IDENTIFYING HIGH-RISK BUILT ENVIRONMENTS FOR SEVERE BICYCLING INJURIES

FINAL PROJECT REPORT

by

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16. Abstract

This study was aimed at filling part of the knowledge gap on bicycling safety in the built environment by addressing two questions. First, are built environment features and bicyclist injury severity correlated, and if so, what built environment factors most significantly relate to severe bicycling injuries? Second, do the identified statistical associations vary substantially among cities with different levels of bicycling and different built environments? The cities of Miami, Seattle, and Minneapolis, which differ in built environments, bicycle mode share, and bicyclist fatality rate, were selected as representative cases for the analysis. The generalized ordered logit (GOL) model was employed to examine the relationship between built environment features and bicyclist injury severity. Bicyclist injury severity was coded into four injury types: no injury (NI), possible injury (PI), evident injury (EI), and severe injury and fatality (SIF). The findings from the three-cities-pooled data included the following: (1) higher percentages of residential land and green space, commercial land, and office or mixed-use land were correlated with lower probabilities of EI and SIF; (2) land-use mixture was negatively correlated with EI and SIF; (3) steep slopes were positively associated with bicyclist injury severity; (4) in areas with more transit routes, bicyclist injury was less likely to be severe; (5) a higher speed limit was more likely to result in SIF; and (6) wearing a was is negatively associated with SIF, but positively related to PI and EI. GOL models for individual cities showed broad consistency with the pooled GOL model in the estimated relationship between built environment features and bicyclist injury severity.

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List of Abbreviations

ACS: American Community Survey

DPW: Public Works - City of Minneapolis

FDOT: Florida Department of Transportation

FGDL: Florida Geographic Data Library

FIRE: Florida Integrated Report Exchange System

MnDOT: Minnesota Department of Transportation

PacTrans: Pacific Northwest Transportation Consortium

PSRC: Puget Sound Regional Council

SDOT: Seattle Department of Transportation

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Executive Summary

General Background

Bicycling is increasingly popular in the U.S. because of the increased awareness of both its health and environmental benefits. However, bicycling mode share remains relatively low, and the likelihood of bicyclists to be involved in serious collisions is relatively high. To improve bicycling safety and promote sustainable transportation, many cities are developing bicycle master plans.

Problem Statement

Thus far few studies have focused on the effects of different built environments on bicyclist injury severity, and this scarcity of literature constrains the development of evidence-based bicycle master plans. This study was aimed at filling part of that knowledge gap by addressing two questions. First, are built environment features and bicyclist injury severity correlated, and if so, what built environment factors most significantly relate to severe bicycling injuries? Second, do the identified associations vary substantially among cities with different levels of bicycling and different built environments?

Key Methodology

The cities of Miami, Seattle, and Minneapolis, which differ in built environments, bicycle mode share, and bicyclist fatality rate, were selected as representative cases for the analysis. The generalized ordered logit (GOL) model was employed to examine the relationship between built environment features and bicyclist injury severity, which was measured as an ordinal categorical variable with four categories: no injury (NI), possible injury (PI), evident injury (EI), and severe injury and fatality (SIF).

Major Findings and Their Implications

Interpretation of Findings

The findings from the three cities' pooled data included the following: (1) Higher percentages of residential land and green space, commercial land, and office or mixed-use land were correlated with lower probabilities of EI and SIF. (2) Land-use mixture was negatively correlated with EI and SIF. (3) Steep slopes were positively associated with bicyclist injury severity. (4) In areas with more transit routes, bicyclist injury was less likely to be severe. (5) A higher speed limit was more likely to result in SIF. (6) Wearing a helmet was negatively associated with SIF but positively related with PI and EI.

GOL models for individual cities showed broad consistency with the pooled GOL model in the estimated relationship between built environment features and bicyclist injury severity.

Impact on Future Research and Engineering Practice

This study indicated that the following: (1) the GOL model is useful for understanding the complexity inherent in categorical ordered data on bicycle injury severity; (2) the risk of severe injury varies among different urban settings, and researchers need to be cautious in interpreting single-case-based empirical results.

Bicycle master planning should be integrated with land-use planning in light of the findings that built environments characterized by higher percentages of residential land and green space, more mixed land use, and flatter roads can help reduce the likelihood of severe bicyclist injuries. Desirable complementary policies should be implemented in the forms of stricter regulations on helmet use, travel speed, and large vehicles entering areas where bicyclists concentrate.

Chapter 1 Introduction

1.1 Bicycling and Road Safety in the U.S.

The U.S. faces many transportation-related health and environmental challenges, such as obesity-related diseases and greenhouse gas emissions. Promoting bicycling is widely perceived as a plausible way to mitigate these challenges and thereby improve livability and sustainability. Promoting sustainable transportation has helped increase popularity of bicycling activities in the U.S. However, the risk of collisions and severe injuries remains the most serious concern that discourages people from bicycling. The bicycle commuting mode share reamins low in the U.S. Only 0.5 percent of people commute by bikes (American Association of State Highway and Transportation Officials and US Department of Transportation, 2013). Although over the past four decades the traffic-related fatality rate has continually declined (The National Highway Traffic Safety Administration, 2012a), reported bicyclist injuries have increased from 45,000 in 2001 to 49,000 in 2012. During the same period, the percentage of total traffic-related deaths attributed to bicyclist fatalities increased from 1.7 percent to 2.2 percent (The National Highway Traffic Safety Administration, 2012b). Therefore, understanding the factors that correlate with bicyclist injury severity is critical to establishing a safe bicycling environment.

Existing bicycle safety studies, especially those conducted in the North America, have typically used bicycle-friendly cities for case studies, such as Seattle, Portland, Washington DC, New York, Vancouver, and Montreal (Chen et al., 2012; Chen, 2015; Chen and Shen, 2016; Dill and Voros, 2007; Larsen and El-Geneidy, 2011; Teschke et al., 2012). These studies have generally agreed upon the positive effect on the renaissance of bicycling of improving the built environment and providing incentives (Dill and Carr, 2003; Pucher et al., 2011). Therefore, many researchers and practitioners are enthusiastic in developing bicycle master plans, launching public bike sharing programs (DeMaio, 2009; Faghih-Imani et al., 2014), implementing "safe routes to school" projects for encouraging children to bike (Boarnet et al., 2005; Buckley et al., 2013), and attracting people to bike through vouchers (Allen et al., 1999).

While the existing studies have provided useful information for bicycle planning and related policy making, additional insights from cities that are less safe for biking are needed. Cities from different parts of the U.S. are making major investments in promoting bicycling as a safer and easier mode of transportation. To be effective, however, a more complete picture of how safety outcomes vary in different built environments needs to be portrayed by including less bicycle-friendly cities in the sample.

1.2 Research Questions

With the above-mentioned concerns and interests, this study asked two research questions. First, are built environment features and bicyclist injury severity correlated, and if so, what built environment factors most significantly correlate with severe bicycling injuries? Second, do the identified statistical associations vary significantly among cities with different levels of bicycling and different built environments? To compare the risk of severe bicyclist injuries in different urban environments, this study included Miami, Seattle, and Minneapolis as comparison cases.

Chapter 2 Literature Review

2.1 Bicycling and Built Environments

The built environment refers to all physical settings for human activities, including where people live, recreate, and work. It ranges in scale from an individual building or a park, to a neighborhood, to a complicated urban system. The most fundamental element of the built environment is land use. To better understand the relationship between the built environment and bicycling, this section reviews three sub-topics: how the built environment correlates with biking; how the built environment correlates with biking safety; and how the built environment correlates with bicyclist injury severity.

