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Are Neighborhood Bicycle Greenways the Answer?
Analyzing the Impact of Bicycle Greenways on Collisions between
Bicycles and Motor Vehicles

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Abstract

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With the population of urban areas growing at a rapid pace, cities are turning to new methods to manage the increased demand placed on space in the roadway. This increased demand carries the unfortunate side effect of bringing greater numbers of people into conflict while operating in traffic, and increases exposure to risk of collision overall. In the current version of the Seattle Bicycle Master Plan, Seattle Department of Transportation is turning to neighborhood bicycle greenways as a major tool to encourage more people to ride a bicycle as a primary mode of transportation – planning to increase the lane miles of neighborhood greenway to comprise 41% of the entire bicycle network at the completion of the Bicycle Master Plan. This thesis examines the role that neighborhood greenways play in relation to other bicycle facilities and asks: how do

neighborhood greenways influence the likelihood of collisions between bicycles and motor vehicles? In order to find an answer to this question, I performed a linear regression analysis examining the relationship between bicycle-motor vehicle collision incidents in Seattle and average traffic volumes, lane miles of arterials, and proportions of bicycle facilities in the roadway. Although my model was unable to identify all of the factors that would predict bicycle-motor vehicle collision incidents, I found that average traffic volumes showed a significant positive correlation with bicycle-motor vehicle collisions, and that non-arterial local streets showed a significant negative correlation. As non-arterial streets are the exclusive domain of neighborhood bicycle greenways, I recommend that Seattle Department of Transportation accelerate the construction and designation of neighborhood greenways; establish a low-barrier method for bicycle riders to report bicycle-motor vehicle collision incident data to the City of Seattle, and; conduct a more thorough average count of bicycle rider traffic volumes across Seattle for improved analysis of bicycle rider safety in the future.

TABLE OF CONTENTS

List of Figures	ii
List of Tables	iii
Chapter 1. Introduction	1
Chapter 2. Review of the Literature.....	5
2.1 Commuting by Bicycle	7
2.2 Factors in Collisions and Safety Risks to Bicyclists.....	10
2.3 Roles of Bicycle Paths and Other Infrastructure.....	15
2.4 Neighborhood Greenways in Seattle	16
2.5 Other Bicycle Facilities’ Relations to Greenways	18
Chapter 3. Research and Data Analysis	20
3.1 Seattle’s Bicycle Network and Bicycle Rider Safety	26
3.2 Study Design.....	28
3.3 Methods.....	30
Chapter 4. Results	41
4.1 Discussion.....	44
Chapter 5. Conclusion.....	51
5.1 Recommendations.....	52
References.....	56
Appendix.....	58

LIST OF FIGURES

<i>Figure 1. Planned Citywide Network, Bicycle Master Plan.</i> Error! Bookmark not defined.	
<i>Figure 2. Planned Local Connectors network, Bicycle Master Plan.</i>	22
<i>Figure 3. Existing neighborhood greenways, Seattle.</i>	24
<i>Figure 4. Planned neighborhood greenways, Bicycle Master Plan, Seattle.</i>	25
<i>Figure 5. Conceptual map of research model.</i>	29
<i>Figure 6. Distribution of bicycle-motor vehicle collisions by census block group.</i>	32
<i>Figure 7. Example of data aggregation process</i> <i>(principal arterial length per block group).</i>	34
<i>Figure 8. Distribution of local streets, aggregated by Seattle census block group.</i>	35
<i>Figure 9. Proposed neighborhood greenways.</i>	36
<i>Figure 10. Distribution of bicycle-motor vehicle collisions.</i>	37
<i>Figure 11. Distribution of average traffic volume counts.</i>	37
<i>Figure 12. Distribution of log of bicycle motor vehicle collisions.</i>	38
<i>Figure 13. Distribution of log of average traffic volume counts.</i>	38
<i>Figure 14. Distribution of bicycle-motor vehicle collisions in Seattle (2004-2017).</i>	47

LIST OF TABLES

Table 1. <i>Bicycle facility designation guidelines</i> <i>(modified from SDOT Bicycle Master Plan 2014)</i>	39
Table 2. <i>Summary statistics of regression model variables.</i>	41
Table 3. <i>Summary statistics for regression model.</i>	42

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Chapter 1. INTRODUCTION

In the United States, urban areas have been growing at a tremendous rate, eclipsing the population of rural areas to now holding over half of the national population. As more people move to cities, demand for housing, jobs, and space in the public right of way increases. This added pressure for space, particularly for space in the roadway, has led to increased traffic volumes and congestion, and so cities have begun to adopt extra methods to manage that demand. One sure method of demand management is to provide for other modes of transportation, particularly active modes that are reliant on a person's own power rather than via motor vehicle. Over the last ten years in the U.S., commuting by bicycle has increased by more than 60% and continues to rise. Cities such as Portland, Oregon and Seattle, Washington have created bicycle-specific transportation plans to accompany larger general transportation and land use planning, using these plans to build out connected bicycle networks to encourage people to transport themselves by bicycle rather than by personal automobile. The majority of daily trips made by people average less than three miles in length¹, which makes riding a bicycle an ideal mode of personal transportation for most trips – especially in dense urban areas.

Why, then, does a city such as Seattle only have four percent of its population ride a bicycle as a primary mode of transportation?² Although traffic congestion has greatly

¹ Litman, *Short and Sweet: Analysis of Shorter Trips Using National Personal Travel Survey Data*.

² U.S. Census Bureau, *Cycling Commuters: Cities (of 100,000 or More) by Percentage of People Biking to Work*.

increased in recent years, people are still far more likely to travel by automobile than by bicycle or any other mode of transportation. There are many factors that influence one's decision to ride bicycle (or not), but one that is known to dissuade people is the real and perceived risks of commuting by bicycle. A sobering reality is that people riding a bicycle face the greatest burden of injury in collisions between motor vehicles and bicycles, regardless of with whom the fault lies.³ Even though riding a bicycle is relatively safe overall, this knowledge and fear of personal injury or fatality is enough to drive most people away from traveling by bicycle.

In spite of the risks involved, commuting by bicycle can bring many benefits to the local environment and public health of cities, such as decreased air pollution, increased rates of daily physical activity among the population, and lower rates of cardiovascular disease and cancer.⁴ It is therefore in the public interest for more people trade the automobile for walking or biking short trips, and in order for them to do so cities will have to mitigate the potential for collisions between bicycle riders and motor vehicle drivers. When researching Seattle's plans for bicycle transportation improvements via the Bicycle Master Plan published by the Seattle Department of Transportation, I noticed that future plans to build out the existing bicycle network in Seattle rely heavily on an interconnected network of neighborhood bicycle greenways. My curiosity was piqued. I was familiar with the concept of neighborhood greenways, having read about them in the Seattle Bike Blog online and having ridden on several greenways on my own

³ Chong, "Relative Injury Severity among Vulnerable Non-Motorised Road Users."

⁴ Celis-Morales, "Association between Active Commuting and Incident Cardiovascular Disease, Cancer, and Mortality."

bicycles, but I knew little about any research into their efficacy as bicycle paths. I decided that if these neighborhood greenways were going to become a major element of Seattle's future bicycle network, I would base my thesis around measuring their potential for improving safety outcomes for people riding bicycles against other types of bicycle path and classes of roadway which a regular bicycle commuter in Seattle might be expected to use.

In order to determine which factors significantly influence the possibility for bicycle-motor vehicle collisions in Seattle, I investigated environmental factors based on traffic volumes, street arterial classifications, and existing bicycle path types and distributions. Several studies have examined factors related to population demographics and behaviors of motor vehicle drivers and bicycle riders; however, I wanted to determine what role these neighborhood greenways could play in reducing collisions between bicycle riders and motor vehicle drivers, and if they were even an effective solution over other forms of bicycle path such as protected bicycle lanes or paint-only bicycle lanes. After a review of literature relevant to the discussion of bicycle-motor vehicle collisions, I arrived at three hypotheses upon which to base my research:

1. Average daily traffic volume counts will show a positive association with bicycle-motor vehicle collisions
2. Lane miles of non-arterial local streets will show a negative association with bicycle-motor vehicle collisions
3. Lane miles of neighborhood greenways will show a negative association with bicycle-motor vehicle collisions

For my analysis, I used publicly available geographic data from King County, Washington and the Seattle Department of Transportation and built a multivariate linear regression model using ESRI's ArcGIS software and the open source R and R Studio statistical analysis software. The results of my analysis confirmed my first and second hypotheses, but surprisingly disproved my third. However, though my regression model proved to have relatively good model significance, it explained only a little over one-third of the story around collisions between bicycle riders and motor vehicle drivers. This led me to posit that there are other likely variables that have statistically significant influence on bicycle-motor vehicle collisions – bicycle rider traffic counts in particular, which I was unable to use in my analysis due to a lack of complete citywide data for Seattle.

Using the information from my literature review and empirical research, I determined that neighborhood greenways have the greatest potential of the bicycle path types included in the Bicycle Master Plan to reduce overall numbers of collision incidents between bicycle riders and motor vehicle drivers in the City of Seattle. Seattle Department of Transportation has a plan for implementation of the future bicycle network; I further recommend they: prioritize funding for and accelerate the designation and construction of neighborhood greenways; prioritize intersection treatments within the bicycle network to mitigate risks to bicycle riders; establish a low-barrier method for bicycle riders to report bicycle-motor vehicle collision incident data to the City of Seattle, and; conduct a thorough citywide count of bicycle riders in Seattle for future analysis.

Chapter 2. REVIEW OF THE LITERATURE

In recent years, population growth in the United States has largely concentrated in urban areas, with over 80% of the country living in cities.⁵ This increased competition for limited space has led to an increase in urban traffic congestion and increasing uses of alternate means of transportation. The U.S. Census Bureau has found that commuting by bicycle has increased 60% in the last decade⁶, with larger urban areas such as Portland, Oregon showing as much as 6.1% of the population commuting by bicycle. While this increase in bicycle use for personal transportation can bring a variety of public benefits, it also produces the side effect of bringing more people on bicycles into conflict with people driving automobiles in city streets. Although traveling by bicycle is and continues to be an attractive option for people living and working in urban areas, there are greater risks to personal safety involved due to a greater burden of injury for bicyclists when in collisions with motor vehicles.

In order to reduce conflicts between bicycle riders and motor vehicle drivers in city streets, local municipalities construct a variety of facilities designed for exclusive use by bicycle riders, and may also employ other instruments designed to alert other road users to the presence of bicycle riders in the roadway. These may include on-street painted bicycle lanes, bicycle signs and markings on the road surface, or off-road paths such as multi-use trails. New forms of bicycle path, such as physically-separated protected

⁵ U.S. Census Bureau, *Growth in Urban Population Outpaces Rest of Nation*.

⁶ U.S. Census Bureau, *Biking to Work Increases 60 Percent Over Last Decade*.

bicycle lanes and “bicycle boulevards” or “neighborhood bicycle greenways” are beginning to be used in urban areas around the country, and more cities are placing emphasis on citywide, connected bicycle facility networks. Cities such as Seattle and Portland are also incorporating bicycle planning into their larger transportation plans, and even drafting separate bicycle transportation plans to further help build cohesive bicycle networks. Through changes in policy and infrastructure, many cities are making efforts to encourage their citizens to use the bicycle as a primary mode of transportation, thereby producing greater variety in the modes used in urban areas and lessening the burden placed on existing street networks by managing demand. However, the share of the national population commuting by bicycle is still miniscule despite its growth, and there is not clear consensus on what actions to take in order to increase the proportion of bicycle riders in urban areas, and many people remain skeptical of commuting by bicycle alongside motorized traffic due to the risks involved. This review of the current literature on the subject of bicycle safety and collision risk will examine probable causes of collisions between bicycles and motor vehicles and will attempt to ascertain how particular types of bicycle path and street design influence the occurrence of bicycle-motor vehicle collisions in urban areas.

2.1 COMMUTING BY BICYCLE

Although personal automobile travel continues to be the dominant mode of transportation for individuals in urban centers in the United States, more commuters are choosing the bicycle as a primary mode. The U.S. Census Bureau's analysis of commute trip data from the 2000 Census and the 2008-2012 American Community Survey found that commuting by bicycle enjoyed the largest percentage increase in commute trips compared with all other transportation modes.⁷ This trend has the capacity to continue in urban areas, given the increasing demands placed on existing city street networks and the resulting increase in traffic congestion. Data from the 2009 National Household Travel Survey shows that 41% of personal trips made are less than three miles in length.⁸ Given that half of the U.S. population lives in urban areas, the share of short trips is likely higher than the national average due to the greater density of urban areas than rural areas. This short trip length is ideal for bicycle use in cities where traffic congestion in the street network slows the average travel time of automobiles.

As more people choose to commute by bicycle, the positive benefits of cycling as transportation are felt at the population-wide scale. The Centers for Disease Control and Prevention and U.S. Department of Health and Human Services recommend that adults engage in at least 150 minutes of moderate-intensity aerobic activity per week.⁹ By

⁷ U.S. Census Bureau, *Biking to Work Increases 60 Percent Over Last Decade*.

⁸ Litman, *Short and Sweet*.

