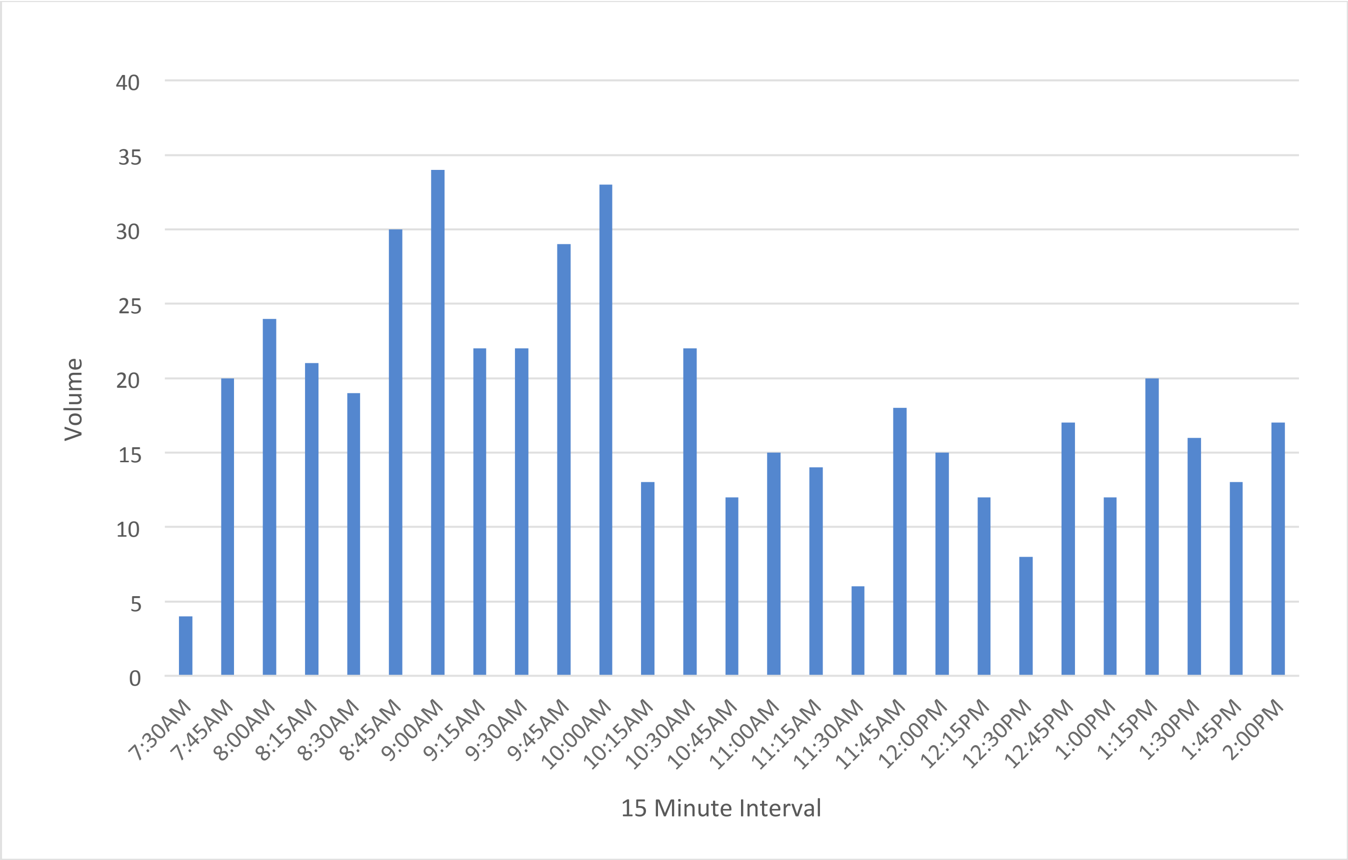
Intersection 2: Weekday Sample Bicycle Volume (All Directions)



Intersection 3: Weekday Sample Bicycle Volume (All Directions)