Bicycling is correlated with many built environment factors. Trip distance, which correlates with city size and many other built environment factors, such as density, mixed land use, road connectivity, block size, and destination accessibility (Heinen et al., 2010; Krizek et al., 2007; Saelens et al., 2003), is a core factor affecting bicycling. Biking is not a popular transportation mode for the general population in the U.S. partly because the general commuting distance is longer than the typical bicycle trip distance, which is less than 3 miles (Buehler, 2012). A compact urban environment—with higher density, greater mixed land use, better road connectivity, denser blocks, and closer proximity to destination—tends to generate shorter trip distances, which are more suitable for non-motorized transportation modes (Heinen et al., 2010; Moudon et al., 2005; Saelens et al., 2003). Although the aforementioned built environment factors have been frequently discussed, other important factors impacting bicycle use, such as slope and the presence of parks, have been mostly ignored in previous studies (Heinen et al., 2010).

Many built environment factors are correlated with bicycle safety. The layout of a road network and the provision of separated bike lanes are essential for encouraging bicycle use (Wardman et al., 2007; Winters et al., 2011), since both a dense street network and separated bike lanes can reduce the perceived risk and conflicts with automobiles. Bike lane connectivity is an important determinant of bicycling (Titze et al., 2008) because an unconnected bicycle network increases bicyclists' exposure to intersecting with automobiles. Road network layout affects driving speeds, and a lower speed limit is essential in establishing a safe bicycling environment. A denser road network results in lower driving speeds (Heinen et al., 2010). In addition, a compactly developed urban environment with a higher density and more mixed land use increases bicycling safety because of better awareness of other road users (Chen, 2015; Chen and Shen, 2016). Furthermore, in U.S. cities, bicyclists commonly share roads with motorists, and hence, building cycle tracks and separated bike lanes to isolate bicyclists from vehicle traffic creates safety benefits and encourages more biking (Reynolds et al., 2009).

Relatively few prior studies have examined the correlation between the built environment and bicyclist injury severity (Chen and Shen, 2016; Kim et al., 2007; Moore et al., 2011). The scarcity of this line of inquiry can be explained by a couple factors. First, investigating this correlation requires high quality recorded injury data, which are often not available. Second, in contrast to other important determinants, such as speed limit, vehicle type, and bicyclist age, built environment factors are regarded as indirectly associated with bicyclist injury severity. Therefore, built environment factors have been mostly treated as confounders, or ignored, in previous research.

Some studies have investigated the variation of safety outcomes in different built environments. Several studies have compared such variation across different parts of a metropolitan region, for example urban, suburban, and rural (Papas et al., 2007; Sandercock et al., 2010). However, cross-city comparisons have rarely been done.

2.2 Factors Explaining Bicyclist Injury Severity

The studies that have been conducted have identified many factors that correlate with bicyclist injury severity, split into the following groups of variables: (1) sociodemographic factors, such as age and gender of motorists and bicyclists; (2) behavioral factors, such as alcohol and drug use, distraction and inattention, and traffic violations; (3) vehicle types; (4) road network features, such as slopes and bicycle routes; (5) traffic controls, such as signals, stop signs, and posted driving speed limits; (6) environmental factors, such as lighting and weather conditions; (7) land-use variables, such as density and land-use mixture; and (8) crash characteristics, such as the temporal movement of motorists and the direction of a collision.

On the basis of the existing studies, driving speed limit, vehicle type, and the age of injured bicyclist are widely regarded as the most important factors explaining bicyclist injury severity (Bíl et al., 2010; Chong et al., 2010; Eluru et al., 2008; Kim et al., 2007; Walker, 2007; Yan et al., 2011). In terms of behavioral factors, the existing safety research efforts, especially those that have focused on human factors, have ascribed causal effects of the momentary behavior of road users on injury outcomes. Furthermore, the use of protective equipment has been examined frequently (Bíl et al., 2010; Boufous et al., 2011; Chong et al., 2010; Kim et al., 2007; Moore et al., 2011). For instance, an empirical study showed that helmet use mitigates the negative effect of bicyclist brain injury by more than 85 percent (Moore et al. 2011).

As noted from the existing research, environmental conditions are related to bicyclist injury severity. Darkness, usually quantified as the time of a day, has been found to be a factor correlated with fatality (Bíl et al., 2010; Boufous et al., 2011; Eluru et al., 2008; Klop and

Khattak, 1999). Additionally, adverse environmental conditions appear to increase the likelihood of severe bicyclist injuries (Moore et al., 2011).

Among road network factors, existing studies have found that signalized intersections with lighting facilities are safer for riding bicycles (Bíl et al., 2010; Eluru et al., 2008; Zahabi et al., 2011). Bicyclist injury severity has been shown to vary between intersections and mid-block areas (Klassen et al., 2014). Zahabi et al.'s study (2011) showed that bicyclist injury severities are more likely to be less severe at intersections than at mid-block areas, which is explained mostly by driving speed reductions at intersections (2011).

A study by Zahabi et al. (2011) indicated that some land-use variables, including population density, land-use mixture, and street connectivity, showed no significant correlation with bicyclist injury severity. Another study suggested that the proportions of industrial and commercial land use were positively associated with evident bicyclist injuries (Narayanamoorthy et al., 2013). In a more recent study using Seattle's data, employment density was negatively associated with bicyclist injury severity (Chen and Shen, 2016).

2.3 Modeling Techniques for Bicyclist Injury Severity

Modeling ordered categorical data, specifically bicyclist injury severity data, involves some challenging methodological issues (Mannering and Bhat, 2014; Savolainen et al., 2011; Yasmin and Eluru, 2013). Injury severity is usually split into five types of ordered categories: no injury, possible injury, evident injury, severe injury, and fatality. In the existing studies, both ordered and unordered response models have been applied to examine how bicyclist injury severities are related to other fixed effects. However, injury severity categories are inherently interrelated. The ordered logit model, also named the proportional odds (PO) model, effectively captures the ordinal nature across different injury types (Mooradian et al., 2013). However, the assumption of an ordered logit model forces the estimated coefficients for covariates to remain constant for all injury levels. In the real world, some variables may decrease the likelihood of one injury type but increase the likelihood of another. Forcing coefficients to be the same across injury types is a big assumption made with the ordered logit model. Under this assumption, the complexities of the relationships between the dependent variable and independent variables are under-represented.

The unordered response models, also noted as discrete choice models, treat injury severity as a categorical variable by allowing factors to influence response levels differently (Yasmin and Eluru, 2013). The weakness of discrete choice models is that they fail to fully account for the ordinal nature of bicyclist injury severity data.

Given the limitations of the abovementioned models, a more flexible method known as the Generalized Ordered Logit (GOL) model has been introduced. The advantage of this method is that it relaxes the assumption that parameters are constant across injury types (Eluru, 2013; Yasmin and Eluru, 2013).

Chapter 3 Research Design

3.1 Selection of Cities

The primary goal of this study was to understand the variation of bicyclist injury severity in different built environments by using data from comparative cities. To facilitate the comparison, this study drew a sample from both bicycle-friendly cities and automobile-dominated cities that were less safe for biking. Figure 3-1 shows the percentage of total traffic-related deaths attributed to bicyclist fatalities by states in the U.S., based on the data reported by the U.S. National Highway Traffic Safety Administration and the U.S. Department of Transportation (2013). This percentage is relatively high in some states, such as Florida and California, in comparison to other states, such as Oregon, Minnesota, and Washington. Therefore, we initially considered large cities in these two types of states for possible inclusion in our sample. However, several of them were excluded for reasons of data availability or data quality. For example, posted driving speed limit was not reported in Los Angeles and San Francisco's collision profiles. In addition, bicyclists with no injury were not recorded in San Francisco's data. Similarly, bicyclist injury severity was coded into only three categories in Portland's crash data: fatality, non-fatal injury, and no injury. These classifications did not match the classifications of the data for the other cities. Consequently, only Miami, Seattle, and Minneapolis were included for this analysis.

