

Bicycle Infrastructure Safety: A Review and Application of the Case-Control Methodology

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Abstract

Bicycle Infrastructure Safety: A Review and Application of the Case-Control
Methodology

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As of 2013 the City of Seattle has 44 miles of bike lanes installed on city roadways. The 2014 Seattle Bicycle Master Plan calls for many new miles of bike lanes, cycle tracks, and neighborhood greenways. This report examines the safety of each type of infrastructure and evaluates the pros and cons of the case-control methodology as a tool for determining the risk of bicycle-motor vehicle collisions. It is important to understand the safety implications of each type of infrastructure so that the City of Seattle can make informed decisions when planning for the bicycle network.

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1. Introduction

Purpose of the Study

Does a bicyclist traveling on an arterial with a bike lane have a lower risk of collision with a motor vehicle than a bicyclist traveling on an arterial without a bike lane?

What are the advantages and disadvantages of using a case-control research method for evaluating the safety of bicycle infrastructure? Seattle's bicycle master plan calls for 403.5 new miles of bicycle infrastructure. Bike lanes, referred to as in street, minor separation facilities in Seattle's Bicycle Master Plan, account for 75.6 miles of proposed new infrastructure. Forty-four miles of bike lanes are already installed (City of Seattle 2013). This study was conducted to determine if biking on bike lanes is more or less safe for cyclists than biking on roads without bike lanes, and to evaluate the use of the case-control method to assess the risk of collisions occurring between cyclists and motorists given different bicycle facilities. A secondary purpose of the paper is to determine the relative safety of cycle tracks and greenways. If bike lanes increase risk of a cyclist colliding with a motor vehicle, than Seattle should focus their efforts and finances into different solutions, such as neighborhood greenways and cycle tracks. If bike lanes have a lower risk of collision than arterial roads without bike lanes, bike lanes may be a good investment for Seattle.

A focus on infrastructure is important because it is something that city governments can control. Behavior of road users may be influenced by education and outreach efforts, but part of the problem with bicycle-motor vehicle crashes is the infrastructure. Some bicyclists may behave like cars, some may behave like pedestrians, and some may switch between the two. This can confuse motorists who

are used to very clear rules of the road and behaviors by other motorists. In reality, bicycles are neither motor vehicles nor pedestrians, so properly designed bicycle infrastructure can help decrease the conflicts between bicyclists and other road users.

2. Trends in Bicycling in the U.S. and Seattle

Bicycling as a mode of transportation has been on the rise in North American in the past decade, with almost twice as many bike commuters in 2009 as 2000 (Pucher, Buehler and Seinen, 2011). Seattle has followed this trend, with a 92% increase in bicyclists riding into downtown during commuting hours from 2000 to 2011 (1,737 bicyclists vs. 3,330) (Seattle Department of Transportation 2014), and a 4.7% increase in people bicycling to work from 2011 to 2013 (Seattle Department of Transportation 2012, 22). According to the 2012 American Community Survey, 4.1% of workers in Seattle age 16 and over used a bicycle as their primary commuting vehicle, and many Seattle census blocks have over 5% of the population commuting by bicycle (U.S. Census Bureau 2012). A few census blocks even have over 10% of residents that commute by bicycle. City-wide bicycle commuting rates are shown in Figure 1.

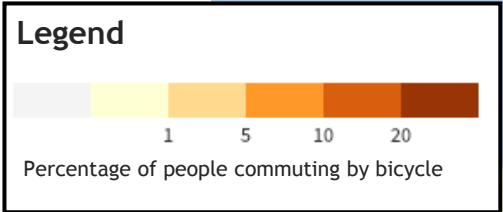


Figure 1: Percentage of bicycle commuters by census block (Census Explorer, Commuting edition 2012)

Biking is beneficial to the environment and promotes healthy activity levels. The 2008 Seattle Community Greenhouse Gas Inventory estimates that 40% of citywide greenhouse gas emissions are caused by road transportation. Seattle residents who choose to switch from driving to bicycling as a mode of transport, even for a few trips, can help reduce this number. In addition to environmental benefits, biking has many health benefits resulting from increased physical activity (de Hartog, et al. 2010). Recommended daily physical activity levels can be met by biking for transportation (Dill 2009), and biking can be an enjoyable form of commuting that avoids traffic congestion. Because of these benefits, bicycling is a mode of transport that should be encouraged.

3. Types of Bicycle Infrastructure

Seattle's 2014 Bicycle Master Plan focuses on five types of bicycle facilities. Those are:

- Shared street (sharrows)
- In street facilities with minor separation (bike lanes)
- Neighborhood greenways
- Cycle tracks
- Off-street facilities

This section will briefly define each type of facility.

Sharrows

Sharrows are markings on the pavement that alert motorists that bicycles may be present.

Sharrows are only painted on to the pavement that reinforces the existing laws that allow bicycles to use any roadway.



Figure 2: Sharrow. Courtesy of streetsblog.org

Bike Lanes

Bike lanes give people on bikes a dedicated lane to ride in, as shown in Figure 3. The National Association of City Transportation Officials (2012) defines a bike lane as follows:



Figure 3: Bicycle Lane. Courtesy of the National Association of City Transportation Officials.

“Bike lanes designate an exclusive space for bicyclists through the use of pavement markings and signage. The bike lane is located adjacent to motor vehicle travel lanes and flows in the same direction as motor vehicle traffic. Bike lanes are typically on the right side of the street, between the adjacent travel lane and curb, road edge, or parking lane.”

Buffered bike lanes provide an extra buffer between the bike lane and the general travel lane. The National Association of City Transportation Officials recommends a minimum buffer width of 18 inches. The buffer does not provide a physical barrier between a bicyclists and motor vehicle traffic, but the extra space allows for a more comfortable distance to be maintained between the two.



Figure 4: Buffered Bike Lane. Courtesy of Seattle Department of Transportation

Figure 5: Cycle Track on Broadway in Seattle

Cycle Tracks

Cycle tracks may be one-way or two-way. The main feature of cycle tracks is that they are separated from moving motor vehicle traffic by a physical barrier, such as bollards, curbs, or planters. Cycle tracks generally have a dedicated traffic signal, which reduces the risk of conflict with motor vehicles.

Neighborhood Greenways/Bicycle Boulevards

Greenways, or bicycle boulevards, are also increasing in popularity. In Seattle, community groups have been advocating strongly for the installation of greenways. This report will use the term



greenways, as that is the term

Figure 6: NW 58th St. Greenway arterial crossing at 24th Ave NW in Seattle.

used in Seattle. Greenways are local streets that have been prioritized for non-motorized travel. Low traffic volumes, traffic calming measures, and safe arterial crossings are common features of greenway corridors.

Off-Street Facilities

Off-street facilities are two-way paths that are sometimes shared with pedestrians. In Seattle, these paths often follow the shoreline or an old railroad right of way, with minimal crossing motor vehicle traffic.



Figure 7: Shared Use Path (Burke-Gilman trail, Seattle)

Biking Infrastructure in Seattle

Seattle has been accommodating the increased number of people bicycling with several different types of infrastructure, though bike lanes are the most prominent. According to the 2013 Seattle Bicycle Master Plan, Seattle currently has 44 miles of bike lanes, 33% of the overall network. When proposed additions recommended in the plan are completed, bike lanes will account for 23% of the overall network. Complete mileage totals are show in Table 1 and a map of the existing network is shown in Figure 8 (Seattle Department of Transportation 2014, 23).

Table 1: Existing and Proposed Seattle Bicycle Network (lengths in miles)

	Existing Network*	Proposed Network Improvements			Total Network	Percent of Total Network
		Upgraded to Existing Bicycle Facilities	New Facilities	Total New or Upgraded Facilities to Build		
Off Street	46.9	0	32.0	32.0	78.9	13%
Cycle Track (protected bicycle lane)	3.2	52.1	49.5	101.6	104.8	17%
Neighborhood Greenway	10.3	0	238.6	238.6	248.9	41%
In Street, Minor Separation	44.4	17.9	75.6	93.5	137.9	23%
Shared Street	30.0	0	7.8	7.8	37.8	6%
Total	134.8	70.0	403.5	473.5	608.3	100%

*Existing network totals include only existing facilities that meet the bicycle network facility designation guidelines or, in some cases, where right-of-way is limited and a higher-quality facility could not be implemented.

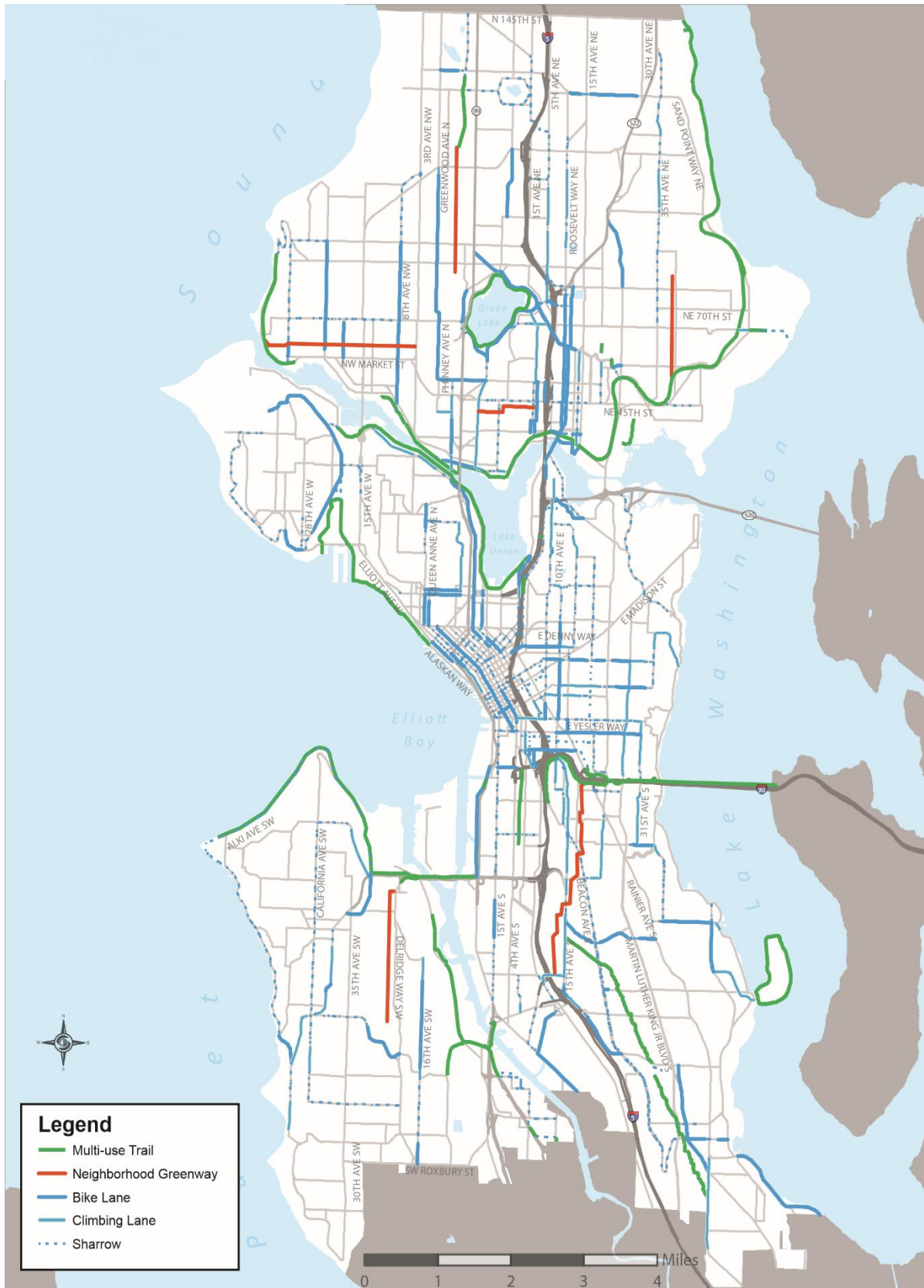


Figure 8: Seattle Existing Bicycle Facilities as of 2013 (Seattle Department of Transportation 2014)