⁹ CDC, *Current Physical Activity Guidelines*.

riding a bicycle for short trips under three miles in length, Americans in urban areas would be able to meet this goal and experience positive outcomes to public health. A recent study by researchers at the University of Glasgow found that active transportation modes of commuting (i.e. bicycling and walking) resulted in lower instances of cardiovascular disease, cancer, and mortality compared to non-active transportation modes.¹⁰ By trading the automobile for the bicycle for non-recreation trips, the average person would be reducing his or her individual carbon output and improving the environmental quality of the local area by reducing air pollution. These positive outcomes to public health are obviously beneficial to the individual, and can also benefit society by reducing dollars spent on health costs associated with obesity and poor air quality. In an urban area, an increase in the use of bicycles for short trips could also lead to positive changes in land use patterns; a parked bicycle takes up a fraction of the space of the average automobile, and cities would likely be able to create denser, more compact development that would in turn further incentivize people to travel by bicycle by shortening the average trip length.

Although bicycle use for personal transportation is on the rise in urban areas across the United States, personal automobile use remains the dominant transportation mode of choice. Portland, Oregon boasts one of the largest shares of people commuting by bicycle, but 94% of its population does not. Compared to other industrialized countries in Western Europe, the United States consistently lags behind. Pucher and Dykstra showed that in 1995, 6% of trips in the United States were made by walking or cycling,

¹⁰ Celis-Morales, "Association between Active Commuting and Incident Cardiovascular Disease, Cancer, and Mortality."

whereas in several continental European countries over 25% of daily trips were made by walking or cycling.¹¹ Not only were Europeans choosing to walk or bike for more trips than Americans, but also at every age group they were substantially more likely to choose an active mode of transportation compared with the U.S. While many European cities are denser than comparably-sized American cities, that alone does not explain the extraordinarily low share of active transportation mode choice among populations. If 41% of average trips made in the U.S. are under three miles in length, then something else must discourage the majority of the population to choose non-active modes of transportation.

As Pucher, Dykstra, and other researchers have discovered, a significant discouragement tends to be real and perceived risks to commuting by bicycle in the U.S. compared to elsewhere. Per kilometer traveled, American bicycle riders are 12 times more likely to die in traffic collisions than automobile drivers, and are two and three times more likely to die in traffic collisions compared to German and Dutch bicycle riders, respectively.¹² New research has shown that distracted driving, particularly through cellular phone use, has become a significant problem in the U.S., with 17.8% of all injuries from motor vehicle collisions in 2012 having involved distracted driving.¹³ Given these grim statistics, it is no wonder that Americans are less likely to feel comfortable commuting by bicycle than by automobile or other motorized transportation modes. While the causes of these collision risks are easy to name, it is

¹¹ Pucher and Dykstra, "Promoting Safe Walking and Cycling to Improve Public Health."

¹² Ibid.

¹³ CDC, *Distracted Driving in the United States and Europe*.

more difficult to determine which carry the greatest influence not only in the severity of personal injury to the bicycle rider, but also in the potential for collisions between bicycle riders and automobile drivers.

2.2 FACTORS IN COLLISIONS AND SAFETY RISKS TO BICYCLISTS

In urban areas, collisions between road users are an unfortunate reality. While collisions between motor vehicles are most common, it is those between bicycle and motor vehicle that carries the greatest burden of injury.¹⁴ Seattle Department of Transportation recorded 354 collision incidents between bicycles and motor vehicles in 2016 alone.¹⁵ Sanders' study in the San Francisco Bay Area found that near misses in traffic by motor vehicles may be statistically common experiences for bicycle riders, and that experiences of near misses and collisions significantly influence bicycle riders' perceptions of risk while riding in traffic.¹⁶ This perception of risk associated with traveling by bicycle is a likely reason for people choosing not to do so, as Roger Geller found when creating his typology of bicycle riders found in Portland, Oregon. Geller's typology describes four types of cyclist: "The Strong and the Fearless," "The Enthused and the Confident," "The Interested but Concerned," and the "No Way No How," which are non-riders. Of these four types, which may be found in any U.S. city, the "Interested but Concerned" are most likely to be concerned about the possibility of collision with motor vehicles in the

¹⁴ Chong et al., "Relative Injury Severity among Vulnerable Non-Motorised Road Users."

¹⁵ Seattle DOT, *Bicycle Collisions After 01/01/2016*.

¹⁶ Sanders, "Perceived Traffic Risk for Cyclists: the Impact of Near Miss and Collision Experiences."

roadway.¹⁷ We can imagine, therefore, that the level of perceived risk is directly tied to risk exposure, which itself is dependent on traffic volumes for a given street. Turner et al.'s findings in New Zealand seem to confirm this: an increase in motor vehicle traffic volumes, and therefore an increase in risk exposure, correlates to an increase in bicycle-motor vehicle collisions.¹⁸ Minikel's study also confirms this nexus between risk exposure and collision rates, finding a positive correlation between the two to be the case for arterial streets in Berkeley, California.¹⁹

Similar to the concept of risk exposure via average traffic volume counts is a kind of risk exposure via points of conflict, in particular at intersections of two or more streets. Given the possibilities of roadway users to make turns in multiple directions or to continue through, more scenarios for conflict between bicycles and motor vehicles exist at intersections than might be found on the mid-block portion of the roadway. Wachtel et al.'s study in Palo Alto found that 74% of reported bicycle-motor vehicle collisions from 1985 to 1989 occurred at intersections.²⁰ Multiple studies have modeled different intersection configurations, in order to study different models of points of conflict between road users. A study by Wang et al. examined three variations of traffic flow at intersections in Tokyo, positing that differences in roadway dimension and configuration influenced the amount of time needed by motorists to perceive and avoid collisions with bicycle riders.²¹ Turner's study, which involved a larger number of theoretical interactions at intersections, as well as interviews with persons involved in

¹⁷ Geller, "Four Types of Cyclists."

¹⁸ Turner, "Predicting Accident Rates for Cyclists and Pedestrians."

¹⁹ Minikel, "Cyclist Safety on Bicycle Boulevards and Parallel Arterial Routes in Berkeley, California."

²⁰ Wachtel, "Risk Factors for Bicycle-Motor Vehicle Collisions at Intersections."

²¹ Wang, "Estimating the Risk of Collisions Between Bicycles and Motor Vehicles at Signalized Intersections."

collisions, found that motor vehicle drivers failing to notice or give way to bicycle riders and pedestrians was a significant factor in collision incidents.²² Wood et al.'s study in Australia found that bicycle riders and motor vehicle drivers held vastly different perceptions of motorists' ability to see bicycles in the roadway, with bicycle riders' distance estimates being twice that of motor vehicle drivers.²³ These would seem to confirm Wang's findings regarding driver attentiveness and perception of non-motor vehicle operators. Given the increased risks to bicycle riders associated with intersections, it would be reasonable to assume that intersections of streets with higher traffic volumes (i.e. greater risk exposure) would likely experience more bicycle-motor vehicle collisions than intersections of streets with lower traffic volumes.

One popular safety intervention is the theory of "safety in numbers." Jacobsen describes this as a non-linear phenomenon in which increased numbers of people walking or biking in urban areas produces a behavior modification in motor vehicle drivers that leads to fewer collision incidents between motor vehicles and bicycles and pedestrians.²⁴ Turner found evidence in his prediction models that increasing the theoretical numbers of bicycle riders produced a distinct "safety in numbers"-induced reduction of collision incidents at intersections.²⁵ The implication of this phenomenon, in which greater regular participation of people riding bicycles with traffic, regardless of physical changes to the roadway, can itself yield results in decreasing bicycle-motor vehicle collisions, has a profound ability to influence regulation and policy regarding transportation via

²² Turner, "Predicting Accident Rates for Cyclists and Pedestrians."

²³ Wood et al., "Drivers' and Cyclists' Experiences of Sharing the Road."

²⁴ Jacobsen, "Safety in Numbers: More Walkers and Bicyclists, Safer Walking and Bicycling."

²⁵ Turner, "Predicting Accident Rates for Cyclists and Pedestrians."

bicycle. However, there is not universal agreement on the validity of the “safety in numbers” effect. Bhatia et al. especially disagree on some of the assumptions made by Jacobsen. His theory holds weight when viewed at the population level and considering the ratio of injury per person, but if increases in overall safety are the primary focus, then the non-linear model does not actually reduce the total number collision incidents.²⁶ The reality of collisions between the motor vehicles and bicycles is that the bicycle rider is the more vulnerable user of the two and, therefore, carries a disproportionately greater burden of injury. This puts more weight onto the argument of reducing the total number of bicycle-motor vehicle collisions, rather than only measuring success on area-wide proportions of collision incidents. Bhatia et al. also argue that the theory fails to consider potentially confounding factors against the effect, such as a theoretical decrease in the number of people driving motor vehicles in a given population, which in turn would lower risk exposure to bicycle riders. It is also conceivable that, as more of the local population travels by foot or by bicycle, the more likely it is for general motorist behavior to change towards pedestrians and bicycle riders. Studies reviewed by Bhatia also failed to account for any physical improvements to intersections, which would remove some of the potency of the “safety in numbers” effect. As the study by Wang et al. also shows, street intersections are inherently problematic for bicycle riders due not only to the increased risk exposure they produce, but also due to differences in user behaviors that result from complexity in the street environment – an issue that is largely independent from overall bicycle or motor vehicle traffic volumes.²⁷

²⁶ Bhatia, “‘Safety in Numbers’ Re-Examined.”

²⁷ Wang, “Estimating the Risk of Collisions Between Bicycles and Motor Vehicles at Signalized Intersections.”

While I have chosen to base my study on environmental factors influencing collision incidents, other studies have included demographic or behavioral factors in their analyses of the causes of collisions between bicycles (and/or pedestrians) and motor vehicles. A study by Hoffman et al. surveyed bicycle commuters in Portland, Oregon to determine causes of injury from traumatic and serious traumatic events. Demographic and behavioral variables used in the study included gender, average age, BMI, skill level, commute history and length, and use of safety devices such as helmets, lights, reflective clothing, and mirrors. Despite their focus on personal demographic variables, Hoffman et al. found that only the absence of helmet use correlated with serious traumatic events, which bicycle helmets are designed to prevent or mitigate. They also found no association with traumatic events by demographic and behavioral factors, but instead found positive statistically significant association with longer commute lengths and on major streets without bicycle facilities.²⁸ Interpreted another way, the primary causes of bicycle rider injury were found to be increased risk exposure via higher traffic volumes and more time spent riding with traffic. A study by Wood et al. focused on the effectiveness of visibility aids for reducing collisions between bicycles and motor vehicles, and on perceptions of general visibility of bicycle riders. Expectedly, the study found significant disagreements in perceptions between bicycle riders and motor vehicle drivers, and in its conclusions encouraged greater use of visibility aids by bicycle riders in order to lower the risk of bicycle-motor vehicle collision.²⁹ However, there is no mention of any differences in speed and sightlines between bicycle riders and motor vehicle drivers, and I find the recommendations for increased use of visibility aids to be

²⁸ Hoffman et al., “Bicycle Commuter Injury Prevention: It Is Time to Focus on the Environment.”

²⁹ Wood et al., “Drivers’ and Cyclists’ Experiences of Sharing the Road.”

problematic. Although the study found agreement in their effectiveness by both bicycle riders and motor vehicle drivers, it seems morally questionable to place greater responsibility on the group of roadway users that are more vulnerable and, therefore, carry a significantly greater burden of injury.³⁰

2.3 ROLES OF BICYCLE PATHS AND OTHER INFRASTRUCTURE

In the 1970s, researcher John Forester argued for a “vehicular” cycling approach to riding a bicycle with traffic. The logic was that a person riding a bicycle would be safer and more respected by other road users were he or she to ride in the same manner as a motor vehicle, using the same turn lanes and obeying the same rules of the road. This idea quickly caught on, and even today its intent has been enshrined into law in state vehicle codes across the country. At the time, however, the United States did not have the menagerie of bicycle paths and other facilities that exist today, and so new approaches were made to accommodate the bicycle as a mode of traffic within the roadway in urban areas. With the growth of cycling as a transportation mode choice for commuting and other non-recreational trips, more cities have begun to incorporate various types of bicycle lane into the street network. Distinctly, the recent invention of neighborhood bicycle greenways, or “bicycle boulevards,” has introduced a new idea complementing existing bicycle lanes. Rather than attempting to separate bicycle traffic from motor vehicle traffic, as a painted bicycle lane would do in part or a protected bicycle lane would do in whole, the neighborhood greenway instead attenuates motor

³⁰ Chong et al., Relative Injury Severity Among Vulnerable Non-Motorised Road Users.”

vehicle traffic to be nearer to the speeds and volumes of bicycle riders while keeping the two transportation modes together in the same streetscape. Requiring less modification to the existing roadway than a protected bicycle lane, the neighborhood greenway is worth exploring as a tool to promote bicycle ridership in urban areas and also to reduce the potential for traffic collisions between bicycle riders and motor vehicle drivers.