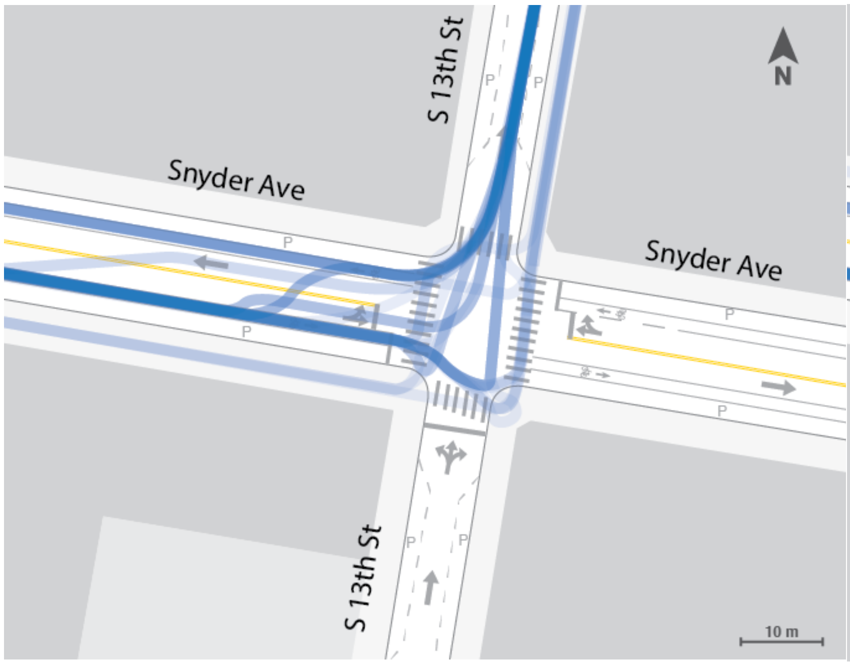


Intersection 4: Weekday Sample Bicycle Volume (All Directions)