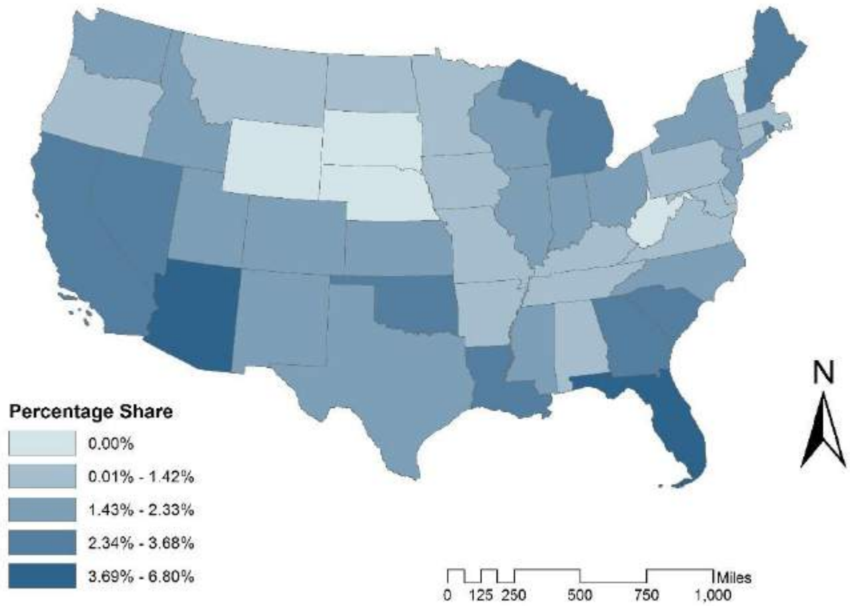

Figure 3-1: Bicyclist fatalities as the share of total traffic fatalities
Source: National Highway Traffic Safety Administration, 2013

Looking more closely at city/county-level bicyclist fatality data, the selected cases represented two types of urban areas differentiated by bicycle safety. According to a Seattle Department of Transportation report, the ten-year average number of bicyclist fatalities was 1.6 bicyclists per year (Seattle Department of Transportation, 2015). As shown in table 3-1, the corresponding ten-year (2005-2014) annual average bicyclist fatality ratio was 0.155 per thousand bicyclist commuters. Similarly, Minneapolis' ten-year annual average number of bicyclist fatalities was 1.2 bicyclists per year (City of Minneapolis, 2013). The corresponding ten-year annual average bicyclist fatality ratio was 0.146 per thousand bicyclist commuters. On the other hand, Miami-Dade County's four-year average number of bicyclist fatalities was 9.0 bicyclists per year (Florida Department of Transportation, 2013). The corresponding bicyclist fatality ratio for this county was 1.739 per thousand bicyclist commuters. These figures indicate that Miami hasbeen a more dangerous city for biking than Seattle and Minneapolis.

Table 3-1: Bicyclist fatality ratio in the three places

	Annual Bicyclist Fatalities	Bicyclist Commuters (ACS 2011)	Annual Bicyclist Fatality Ratio (number /10^3 bicyclists)
Seattle	1.6 (2005-2014 avg.)	10,343	0.155
Minneapolis	1.2 (2001-2010 avg.)	8,195	0.146
Miami-Dade County	9.0 (2007-2010 avg.)	5,174	1.739

The selected cities also showed different mode shares for bicycling as shown in figure 3-2. According to the bicycle commuting mode share data provided by the U.S. American Community Survey 2012, Minneapolis (4.1 percent), and Seattle (3.4 percent) ranked second and the third, respectively, among large U.S. cities. Miami (0.7 percent), on the other hand, was among the cities of relatively low bicycle mode share.

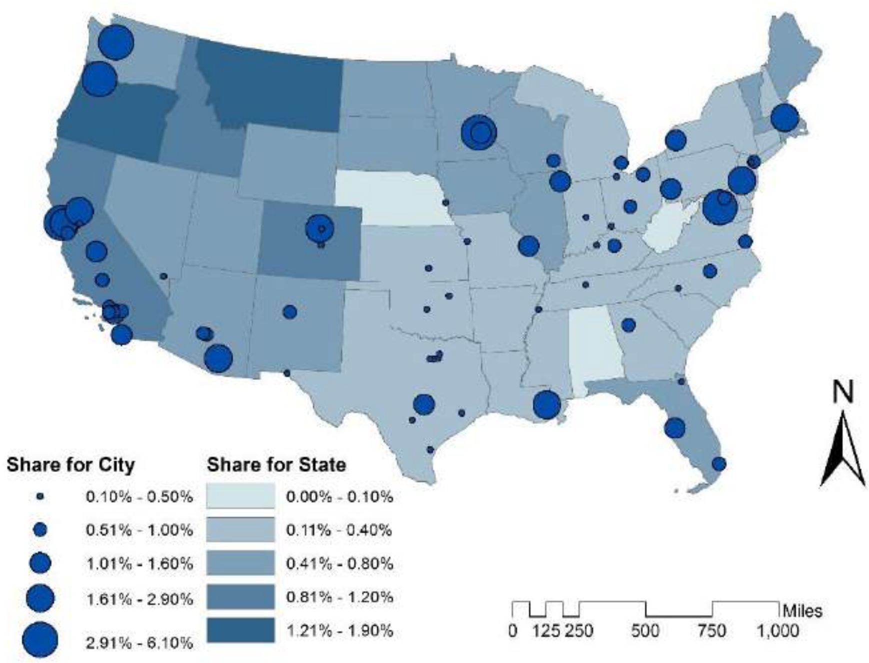

Figure 3-2: Bicycle mode shares for states and large cities
Source: American Community Survey, 2008-2012

3.2 Data Sources

The data used for this analysis were obtained from multiple sources. This study considered five sets of variables, including crash characteristics, socio-demographics from census or travel demand output, traffic controls, road network features, and land-use variables. The crash characteristics were (1) bicyclists' and motorists' demographics, such as age and gender, (2) bicycle equipment such as helmet use, (3) motorists' momentary behaviors such as turning, and (4) environment characteristics such as weather and lighting condition. Table 3-2 presents the sources of the used data.

Table 3-2: Data sources

Data	Seattle	Minneapolis	Miami
Collision characteristics (2011-2014)	SDOT	MnDOT	FIRE
Demographics (2011)	ACS	ACS	ACS
Traffic controls (2011-2014)	SDOT	MnDOT	FIRE
Road network (most current data available)	SDOT	DPW/ Minneapolis-St. Paul Metropolitan Council	Miami-Dade County/FDOT
Land use (most current data available)	PSRC	DPW/ Minneapolis-St. Paul Metropolitan Council	Miami-Dade County /FGDL
ACS: American Community Survey DPW: Public Works - City of Minneapolis FDOT: Florida Department of Transportation FGDL: Florida Geographic Data Library FIRE: Florida Integrated Report Exchange System MnDOT: Minnesota Department of Transportation PSRC: Puget Sound Regional Council SDOT: Seattle Department of Transportation			

3.3 Generalized Ordered Logit Model

The dependent variable of this research was bicyclist injury severity, which had five categories: no injury, possible injury, evident injury, severe injury, and fatality. To ensure each category had a sufficient sample size to validate the statistical inference, severe injury and fatality were merged into one category. Hence, bicyclist injury severities were aggregated into four ordered categories: no injury (NI), possible injury (PI), evident injury (EI), and severe injury and fatality (SIF).