2.4 NEIGHBORHOOD GREENWAYS IN SEATTLE

As a recent addition to Seattle’s streetscape, it is important to produce a definition for the neighborhood greenway, also known as a “bicycle boulevard” in other locations. In the Bicycle Master Plan, Seattle Department of Transportation describes neighborhood greenways as “non-arterial streets with low motorized traffic volumes and speeds, designated and designed to give bicycle and pedestrian travel priority.”³¹ This vague definition leaves a lot to the imagination: how are these streets designated as neighborhood greenways? In what way are they designed to be functionally different from a “normal” local street? The *Fundamentals of Bicycle Boulevard Planning & Design* published by Portland State University’s Center for Transportation Studies provides a more detailed description:

[...] bicycle boulevards are low-volume and low-speed streets that have been optimized for bicycle travel through treatments such as **traffic calming** and

³¹ Seattle DOT, *Seattle Bicycle Master Plan: April 2014*, 56.

traffic reduction, signage and pavement markings, and intersection crossing treatments.³² (emphasis added)

The National Association of City Transportation Officials' (NACTO) Urban Bikeway Design Guide gives a similar definition³³, as does the Regional Bike Facility Typology recommendations published by the Puget Sound Regional Council (PSRC).³⁴ In contrast, Washington State Department of Transportation's Design Manual gives bicycle boulevards a passing mention as locations in which one will usually find shared lane markings.³⁵ Usefully, the Bicycle Master Plan lists speed bumps, traffic circles, stop signs, chokers, partial street closures, median islands, and motor vehicle turn restrictions as common traffic calming techniques to be employed when designing neighborhood greenways in Seattle.³⁶ Combining these definitions, we come to an understanding that quite unlike bicycle facilities built as improvements onto the existing street (e.g. painted bicycle lanes), the neighborhood greenway is *an entire street transformed into a bicycle facility that physically encourages the perception of bicycles and motor vehicles as equal users of the street.*

This attempt to ascertain the definition of a neighborhood greenway begs the question: when is a greenway not a greenway? If a local non-arterial street carries a sign proclaiming it "Neighborhood Greenway" but has no traffic calming measures or other modifications, is it truly a greenway? If that sign is erected on a street classified as non-

³² Walker et al., *Fundamentals of Bicycle Boulevard Planning & Design*, 2.

³³ National Association of City Transportation Officials, *Urban Bikeway Design Guide*, 2nd ed.

³⁴ Puget Sound Regional Council, *Regional Bike Facility Typology*.

³⁵ Washington State DOT, *Design Manual M22-01.12*, 1520-7.

³⁶ SDOT, *Bicycle Master Plan*, 57.

arterial, with a posted speed limit of 20 miles per hour and an annual daily traffic volume of 1,500 motor vehicles or less, it meets the Bicycle Master Plan's facility designation guidelines for the installation of a neighborhood greenway.³⁷ Just as no two streets are perfectly alike in composition, it may be the case that not every designated greenway requires the same degree of modification to achieve a desired level of perceived rider comfort and safety. Additionally, as mentioned in Portland State University's design guidebook, wayfinding is an essential and important component of neighborhood greenway designation and design.³⁸ A properly calmed street is of little utility if a bicycle rider cannot easily navigate to desired destinations. With the idea of visual clarity in mind, perhaps it is appropriate that the Bicycle Master Plan makes an attempt at relative cohesion in neighborhood greenway design across the city.³⁹

2.5 OTHER BICYCLE FACILITIES' RELATIONS TO GREENWAYS

With a clearer understanding of the design of the neighborhood greenway, it is important to compare the functional relationships of other facilities in the bicycle network to greenways. Protected bicycle lanes and off-street trails play an almost exclusive role in the Citywide Network, but do so in opposite ways from neighborhood greenways by removing bicycles from motor vehicles rather than integrating them in the same street space. This is most commonly due to major differences in traffic volumes, protected bicycle lanes especially being constructed on arterial streets with average daily

³⁷ SDOT, *Bicycle Master Plan*, 38.

³⁸ Walker et al., *Fundamentals of Bicycle Boulevard Planning & Design*, 8.

³⁹ SDOT, *Bicycle Master Plan*, 39.

traffic volumes orders of magnitude higher than local streets designated for neighborhood greenways.⁴⁰ Painted-only bicycle lanes (in street, minor separation) and shared lane markings (“sharrows”) are two constituent elements of the Local Connectors network, their functions being to provide connections between local destinations, as well as between parts of the Citywide Network and to other areas of the city.⁴¹ In the existing bicycle network (as of Bicycle Master Plan publication 2014), there are 44.4 miles of in street, minor separation facilities and 30.0 miles of shared streets; the proposed network total increases these to 137.9 miles and 37.8 miles, respectively.⁴² Combined, these two facility types nearly equal the proposed length of neighborhood greenway miles in the Local Connectors network (175.7 mi vs. 177.9 mi), which will retain their importance in Seattle’s bicycle network for some time to come. However, if we are to find the “Strong and Fearless” and “Enthused and Confident” bicycle riders in Seattle’s painted lanes and sharrows, as Dill and McNeil found in Portland⁴³, we are likely to find the less confident bicycle riders elsewhere.

⁴⁰ Seattle DOT, *Bicycle Master Plan*, 37-38.

⁴¹ Seattle DOT, *Bicycle Master Plan*, 39.

⁴² Seattle DOT, *Bicycle Master Plan*, 40.

⁴³ Dill, *Four Types of Cyclists? Testing a Typology to Better Understand Bicycle Behavior and Potential*.

Chapter 3. RESEARCH AND DATA ANALYSIS

In the current Bicycle Master Plan, the Seattle Department of Transportation divides the city's existing and proposed bicycle network into two categories: the Citywide Network and the Local Connectors network. The primary purpose of these two designations is to identify parts of the bicycle network best suited to bicycle users of all ages and abilities.⁴⁴ In the context of this study, I define "all ages and abilities" to mean bicycle riders that span the range of experience from little/no experience to expert user, which includes those of any age able to ride a bicycle. According to the Seattle Department of Transportation, the two networks function in distinct but complementary ways: the Citywide Network (Figure 1) functions as an *interurban* network connecting urban centers and neighborhood destinations, and prioritizes separation from motor vehicles; the Local Connectors network (Figure 2) functions as an *intraurban* network connecting destinations within neighborhoods, and also provides routes to access parts of the Citywide Network.⁴⁵ Neighborhood greenways, protected Bicycle lanes, and off-street multi-use trails comprise the Citywide Network; shared streets ("sharrows"), in street, minor separation (painted-only) bicycle lanes, and the previously mentioned three facilities comprise the Local Connectors network.

⁴⁴ Seattle DOT, *Bicycle Master Plan*, 38.

⁴⁵ Seattle DOT, *Bicycle Master Plan*, 38-39.

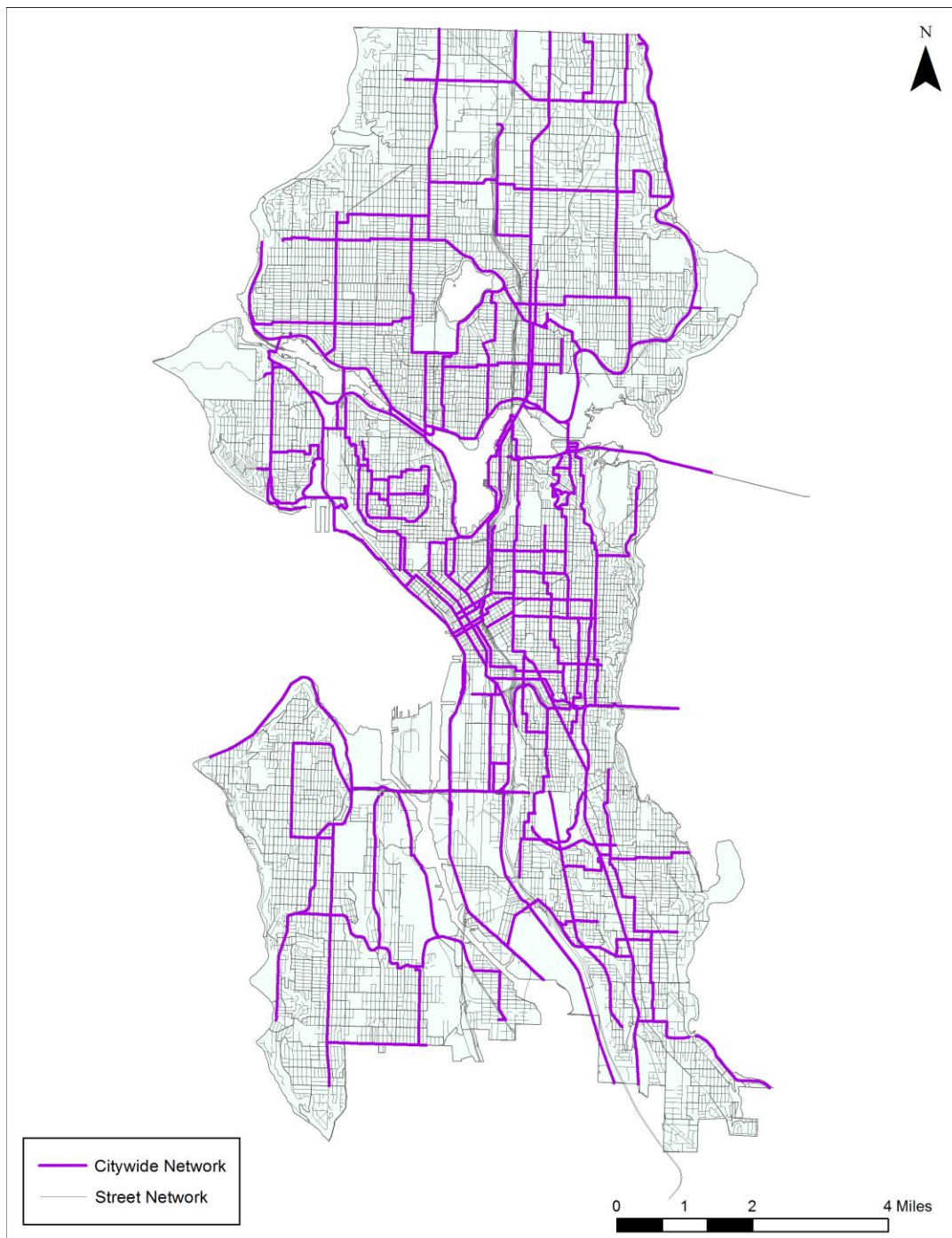


Figure 1. *Planned Citywide Network, Bicycle Master Plan.*
Map by Author (2017). Data source: Seattle Department of Transportation.

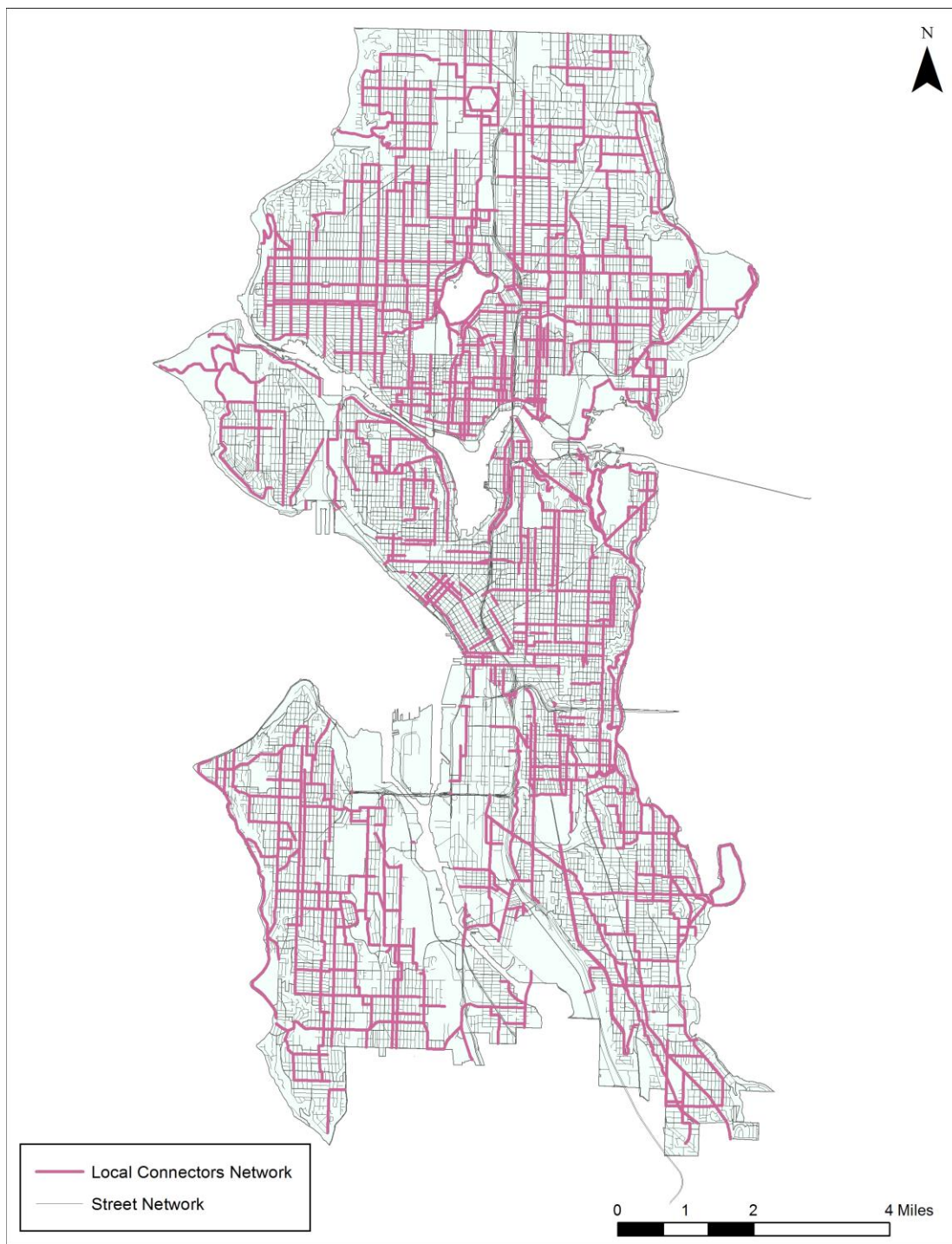


Figure 2. Planned Local Connectors network, Bicycle Master Plan.
Map by Author (2017). Data source: Seattle Department of Transportation.