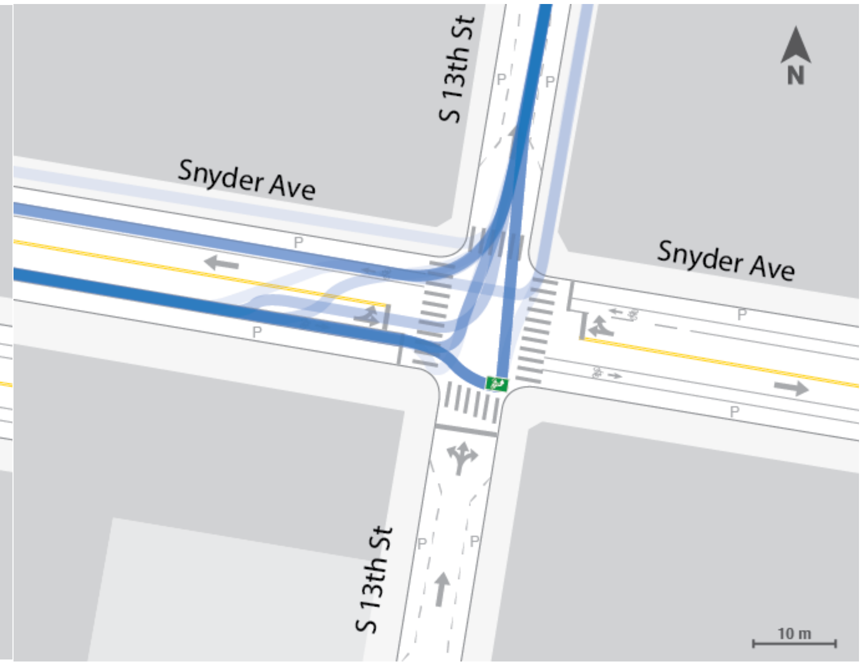


APPENDIX F: 13th St & Snyder Ave Before and After Side-by-side

Before

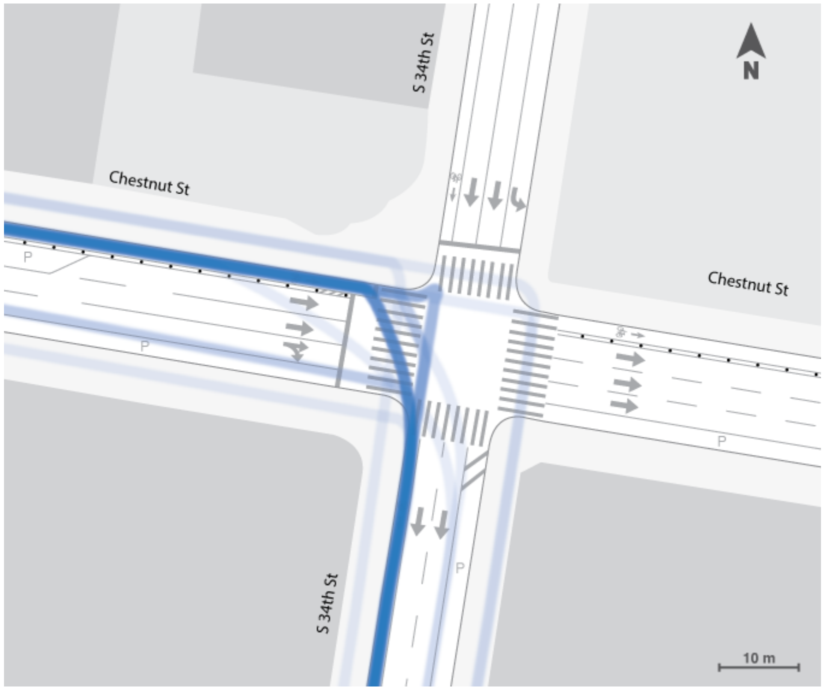


After

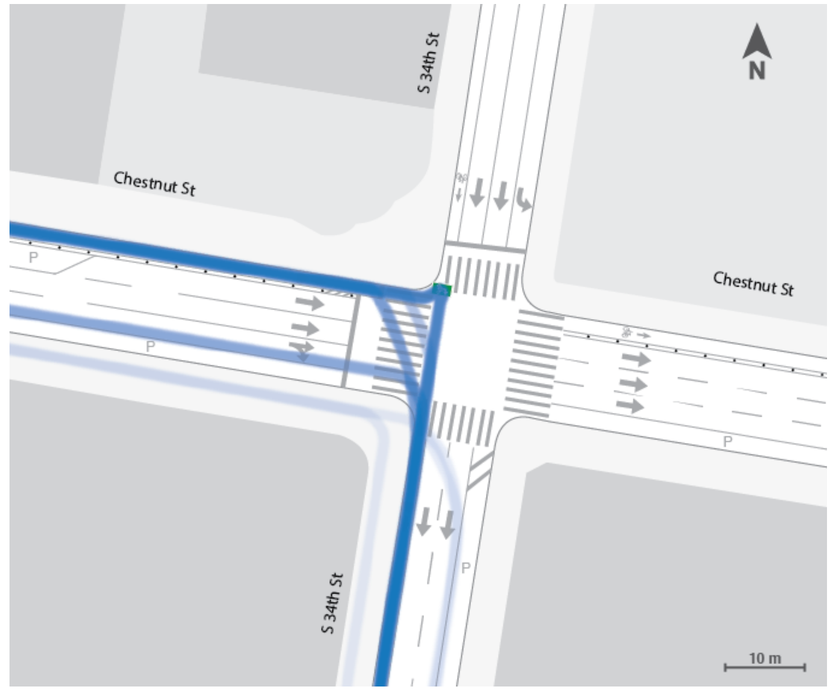


APPENDIX G: 34th St & Chestnut St Before and After Side-by-side

Before



After



Glossary of Terms

Bulb-out: Also known as a curb extension, bulb-outs are a traffic calming measure that extends the sidewalk to provide a shorter crossing distance for pedestrians at signalized intersections

Bicyclist OR *Cyclists:* A person operating a two or three wheeled human powered pedal bicycle.

Bph: Bicycles per Hour

Car OR *auto* OR *motor vehicle*: A motor vehicle which requires a license and insurance to operate on public roads.

Carriageway: part of the road intended for vehicles, opposed to pedestrians

CBD: Central business district

Desire Line: A preferred route or path that is easiest to navigate, often apparent for being more direct.

Line of sight: The visible unobstructed distance from between a subject and an object.

Mode share: The proportion of people using a particular mode of transportation. For example, stating that 15% of trips are made by bicycle means that the mode share of bicycles is 15%.

NACTO: National Association of Transportation Officials.

Red light running: When a vehicle proceeds through an intersection on a red light when the law does not permit.

Road-space position: The position of a bicyclist in the carriageway

Signal phase: The pattern or organization of controlling traffic flow, commonly controlled with green, amber and red lights. Simple signal phase design have two phases, for example, one to permit east-west travel, then another to permit north-south travel.

Trip: The act of moving from one place to another.

Vph: Vehicles per Hour