As discussed in the literature review, the GOL model is a better choice for modeling categorical ordered variables because it allows the estimated coefficients for different injury types to be different from each other. At the same time, the GOL model has the more rigid data requirement that the distribution of an independent variable cannot be highly skewed under each category of the dependent variable. Unfortunately, many independent variables have highly skewed distribution because they measure such phenomena as motorists' speeding and alcohol use that are rare in bicycle collisions. This issue could potentially lead to the problem of computationally singular results (too few observations for a particular category) or crashint of the models (0 observations for a particular category) when GOL models are estimated.

Equations (3.1) and (3.2) represent the GOL model, which was obtained by assuming that the vector of utility had a standard logistic cumulative distribution (Agresti and Kateri, 2011; Eluru and Yasmin, 2015; Williams, 2006). More specifically, supposing an ordinal categorical dependent variable Y_i has M values, the GOL model produces a set of estimates, including $M-1$ cutoff points, at which Y_i can be dichotomized.

$$\ln\left(\frac{P(Y_i > j)}{1 - P(Y_i > j)}\right) = \ln\left(\frac{g(\beta_j \mathrm{X}_i)}{1 - g(\beta_j \mathrm{X}_i)}\right) = \alpha_j + \beta_j \mathrm{X}_i, \quad j = 1, 2, ..., M-1 \tag{3.1}$$

$$g(\beta_j \mathrm{X}_i) = \frac{\exp(\alpha_j + \beta_j \mathrm{X}_i)}{1 + \exp(\alpha_j + \beta_j \mathrm{X}_i)} \tag{3.2}$$

Y_i will take on each of the values *1, 2, ..., M,* and the probability functions are noted in equations (3.3), (3.4) and (3.5) (Eluru et al., 2008; Kaplan and Prato, 2012; Williams, 2005).

$$P(Y_i = 1) = 1 - g(\beta_1 \mathrm{X}_i) \tag{3.3}$$

$$P(Y_i = j) = g(\beta_{(j-1)} X_i) - g(\beta_j X_i), \quad j = 2, ..., M-1 \tag{3.4}$$

$$P(Y_i = M) = g(\beta_{(M-1)} X_i) \tag{3.5}$$

where

M is the number of ordinal categories of bicyclist injury types;

$P(Y_i)$ is the probability of any given injury type for case i;

j represents the cutoff points between different injury types;

X_i is a set of independent variables that explain bicyclist injury severity;

α_j is the intercept; and

β_j is the vector of corresponding estimates.

In the GOL model, three thresholds were specified, including the cutoff points between NI and PI, PI and EI, EI and SIF (severe injury and fatality). equation. (3.3) represented the probability of the first category (NI), equation. (3.4) represented the probabilities for the middle categories (EI and PI), and equation (3.5) represented the probability of the last category (SIF).

Elasticity is a commonly used measurement that describes the substitutional effect of percent change between the dependent variable and an independent variable. In this research, for independent variables measured at interval and ratio scales, the elasticities for the four injury types in the GOL model were computed using equations. (3.6), (3.7), (3.8) and (3.9).

$$E_{PDO} = -\beta_1(1 - P_{Y_i=1})X_i \tag{3.6}$$

$$E_{PI} = \beta_1 * (1 - P_{Y_i=1}) * P_{Y_i=1} \frac{X_i}{P_{Y_i=2}} - \beta_2 * (P_{Y_i=1} + P_{Y_i=2}) * (P_{Y_i=3} + P_{Y_i=4}) \frac{X_i}{P_{Y_i=2}} \tag{3.7}$$

$$E_{EI} = \beta_2 * (P_{Y_i=1} + P_{Y_i=2}) * (P_{Y_i=3} + P_{Y_i=4}) \frac{X_i}{P_{Y_i=3}} - \beta_3 * P_{Y_i=4} * (1 - P_{Y_i=4}) \frac{X_i}{P_{Y_i=3}} \tag{3.8}$$

$$E_{SIF} = \beta_3(1 - P_{Y_i=4})X_i \tag{3.9}$$

For independent variables quantified as dummy variables, an arc-elasticity was calculated by using equation (3.10) (Hensher et al., 2005).

$$E_{Arc} = \frac{P_{X=1} - P_{X=0}}{P_{X=1} + P_{X=0}} \tag{3.10}$$

The GOL models were implemented with the R “VGAM” package (Yee, 2010).

3.4 Conceptual Framework

The factors assumed to be associated with bicyclist injury severity are presented in the conceptual framework shown in figure 3-3. Eleven types of variables were initially considered, including land use, road network, traffic controls, individual profiles of bicyclists and motorists, behavioral factors, vehicle types, motorist momentary activities, and other conditions possibly correlated with bicyclist injury severities.

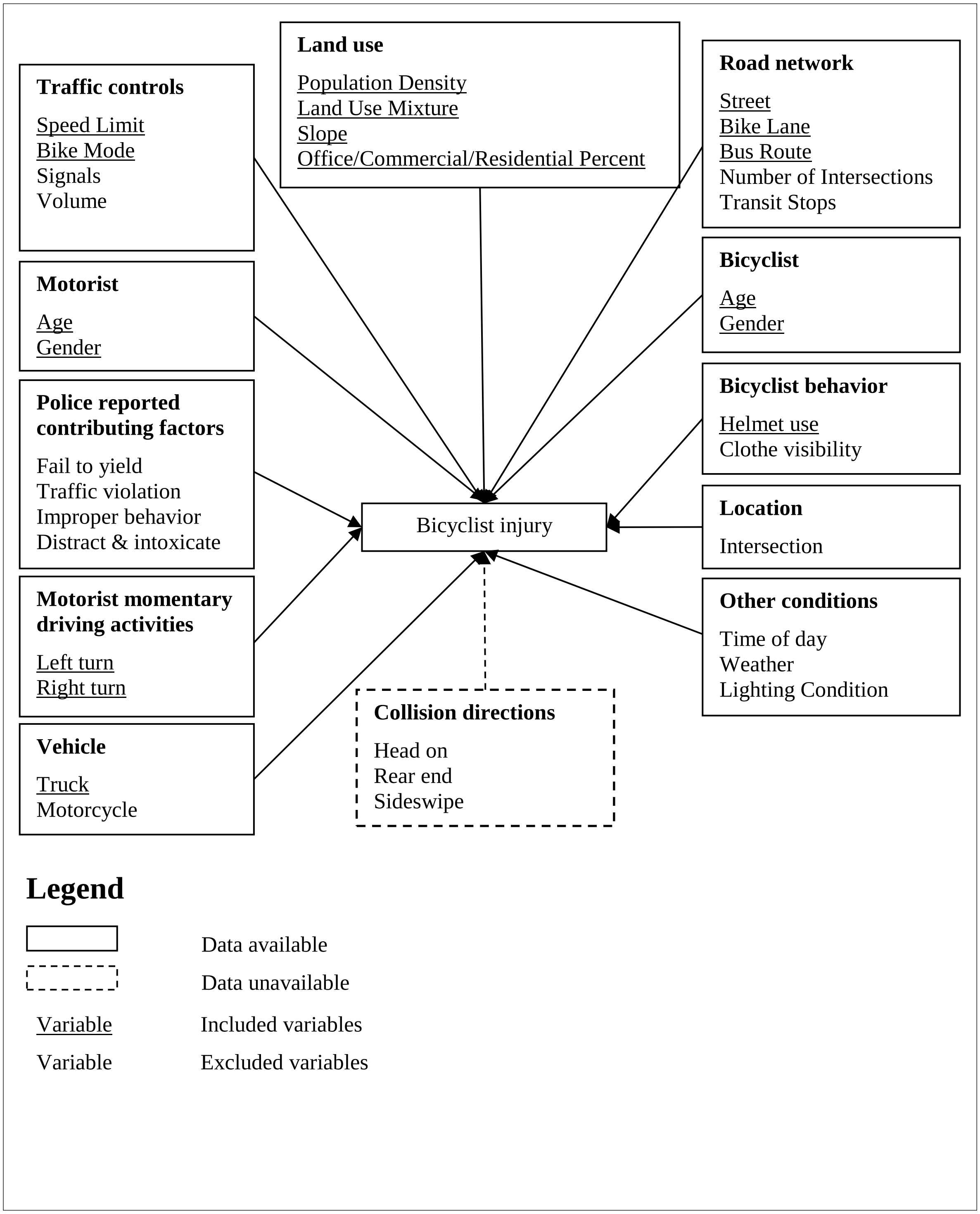

Figure 3-3: Conceptual framework for modeling bicyclist injury severity

3.5 Data Cleaning and Variable Selection

Many bicyclist injury records had missing values for various fields, such as bicyclist helmet use, bicyclist age, bicyclist gender, and posted speed limit. The full sample for injury severity reports had 3,931 records. After records with missing values were excluded, a sample of 1,813 observations remained for the pooled model. Table 3-3 presents the number and percentage of each type of bicyclist injury for different cities. The full sample with complete injury severity information and the final sample yielded similar percentage distributions across different injury categories. Therefore, the estimation based on the remaining sample did not distort the modeling results greatly.