By defining a purpose of the Citywide Network as to specifically provide facilities for bicycle riders of all ages and abilities, the Seattle Department of Transportation has created a hierarchy of perceived rider comfort and safety. This appears to complement the “four types of cyclists” hierarchical typology suggested by Geller in Portland⁴⁶, with the proposed bicycle network providing facilities options to match the preferences of bicycle riders in Seattle. Bicycle riders identified as the “Strong and Fearless” or “Enthusied and Confident” would more likely use the Local Connectors routes that offer shorter and more direct routes to destinations at the cost of decreased separation from motor vehicle traffic.⁴⁷ However, it is reasonable to assume that bicycle riders of all kinds place personal safety as a priority, and would likely choose routes with the least possible conflict with motor vehicles, if there are easily navigable bicycle facilities that provide said routes.⁴⁸ This is where the neighborhood greenway enjoys a unique position in the Bicycle Master Plan as a key facility in both the Citywide Network and the Local Connectors network. As of publication of the current Bicycle Master Plan in 2014, there were only 10.3 miles of neighborhood greenway in the City of Seattle (Figure 3). Seattle Department of Transportation’s proposal for the completion of the bicycle network calls for 71.0 mi as part of the Citywide Network and 177.9 mi as part of the Local Connectors – a 240.17% increase in neighborhood greenways citywide (Figure 4).⁴⁹ When complete, neighborhood greenways will comprise 41% of the entire bicycle network in Seattle. With this major change in bicycle network composition, it is important to understand exactly how neighborhood greenways influence the risk of

⁴⁶ Geller, “Four Types of Cyclists.”

⁴⁷ Seattle DOT, *Bicycle Master Plan*, 39.

⁴⁸ Broach, “Where Do Cyclists Ride? A Route Choice Model Developed with Revealed Preference GPS Data.”

⁴⁹ Seattle DOT, *Bicycle Master Plan*, 40.

collisions between bicycle riders and motor vehicle drivers, and how this decision of neighborhood greenway primacy will likely affect overall bicycle rider safety in Seattle.

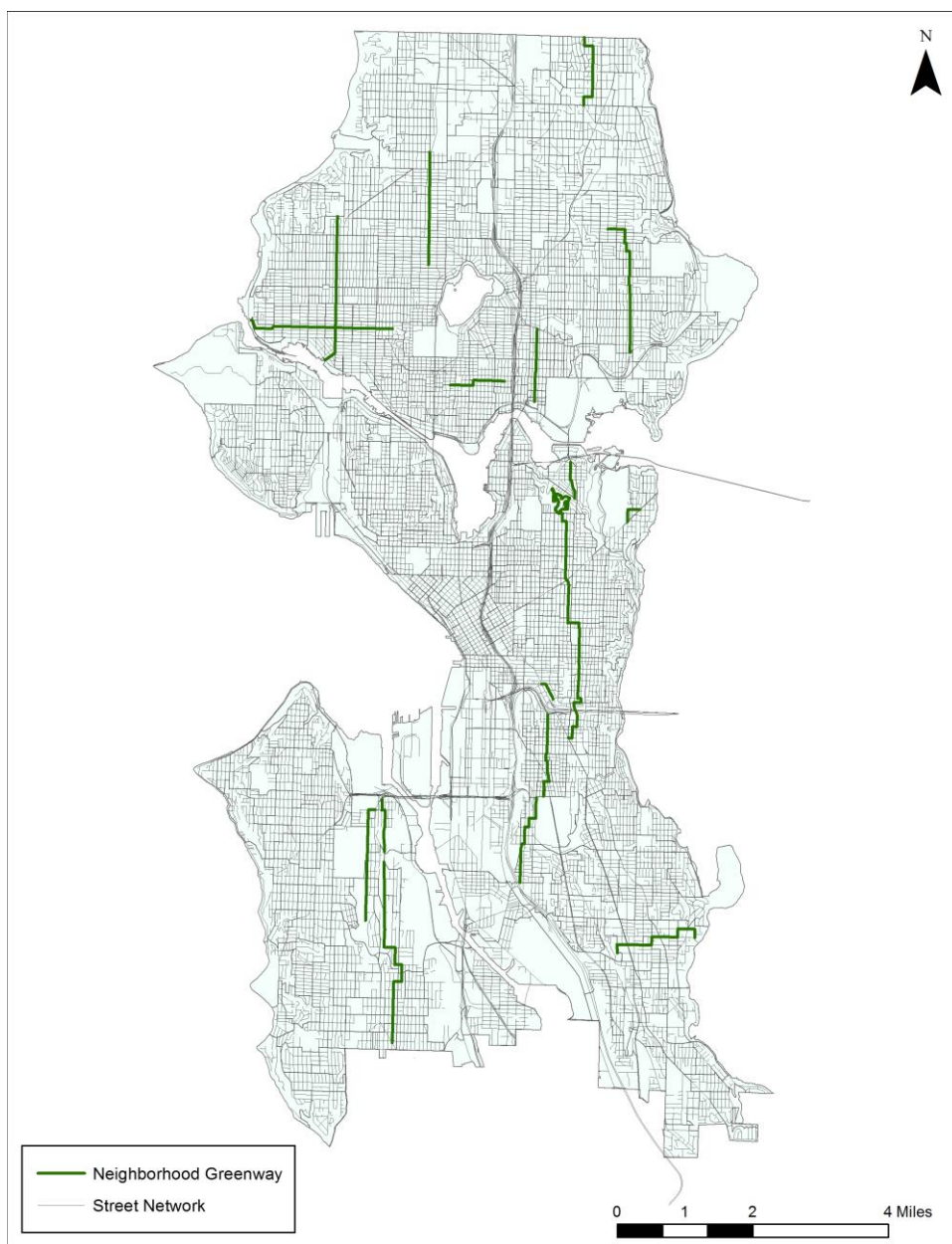


Figure 3. Existing neighborhood greenways, Seattle.
Map by Author (2017). Data source: Seattle Department of Transportation.

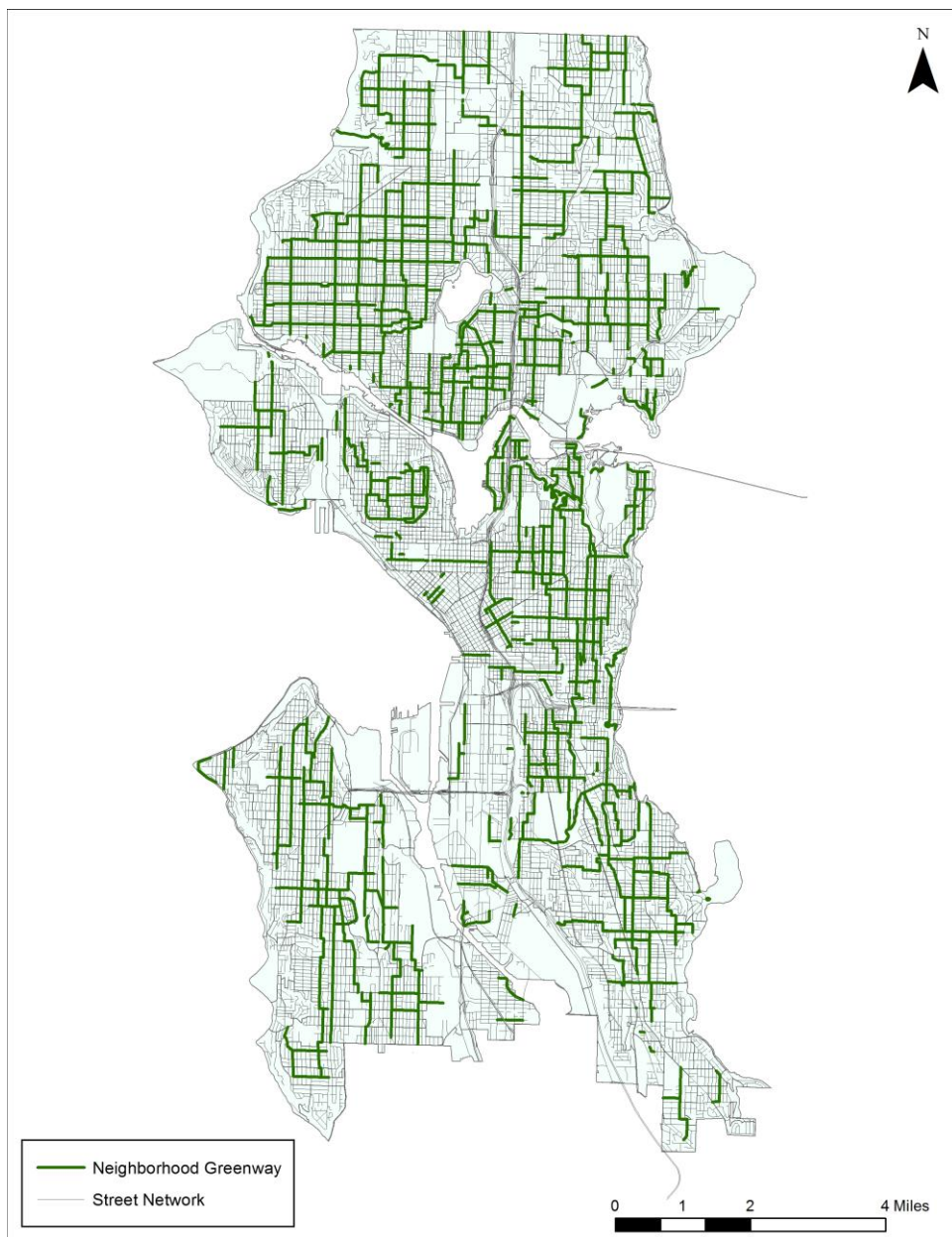


Figure 4. Planned neighborhood greenways, Bicycle Master Plan, Seattle. Map by Author (2017). Data source: Seattle Department of Transportation.

3.1 SEATTLE'S BICYCLE NETWORK AND BICYCLE RIDER SAFETY

Given the varying degrees of risk experienced by bicycle riders operating with traffic, what methods exist to mitigate that risk with respect to Seattle's bicycle network?

Seattle Department of Transportation's purpose of separating facilities into Citywide Network and Local Connectors, allowing bicycle riders to identify which routes present greater individual comfort and lower risk to safety, correlates to evidence shown by Broach et al. that preferred routes follow a path of least resistance.⁵⁰ In the case of the Bicycle Master Plan, those routes are designed around facilities that lower risk exposure to bicycle riders, either by separation of space for bicycles from traffic (protected bicycle lanes and off-street trails), or by directing bicycle riders to streets that have much lower traffic volumes and may contain traffic calming devices (neighborhood greenways). If risk exposure is greater at intersections due to greater points of conflict, then a reasonable solution would be to alter intersection designs to decrease points of conflict to the benefit of bicycle riders. However, Wachtel et al.'s study found that bicycle riders in the road experienced less frequent collisions with motor vehicles than bicycle riders on the sidewalk⁵¹, and the risk associated with driver inattentiveness at intersections found in studies by Turner and Wood leads me to believe that complete separation of bicycle and motor vehicle within an intersection may not produce the desired improvements in collision risk. If only focusing on points of conflict at intersections, then Turner's findings supporting Jacobsen's theory of "safety in numbers" inducing motorist behavioral change *at the intersection* may actually hold true.

⁵⁰ Broach, "Where Do Cyclists Ride?"

⁵¹ Wachtel, "Risk Factors for Bicycle-Motor Vehicle Collisions at Intersections."

With the findings stated above in mind, it seems logical to conclude that SDOT's plan to greatly increase the number of miles of neighborhood greenway within the bicycle network should produce positive outcomes to safety. The perception of risk by current and potential bicycle riders is real, and if facilities exist that lower this perceived risk, the likely outcome is that more people would choose to travel by bicycle in Seattle. This would theoretically reduce the number of people driving motor vehicles within the city, thereby also lowering risk exposure faced by people choosing to ride bicycles on city streets, in turn achieving the "safety in numbers" effect while also reducing the potential for bicycle-motor vehicle collisions. Given these assumptions, the evidence from the literature, and the actions proposed by SDOT, I will construct a multivariate linear regression model to determine which environmental factors show statistically significant correlations to bicycle-motor vehicle collisions, and therefore which elements of the Bicycle Master Plan SDOT will need to potentially modify or reinforce.

3.2 STUDY DESIGN

While changes to policy undoubtedly influence peoples' perceptions and behavior in regards to personal transportation, findings from my review of the literature indicate that environmental factors hold significant influence over bicycle-motor vehicle collisions. By drafting the Bicycle Master Plan, the Seattle Department of Transportation has created a framework dedicated to environmental changes through processes designed around bicycle facility prioritization, project delivery, and investment and funding strategies.⁵² Based on the literature, it appears that one of the primary culprits for collision incidents is the risk from bicycle riders' exposure to traffic volumes.⁵³ SDOT's emphasis on increasing miles of neighborhood greenways in Seattle would seem to follow this reasoning: create bicycle routes that encourage more people to travel by bicycle by decreasing their exposure to risk.

Thinking critically about environmental factors versus personal demographic or behavioral factors, a person's decision whether or not to wear a bicycle helmet does not influence overall risk exposure, and behavior modification by bicycle riders does not necessarily modify the behavior of motor vehicle drivers. For these reasons, I have chosen to only investigate environmental variables against the risk of bicycle-motor vehicle collision. To do so, I have used spatial geographic data to construct a multivariate linear regression model comparing differences in traffic volumes, arterial lane miles, and bicycle facility type and lane miles against bicycle-motor vehicle collision

⁵² Seattle DOT, *Bicycle Master Plan*, ii.