Seattle has just recently started recommending and installing cycle tracks on arterial roadways and greenways on non-arterials. There are six existing greenways, and plans for six more in 2014, in addition to two existing cycle tracks with plans for 100 additional miles (Seattle Neighborhood Greenway Work Plan 2014). Most previous efforts have been focused on sharrows or bike lanes.

4. Previous Research on Bicycle Infrastructure Safety

The main issue facing researchers focusing on bicycle infrastructure is accurate bicycle volume counts. If bicycle counts are not accurately recorded, results will be skewed. Temperature, precipitation, time of year, and time of day all have an impact on bicycle volumes. Precipitation and lower temperatures tend to lower bicycle volumes, and there are more bicyclists in summer months. Time of day matters as well. Morning peak commuting hours gives a good count of commuter cyclists, while the PM peak period includes utility cyclists as well as recreational cyclists. (Niemeier 1996). Bicycle volumes are important to determine the rate of crashes, which is the number of crashes over a period of time divided by the number of bicyclists. For example, 32% of recorded bicycle-motor vehicle collisions in 2013 occurred on bike lanes (Seattle Department of Transportation 2013). Given that bike lanes account for less than 3% of total roadway miles in Seattle, it would seem that bike lanes are very dangerous. However, bike lanes attract bicycle riders (Lott, Tardiff and Lott 1978), so the rate of crashes on roadways with bike lanes may actually be less than other roadways. In addition, bike lanes in Seattle are only installed on arterial streets, which have higher speeds and traffic volumes than local streets, which may account

for the higher number of crashes. Therefore, most research on bicycle safety must include primary data collection for bicycle volumes. Research must be carefully reviewed to make sure that bicycle volumes are accounted for and adjustment for. In addition, confounding factors such as motor vehicle speeds and volumes should be taken into account. Motor vehicle speeds and volumes are usually readily available from the local department of transportation.

The literature review will consider bike lanes, cycle tracks, and greenways, since these features account for 81% of the bicycle facilities in the proposed 2014 Seattle Bicycle Plan. (Seattle Department of Transportation 2014, 40).

Bike Lane Safety

Bike lanes provide space on the roadway dedicated solely to bikes, and bicyclists prefer roads with bike lanes to those without (Tilahun, Levinson and Krizek 2007). However, there are safety hazards associated with bike lanes. Motor vehicle drivers often turn right across the bike lane into bicyclists, in a type of collision known as a “right hook,” illustrated in Figure 9: Right hook. Courtesy of bicycling.com. This occurs when vehicle drivers either misjudge the speed of the bicyclists or do not see them.

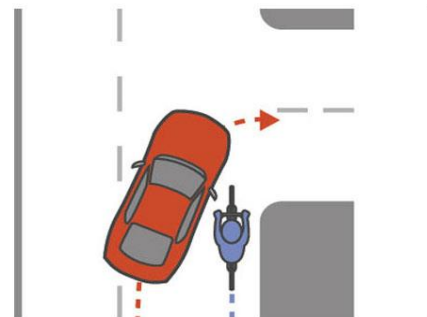


Figure 9: Right hook. Courtesy of bicycling.com

Another common type of collision is known as “dooring”, in which someone exiting a parked car opens a door in the path of an oncoming bicyclists, as illustrated in Figure 910.



Figure 10: Cyclist in the door zone. Courtesy of BikeWalk Tennessee.

NAACTO recommends a width of 6 feet and wider if possible, for bicyclists’ comfort and side-by-side riding. The Seattle right-of-way improvements manual requires a minimum of only 5 feet wide bike lanes, 4 feet if not adjacent to parking. But with smaller widths, a bike lane may not even be wide enough for the bicyclists to ride outside of the “door zone”, the area in which a car door would open and impede upon the bike lane. Recommended solutions for this issue are driver education and designing bicycle facilities that keep cyclists away from the door zone (Johnson, et al. 2013). Fatalities can occur in this type of crash, especially if the bicyclist swerves to avoid the door or hits the door and gets knocked into oncoming traffic.

To address the dooring issue, bike lanes must be installed with enough room for the bicyclist to clear the door zone. Seattle has installed a few buffered bike lanes, such as those on Dexter Avenue, that provide enough space for the cyclist to ride outside the door zone. The buffered zone also provides increased distance from passing motor vehicle traffic, which can increase the comfort level of the cyclist.



Figure 11: Buffered bike lane on Dexter Ave in Seattle. Courtesy of SDOT.

A 2009 review of previous research found that, in five studies, on-road marked bike lanes had a positive effect on safety, reducing collision frequency by approximately 50% compared to roadways with no bike lanes. One study found an increase in collision rates on roads with bike lanes the year after installation, but after that year the collision rates were not significantly higher than before the installation. (Reynolds, et al. 2009). The increase in collision rates in the initial year after installation is likely because road users were getting used to the new configuration of the road, which suggests education and outreach should accompany road redesigns.

A thesis project by a student at the University of Washington studied crashes in downtown Seattle between 2007 and 2009. A correlational study was used to determine if the presence of a bicycle facility influenced the number of bicyclists or the number of collisions on a particular corridor. Bicycle volume counts in this study were not precise, as a mile-long corridor was studied, but bicycle volumes were only counted at one point in the corridor. Volumes near the actual crash site may be higher or lower than at the count location. The study found that bike lanes were correlated with an increase in bicyclist volume and a decrease in the rate of crashes (Rose 2011).

However, not all research suggests bike lanes make cyclists safer. A study in Palo Alto, CA, did not find any significant difference in crash risk between roadways with bike lanes and those without (Wachtel and Lewiston 1994). A subset of the biking population, “vehicular bicyclists,” do not think that bicycle lanes make the road safer for bicycles, and they prefer to ride with traffic in the roadway. One prominent

vehicular cycling advocate, John Forester, sees bike paths as a “smokescreen for those motorists and highway officials who don’t want cyclists on what they consider to be their roads” (Forester 2012), and stresses that bicycles should ride in the middle of the travel lane so that motorists will see them and react in a safe manner.

Forester’s book, relying on three studies done between 1975 and 1980, lists the main causes of car-bike collisions as cyclists’ failure to yield to crossing traffic, wrong-way cycling, and sidewalk cycling. Recent bicycle facility design guidelines attempt to compensate for the issues discussed by Forester, and more current studies analyzing modern bicycle infrastructure show that cycle tracks and bike lanes are slightly safer than roads with no bicycling infrastructure.

One of the most comprehensive studies on bike lane safety was done by the Federal Highway Administration (FHWA), which published a Pedestrian and Bicycle Intersection Safety Index report in 2006. This report analyzed many intersections, cataloging actions of motor vehicle drivers, bicycle riders, and pedestrians. The FHWA formulated a safety index for bicyclists at intersections, taking into account parking, presence of a bike lane, number of motor vehicle lanes, average daily traffic, speed limits, and presence of traffic controls. The safety index is a tool for municipalities to use to rate intersections. A higher index means that an intersection is less safe, and the municipality should focus its efforts on intersections with high safety indices. The report did not analyze roads that were greenways or had cycle tracks. The safety index on two roads which were both two lanes, both without parking, but one road with a bike lane and one without, the road without the bike lane had a slightly higher safety index for straight through intersection movements. For a bicyclist making a left

turn, however, the road with the bike lane was more dangerous (Federal Highway Administration 2006). Adding on-street parking into the equation made bike lanes even more dangerous for left-turn movements on a road with a bike lane. The safety index for bicyclists traveling straight through the intersection showed a slight improvement with bike lanes. Table 2 shows a comparison of the safety indices as calculated by the FHA for a two lane road with 20,000 ADT (Average Daily Traffic) intersecting a two lane road with an ADT of 15,000 at a signalized intersection. Lower numbers indicate a lower risk of bicyclist-motor vehicle collision.

The study results show that parking makes each situation slightly more dangerous, which matches a Canadian study that found that major streets with bike lanes and parked cars had an odds ratio (chance of injury over a baseline) of 0.69, versus an odds ratio of 1.00 (the baseline) for the same type of street without a bike lane (Teschke, et al. 2012). A major street without parked cars and no bike infrastructure was even safer than the street with parked cars and bike lanes, with an odds ratio of 0.63. A major street without parked cars and with bike lanes had an odds ratio of 0.54. Table 2 summarizes the results of both studies.

Table 2: FHA Safety indices on similar streets at signalized intersections and the odds ratio calculated by Teschke et. al.

	<i>FHA Safety Index</i>			<i>Odds Ratio (Teschke) Baseline is major street with no parked cars and no bike lane.</i>
	Through	Right Turn	Left Turn	
With a bike lane, no parking	2.2	1.9	2.9	0.54
Without bike lane, no parking	2.9	1.9	2.1	0.63
With bike lane, with parking	2.4	2.1	3.1	0.69
Without bike lane, with parking	3.1	2.1	2.3	1.0

Cycle Tracks

Cycle tracks have been gaining popularity in the U.S. in recent years. In the past year, Seattle has installed two two-way cycle tracks. One 0.8 mile segment was installed on Linden Avenue N., and one 1.2 mile segment on Broadway. These types of infrastructure have been used with success in European countries, which have much lower rates of crashes overall (Pucher and Dijkstra 2000). Cycle tracks have been used in North American in New York City, Washington D.C., and Montreal. Cycle tracks can be either one-way or two way. The defining feature of a cycle track is that they are separated from moving motor vehicle traffic with a physical barrier (parked cars, bollards, and curbs have been used).