Table 3-3: Comparison between the sample with injury records and the final sample

	Num. of cases	**No injury**	**Possible injury**	**Evident injury**	**Severe injury**	**Fatality**
Miami	1,159	185 (15.96%)	341 (29.42%)	450 (38.83%)	153 (13.20%)	30 (2.59%)
	802	94 (11.72%)	238 (29.68%)	312 (39.90%)	131 (16.33%)	27 (3.37%)
Seattle	1,507	134 (8.89%)	474 (31.45%)	798 (52.95%)	95 (6.30%)	6 (0.40%)
	774	55 (7.11%)	237 (30.62%)	424 (54.78%)	54 (6.98%)	4 (0.52%)
Minneapolis	1,265	63 (4.98%)	831 (65.69%)	313 (24.74%)	52 (4.11%)	6 (0.47%)
	237	4 (1.69%)	156 (65.82%)	67 (28.27%)	10 (4.22%)	0 (0.00%)

The data cleaning process involved several steps. First, collision records with missing data were excluded. This process resulted in a significant loss of observations, especially for the city of Minneapolis. Minneapolis' collision profile had 1,265 bicycle collision records in the full sample, but only 338 bicyclists had reported their helmet use. The second step was to exclude unreasonable data. For instance, many cases reported 0 mph posted speed limit, and a small number of cases recorded a posted speed limit of greater than 65 mph. These unreasonable observations were excluded. The third step was to exclude irrelevant records. For example, motorcycle-involved bicycle crash records were excluded.

The sample with bicyclist injury severity reported had 1,159 observations from Miami, 1,507 observations from Seattle, and 1,265 observations from Minneapolis. The resulting sample for the pooled model had 1,813 observations, including 802 from Miami, 774 from Seattle, and 237 from Minneapolis. In general, the final sample slightly under-represented observations of no injury and fatality.

Initially, this study considered a large set of variables, but many of them were excluded for various reasons. The first rationale for exclusion was collinearity. The second issue was computationally singular results. Many variables were highly skewed in distribution. For example, more than 95 percent of collisions occurred on sunny or cloudy days. Several variables had mostly identical values of a specific injury type and resulted in the issue of computationally singular results. Many momentary behavior variables shared this problem, such as alcohol and drug use, speeding, and motorist changing lanes. Thirdly, the value of some variables appeared to be unreasonable. For example, speed limits of less than 5 mph or more than 65 mph, motorists younger than 16 years old, and bicyclists younger than 6 years old were excluded. The age requirements in the state driver laws of Florida, Washington, and Minnesota were verified in setting the upper boundary for motorist age. Florida requires a physical test or a letter from a physician if the driver is older than 80 for every six years, while Washington and Minnesota have no restriction on motorist age. Therefore, no upper boundary for motorist age was used in selecting the final sample.

In the final model, the factors of collision direction, police-reported contributing factors, and other conditions were excluded. Collision direction for bicycle crashes was not available in the data for Seattle. Police-reported contributing factors, such as speeding and alcohol or drug use, were rare events in the sample. For many injury categories, there was no observation of inappropriate driving behavior. Other police-reported contributing factors, such as a motorist performing improper turning or changing lanes, a motorist being distracted or intoxicated, and a motorist violating traffic regulations, ere considered but excluded from the final models for being insignificant. Other conditions (the time of a day and weather) were excluded for showing no significance.

Vehicle type has been an important factor commonly investigated in previous research. The involvement of a large vehicle in a bicycle collision was selected for modeling. Motorists turning left and turning right were the momentary driving behaviors included in the final models.

The built-environment factors, which were key elements investigated in this research, consisted of the categories of land use, road network, and traffic controls. Several land-use variables—population density, land-use mixture, slope, and the percentages of land allocated for residential land and green space, office or mixed use, and commercial use—wee included for modeling. As for traffic control factors, because the momentary driving speed when a collision occurred was not available, police-reported posted speed limits were included in the models as a substitute.

Chapter 4 Results

4.1 Descriptive Analysis

Table 4-1 shows the summary of the pooled data. Table 4-2 presents the summary of data from the three selected cities. The dependent variable, bicyclist injury severity, had a lower mean value for Minneapolis, but it was higher for Miami and Seattle. Regarding the built environment, population density was the highest in Seattle.

For road network features, Seattle had better coverage of bike lanes and a denser street network, followed by Minneapolis, and then Miami. The three cities showed no significant difference regarding the cumulative length of transit routes surrounding bicycle collision sites (multiple transit routes using the same bus lane were considered to be a single bus route). The posted speed limit in Seattle was slightly lower than that in the other two cities. In terms of slope, Seattle was much steeper. For vehicle types, the percentages of truck-involved bicycle collisions were similar, generally around 3 percent to 4 percent, in the three selected cities.

As for bicyclist and motorist demographics, bicyclist age was generally younger in Minneapolis and older in Miami. Most bicyclists involved in collisions were male, and Miami had the highest percentage, at 80 percent. Most motorists involved in bicycle collisions were also male, roughly around 60 percent in the three cities. The variable that showed the largest difference among the three cities was the percentage of helmet use. Because of different regulation efforts, Seattle had the highest percentage of helmet use, at 71 percent; while use was only about 13 percent in Miami.

Table 4-1: Data summary for the four selected cities

	Mean	S.D.	Min.	Max.	Description
injury	2.61	0.81	1.00	4.00	coded into an ordinal categorical scale, including no injury (1), possible injury (2), evident injury (3), severe injury and fatality (4)
population density	16.86	13.68	0.00	162.41	census block group-based population density, in persons per acre
residential percentage	36.70	34.75	0.00	100.00	percent of residential land and green space in a 250-feet buffer area
commercial percentage	24.21	29.34	0.00	100.00	percent of commercial land in a 250-feet buffer area
office percentage	17.01	28.03	0.00	100.00	percent of office or mix-used land in a 250-feet buffer area
LU mix	0.32	0.22	0.00	0.96	land use mix entropy, measured by four types of land use, including residential land and green space, commercial, office or mixed use, and industrial, ranging from 0 to 1
bike lane	0.01	0.01	0.00	0.08	length of bike lanes in a 50-feet buffer area, in mile
bus route	0.02	0.01	0.00	0.07	length of bus routes in a 50-feet buffer area, in mile
street	0.22	0.08	0.03	0.86	length of streets in a 250-feet buffer, in mile
speed limit	30.70	7.67	5.00	45.00	police-reported posted speed limit, in mph
truck	0.03	0.18	0.00	1.00	1 if a truck was involved in a collision; 0 otherwise
bicyclist age	35.05	16.24	7.00	92.00	bicyclist age
bicyclist gender	0.77	0.42	0.00	1.00	1 for male; 0 for female
helmet use	0.43	0.50	0.00	1.00	1 for helmet used; 0 otherwise
motorist age	44.21	17.46	16.00	102.00	motorist age
motorist gender	0.60	0.49	0.00	1.00	1 for male; 0 for female
bike mode share	1.36	2.09	0.00	16.53	bicycle commuting mode share in census block group, in percentage
left turn	0.19	0.39	0.00	1.00	1 if the motorist was turning left; 0 otherwise
right turn	0.24	0.43	0.00	1.00	1 if the motorist was turning right; 0 otherwise

slope	0.01	0.02	0.00	0.22	road segment slope of collision site, in gradient

Table 4-2: Data summary for variables from the three selected cities (N=1,813)