⁵³ Turner, "Predicting Accident Rates for Cyclists and Pedestrians."

incidents in the City of Seattle. My hypotheses for this study are: (1) that average daily traffic volume counts will show a positive association with bicycle-motor vehicle collisions; (2) that lane miles of non-arterial local streets will show a negative association with bicycle-motor vehicle collisions, and; (3) that lane miles of neighborhood greenways will show a negative association with bicycle-motor vehicle collisions (Figure 5).

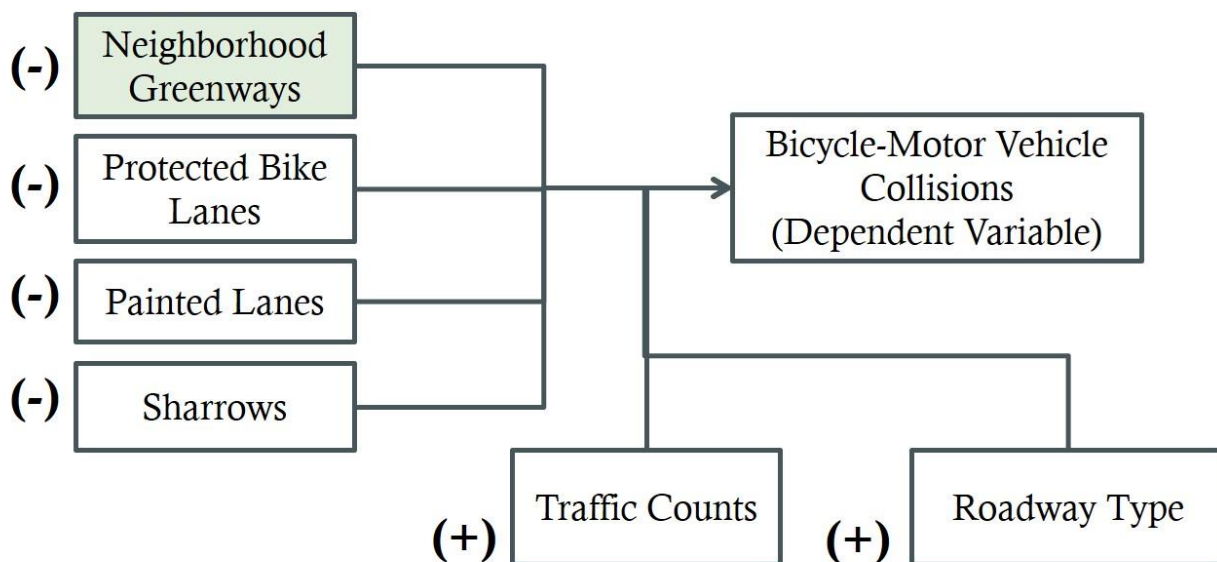


Figure 5. Conceptual map of research model.

3.3 METHODS

For this analysis, I collected publicly-available data from the City of Seattle's Open Data Program⁵⁴ and from King County's GIS Data Portal.⁵⁵ These data include:

- 2010 U.S. Census Block Groups (King County)
- Existing and Planned Bicycle Facilities – City of Seattle (SDOT)
- Traffic Volume Counts – City of Seattle (SDOT)
- Street Network – City of Seattle (SDOT)
- Traffic Collisions – City of Seattle (SDOT)

All data were available pre-formatted as “.shp” shapefiles suitable for use with geographic information systems (GIS) software; for this study, I made use of ESRI's ArcGIS 10.4 software suite for geographic data visualization and processing and performed the statistical analysis with R version 3.4.0 and R Studio version 1.0.143. The 2010 U.S. Census Block Groups were chosen to function as aggregation units with which to collect citywide data from the other shapefiles. Seattle Department of Transportation's data for existing and planned bicycle facilities allowed me to collect information on the bicycle facilities utilized in the Bicycle Master Plan, and allowed me to differentiate by attribute whether a facility currently existed or was planned for future projects. This dataset also included attributes for facility type and shape length in linear feet per object. Traffic volume counts for Seattle were seven-day counts conducted by

⁵⁴ City of Seattle, WA, Open Data Program, <https://data.seattle.gov>.

⁵⁵ King County, WA, GIS Data Portal, <http://www5.kingcounty.gov/gisdataportal>.

Seattle Department of Transportation from 1999 to 2017 and included average annual daily traffic for each study. Traffic collision incidents were recorded from 2004 to early 2017 and included collision incidents for all roadway users. This dataset included 179,978 collision incidents, of which 4,425 (2.46%) involved a bicycle and motor vehicle. The dataset for the City of Seattle's street network included roadway classification attribute information and allowed me to differentiate sections of roadway based on arterial class set by the Washington State Department of Transportation.

To begin the task of processing the data for analysis, I began by selecting collision records in the Traffic Collisions file that were recorded as between a motor vehicle in operation and a pedalcyclist in traffic (Seattle DOT collision codes: 17-23, 57-63) and exported those records to a separate data file. Records that contained no recorded personal injuries and were listed as "Property Damage Only Collision" were retained, since this study focuses on bicycle-motor vehicle collision incidents and not just injury incidents. I then added an attribute field named "COLL_COUNT" and gave every entry a value of "1" to create a count of collision incidents (4,425 total) and used a spatial join process to assign bicycle-motor vehicle collisions to the census block groups with which they overlapped. I used the sum of bicycle-motor vehicle collisions per block group as my dependent outcome variable for the regression analysis (Figure 6).

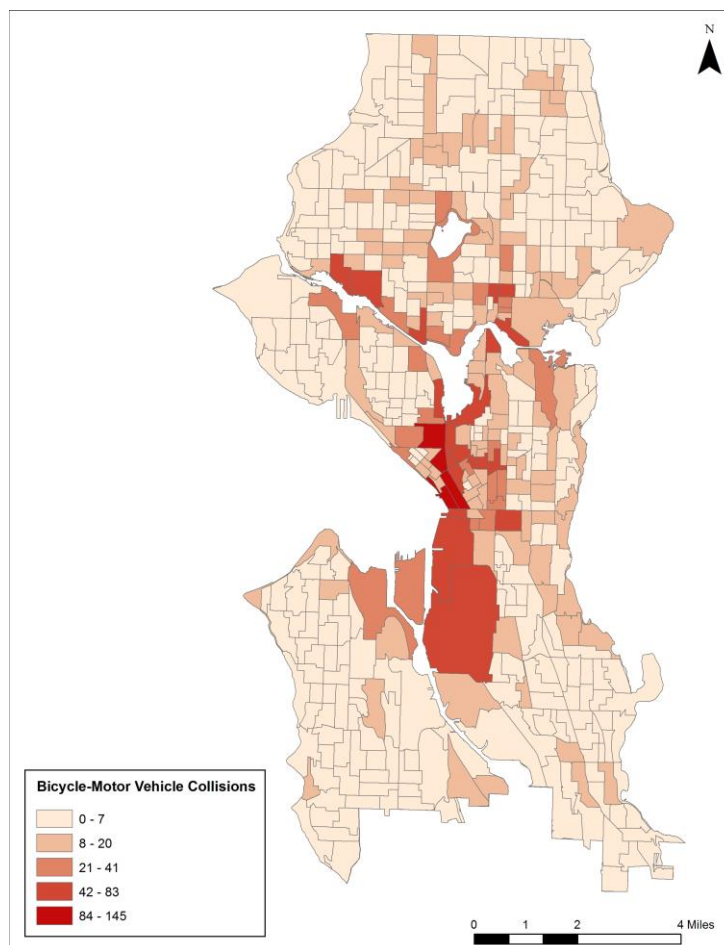


Figure 6. Distribution of bicycle-motor vehicle collisions by census block group. Map by Author (2017). Data source: Seattle Department of Transportation.

For my explanatory independent variables, I decided to use linear feet of street arterial classes, linear feet of bicycle facilities, and the mean of average daily traffic volume counts, and aggregated each by census block group. The Bicycle Master Plan contains guidelines for bicycle facilities based on arterial class traffic volumes⁵⁶, and evidence from the literature review shows that higher average traffic volumes are associated with increased bicycle-motor vehicle collisions.⁵⁷ I selected segments of the street network by arterial class (principal arterial; minor arterial; collector arterial; local street) and

⁵⁶ Seattle DOT, *Bicycle Master Plan*, 38.

⁵⁷ Turner, "Predicting Accident Rates for Cyclists and Pedestrians."

exported records of each class into four separate datasets. I performed a similar process for the bicycle network data by selecting entries that were coded as existing facilities (rather than planned) and by facility type (neighborhood greenway; protected bicycle lane; minor separation (painted lane); shared street (sharrow), and extracted those into four separate datasets. A fifth bicycle facility, off-street trails, was excluded from this analysis due to my assumption that collisions found on those facilities would involve other bicycle riders or pedestrians and not motor vehicles. To match the data of each variable to the census block groups in Seattle, I created an iterative process similar to the one I used to aggregate the bicycle-motor vehicle collision data and ran the process for each of my nine explanatory variables:

- (1) I used a spatial join to assign each observation to one of the 501 block groups by block group ID string;
- (2) I then dissolved all observations in the dataset by the census block group string and added a statistics field (sum for arterial/bicycle facility lengths; mean for average ADT counts);
- (3) before joining the dissolved variable dataset to the block group dataset, I added a blank field to the attribute table of the block group dataset to copy the aggregated numbers from the dissolved data;
- (4) I then joined the dissolved variable dataset to the block group dataset and copied the necessary statistics data to the blank field I added to the block group table, and then removed that join (Figure 7).

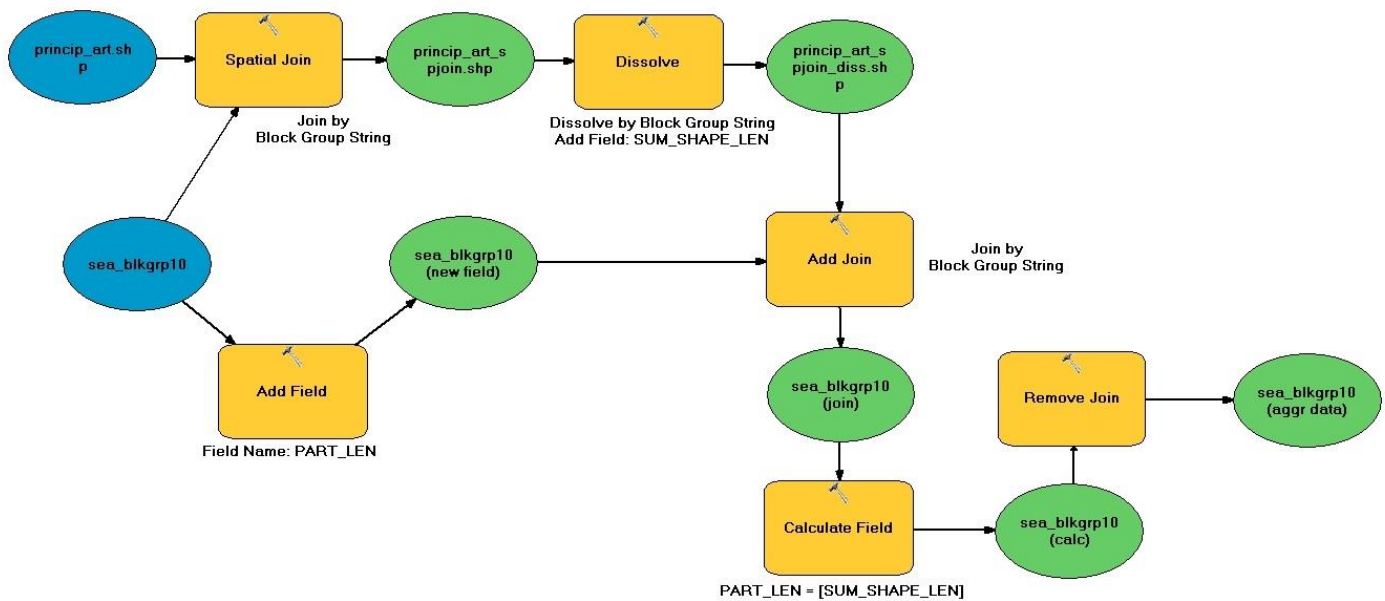


Figure 7. Example of data aggregation process (principal arterial length per block group).

As a final step in the process, I checked a summary of the bicycle-motor vehicle collisions recorded for each census block group. Of the 501 block groups, 84 contained no recorded motor vehicle collisions. As my study is examining bicycle-motor vehicle collisions *as a function* of several environmental variables, it would be of little explanatory value to calculate the predicted effects of those variables for a block group in which no bicycle-motor vehicle collisions had occurred. I decided to remove those block groups from my dataset and pursued my analysis with the remaining 417 block groups across Seattle.