Cycle tracks had the lowest risk of injury in Teschke's study. The study included a survey of bicyclists' preferred routes to gauge the risk of injury versus bicyclists' preferred routes. Results from the study are shown in Figure 12.

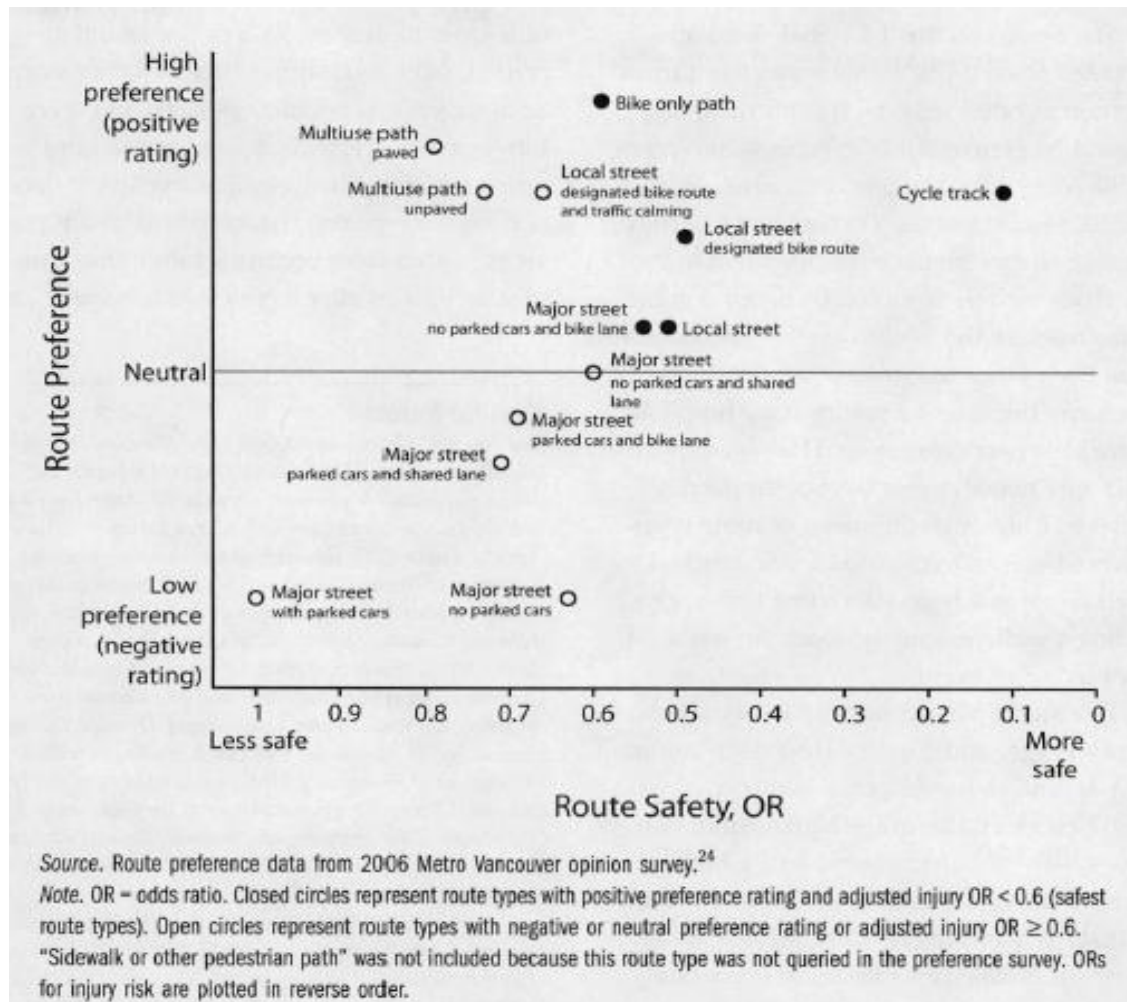


Figure 12: Route preference and risk of injury (Teschke, et al. 2012).

Another Canadian study that examined cycle tracks in Montreal found that cycle tracks have a reduced risk of injury compared to parallel routes without cycle tracks. The study analyzed sets of similar, parallel streets, one with a cycle track and one without. The cycle tracks in this Canadian study are two-way, similar in design to the cycle tracks recently completed in Seattle on Linden Ave. N and Broadway. A recent U.S. study analyzing crash rates on both one-way and two-way cycle tracks found them to be safer than bicycling on roadways (Lusk, Furth, et al. 2011).

A Belgian study found that right-of-way intersections with cycle tracks had a high accident risk for cyclists, likely because of motorists' failure to yield right of way. The study did not directly account for bicycle volumes by collecting primary data at the sites, but rather used a bicycle traffic index calculated using census data on the number of inhabitants reporting that they cycle. This model did not take into account the preference of bicyclists to choose paths including bicycle infrastructure, which could cause significant error in the results.

A study in Palo Alto found that riding in bike paths adjacent to the road was more dangerous than riding on the roadway, which conflicts with the Canadian studies (Wachtel and Lewiston 1994). Part of the reason for the conflicting results from different studies may be the design of the bicycle facility. The Palo Alto study collected data from 1985-1989, the Teschke study was done in 2008 and 2009, and the Montreal study used data from 1999-2008. Cycle track design has evolved in the past decade. The American Association of State Highway and Transportation Officials (AASHTO) guides for bicycle facilities published in 1974, 1981, 1991, and 1999 did not endorse for cycle tracks (Lusk, Morency, et al. 2013). More recently, in 2011, the National Association of City Transportation Officials (NACTO) released an Urban Bikeway Design Guide that endorses and provides guidance for the design of cycle tracks. The cycle tracks assessed in the Palo Alto study have key differences from the cycle tracks in the two Canadian studies. The cycle tracks in the Canadian study are designed specifically for use of bicyclists only, not pedestrians. The bicycle paths studied in Palo Alto were sidewalks signed for bicycle use, but they were not bicycle-specific infrastructure. They were designed as sidewalks, not the modern definition of

cycle tracks. The sidewalks had many obstacles, such as pedestrians, driveways, and blind intersections that may have contributed to the increase in crash risk compared to roadway riding. In Palo Alto's Bicycle + Pedestrian Transportation Plan prepared by Alta Planning + Design, the distinction is made between sidewalk riding and newer facilities that are recommended in the plan. The difference in level of design is clear in Figure 13. If design standards concerning signal controls, signage, and markings are followed, cycle tracks can be made safer than sidewalk riding. Future research must be clear in defining the exact type of infrastructure to be studied. The National Association of City Transportation Officials has developed a guidebook for identifying types of bicycle infrastructure. Research projects should match the definition of studied infrastructure to the NACTO guide.



Figure 13: Sidewalk riding and cycle tracks, City of Palo Alto

Neighborhood Greenways

One method that has gained popularity in Seattle and Portland in the last few years is greenways, also called bicycle boulevards. This type of infrastructure utilizes existing local, low speed and low traffic roads prioritized for bicyclists. Traffic diverters and speed calming measures are used to lower the motor vehicle volumes and speeds so that bicyclists can comfortably use the road. Crosswalks or signalized crossings are added at arterial crossings to improve safety. Since this type of infrastructure is relatively new in the United States, not much research has yet been done on its safety. Since we know that lower motor vehicle speeds reduce the severity of a collision (Kim, et al. 2007), and that local streets are generally safer (Teschke, et al. 2012) and more preferred by bicyclists than major streets with bike lanes (Winters n.d.), we can estimate that greenways could be a safe and popular type of infrastructure. The limited amount of research published on the subject has indeed shown positive safety effects. Traffic calming measures on local roads in Europe significantly reduced all traffic accidents (Pucher and Dijkstra 2000, 21), and a study in Berkeley found a significantly lower rate of bicycle collisions on traffic calmed, bicycle-prioritized streets than on parallel arterial streets (Minikel 2012).



Figure 14: Seattle's NW 58th St. Greenway

Conclusions Based on Literature

The literature indicates that cycle tracks are safer than roads without bicycle infrastructure, but results on the safety of bike lanes have been mixed, depending on other street factors (such as on-street parking). Based on the reviewed literature, the hypothesis for the case-control study is that bike lanes are only slightly safer than roads without bike lanes.

5. Bicycle Crash Statistics in Seattle

People on bicycles are exposed to a certain amount of risk of injury. Sharing the road with motor vehicles can be hazardous, as a disproportionate amount of fatalities and injuries that occur on the nation's roads involve bicyclists. In 2012, 2.16% of fatalities occurring in traffic crashes were bicyclists, and 2.07% of injuries resulting from crashes were bicyclist injuries (U.S. Department of Transportation 2013). The national bicycle commuting rate is only 0.6% (McKenzie 2014).

In Seattle, there was one fatal collision resulting from a collision involving a person riding a bicycle in 2012. There were 24 serious injury collisions, and 354 other low or no injury collisions involving cyclists. The most common cause of these 359 collisions in 2012 was the failure of a motorist to give right of way to the bicyclist. Data for 2013 shows a total of 428 crashes and three fatalities. The frequency of crash and type of severity for each type of infrastructure is shown in Figure 16: Mid-block and Intersection Collision Locations. Most crashes in Seattle in 2013 occurred on arterials. Slightly more collisions occur on arterials without bike lanes than those with bike

lanes. Few crashes occur on local roads or greenways, but this may be because bicycle volume is higher on arterials.