	Miami (N=802)				**Seattle (N=774)**				**Minneapolis (N=237)**			
	Mean	S.D.	Min.	Max.	Mean	S.D.	Min.	Max.	Mean	S.D.	Min.	Max.
injury	2.67	0.92	1.00	4.00	2.63	0.73	1.00	4.00	2.35	0.59	1.00	4.00
population density	15.86	13.79	0.00	162.41	18.38	14.46	0.50	93.75	15.28	9.69	1.12	65.00
residential percentage	31.67	25.81	0.00	100.00	39.56	40.64	0.00	100.00	44.35	37.93	0.00	100.00
commercial percentage	17.93	19.24	0.00	100.00	31.90	36.53	0.00	100.00	20.32	25.29	0.00	100.00
office percentage	11.03	14.19	0.00	100.00	22.05	36.85	0.00	100.00	20.81	26.11	0.00	100.00
LU mix	0.38	0.16	0.00	0.72	0.23	0.23	0.00	0.90	0.41	0.26	0.00	0.96
bike lane	0.00	0.00	0.00	0.02	0.02	0.01	0.00	0.05	0.01	0.01	0.00	0.08
bus route	0.02	0.02	0.00	0.07	0.02	0.01	0.00	0.07	0.02	0.01	0.00	0.06
street	0.19	0.05	0.03	0.48	0.24	0.10	0.09	0.86	0.22	0.08	0.09	0.64
speed limit	32.57	18.11	5.00	65.00	28.97	3.43	5.00	45.00	30.00	2.30	10.00	40.00
truck	0.03	0.18	0.00	1.00	0.04	0.19	0.00	1.00	0.03	0.18	0.00	1.00
bicyclist age	37.87	18.11	6.00	89.00	34.73	13.35	6.00	79.00	26.52	15.11	6.00	92.00
bicyclist gender	0.80	0.40	0.00	1.00	0.76	0.43	0.00	1.00	0.73	0.44	0.00	1.00
helmet use	0.13	0.34	0.00	1.00	0.71	0.45	0.00	1.00	0.53	0.50	0.00	1.00
motorist age	44.80	17.56	16.00	89.00	43.70	16.27	16.00	102.00	43.88	20.59	16.00	93.00
motorist gender	0.60	0.49	0.00	1.00	0.59	0.49	0.00	1.00	0.60	0.49	0.00	1.00
bike mode	0.45	1.62	0.00	16.53	1.87	2.06	0.00	12.83	2.72	2.29	0.00	9.00
left turn	0.11	0.32	0.00	1.00	0.25	0.43	0.00	1.00	0.26	0.44	0.00	1.00
right turn	0.29	0.45	0.00	1.00	0.21	0.41	0.00	1.00	0.16	0.37	0.00	1.00
slope	0.00	0.00	0.00	0.00	0.03	0.03	0.00	0.22	0.01	0.01	0.00	0.08