After completing the aggregation processes, I was left with all ten variables necessary for my regression model. Looking at a geographic distribution of the data, it is immediately clear that the majority of the street network in Seattle is composed of non-arterial local

streets, which are fairly well distributed around the city (Figure 8). It would therefore make sense, from a facilities standpoint, for Seattle Department of Transportation to create a tremendous amount of neighborhood greenways as part of the proposed bicycle network, given that the Bicycle Master Plan's Facility Designation Guidelines use average traffic volume and street classification for bicycle facility designation (Figure 9).⁵⁸

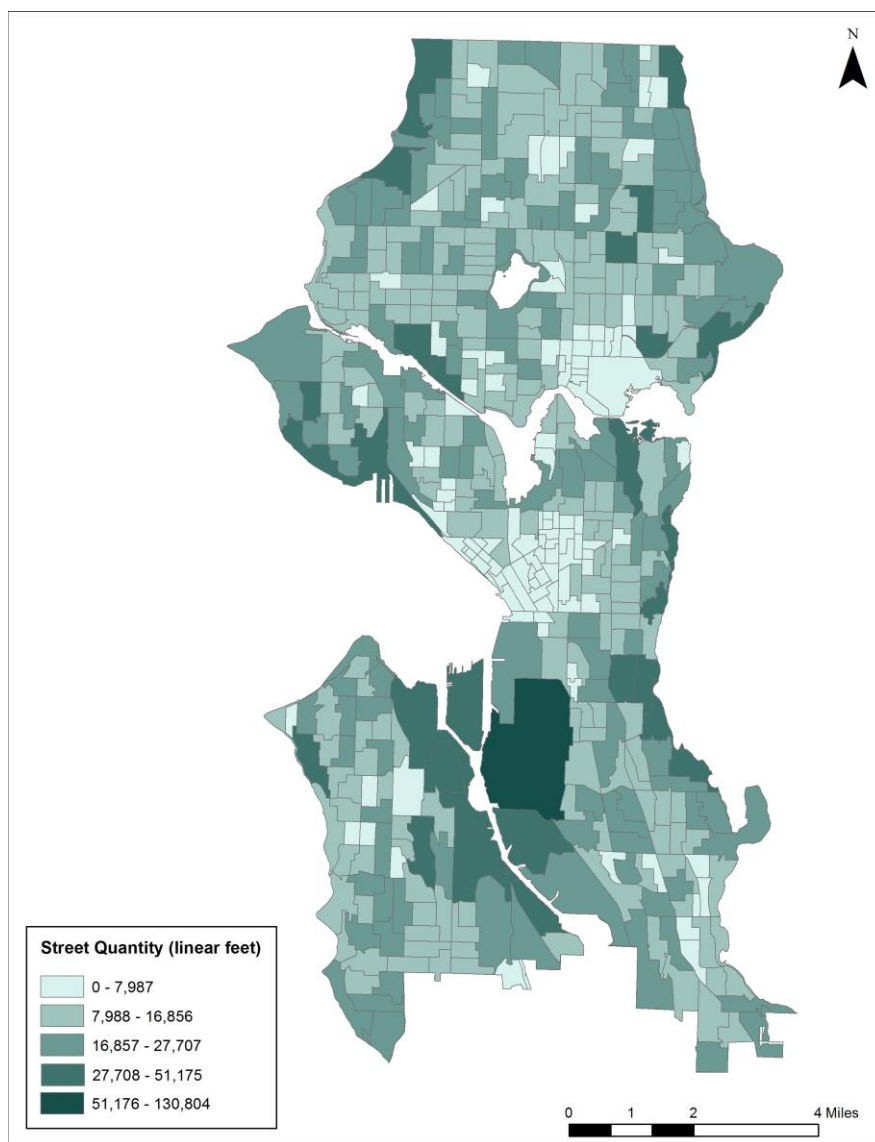


Figure 8. Distribution of local streets, aggregated by Seattle census block group. Map by Author (2017). Data source: Seattle Department of Transportation.

⁵⁸ Seattle DOT, *Bicycle Master Plan*, 38.

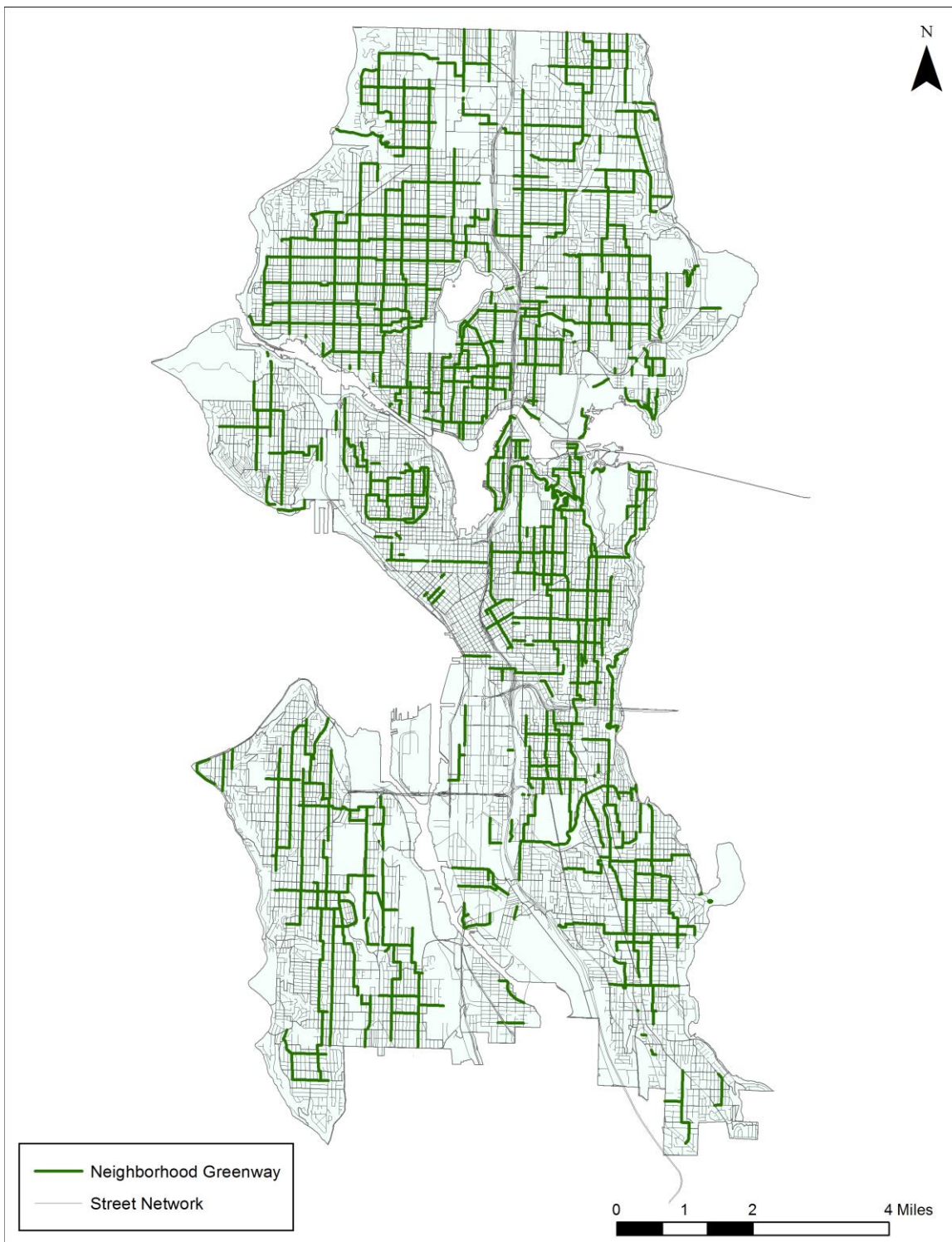


Figure 9. Proposed neighborhood greenways.
Map by Author (2017). Data source: Seattle Department of Transportation.

With the aggregated data in hand, I exported the shapefile attribute information into an Excel spreadsheet file and loaded the data into R Studio in order to conduct the statistical analysis. Upon my first review of the data, I noticed that bicycle-motor collisions and average traffic volume counts were extremely skewed with positive distribution biases (Figures 10 and 11). In order to normalize the distributions of the data, I appended the dataset with two new attributes containing the natural log transformations of bicycle-motor vehicle collisions and average traffic volume counts. These new data were not perfectly distributed, but had much better fit than the original distributions (Figures 12 and 13).

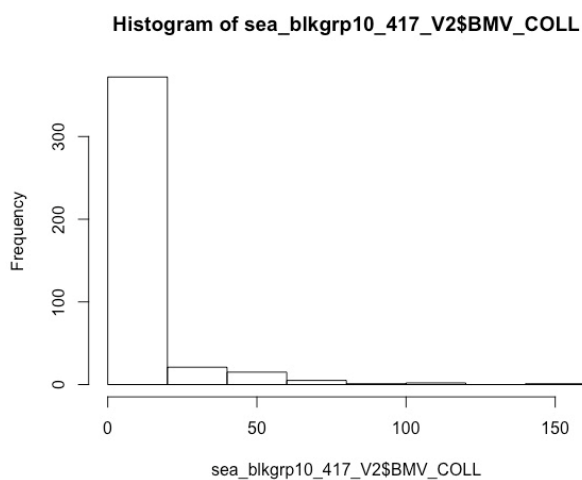


Figure 11. Distribution of bicycle-motor vehicle collisions.

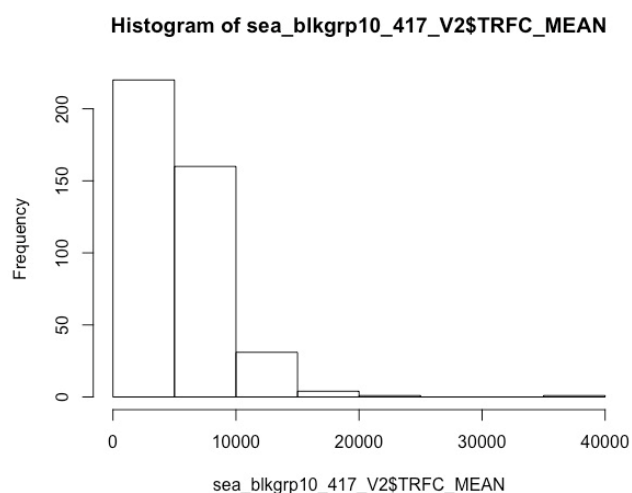


Figure 10. Distribution of average traffic volume counts.

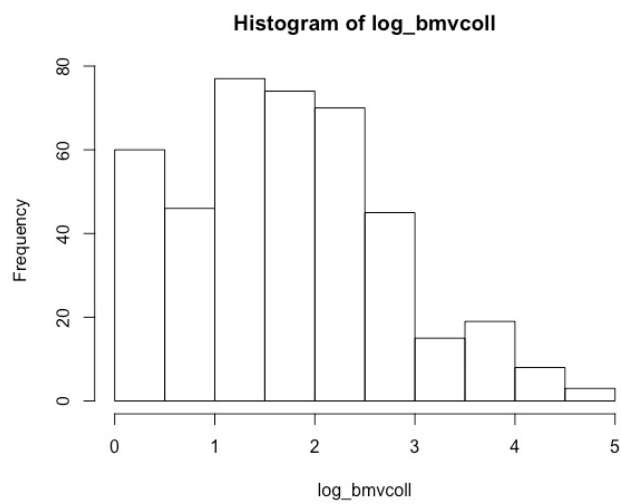


Figure 13. Distribution of log of bicycle-motor vehicle collisions.

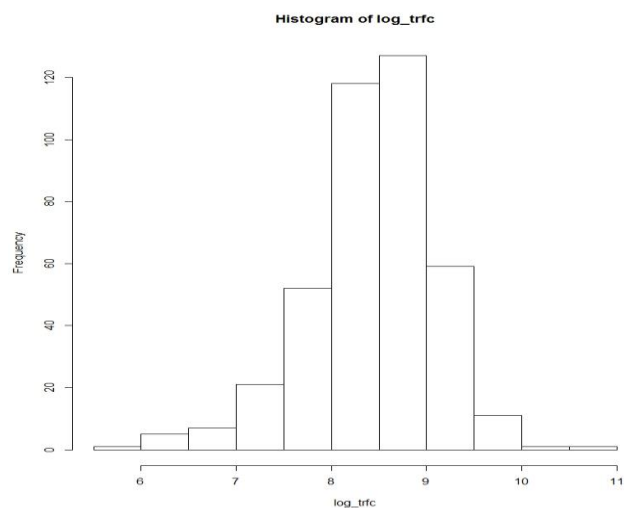


Figure 12. Distribution of log of average traffic volume counts.

Examining the rest of the data, I decided to also transform the total lane feet of bicycle paths (i.e. protected bicycle lane, paint-only lane, sharrows, and neighborhood greenways) into percent of street arterial lane feet. My rationale for this decision was that, unlike an off-street path, the bicycle paths I was investigating were part of the existing street scape, and therefore it would be logical to examine them as proportions of the roadway. In other words, if a census block group had 200 lane feet of painted bicycle lanes and 5,000 combined lane feet of collector arterials, that census block group would have painted bicycle lanes along 4% of those collector arterial streets. In order to calculate these data, I consulted Seattle Department of Transportation's Facility Designation Guidelines to classify each bicycle path type according to the street arterial class to which each facility type is designated (Table 1). The process for this initial data transformation was as follows:

- $Percent\ of\ Neighborhood\ greenways = (lane\ ft\ of\ NG / lane\ ft\ of\ local\ streets) * 100$
- $Percent\ of\ sharrows = (lane\ ft\ of\ sharrows / (lane\ ft\ of\ local\ streets + collector\ arterials + minor\ arterials)) * 100$
- $Percent\ of\ painted\ bike\ lanes = (lane\ ft\ of\ painted\ lanes / (lane\ ft\ of\ collector\ arterials + minor\ arterials)) * 100$
- $Percent\ of\ protected\ bike\ lanes = (lane\ ft\ of\ PBL / (lane\ ft\ of\ minor\ arterials + principal\ arterials)) * 100$

Table 1. Bicycle facility designation guidelines (modified from SDOT Bicycle Master Plan 2014).