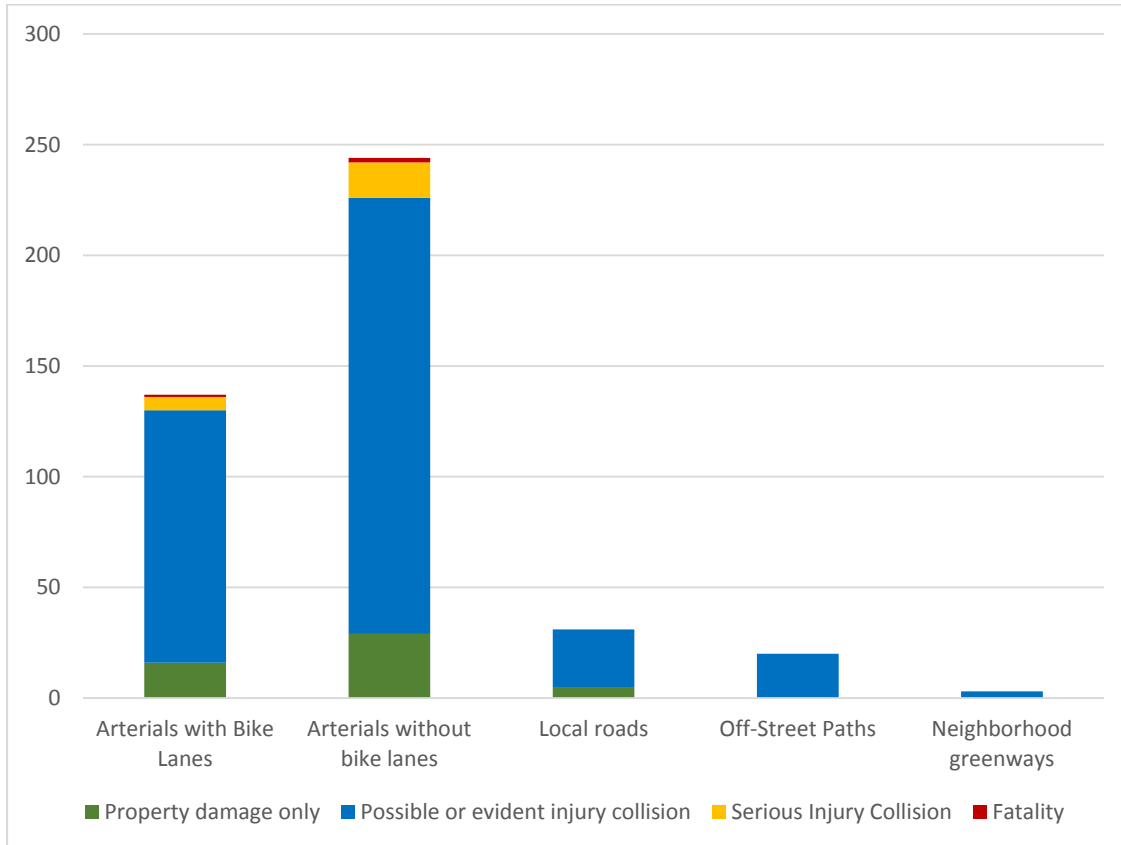


Figure 15: Frequency and severity of injury in collisions involving cyclists in Seattle, 2013

It is not surprising that the three bicyclist fatalities in 2013 in Seattle happened on arterial streets. Arterials have a higher volume of motor vehicles, and motor vehicle collisions account for approximately 90 percent of cycling deaths (Pucher and Buehler 2012, 143). Motor vehicle involvement in a bicycle crash has been found to be an important predictor of severe and fatal injuries (Rivara, Thompson and Thompson 1997). Bicycle injuries resulting from collision with motor vehicles were 2.6 times more likely to require hospitalization or special medical care than those that did not

involve a motor vehicle (Haileyesus, Annest and Dellinger 2007). Occupants of motor vehicles are protected by seatbelts, airbags, and several thousand pounds of steel. Bicyclists, however, often only have a helmet for protection. In the event of a bicycle-motor vehicle crash, no matter who is at fault, the bicyclist will always have the most severe injuries. Many countries have taken measures to physically separate bicyclists from motor vehicles traveling at speeds over 20 km/hr (or about 12 mph), using curbs, parked cars, planting strips, and other innovative solutions. The U.S., including Seattle, has mostly focused its infrastructure efforts on bike lanes (Lusk, et al. 2011), which do not offer any physical barrier between bicyclists and motor vehicles.

6. Bike Lane Safety Case-Control Study

Case-Control Studies

Case-control studies have been used in modern epidemiology since 1926. The first case-control study was a study of breast cancer. Four case-control studies in 1950 linked smoking to cancer and provided a solid foundation for the use of case-control studies. Case-control studies attempt to determine if there is a higher risk of injury or disease because of exposure to some variable. A case-control study measures relative risk of an outcome based on a variable. In the study that linked smoking to cancer, 71.2% of lung cancer patients at an Illinois hospital smoked more than 10 cigarettes per day. Hospital patients with cancers not related to the respiratory system or upper gastrointestinal tract were used as the control group. The control group had a much lower rate of smoking. Only 48.8% of the control group smoked

more than 10 cigarettes per day, leading to the conclusion that smoking is a predictor of lung cancer (Paneth, Susser and Susser 2002).

Case-control studies have been adapted to injury prevention research. The goal of case studies in injury prevention is to provide a basis for developing intervention strategies to prevent injury or death (Rivera and Wolf 1989). Several studies involving pedestrian and motor vehicle collisions have been performed, but few studies have applied case-control methodology to bicycle and motor vehicle crashes.

A case-control study with 147 case and control sites was conducted on rural roads in Iowa, finding that on-road bike lanes or shared lane markings was associated with a decrease in crash risk (Hamann and Peek-Asa 2013). Another case-control study was used to determine risk factors for motor vehicle collisions, but it did not account for bicyclist volumes (Romanow, et al. 2012).

A similar method, a case-crossover study, was used by Teschke, et al. to attempt to determine safer types of bicycle infrastructure. This method uses the individual bicyclist and his or her route as the control for the study. Study participants were recruited through hospital emergency room visits. The participants were asked about the route they took immediately preceding the crash, and two control locations were randomly picked from their route. This methodology accounts for characteristics of individual bicyclists and controls for confounding factors (age, sex, risk tolerance, cycling experience, knowledge of traffic rules, bike and clothing visibility, weather,

etc.) (Harris, et al. 2011). The case-crossover approach can also account for bicycle volumes.

Methodology

This study attempts to determine if there is a higher risk of bicycle-motor vehicle collisions when a bicyclist is riding on a roadway with a bike lane than when riding along a street without a bike lane. A simple epidemiology case-control study finds the ratio of the odds of the disease in exposed individuals to the odds of disease in unexposed individuals. In this injury prevention case-control study, our outcome of



Figure 16: Mid-block and Intersection

interest (the “disease”) is a bicycle-motor vehicle collision. The unit of study for this project (the “patient”) is a section of roadway, either a mid-block or intersection location as shown in Figure 16. The variable of interest is the presence or absence of bike lanes. If the roadway has bike lanes, it is “exposed” to the variable of interest, much as exposure to smoking has been shown to cause increased risk of lung cancer.

In this study, the odds ratio is the odds of a crash in roadway sections with a bike lane compared to the odds of a crash in a section of roadway without a bike lane. Table 3 provides further explanation.

Table 3: General Case-Control Matrix

Exposure (presence of bike lanes)	Disease (Crash occurred)	
	Yes	No
Yes	<i>A</i>	<i>B</i>
No	<i>C</i>	<i>D</i>

The odds ratio, ψ , is calculated by $\psi = AD/BC$. This ratio does not adjust for confounding factors or bicycle and motor vehicle traffic volumes. Detailed calculations will be discussed further in the Data Analysis section.

Data Source and Collection

Bicycle Collision Data

Bicycle crash data was obtained from the Seattle Department of Transportation (SDOT). A complete description of the data set can be found in Appendix A: Description of SDOT Collision Data Set. Crash data from October 2012 to March 2013 and October 2013 to December 2013 will be used.

Dependent and independent variables

The dependent variable in this study is the locations where collisions did or did not occur (the case and control sites). Independent variables are the presence of bike lanes, number of motor vehicle lanes, average daily traffic, bicycle counts, and presence of on-street parking.

Selecting controls

Sixty crash sites were selected from October 2012-March 2013 and October 2013 to December 2013. This time period was selected to roughly correspond with the

weather and lighting conditions during the time when the sites will be retroactively visited, February 2014-March 2014. Selected crash sites will be the case sites. Control sites, where a crash did not occur, will be randomly selected from within a half-mile radius of the case site. Since a crash occurs at a specific moment of time, an intersection may be used as a case and also a control, at a different time of day. For example, 15th Ave NE and 68th St. was included as the study as a case that had a collision at 7:58 am. This intersection was also randomly selected as a control for a collision that occurred at 5:34 pm. Controls will be either mid-block or intersection sites, matched with the condition of the case site.

Documenting Site Conditions

Sites will be visited within an hour on either side or the time of the crash. Sites will be visited on a weekend or weekday, matched with the day of the crash. Raining and dry conditions will also attempt to be matched. Each site will be documented, and the following will be recorded:

- Posted motor vehicle speed
- Presence of bike lanes
- Number of motor vehicle lanes
- Average daily traffic (obtained from SDOT, not directly observed)
- Count of bicycles through the site for 10-15 minutes.
- Presence of on-street parking

Along with this information, SDOT records will be consulted to see if the site was different at the time when the crash occurred (for example, if bike lanes had been added after the crash). Since bike infrastructure tends to attract more bicyclists (Lott, Tardiff and Lott 1978), number of bicycles through the sites will be recorded and accounted for when analyzing the data.

Sample Size

Sample size in case-control studies is dependent on many factors, including the confidence level, power, and expected exposure level among the general population.

The miles of bike lanes installed on arterials in Seattle were used to calculate the expected exposure among the general population. All arterial roadway miles in Seattle are considered the general population. The section of road or intersection with a bicycle crash is the case. Exposure, in this study, refers to the presence of bike lanes.

Since SDOT has only installed bike lanes on principal arterials, minor arterials, and collector arterials, only those streets were included in this study. All streets in this category will be referred to as arterials. Using the street network shapefile from the city of Seattle GIS department, the field ARTCLASS was selected at values of 1,2,3, or 9, corresponding to principal arterials, minor arterials, collector arterials, and county arterials, respectively. The total length of arterial streets in Seattle is 501.693 miles. Bike lanes are present on 77.49 miles of roadway in Seattle (using the bike shapefile from SDOT). Using these numbers, we find that 15.5% of arterial miles have bike lanes

on them. Given this information, we can expect approximately 15.5% of our control sites to have bike lanes. If the case sites have a significantly higher or lower percentage of bike lanes, then we can conclude that bike lanes have an effect on the risk of a bicycle-motor vehicle collision.

The sample size of 60 cases and 60 controls allows us to determine a relative risk of approximately 3.5 with an alpha at 0.10 and a beta of 0.20. (Schlesselman 1982). Ideally, the sample size would be much larger to determine a smaller increment of risk.

Selection Process

There were 157 records for intersection crashes and 102 records for mid-block crashes in the period of winter 2013 to winter 2012 (October to January 2013 and October 2012 to March 2013). Some of these records did not have time of crash, and were removed from consideration. Thirty records had no time associated with them. There were 13 records coded as 12:00:00 AM. It is unlikely that 13 crashes occurred at midnight, and it was assumed that the time defaults to 12:00:00 AM if no time is entered. These records were removed as well.