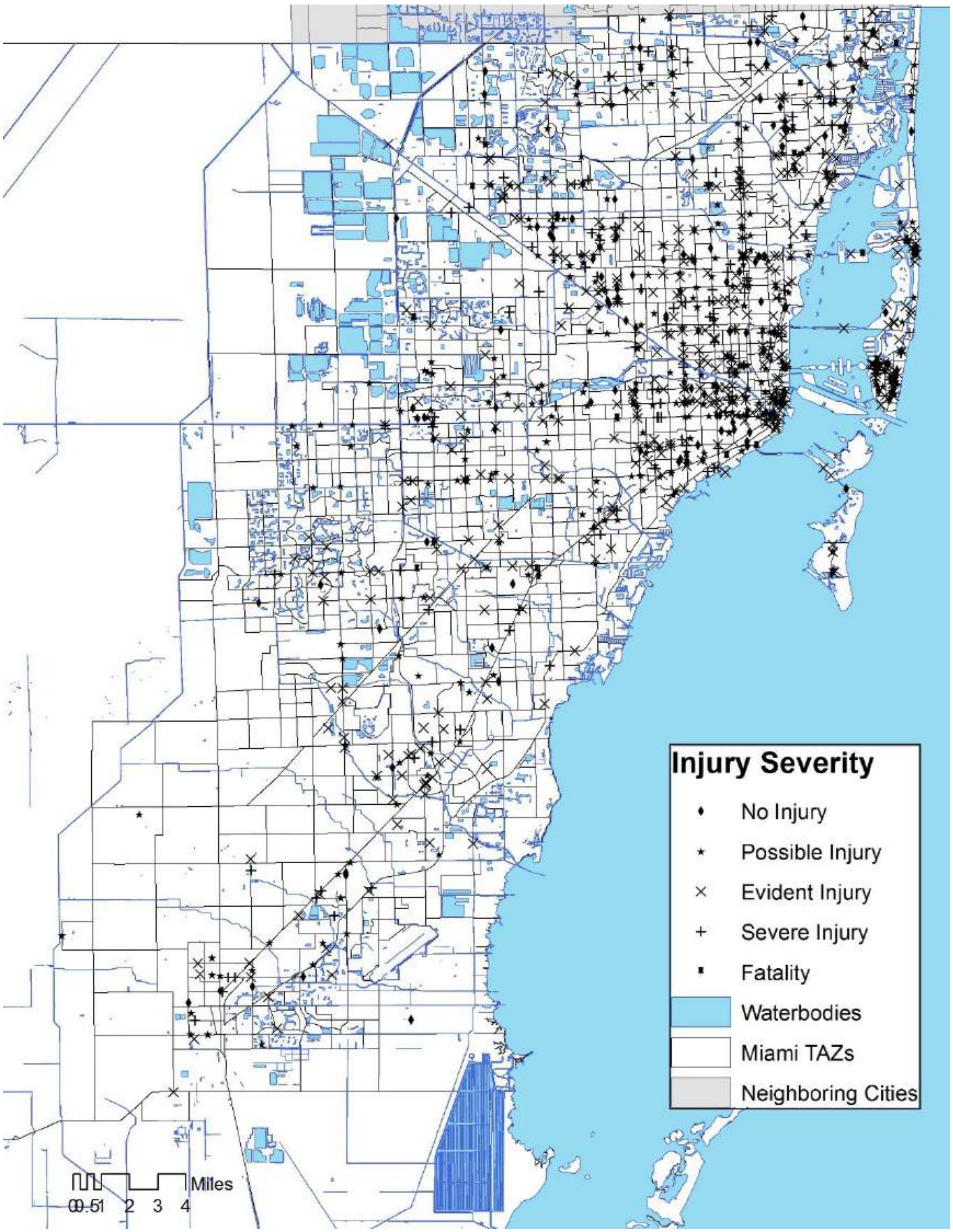

Figure 4-1: Bicycle collision and injury severity in Miami (N=1,159), 2011-2014

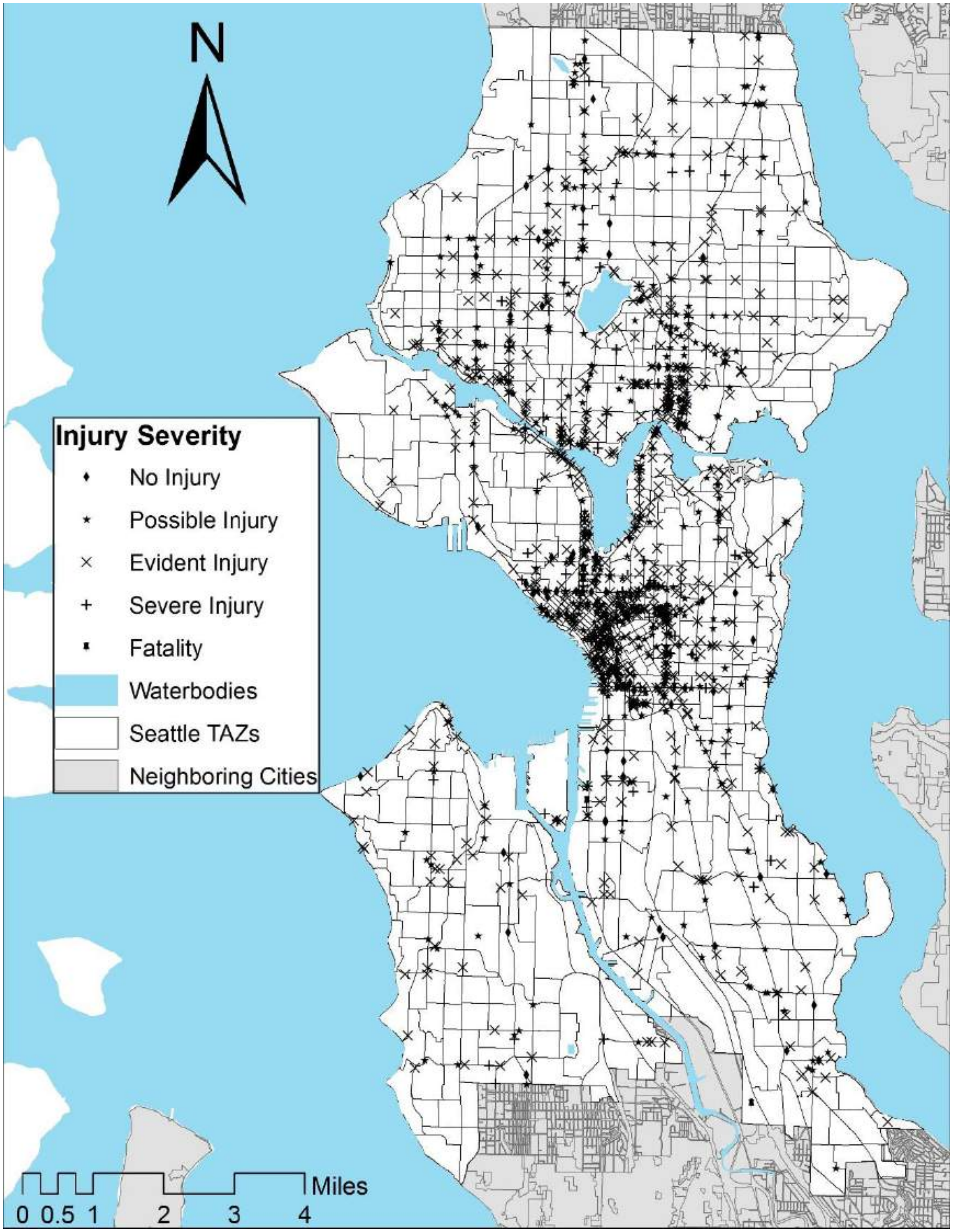

Figure 4-2: Bicycle collision and injury severity in Seattle (N=1,507), 2011-2014

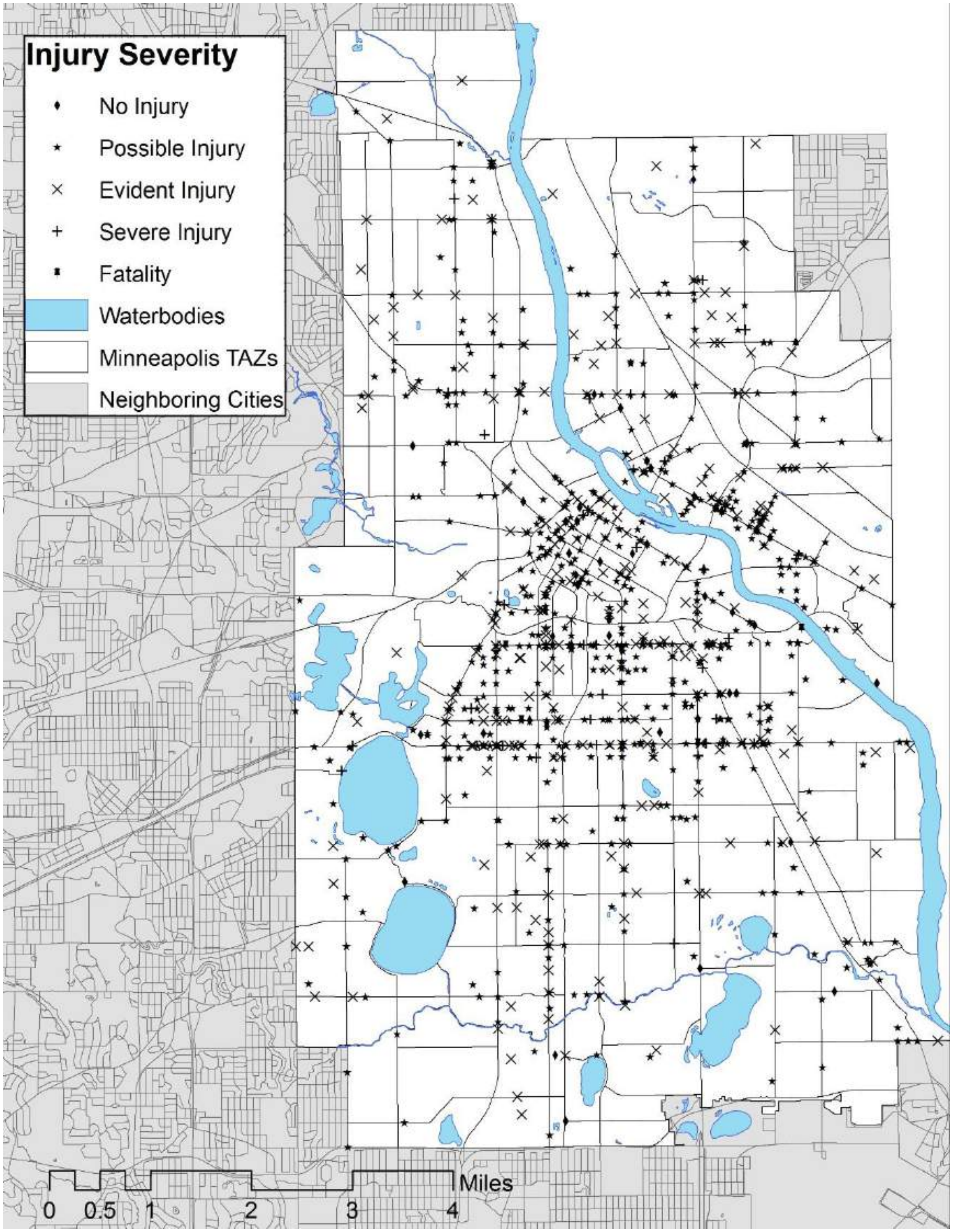

Figure 4-3: Bicycle collision and injury severity in Minneapolis (N=1,265), 2011-2014

4.2 Inferential Analysis for the Pooled Model

Table 4-3 shows the modeling outcome of the pooled GOL model. Population density did not have any significant correlation with bicyclist injury severity. Regarding land use, in areas with a greater percentage of residential land, green space, commercial land use, office or mixed use, the likelihood of bicyclists being involved in an evident injury or severe injury and fatality was lower. These results suggested that new bike lanes should be placed in or nearby residential neighborhoods, commercial districts, employment centers, and public parks. Land-use mixture is a composite measurement of the concentration of human activities in an area. This index showed negative associations with the probabilities of evident injury or severe injury and fatality. Therefore, mixed land use should be a primary zoning strategy for improving bicycle safety.