Generalized Bicycle Facility Designation	Bicycle Facility Types	Posted Speed Limit (mph)	Average Daily Traffic (ADT) per day	Street Classification
Neighborhood greenway	Neighborhood Greenway	20	1,500 or less	Non-arterial
Shared street	Shared lane pavement marking (sharrow)	25 – 30	To be used due to ROW constraints or topography	Non-arterial and Collector/Minor
In street, minor separation	Bicycle lane; Climbing lane	30	8,000 or less	Collector arterial
	Buffered bicycle lane	30	15,000 or less	Collector/minor
Protected bicycle lanes	Physically separated (raised or with barrier on-street facility)	30 and greater	15,000 and above	Minor/Principal arterials

After transforming the data, I noticed unusual results. My calculations for the proportions of bicycle facility types produced maximum values of 100% or greater; in particular, painted-only bicycle lanes had a maximum value of 685% of the sum length of collector and minor arterials. To me, this signaled the fact that although Seattle Department of Transportation intends to follow these guidelines *moving forward* with planned bicycle facility construction, the facts on the ground were that Seattle

Department of Transportation previously built much of the existing bicycle network without strictly following these guidelines. In the case of painted-only bicycle lanes, which according to the Bicycle Master Plan facilities guidelines *should only* be built on collector and minor arterials, it was evident given my calculations that Seattle Department of Transportation had likely built a significant amount of painted-only bicycle lanes on principal arterials in the past. A review of the geographic attribute data in ArcMap confirmed my theory, in which many street segments with planned protected bicycle lanes had existing painted-only lanes. Therefore, I created a new value in my dataset that was the sum of the lane feet of all four arterial classes (principal, minor, collector, non-arterial). I then created four new data transformations of the original data using the previous method (*percent of [bike path] = (lane ft of [bike path] / total lane ft of streets) * 100*) and appended those values to the dataset. Using these revised variables that better reflected what I had discovered, I constructed a multivariate linear regression model within R Studio using the following equation:

$$\begin{aligned} \log \text{ of collisions} \sim & \log \text{ of traffic volume counts} + \text{principal arterial length} + \text{minor arterial length} \\ & + \text{collector arterial length} + \text{non-arterial length} + \% \text{ of protected bicycle lane length} + \\ & \% \text{ of painted-only lane length} + \% \text{ of sharrows length} + \% \text{ of greenways length} \end{aligned}$$

After running the model above, I found it to be statistically significant. Subsequent models removing variables not showing statistical significance did not improve overall model goodness of fit, which led me to use the first model for my analysis.

Chapter 4. RESULTS

Table 2. Summary statistics of regression model variables.

Variable	Mean	Median	Min	Max	Std. Dev.
Explanatory Variables					
Neighborhood greenways (% lane ft of streets)	1.81	0	0	30.98	4.81
Protected bicycle lanes (% lane ft of streets)	1.07	0	0	49.12	4.56
Painted-only bicycle lanes (% lane ft of streets)	5.24	0.85	0	49.06	7.38
Sharrows (% lane ft of streets)	5.5	1.38	0	43.68	8.11
Average traffic volume counts (n)	5,380	4,763	0	38,358	3,725.18
Principal arterials (n lane ft per block group)	2,271.8	679.1	0	69,203.5	5,082.39
Minor arterials (n lane ft per block group)	2,131.4	1,526.8	0	34,317.7	2,744.92
Collector arterials (n lane ft per block group)	1,513	840.1	0	14,748.2	2,715.66
Non-arterials (n lane ft per block group)	13,810	12,558	0	130,804	9,984.64
Dependent Variable					
Bicycle-motor vehicle collisions (n)	10.57	5	1	145	15.73

Data from Table 2 show an average of more than 10 bicycle-motor vehicle collision incidents per Seattle census block group of a total of 4,407, with a maximum of 145 collisions recorded from 2004 to 2017 in a single block group. On average, 72% of the total linear feet of streets per block group was composed of non-arterial local streets, indicating a wide distribution across the city (Figure 7). Each block group had an average of 5,380 motor vehicles counted driving within that block group per day, with the busiest block group experiencing more than seven times that amount. The average linear feet of non-arterial local streets per block group was greater than the averages of all other arterial classes combined, clearly making it the most commonly found street type in Seattle. On average, each block group had no greater than 13.6% of the existing roadway featuring any type of bicycle facility; per block group, painted sharrows were

mostly likely (5.5%) to be found in the street network and protected bicycle lanes were least likely (1.07%) to be found.

Table 3. Summary statistics for regression model.

Dependent variable: Bicycle-motor vehicle collisions		
	Est. Coefficient	p-value
Neighborhood greenways (% lane ft of streets)	0.02017	< 0.05
Protected bicycle lanes (% lane ft of streets)	0.02137	< 0.05
Painted-only bicycle lanes (% lane ft of streets)	0.03209	< 0.05
Sharrows (% lane ft of streets)	0.00786	> 0.05
Average traffic volume counts (log transformed)	0.4276	< 0.05
Principal arterials (lane ft per block group)	0.000051	< 0.05
Minor Arterials (lane ft per block group)	0.000096	< 0.05
Collector Arterials (lane ft per block group)	0.000057	< 0.05
Non-Arterials (lane ft per block group)	-0.000025	< 0.05
Intercept (log transformed)	-2.197	< 0.05
Adjusted R-squared	0.3625	
F-statistic	26.33	
p-value	< 0.00	

Looking at a summary of the regression model in Table 3, it is clear that all but one of the explanatory variables show statistical significance (p-value < 0.05). Average traffic volume counts per block group showed the greatest positive correlation, and by also having a statistically significant p-value the results support my first hypothesis that average daily traffic volume counts will show a positive association with bicycle-motor vehicle collisions. Lane feet of non-arterial local streets per block group was the only variable with a negative correlation, which supports my second hypothesis that lane miles of non-arterial local streets will show a negative association with bicycle-motor

vehicle collisions. Curiously, all four of the bicycle facility types showed positive correlations to bicycle-motor vehicle collision incidents, but the percent of sharrows per block group was the only variable in the entire model not to show statistical significance ($p = > 0.05$). The positive correlation shown by the percent of neighborhood greenways per block group did not support my third hypothesis that lane miles of neighborhood greenways will show a negative association with bicycle-motor vehicle collisions.

Goodness of fit for my regression model was calculated as R-squared = 0.3625 and the F-statistic was significant (p -value < 0.05), meaning that the explanatory variables in the model provided a better fit than a model of only the intercept, and also proved the statistical significance of the R-squared value. Additional diagnostic tests of my regression model indicated that predicted residuals were normally distributed and that the model displayed no violations of the normal assumptions of ordinary least squares linear regression (see Appendix). Taking into account the log transformations of average traffic volume counts and bicycle-motor vehicle collisions, the model would predict a 4.2% increase in bicycle-motor vehicle collisions for any 10% increase in motor-vehicle traffic ($1.10^{0.4276} = 1.0416$). For every additional mile of non-arterial local streets in a given block group, the model would predict a 12.4% decrease in bicycle-motor vehicle collisions ($\exp(5280 * -0.000025) - 1 = -0.1237$).

4.1 DISCUSSION

Results from the linear regression model (Table 3) largely proved my assumptions, but delivered some surprises. Aggregated mean average daily traffic volume counts, which I predicted to show a strong association with bicycle-motor vehicle collisions, were statistically significant and displayed the strongest correlation of the explanatory variables. All four variables of street arterial class showed statistical significance, and local streets showed a negative association with the log of bicycle-motor vehicle collisions – affirming two of my hypotheses. The four variables of bicycle facility type all showed positive associations with bicycle-motor vehicle collisions, and of those four only the percent of sharrows per block group showed a statistically insignificant association. Although the results from this analysis show overall model significance, the variables examined in the model only explain 36.3% of the factors influencing bicycle-motor vehicle collision incidents in Seattle. With the combined results in hand, it was clear that additional information would be required to determine all statistically significant causes of bicycle-motor vehicle collisions in the city.

A study performed by Wier et al. used a similar multivariate linear regression analysis to study collisions between pedestrians and motor vehicles in San Francisco. Aggregated at the census tract level, they used explanatory variables of street characteristics, land use characteristics, and population demographics to model which factors produced statistically significant associations with pedestrian-motor vehicle injury collision

incidents.⁵⁹ They found traffic volume per census tract to have the highest positive correlation with pedestrian-motor vehicle injury collisions, followed by number of employees, proportion of land zoned neighborhood commercial, proportion of arterial streets without mass transit, and resident population. Wier et al.'s study did not use non-arterial local streets as an explanatory variable, but if they had I would assume that they would find a negative correlation similar to my own findings. Based on these results, as well as evidence from other studies, it would appear to be conclusive that traffic volume in the roadway carries a strong association with collision incidents between motor vehicles and non-motorized users (bicycle riders or pedestrians). This conclusion also supports my first hypothesis, in which I felt the most confident. If the results of my model were significant, why didn't it show a better overall goodness of fit?

My regression analysis, based on geographic distributions aggregated at the census block group scale, was a form of ecological statistical analysis; that is, it attempted to associate variables at an area observation level (via block groups) rather than at an individual observation level. This coarser grain of detail in regards to the data likely leaves out some nuance in the associations between variables. When building my model, I purposefully chose explanatory variables that were not related to weather, population demographic, or user behavior; in other words, only factors that could in theory be altered by the municipality. Rather successfully, my model was able to predict over one-third (36.3%) of all bicycle-motor vehicle collisions in Seattle, which could likely influence policy decisions on the small subset of all potentially significant variables that

⁵⁹ Wier et al., "An Area-Level Model of Vehicle-Pedestrian Injury Collisions..."

I analyzed. However, there was a significant absence of a crucial piece of data: bicycle rider traffic counts. At the time of study, the City of Seattle had no citywide aggregated bicycle rider traffic counts available, and only limited counts performed at a handful of intersections and bridge crossings. Similar to the average traffic volume counts, this information would help illuminate overall bicycle rider traffic volumes per census block group, and the absence of this information automatically reduces the reliability of any regression model using average traffic volume counts as explanatory variables. As a test during the data analysis, I decided to perform the same regression model using the original dataset of all 501 block groups, in which 84 block groups contained no bicycle-motor vehicle collision incidents. One might assume that these 84 block groups contained the right proportion of the explanatory variables in which a bicycle-motor vehicle collision *would not* occur. However, there was no significant difference in the results of this second model (adjusted R-squared was also 0.3625), and so I could not conclude that the absence of bicycle-motor vehicle collisions in a block group was the result the combined influence of my explanatory variables. If Jacobsen's theory of "safety in numbers" holds any validity, then a citywide record of bicycle rider traffic counts could potentially prove or disprove that theory with respect to bicycle-motor vehicle collisions in Seattle. However, that still may not assist the regression model to explain the observed geographic clustering of bicycle-motor vehicle collision incidents (Figure 14). If intersections and their attendant increases in risk exposure are shown to correlate with bicycle-motor vehicle collisions⁶⁰, then perhaps there is a similar phenomenon occurring at the locations of the clustering. This would be an important

⁶⁰ Wang, "Estimating the Risk of Collisions Between Bicycles and Motor Vehicles at Signalized Intersections."

variable to study in a future model, as 57.2% of bicycle-motor vehicle collision incidents recorded in Seattle from 2004 to 2017 occurred at intersections of streets.

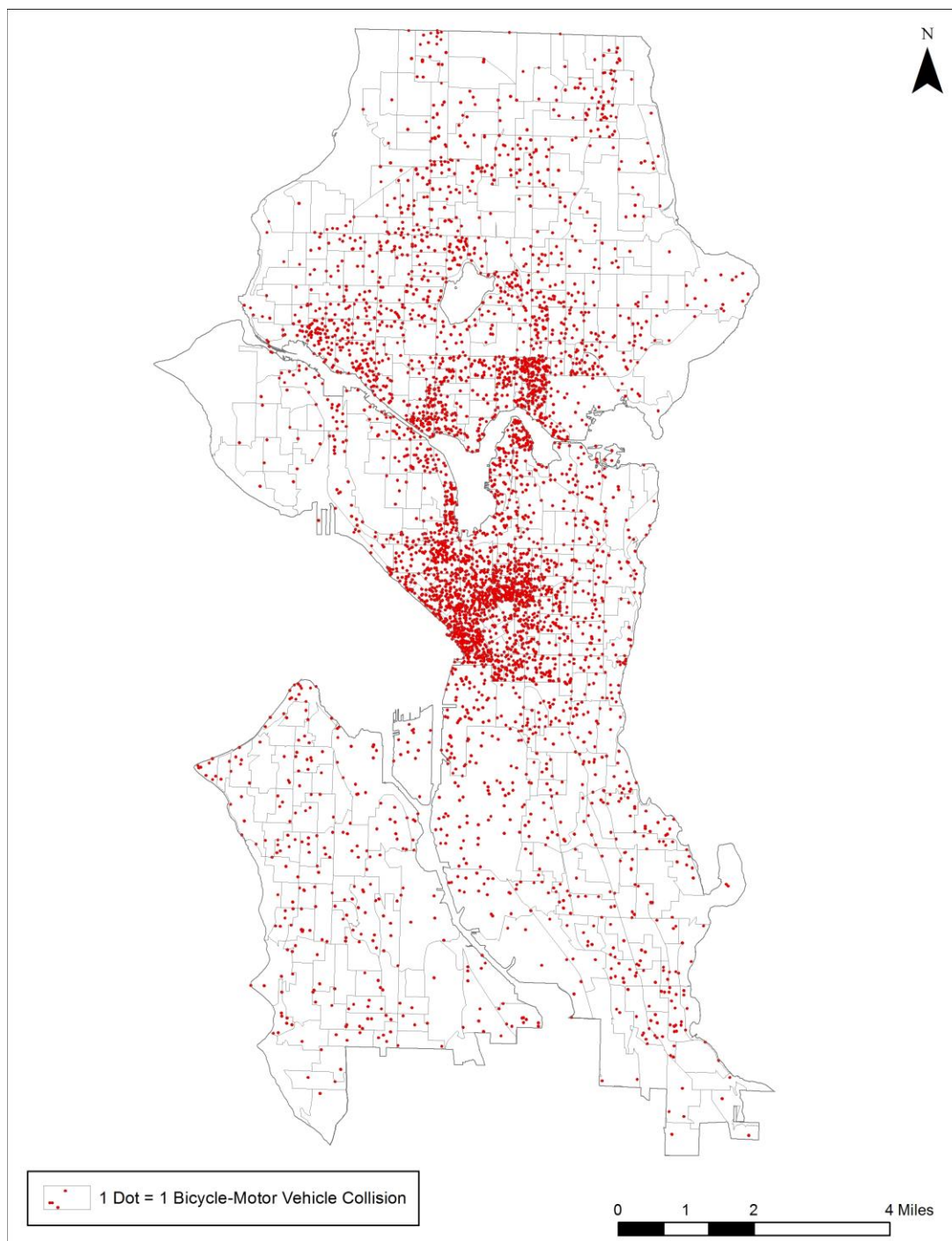


Figure 14. Distribution of bicycle-motor vehicle collisions in Seattle (2004-2017).
Map by Author (2017). Data source: Seattle Department of Transportation.