Since SDOT does not install bike lanes on residential streets, only collisions on arterials are used. Ninety-six midblock cases and 102 intersection cases were on arterials. Sixty cases were selected out of the total pool of 198 crash records. Some selected cases were discarded due to time of day (very early morning and late night crashes were discarded for the researcher's safety) and some were discarded that

involved the Burke-Gilman trail, which is an off-road bicycle and pedestrian trail. This study is only concerned with bicyclists riding on streets shared with motor vehicles.

Control sites were matched on whether the case was an intersection or midblock site. Control sites were selected by drawing a half-mile radius circle around the crash site and numbering all possible control sites. Microsoft Excel's random number generator was used to pick a number and the corresponding numbered site became the control site.

For more accurate results, the controls could have been matched on type of street. One or two factors could have been chosen, such as matching on one-way or two-way streets, presence or absence of parking, or number motor vehicle lanes. However, too many criteria for matching might limit the selection of controls to the same street where the crash occurred, which would not be useful. More precise matching could have been accomplished by removing the half-mile radius and including all streets with the exact characteristics of the case streets, with the exception of the presence of bike lanes. This would involve categorizing all arterial streets in Seattle on traffic volume, number of motor vehicle lanes, parking, and motor vehicle speeds. This study did not contain enough time to select such precise matching controls.

Bicycle Volume Data Collection

Bicycle volume data was collected near the recorded time of day that the crash occurred. Most sites (cases and controls) were visited within an hour on either side of the recorded crash time. A few site visits extended past the hour window to an hour and 15 minutes. The researcher visited the sites, diagrammed the roadway, and counted the number of people on bicycles through the intersection for approximately 10 minutes. Helmet use, age, gender, and sidewalk riding were also recorded. Age and gender were not always recorded due to difficulty seeing the bicyclist. These statistics are of no importance to this study, but someone else may find them useful in the future. Example data collection sheets are found in Appendix B: Data Collection Examples. Volumes of bicyclists through each site are mapped in Figure 17.

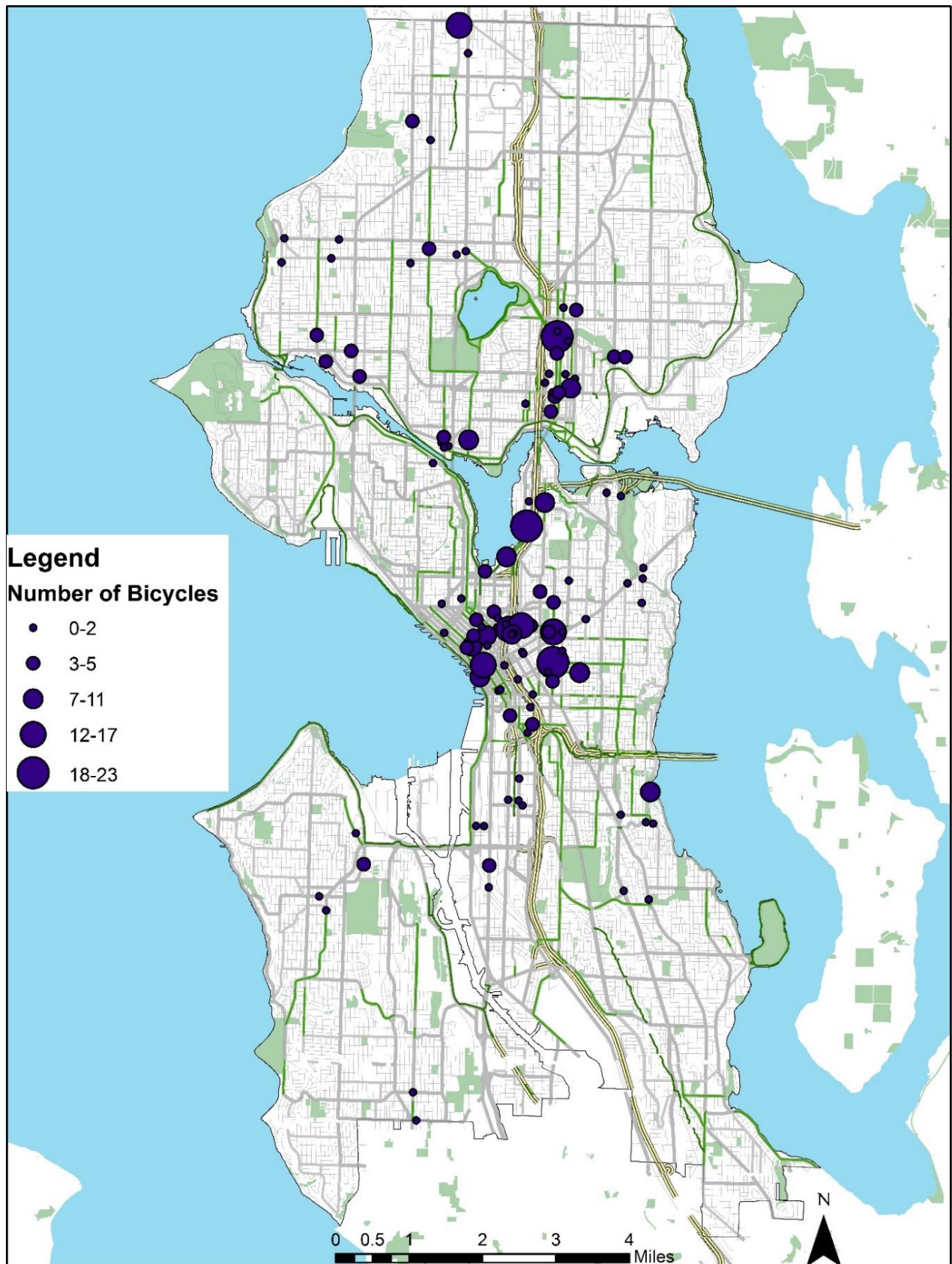


Figure 17: Bicycle volumes through case and control sites

Issues with Data Collection

Bicycle counts at the case and control locations may not be accurate. People who use a bicycle for commuting may have very set habits, and the hour-long window for observation may have been too long. For example, bicycle volume through a crash site at 7:45 am may be much heavier than at 8:30 am, since many office workers may need to be at work by 8:30. A specific example I noticed was sites near schools.

Schools have a very specific start time, and generate a high amount of traffic volumes (vehicles, bicycles, pedestrians, and buses) in a short amount of time. There was one crash at Roosevelt High School at 7:58am, one at Nathan Hale High School at 8:26 am, and a control site near the Bertschi school at 8:07 am. Roosevelt High starts at 8:00am, and Nathan Hale at 8:30, from the Seattle Public Schools website. Based on the amount of child drop-off traffic at Bertschi, they started around 8:30 am. If these sites were visited even a few minutes after school start times, the volume of traffic would be much different than it was at the time of the crash. At the Bertschi control site, I was attempting to control for a crash at 8:07 am but was at the control site right before school started, 8:18-8:28 am. Bike traffic was likely similar to traffic at 8:07, since this was an elementary school, and I did not see anyone arriving via bike. Due to time limitations, it was unrealistic to adjust count times to visit each site at exactly the time of the crash.

The crashes happened up to a year and half before this study. Google street view and SDOT records were used to attempt to verify what the infrastructure was at the time of the crash, but errors may exist. In addition, bicycle volume levels may have changed since the time of the crash. Several areas had construction nearby which may

have directed bicyclists on or off a route that was being studied. Broadway is a prime example of this; Broadway is under construction from Yesler to E. John Street, and north-south through cyclists are directed to use 12th Avenue instead. This may have inflated counts on 12th Avenue and deflated counts on Broadway (including the part that is not under construction, north of E. John St).

Data Analysis

Sixty cases with 60 controls were used for this study. Cases are sections of roadway (intersection or mid-block) where a bicycle-motor vehicle crash occurred. Controls are the randomly selected sections of roadway within a ½ mile of the case where no bicycle-motor vehicle crash occurred. Seventeen case sites had a bike lane, and 12 control sites had a bike lane. Table 4 shows the simple case-control matrix.

Table 4: Presence of bike lanes in case and control sites

Bike Lane	Case	Control
yes	17	12
no	43	48

If no other factors were considered, the odds ratio would be $\psi = 17 \cdot 48 / 12 \cdot 43 = 1.58$.

The odds ratio, OR, means that, not accounting for any other factors, a bicyclist would be 1.58 times more likely to experience a crash while on a roadway with a bike lane than one without. However, there are many other factors to consider when calculating the odds ratio. Presence of parking, number of motor vehicle lanes, downhill grades, motor vehicle speeds, motor vehicle volumes and bicycle volumes all may have an impact on the likelihood of a crash.

Bicycle volumes were higher on streets with bike lanes. There was an average of of three people on bicycles through the sections of roadway during the observation period. Roadways with bike lanes had an average of 5 people on bikes. These numbers support previous research that bike lanes attract bicyclists.

Mantel Haenszel method

To account for confounding factors, the Mantel Haenszel method was used. This method separates the data into groups, called stratification. For example, the presence of parked cars may affect the odds ratio. Therefore, we will divide the data into two tables: one containing records with parked cars, one without. Table 5 shows the resulting table stratified on presence of parking.

Table 5: Presence of bike lanes in case and control sites, stratified on presence of parking

<u>Bike Lane</u>	<u>Parking</u>		<u>No Parking</u>	
	Crash	No Crash	Crash	No Crash
Yes	13	10	4	2
No	26	29	17	19
Total	39	39	21	21

The Mantel Haenszel calculation for the stratified odds ratio is:

$$\varphi_{mh} = \sum_{i=1}^k \left(\frac{a_i d_i}{n_i} \right) / \left(\frac{b_i c_i}{n_i} \right) \quad (\text{Schlesselman 1982, 183})$$

Where there are k tables organized as shown in Table 6.

Table 6: Mantel-Haenszel table format. Each variable (sites with parking, without parking, etc., receives its own table.

Bike Lane	Case	Control	
yes	a	b	m_1
no	c	d	m_2
	n_1	n_2	

There are many more factors to consider other than parking. Bicycle volume must be accounted for, so all variables should account for bike volume. Table 7 is the resulting stratified table used to calculate the odds ratio according to the Mantel Haenszel method. The resulting OR, adjusting for bicycle volumes, parking, motor vehicle lanes and ADT, is 1.46, less than the rough estimate of 1.58.