The results of the model in relation to the different types of bicycle path were unusual. I assumed that my model would show a negative correlation between bicycle facilities and bicycle-motor vehicle collision incidents, but was perplexed when all four types displayed positive correlations. Why would this be the case? Two thoughts came to mind: first, if a street with a bicycle facility draws bicycle riders to it, a collision between bicycles and motor vehicles would be predicted to occur; there would be no prediction of a collision if bicycle riders are not present on a given street. Second, there may be a behavioral element involved due to relative inexperience of bicycle riders new to using these facilities and of drivers new to increased numbers of bicycle riders on Seattle streets. With more facilities attracting more bicycle riders, and with those new riders gaining more experience, there may be a change in the trends shown by the model. Although this second idea is beyond the predictive ability of my model, what the model does show is that of the three bicycle facility types showing statistical significance, neighborhood greenways predicted the smallest increase in bicycle-motor vehicle collisions (see estimated coefficients in Table 3).

A problem that remains is the presence of census block groups that contained no bicycle-motor vehicle collision incidents. Since the spatial join I employed to assign collision incidents to block groups relied on a simple geographic intersection of points and polygons within ArcMap, it is possible that errors occurred during the assignment. However, I do not believe that any potential errors would have been significant enough as to remove collision incidents from 84 of the 501 block groups. These block groups truly could have no record of collisions between bicycles and motor vehicles, which leads me to consider another potential source of bias in the data: missing collision incident

reports. Juhra et al. found a large discrepancy in Münster, Germany between hospitalization records of injuries related to bicycle-motor vehicle collisions and the same incidents in police records, indicating that the majority of collision incidents there go unreported.⁶¹ Turner et al. also found evidence of under-reporting in their study in New Zealand⁶², indicating that this problem is not confined to particular countries and cities. Anecdotally, I have personally witnessed a bicycle-motor vehicle collision occur in which neither party discovered personal injury at the scene and declined to call for police assistance – an example of one missing data point in Seattle’s collision records. If there are significant numbers of unreported bicycle-motor vehicle collision incidents in Seattle (which I can neither prove nor disprove), then that might explain some of the unusual results and poor model performance found in my regression analysis.

Ultimately, the results showed statistical significance for my first and second hypotheses: that average daily traffic volume counts will show a positive association with bicycle-motor vehicle collisions, and; that lane miles of non-arterial local streets will show a negative association with bicycle-motor vehicle collisions. Even though my regression model could not explain all of the possible reasons why collisions between bicycle riders and motor vehicle drivers occur, it did raise several questions. Minikel et al.’s study in particular showed a case for reducing risk exposure to bicycle riders, finding that arterial roads with higher traffic volumes were associated with significantly more bicycle-motor vehicle collision incidents than local streets with lower traffic

⁶¹ Juhra et al., “Bicycle Accidents – Do We Only See the Tip of the Iceberg?”

⁶² Turner, “Predicting Accident Rates for Cyclists and Pedestrians.”

volumes⁶³, which agrees with the results seen in the study by Wier et al. and in my own study. Several studies advocate the use of various forms of bicycle infrastructure, but a literature review by Mulvaney et al. found no conclusive evidence to suggest that bicycle infrastructure displayed any effectiveness at reducing injuries.⁶⁴ This study might appear to make the results of my regression analysis seem more credible, but the authors themselves cautioned against inferring that bicycle infrastructure was without value, and attributed their results to likely cases of operator error. Additionally, given the preponderance of evidence that suggests otherwise, I would have to argue that bicycle facilities have merit, but perhaps there are other non-roadway factors diminishing their effectiveness in reducing bicycle-motor vehicle collisions. It is possible that my idea of user inexperience is a factor *at present*, and so it would be wise to revisit this model once more of the planned bicycle network has been built. Given the entirety of the evidence presented above, it is highly likely there are unknown factors influencing the likelihood of collisions between bicycle riders and motor vehicle drivers.

⁶³ Minikel, *Cyclist Safety on Bicycle Boulevards and Parallel Arterial Routes.*”

⁶⁴ Mulvaney et al., “*Cycling Infrastructure for Reducing Cycling Injuries in Cyclists (Review).*”

Chapter 5. CONCLUSION

Although my regression model was limited in its explanatory power (adjusted R-squared = 0.3625), there are several conclusions that can be drawn from the results. Non-arterial local streets were shown to have a statistically significant negative association with bicycle-motor vehicle collision incidents, and although neighborhood greenways did not show the same association in my study, the fact that they are designated and built on non-arterial low volume streets leads me to conclude that neighborhood greenways should be considered to possess an increased likelihood of bicycle rider safety compared to arterial streets alone. Results from other studies have shown positive safety outcomes from the presence of neighborhood greenways⁶⁵, and although facilities that physically separate bicycle riders from motor vehicle traffic are clear ways to reduce risk exposure, the data from my study and others suggest that greenways are an appropriate bicycle facility for low-volume local streets. Conversely, the data from my study show a significant positive association between painted bicycle lanes and bicycle-motor vehicle collisions; if numbers of bicycle riders were to increase, then it is likely that collision incidents would increase at these bicycle facilities. Although the lines of a painted-only bicycle lane create a legally separate lane of traffic, it is an unfortunate reality that motor vehicle drivers routinely violate that lane separation, and so some proportion of collision incidents is to be expected. However, we expect that a protected bicycle lane will mitigate those expected collisions. The reality here is that a protected bicycle lane is not completely protected along all of its path, and so conflict points such as street

⁶⁵ Minikel, "Cyclist Safety on Bicycle Boulevards and Parallel Arterial Routes."

intersections and vehicle driveways provide the possibility for bicycle-motor vehicle collisions to occur. Given these findings, in an effort to improve the planning and implementation process for the Citywide and Local Connectors networks of the Bicycle Master Plan for Seattle, I propose the following actions:

5.1 RECOMMENDATIONS

1) **Prioritize funding for and accelerate the designation and construction of neighborhood greenways.**

Seattle Department of Transportation's 2015-2019 Implementation Plan for the Bicycle Master Plan projects 52 miles of new bicycle greenways to be added to the bicycle network by 2019.⁶⁶ SDOT should revise the implementation plan to increase the rate of new greenways to be built by 2019. More neighborhood greenways equates to better overall connectivity in the bicycle network, and would likely attract greater ridership numbers from the "interested but concerned" potential bicycle riders in the City of Seattle.

2) **Prioritize intersection treatments within the bicycle network to mitigate risks to bicycle riders.**

More than half of collision incidents between bicycles and motor vehicles from 2004 to 2017 in Seattle occurred at the intersection of streets. Although I did not include this data point in my analysis, it should be noted that the literature suggests that intersections play a role in bicycle-motor vehicle collisions due to

⁶⁶ Seattle DOT, *Seattle Bicycle Master Plan: Implementation Plan 2015-2019*.

increases in risk exposure and changes in visual perception by motor vehicle drivers. This increase in risk to the more vulnerable bicycle rider is evident at intersections with all bicycle paths, even at intersections with protected bicycle lanes and off-street paths such as the Burke-Gilman Trail. At as many intersections of general purpose traffic with bicycle paths as possible, Seattle Department of Transportation should implement treatments that prioritize the safety of vulnerable users, such as pedestrians and bicycle riders.

3) **Establish a low-barrier method for bicycle riders to report bicycle-motor vehicle collision incident data to the City of Seattle.**

The task of contacting the police, EMT, and insurance companies is daunting for many people, and most will likely not considering doing so for a collision between bicycle and motor vehicle if no obvious physical pain or property damage has occurred. However, police reports are the likeliest way for cities to gather collision data, and so there needs to be a way for bicycle riders to quickly and easily report collisions with motor vehicles. The City of Seattle, Seattle Department of Transportation, or another entity should develop a way to encourage the public to officially report collision incidents to the City, potentially through a smartphone application or public website.

4) **Conduct a thorough citywide count of bicycle riders in Seattle.**

While gathering data for my analysis, I discovered a paucity of thorough, citywide bicycle traffic counts. Within the Bicycle Master Plan, Seattle Department of Transportation has Strategy 7.3 to track and review bicycle-related collision

incidents and use that data to improve the bicycle network implementation process.⁶⁷ It is welcome that Seattle Department of Transportation has plans to conduct its own bicycle-motor vehicle collision studies; however, I believe that they will require much more data about bicycle traffic volumes across the city, and would hypothesize that gathering that data would improve the results of both my own regression model and of any future analyses conducted by the Seattle Department of Transportation.

Overall, the problem of traffic collisions between bicycle riders and motor vehicle drivers is complex, and likely has more statistically significant factors influencing the probability of collisions than any one study has found to date. My research only analyzed environmental roadway variables that could theoretically be controlled by the City of Seattle and Seattle Department of Transportation; however, other studies have shown that weather conditions (such as precipitation and general visibility) and behavioral factors of roadway users hold significant influence in safety outcomes for bicycle riders. Changes in roadway and bicycle path design and changes in traffic laws and legislation can influence bicycle riders and motor vehicle drivers to modify their behavior, but without a much more complex regression model I am unable to hypothesize with any certainty what the most effective interventions would be. At the very least, my analysis has shown that non-arterial local streets are likely the safest streets for the majority of bicycle riders to use due to a lower exposure to risk. This conclusion, in tandem with improved wayfinding amenities and user education, could

⁶⁷ Seattle DOT, *Bicycle Master Plan*, 97.

lead to more of the “Interested but Concerned” population of potential bicycle riders in Seattle to make the decision to switch their primary mode of transportation to commuting by bicycle, which is a desired result of any bicycle transportation plan. I would therefore say that neighborhood bicycle greenways are likely to be the most attractive bike path for the majority of bicycle riders, and once Seattle Department of Transportation has completed a well-connected network of bicycle greenways in Seattle, we should expect to see greater numbers of people commuting by bicycle and a decrease in collision incidents between bicycles and motor vehicles.

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APPENDIX

Multiple Regression Analysis -- Results

Call:

```
lm(formula = log_bmvcoll ~ log_trfc + PRART_LEN + MNART_LEN +
    CLART_LEN + LCSTR_LEN + mjsep_per_strt + mnsep_per_strt +
    shrw_per_strt + grnwy_per_strt, data = sea_blkgrp10_417_V2,
    na.action = na.exclude)
```

Residuals:

Min	1Q	Median	3Q	Max
-2.14958	-0.63079	0.00728	0.60884	2.42253

Coefficients:

	Estimate	Std. Error	t value	Pr(> t)							
(Intercept)	-2.197e+00	6.232e-01	-3.525	0.000473	***						
log_trfc	4.276e-01	7.213e-02	5.929	6.70e-09	***						
PRART_LEN	5.088e-05	1.193e-05	4.266	2.50e-05	***						
MNART_LEN	9.642e-05	2.260e-05	4.267	2.49e-05	***						
CLART_LEN	5.673e-05	2.344e-05	2.421	0.015941	*						
LCSTR_LEN	-2.519e-05	6.921e-06	-3.640	0.000309	***						
mjsep_per_strt	2.137e-02	9.945e-03	2.149	0.032264	*						
mnsep_per_strt	3.209e-02	6.344e-03	5.059	6.50e-07	***						
shrw_per_strt	7.860e-03	5.814e-03	1.352	0.177225							
grnwy_per_strt	2.017e-02	9.181e-03	2.196	0.028649	*						

Signif. codes:	0	'***'	0.001	'**'	0.01	'*'	0.05	'.'	0.1	' '	1

Residual standard error: 0.883 on 392 degrees of freedom
(15 observations deleted due to missingness)

Multiple R-squared: 0.3768, Adjusted R-squared: 0.3625

F-statistic: 26.33 on 9 and 392 DF, p-value: < 2.2e-16

Koenker's studentized Breusch-Pagan test

data: mreg_model4

BP = 12.917, df = 9, p-value = 0.1664

Non-constant Variance Score Test

Variance formula: ~ fitted.values

Chisquare = 2.787641 Df = 1 p = 0.09499396

Variance Inflation Factor (VIF) Test

log_trfc	PRART_LEN	MNART_LEN	CLART_LEN	LCSTR_LEN
1.192336	1.947873	2.020918	1.372322	2.493401

mjsep_per_strt	mnsep_per_strt	shrw_per_strt	grnwy_per_strt
1.094425	1.151432	1.165873	1.031221