Table 7: Stratified table used to calculate the Mantel-Haenszel odds ratio

		Bicycle Volumes	Low (0 to 3)		Mid (4 to 9)		High (10 to 23)	
		<u>Bike Lane</u>	Yes	No	Yes	No	Yes	No
Stratified on: Parking	<u>Parking</u>	Crash	5	18	5	4	3	4
		No Crash	6	21	3	6	1	2
	<u>No Parking</u>	Crash	2	15	1	2	1	0
		No Crash	2	15	0	3	0	1
Stratified on: Center Turn Lane	<u>With Center Turn</u>	Crash	1	5	4	1	0	2
		No Crash	0	2	1	0	0	2
	<u>Without Center Turn</u>	Crash	6	28	2	5	4	2
		No Crash	8	34	2	9	1	3
Stratified on: Motor vehicle volume	<u>ADT <5000</u>	Crash	2	6	0	2	1	1
		No Crash	5	11	0	2	1	1
	<u>ADT 5000-15000</u>	Crash	3	14	5	4	3	3
		No Crash	1	11	2	5	0	2
	<u>ADT >15000</u>	Crash	2	13	1	2	1	1
		No Crash	2	14	1	2	1	1
Stratified by: Motor vehicle lanes	<u>2 lanes</u>	Crash	5	16	5	4	3	4
		No Crash	6	18	3	5	1	1
	<u>>2 lanes</u>	Crash	2	17	1	2	1	0
		No Crash	2	18	0	4	0	2

Discussion

While the sample size is not large enough to draw definitive conclusions, the results point in the direction of bike lanes being marginally more dangerous than riding in the roadway. Several factors may account for the increase in risk, such as bike lanes that are too narrow or too close to the door zone (the Seattle right-of-way improvements manual requires a minimum of 5 foot lanes if installed next to parking, but NACTO recommends a width of 6 feet and wider if possible). Unclear intersection markings

may increase the risk of right hooks for bicyclists traveling in the bike lane. Both problems could be substantially addressed with infrastructure and safety campaigns. Motorists must remember to check their blind spot before opening their doors or before turning, and generally be aware that bicyclists may be present.



Figure 18: Right turn lane merging into bike lane, Chicago.

Infrastructure should be designed to keep bicyclists away from the door zone, and intersection treatments must address the issue of a right-turning motorist crossing a through-routed bicyclist's path. Figure 18 shows a right turn lane that requires the motorist to yield to bicyclists in the bike lane. Historically, all bike lane markings have been dropped at intersections to avoid this conflict. Bicyclists must then navigate the intersection exactly as if they were a motor vehicle. This causes some comfort concerns for less experienced bicyclists and new infrastructure treatments are beginning to address the problem.

Pros and Cons of the Case Control Method

There are many benefits to using a case-control study to evaluate the risk of a bicycle-motor vehicle crash. Case-controls are used to evaluate rare outcomes. A bicycle-motor vehicle collision is a relatively rare outcome. The study can be performed retroactively, so it can draw on many years of crash data, if conditions of the roadway at the time of the crash are known. The case-control study can be undertaken relatively easily, as crash data is readily available from local or state

transportation departments. The case-control methodology is a timely and cost-efficient method for examining the effect of the built environment on risk of injury (Rivera and Wolf 1989). A case-control method is a good method for generality, as it can apply to many different types of streets. The results, taking into account many different street characteristics, can provide a formula for city officials to consider when reconfiguring a street.

Most of the drawbacks of the case-control method involve data collection. The data collection must be precise, with bicycle volume data collected as near to the crash time as possible, and in the same weather and lighting conditions. Accuracy is increased with each case and control site added to the study, but each site adds approximately an hour to the data collection process. A balance must be obtained between number of sites and the research team's time. To get enough samples, several days or even weeks must be spent on observations. To detect an odds ratio of 1.5 or 0.5 with a confidence of 95% and a power of 0.9, 878 case-control pairs must be studied (Schlesselman 1982). If sites are studied for a half-hour each, this makes for almost 6 months of work for one person. In addition to time constraints, the crash data obtained from the local department of transportation may be incomplete, lacking information about whether the bicyclist was actually traveling in the bike lane or not.

Recommendations for future safety research

The main issue with bicycle infrastructure safety studies is accounting for the volume of bicyclists through sections of roadway, so that the rate of collision or injuries can

be calculated. Seattle does not yet have year-long accurate counts on multiple sections of roadways. Therefore, in any study, case-control and other studies, data collection must be undertaken by the researcher. Data collection should be undertaken by a paid researcher or a large group of researchers, to split up the hours required. One solution would be to place an automated bicycle and vehicle counter at the case and control locations for several days, to obtain more precise information about bicycle and vehicle volumes at the time of day that the crash happened, instead of just visiting the site once to record traffic volumes.

Bicycle counts and roadway conditions should be collected as close as possible to the time of the crash. It would be ideal to work with local police and obtain detailed records of the crash as soon as possible after it happened. Roadway conditions may change over time (addition or removal of parking, lane reconfigurations, more or less traffic, etc.), and the sooner the crash site is visited, the more accurate the study can be. Research on bicycle infrastructure should be conducted in cooperation with both the Seattle Department of Transportation (SDOT) and the Seattle Police Department (SPD). Researchers should consult SDOT for a schedule of bicycle infrastructure construction. They can then study streets before and after bicycle infrastructure was added, and researchers can gather accurate counts of bicycle and motor vehicle volume. SPD could provide detailed information of collisions soon after they happen, allowing the researchers to visit the collision site before conditions have changed.

This study recorded posted motor vehicle speed, but speeds were not included in the analysis since only four sites had posted speeds different from the rest. Actual motor

vehicle speed would be a good data point to collect, because the actual speed may vary from the posted speed. Fatalities in bicycle-motor vehicle crashes rise sharply with an increase in motor vehicle speed (Stone and Broughton 2003, Kim, et al. 2007). Width of the bike lane and increased distance from the door zone could also have an effect on bicyclist safety and could be measured in future studies to determine whether wider bike lanes are safer than narrower bike lanes, or if special treatment, such as green paint or signage, has an effect on safety.

In future case-control studies, control sites should be matched more accurately to the cases. There are two ways to match more precisely. One is to keep a radius around the crash site, but perhaps extend to one mile to increase the pool of controls. One or two factors would be chosen to match on, such as presence of parking or a center turn lane. The other option is to open up the control selection to the entire city of Seattle, and match on many potential confounding factors, such as parking, number of motor vehicle lanes, motor vehicle speeds, center turn lanes, and one- or two-way streets. The latter method would require additional data files from SDOT detailing the characteristics of all arterial streets, allowing a precise pool of controls to match with each case.

7. Conclusions

Previous research on bike lane safety has produced conflicting results. The majority of studies show that bike lanes on arterial roads are somewhat safer than arterial roads without bike lanes, although a few studies show bike lanes to be slightly less safe, including my own preliminary case-control study. The conflicting results of different studies may be due to different bike lane designs. Older bike lanes may be 4-5 feet wide, while new publications such as NACTO recommend a bike lane width of 6 feet. A wider lane width allows a bicyclist to ride farther away from the door zone, and allows more room to maneuver if there are unexpected potholes or other road hazards. In addition, newer bike lane treatments such as green pavement and buffered bike lanes may have an effect on safety. Buffered bike lanes increase the distance between a bicyclist and moving traffic, and green bike lanes increase motorist awareness of bicyclists. Any future research undertaken on bicycle facility safety must clearly define the type of facility under study so that accurate comparisons can be made.

Research does show that street configuration, including parking, number of lanes, and motor vehicle volume and speed, has an effect on safety. Higher vehicle speeds increase the severity of injury resulting in a collision, and a larger volume of vehicles may increase the chance of a collision. On-street parking causes conflicts between bicyclists and cars that are parking, as well as car doors opening onto a bicyclist's path. Therefore, the type of road must be taken into account when designing bicycle infrastructure. If parallel routes with lower motor vehicle volumes or without on-

street parking are available, perhaps those roads should receive bike lanes first, since they will be safer for bicyclists. Copenhagen has a complete guide for what types of bicycle facilities should be installed on what types of roads, shown in Figure 19. Seattle should consider adopting similar guidelines so that bicycle infrastructure can be installed quickly and consistently throughout the city, without the need for a detailed study on each street to determine the appropriate type of bicycle infrastructure.

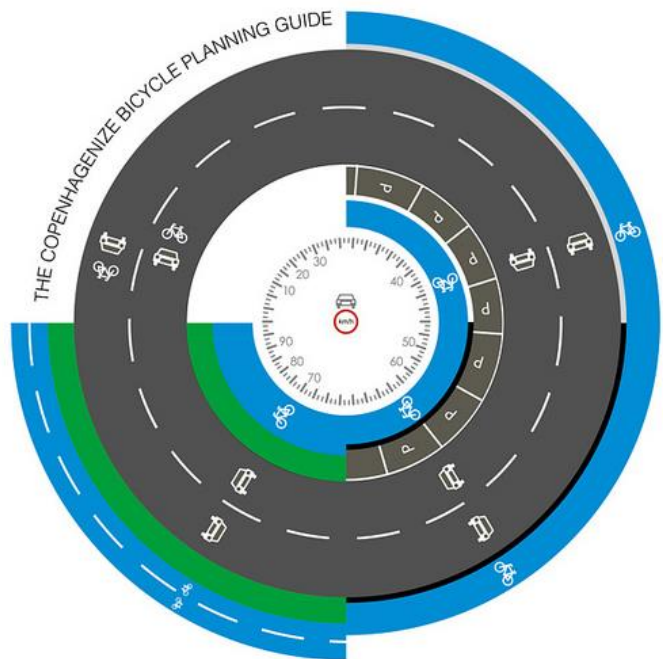


Figure 19: Copenhagen Bicycle Planning. Motor vehicle speeds 10-30km/hr, no separation. Motor vehicle speeds 40 km/hr, painted lanes. Motor vehicle speeds 50-60km/hr, curb separated lanes. Motor vehicle speeds 70-130 km/hr, fully separated by a median. If parked cars are present, bicycle infrastructure is placed on the right side. Two way paths are for off-street infrastructure only. Courtesy of Copenhagenize.com.

The research suggests that separated facilities, such as cycle track and greenways are safer than arterial roads without any bicycle infrastructure. Some studies have shown greenways and cycle tracks to be even safer than bike lanes. Seattle's current trajectory in terms of installing bicycle infrastructure, focusing on cycle tracks and greenways, is appropriate. However, if certain streets do not have enough room for bike lanes, and traffic volumes and speeds are not high, bike lanes may be installed as an important link in the overall network.

Future research would benefit greatly from a standardized bicycle counting program. If SDOT collected bicycle volume data in a similar manner as they collect motor vehicle data, research studies would be much easier, since the work of collecting bicycle volumes would be done by automated counters. SDOT has already started to move in this direction, with several new counters installed this year along bike routes.

Additional research is necessary to determine the safety of bicycle infrastructure. However, safety of a facility is not the only reason people may choose to ride bikes on it. Bicycle infrastructure, including bike lanes, has been shown to attract bicycle riders. Bicycling has many positive environmental and health impacts, and is also an efficient mode of transportation in a dense city. Bicycling should be encouraged with bicycle infrastructure, including bike lanes where cycle tracks and greenways are not feasible.

8. References

Bushell, Max A, Bryan W Poole, Charles V Zegeer, and Daniel A Rodriguez. 2013. *Costs for Pedestrian and Bicyclist Infrastructure Improvements: A Resource for Researchers, Engineers, Planners, and the General Public*. UNC Highway Safety Research Center.

2012. *Census Explorer, Commuting edition*. Accessed May 9, 2014.

<http://www.census.gov/censusexplorer/censusexplorer-commuting.html>.

City of Palo Alto. 2011. "2011 Draft Bicycle + Pedestrian Plan." Accessed April 5, 2014.

<http://www.altaprojects.net/palo-alto>.

City of Seattle. 2013. "Bicycle Facilities in the Recommended Bicycle Network." *2013 Bicycle Master Plan*.

Dada, Ezekiel, and Mike Furuya. 2010. "Parking Dimensions." *The Parker* (2nd Quarter).

de Hartog, Jereon Johan, Hanna Boogaard, Hans Nijland, and Gerard Hoek. 2010. "Do the Health Benefits of Cycling Outweigh the Risks?" *Environmental Health Perspectives* 118 (8): 1109-1116.

Dill, Jennifer. 2009. "Bicycling for Transportation and Health: The Role of Infrastructure." *Journal of Public Health Policy* 30: 95-110.

Federal Highway Administration. 2006. "Pedestrian and Bicyclist Intersection Safety Indices Final Report."

Forester, John. 2012. *Effective Cycling*. Cambridge: MIT Press.

Haileyesus, Tadesse, Joseph L Annest, and Ann M Dellinger. 2007. "Cyclists Injured while Sharing the Road with Motor Vehicles." *Injury Prevention* (13): 202-206.

Hamann, Cara, and Corinne Peek-Asa. 2013. "On-road Bicycle Facilities and Bicycle Crashes in Iowa, 2007-2010." *Accident Analysis and Prevention* (56): 103-109.

Harris, Anne, Conor C O Renynolds, Meghan Winters, Mary Chipman, Peter A Cripton, Michael D Cusimano, and Kay Teschke. 2011. "The Bicyclists' Injuries and the Cycling Environment Study: A Protocol to Tackle Methodological Issues Facing Studies of Bicycling Safety." *Injury Prevention* 17 (6).

Johnson, Marilyn, Stuart Newstead, Jennie Oxley, and Judith Charlton. 2013. "Cyclists and Open Vehicle Doors: Crash Characteristics and Risk Factors." *Safety Science* 59: 135-140.

Kim, Joon-Ki, Sungyop Kim, Gudmunder F Ulfarsson, and Luis A Porrello. 2007. "Bicyclist Injury Severities in Bicycle-Motor Vehicle Accidents." *Accident Analysis and Prevention* (39): 238-251.

- Lott, Dale F, Timothy Tardiff, and Donny Y Lott. 1978. "Evaluation by Experienced Riders of a New bicycle Lane in an Established Bikeway System." *Transportation Research Record* (683): 40-46.
- Lusk, Anne C, Patrick Morency, Luis F Miranda-Moreno, Walter C Willet, and Jack T Dennerlein. 2013. "Bicycle Guidelines and Crash Rates on Cycle Tracks in the United States." *American Journal of Public Health* 103 (7): 1240-1248.
- Lusk, Anne C, Peter G Furth, Patrick Morency, Luis F Miranda-Moreno, Walter C Willett, and Jack T Dennerlein. 2011. "Risk of Injury for Bicycling on Cycle Tracks versus in the Street." *Injury Prevention*.
- McKenzie, Brian. 2014. *Modes Less Traveled-Bicycling and Walking to Work in the United States: 2008-2012*. United States Census Bureau. Accessed May 26, 2014. <http://www.census.gov/hhes/commuting/>.
- Minikel, Eric. 2012. "Cyclist Safety on Bicycle Boulevards and Parallel Arterial Routes in Berkely, California." *Accident Analysis and Prevention* (45): 241-247.
- National Association of City Transportation Officials. 2012. *Urban Bikeway Design Guide*. 2nd. New York.
- Niemeier, Debbie A. 1996. "Longitudinal Analysis of Bicycle Count Variability: Results and Modeling Implications." *Journal of Transportation Engineering* 200-206.

- Paneth, Nigel, Ezra Susser, and Mervyn Susser. 2002. "Origins and Early Development of the Case-Control Study: Part 2, the Case-Control Study from Lane-Clayton to 1950." *History of Epidemiology* (Birkhauser Verlag) (47): 359-365.
- Pucher, John, and Lewis Dijkstra. 2000. "Making Walking and Cycling Safer: Lessons from Europe." *Transportation Quarterly* 54 (3).
- Pucher, John, and Ralph Buehler. 2012. *City Cycling*. Cambridge: MIT Press.
- Pucher, John, Ralph Buehler, and Mark Seinen. 2011. "Bicycling Renaissance in North America? An Update and Re-appraisal of Cycling Trends and Policies." *Transportation Research Part A* (45): 451-475.
- Reynolds, Conor C O, Anne Harris, Kay Teschke, Peter A Cripton, and Meghan Winters. 2009. "The Impact of Transportation Infrastructure and Crashes: A Review of the Literature." *Environmental Health* 8 (47).
- Rivara, Frederick P, Diane C Thompson, and Robert S Thompson. 1997. "Epidemiology of Bicycle Injuries and Risk Factors for Serious Injury." *Injury Prevention* 110-114.
- Rivera, Frederick P, and Marsha E Wolf. 1989. "Injury Research: Where Should We Go From Here?: Commentary." *Pediatrics* 1 (180).

- Romanow, Nicole T.R., Amy B. Couperthwaite, Gavin R. McCormack, Alberto Nettel-Aguirre, Brian H. Rowe, and Brent E. Hagel. 2012. "Environmental Determinants of Bicycling Injuries in Alberta, Canada." *Journal of Environmental and Public Health*.
- Rose, Danielle. 2011. *An Evaluation of the Implementation of the Seattle Bicycle Master Plan*. Master's Thesis, University of Washington.
- Schlesselman, James J. 1982. *Case-Control Studies*. New York: Oxford University Press.
- Seattle Department of Transportation. 2012. "2012 Traffic Report."
- Seattle Department of Transportation. 2013. "SeaBikeCollisions."
- Seattle Department of Transportation. 2014. "Seattle Bicycle Master Plan."
2014. *Seattle Neighborhood Greenway Work Plan*. March 10. Accessed April 21, 2014. <http://www.seattle.gov/transportation/greenwaysworkplan.htm>.
- Seattle Office of Sustainability & Environment. 2008. "2008 Seattle Community Greenhouse Gas Inventory."
- Stone, Mervyn, and Jeremy Broughton. 2003. "Getting off your Bike: Cycling Accidents in Great Britain in 1990-1999." *Accident Analysis and Prevention* (39): 555.

- Teschke, Kay, Anne Harris, Conner C.O. Reynolds, Meghan Winters, Shelina Babul, Mary Chipman, Michael D Cusimano, et al. 2012. "Route Infrastructure and Risk of Injuries to Bicyclists: A Case-Crossover Study." *American Journal of Public Health* 102 (12): 2336-2343.
- Tilahun, Nebiyou Y, David M Levinson, and Kevin J Krizek. 2007. "Trails, Lanes, or Traffic: Valuing Bicycle Facilities with an Adaptive Stated Preference Survey." *Transportation Research Part A* (41): 287-301.
- U.S. Census Bureau. 2012. Accessed May 15, 2014. <http://factfinder2.census.gov>.
- U.S. Department of Transportation. 2013. "Traffic Safety Facts." National Highway Traffic Safety Administration.
- Wachtel, Alan, and Diana Lewiston. 1994. "Risk Factors for Bicycle-Motor Vehicle Collisions at Intersections." *Institute of Transportation Engineers* 30-35.
- Winters, Meghan Lesley. n.d. "Improving Public Health through Active Transportation: Understanding the Influence of the Built Environment on decisions to travel by bicycle."

9. Appendices

Appendix A: Description of SDOT Collision Data Set

Bicycle crash data was obtained from Craig Moore at the Seattle Department of Transportation (SDOT). The data set included locations of police-recorded bicycle-motor vehicle collisions from 2003 to 2013. The data includes two tables, one for data on the cyclist, and one for the circumstances surrounding the collision. The first table is labeled `cyclist_data` and contains the fields in table X

Field Name	Description
REPORTNO	Report Number
ST_GENDER	Gender of bicyclist
ST_AGE	Age of bicyclist
ST_HELMENT	Bicyclist wearing helmet or not
ST_PED_ACT_CD	Pedestrian action code
ST_PED_WAS_USING_CD	Pedestrian right-of-way type code (e.g. Marked Crosswalk)

The second table, `SDOT_ColCodes`, contains the fields

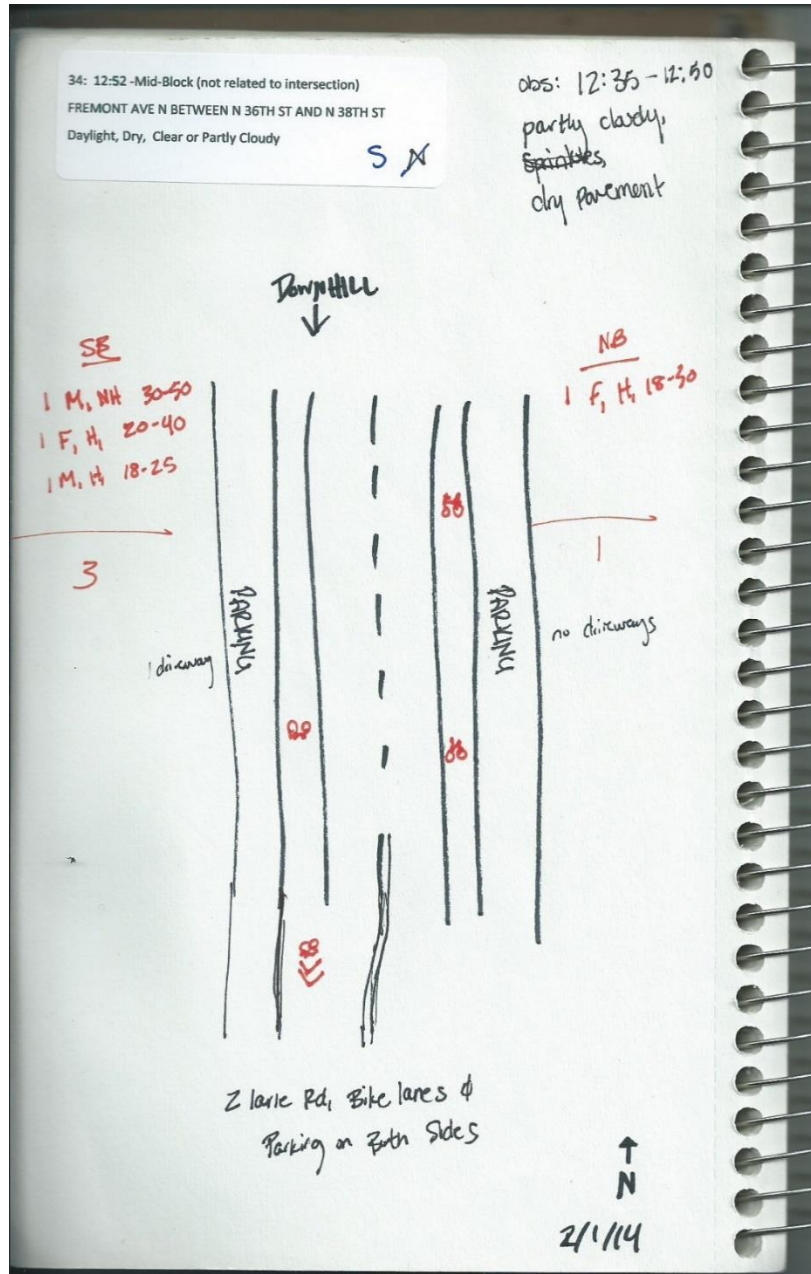
Field Name	Description
REPORTNO	Report Number
ST_VEHCT	Number of vehicles involved
ST_PEDCYC	Number of pedal cyclists involved
ST_PEDCT	Number of pedestrians involved
COL_DGM_CD	Collision diagram code
UNIT1COLLISIONCD	Type of vehicle and striking action
UNIT2COLLISIONCD	2 nd type of vehicle and striking action
UNIT1DIRPRIOR	1 st vehicle direction prior to impact
UNIT1DIRATIMPACT	1 st vehicle direction after impact
UNIT2DIRPRIOR	2 nd vehicle direction prior to impact
UNIT2DIRATIMPACT	2 nd vehicle direction after impact

Fields contained in the GIS file are:

Field Name	Description
INCKEY	Database ID
COLDETKEY	Database ID
ADDRTYPE	Address type
COLLISIONTYPE	Collision type
EXCEPTRSNCODE	Exception code (SDOT reason for not coding collision report)
EXCEPTRSNDESC	Exception reason (SDOT reason for not coding collision report)
FATALITIES	Number of fatalities
INATTENTIONIND	Inattention indicator (y/n)
INCDATE	Date of collision
INCDTTM	Date and time of collision
INJURIES	Number of injuries (total)
INTKEY	Intersection ID
JUNCTIONTYPE	Intersection, mid-block, or driveway junction
LIGHTCOND	Daylight, Dusk or Dark
LOCATION	Location of collision
PEDCOUNT	Number of pedestrians involved
PEDCYLCOUNT	Number of pedal-cyclists involved
PEDROWNOTGRNT	Pedstrian not granted ROW indicator (y/n)
PERSONCOUNT	Number
REPORTNO	Report Number
ROADCOND	Dry, Wet, or Unknown
SDOT_COLCODE	Code for type of collision
SDOT_COLDESC	Description of type of collision
SDOTCOLNUM	SDOT legacy collision ID number
SERIOUSINJURIES	Number of serious injuries
SEVERITYCODE	Severity code
SEVERITYDESC	Description of severity code (property damage, injury, or fatal)
SPEEDING	Speeding indicator
ST_COLCODE	Code for direction of vehicle impacts
ST_COLDESC	Description of vehicle impact
STATUS	Record status (matced/unmatched)
UNDERINFL	Under influence indicator (y/n)
VEHCOUNT	Number of vehicles involved
WEATHER	Weather code
YEAR_	Year of collision

Appendix B: Data Collection Examples

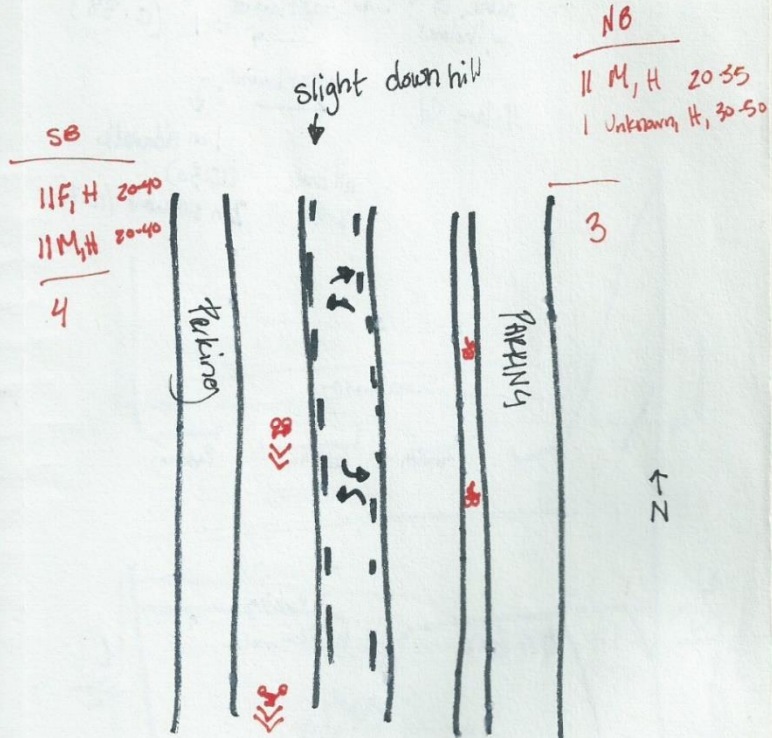
Data was collected at each site for 10-15 minutes. The site was diagrammed, conditions noted, and bicycles counted with tally marks. Gender (M or F), helmet (H or NH) and approximate age was also noted.



OBS: 12:10 - 12:25

Overcast
couple sprinkles
Dry pavement

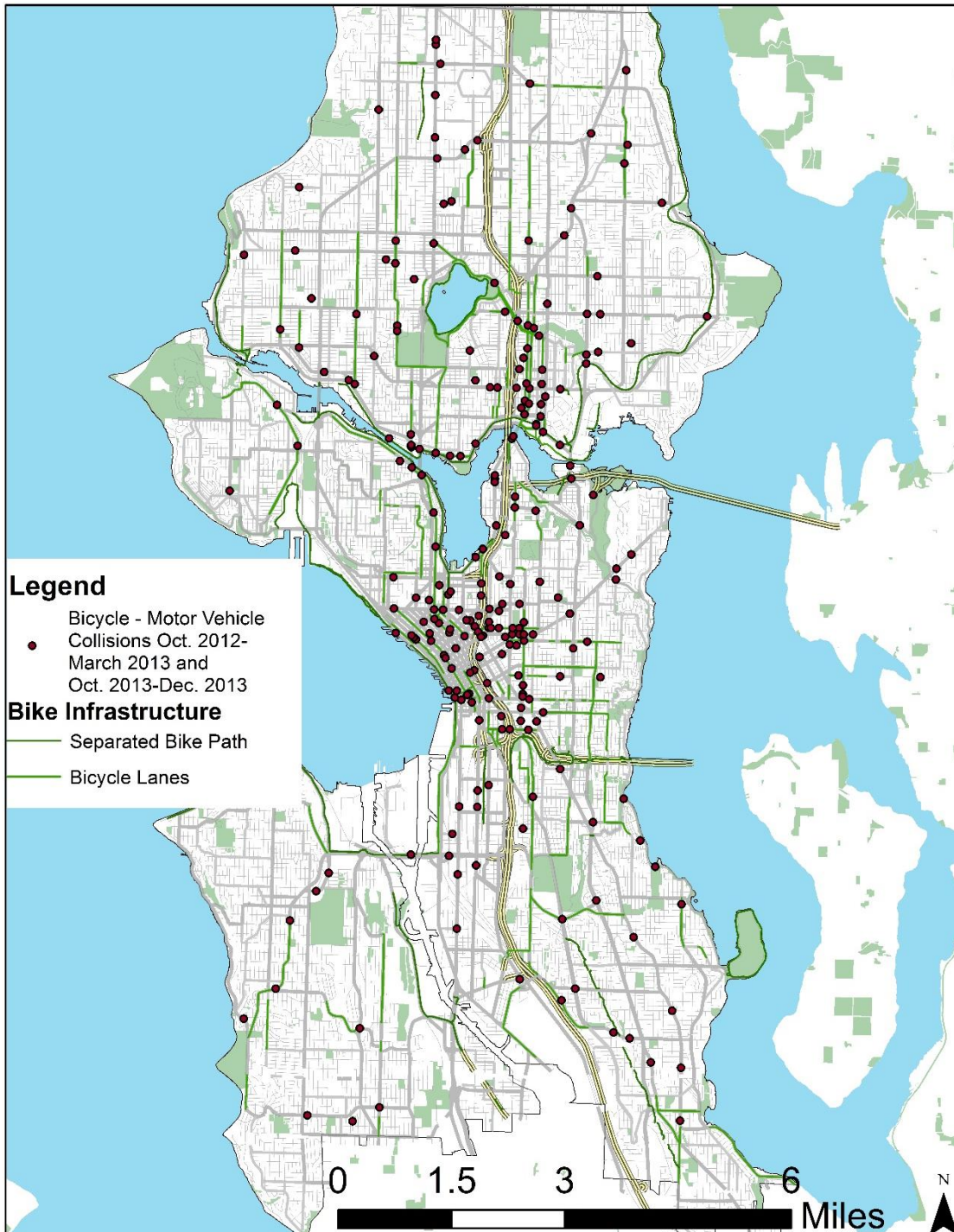
CONTROL 34 Block
Stone way between 36th and 38th
Weekend



2 lane Rd w/ center turn lane
Downhill Sharrows
uphill bike lane

Saturday. 2/1/14

Appendix C: All Bicycle - Motor Vehicle Crashes October 2012-March 2013 and October-December 2013



Appendix D: Case and Control Sites

Case and Control Locations