Regarding road network factors, the aggregated length of bus routes was negatively correlated with bicyclist injuries. This is likely due to traffic speed reductions caused by the presence of buses. Connecting public transit service and bicycle infrastructure may help each support the other. Street network density was marginally and negatively correlated with bicyclist injury severity, which supports the claim that a denser street network is more desirable for bicycling (Cervero et al., 2009). Slope was a significant positive predictor of bicyclist injury severity. Therefore, avoiding placing bike lanes on steep areas is an essential principle of bicycle master planning.

The posted speed limit was positively associated with severe injury and fatality. This indicates that the posted speed limit is a critical factor contributing to severe bicyclist injuries. The involvement of large vehicles was also a contributor to bicyclist injury severity, especially for evident injury, and severe injury and fatality. Therefore, in time periods and areas with high concentrations of human activities, large vehicles should be prevented from entering.

Table 4-3: Modeling results of the generalized ordered logit model (N=1,813)

Variable	**Threshold between no injury and possible injury**		**Threshold between possible injury and evident injury**		**Threshold between evident injury and severe injury versus fatality**	
	Estimate	P-value	Estimate	P-value	Estimate	P-value
intercept	3.67***	0.00	1.06**	0.01	-2.76***	0.00
population density	0.01	0.36	0.01	0.14	0.00	0.50
residential percentage	*-0.77.*	*0.09*	-0.96***	0.00	-1.31***	0.00
commercial percentage	-0.25	0.62	-0.44	0.10	-1.23**	0.00
office percentage	-0.26	0.63	-0.72**	0.01	-1.08**	0.00
LU mix	-0.06	0.89	-0.98***	0.00	-0.39	0.27
bike lane	3.32	0.72	-2.33	0.62	-4.83	0.41
bus route	-13.38*	0.03	*-6.12.*	*0.09*	4.02	0.29
street	-1.85.	0.06	-0.59	0.34	-0.74	0.43
speed limit	0.01	0.50	0.00	0.46	0.06***	0.00
truck	*1.81.*	*0.07*	0.6***	0.00	0.95***	0.00
bicyclist age	-0.01	0.31	0.01*	0.04	0.01**	0.00
bicyclist gender	-0.60*	0.02	-0.11	0.37	0.09	0.65
helmet use	0.68**	0.00	0.11	0.31	-0.42*	0.01
motorist age	-0.01	0.19	0.00	0.30	-0.01***	0.00
motorist gender	-0.23	0.18	0.08	0.41	0.45**	0.00
bike mode	8.54	0.12	-0.66	0.79	-10.7*	0.03
left turn	-0.02	0.94	*-0.22.*	*0.07*	-0.02	0.88
right turn	0.16	0.44	-0.24*	0.04	-0.78***	0.00
slope	12.24*	0.03	9.25***	0.00	5.50	0.11
Residual deviance: 4,097.38 on 5,379 d.f. Log-likelihood: -2,127.70 on 5,379 d.f. Significance: "***", 0.001; "**", 0.01; "*", 0.05; *italic, 0.10.*						

As for bicyclist and motorist socio-demographic factors, both age and gender correlated with bicyclist safety outcomes. Older bicyclists were more likely to be involved in evident injury and severe injury and fatality accidents. This indicates that individual physical condition is greatly related to bicyclist injury severity. On the other hand, older motorists were less likely to cause bicyclist severe injury and fatality accidents. This may reflect a tendency among seniors to drive more conservatively. Female bicyclists were more likely to be injured, and male motorists were more likely to be involved in a severe bicyclist injury or fatality.

Regarding behavior factors, bicyclists equipped with helmets are less likely to experience a severe injury or fatality, but helmets do not help prevent possible injury and evident injury. In fact, the outcomes for possible injury and evident injury were the opposite of those expected, possibly because of the risk compensation effect of helmet use and because the body parts not covered by helmets are still exposed to injuries. In light of the fact that helmets can help reduce severe injuries and fatalities, possibly by reducing head injuries, requiring bicyclists to use helmets should be a national policy. Bicycle collisions that occurred when motorists were turning were unlikely to be evident injury or severe injury and fatality. This could be explained by more cautious driving and less exposure due to shorter turning distances at intersections when motorists turn right.

As shown in table 4-4, built environment variables showed various levels of elasticities, which mostly had relatively low values. Among the variables that had significant relationships with the dependent variable, the elasticities ranged from 0.02 to 0.49. The most important built environment factor is the percentage of residential land and green space, for which a 1 percent increase was associated with a 0.43 percent decrease in the probability of severe injury and fatality. Therefore, in selecting the locations of new bicycle programs, areas near residential land and green spaces should be prioritized in placing new bike lanes.

Among other variables, speed limit hd the largest elasticity. A 1 percent increase in speed limit was associated with a 1.26 percent increase in the probability of severe injury and fatality. This indicates that the most effective measure to mitigate the risk of bicyclist injury severity is to manage speeds.

Table 4-4: Calculated elasticities for bicyclist injury types

	No injury		**Possible injury**		**Evident injury**		**Severe injury and fatality**	
	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.
population density	-0.17	0.14	-0.13	0.11	0.01	0.00	0.00	0.00
residential percentage	0.27	0.25	0.20	0.17	-0.08	0.11	-0.47	0.45
commercial percentage	0.06	0.07	0.07	0.09	0.00	0.01	-0.29	0.35
office percentage	0.04	0.07	0.08	0.13	-0.02	0.04	-0.18	0.30
LU mix	0.02	0.01	0.22	0.14	-0.05	0.05	-0.12	0.08
bike lane	-0.03	0.04	0.02	0.03	0.00	0.00	-0.04	0.06
bus route	0.24	0.18	0.06	0.04	-0.02	0.02	0.07	0.05
street	0.39	0.14	0.04	0.01	0.00	0.00	-0.15	0.06
speed limit	-0.30	0.08	0.02	0.00	-0.99	2.10	1.26	0.18
truck	-0.71		-0.20		0.01		0.41	
bicyclist age	0.34	0.15	-0.46	0.31	-0.03	0.02	0.32	0.14
bicyclist gender	0.28		0.00		-0.02		0.04	
helmet use	-0.32		-0.02		0.03		-0.20	
motorist age	0.42	0.16	-0.08	0.05	0.02	0.01	-0.43	0.17
motorist gender	0.11		-0.05		-0.01		0.21	
bike mode	-0.11	0.18	0.02	0.02	0.01	0.01	-0.14	0.22
left turn	0.01		0.09		-0.03		-0.01	
right turn	-0.08		0.10		-0.01		-0.36	
slope	-0.17	0.29	-0.10	0.19	0.00	0.01	0.07	0.12

4.3 Inferential Analysis for the Three-City Models

Tables 4-4, 4-5, and 4-6 present the GOL modeling outcomes for the three cities. Some differences in model specifications should be noted. Several variables were excluded in the three GOL models. For Minneapolis, including “helmet use” and “truck” would have resulted in either computationally singular results or a model crash because some injury categories had no or very few observations related to helmet usage or truck involvement. Because land areas in Minneapolis and Miami are quite flat, including “slope” would have caused a crash of the two sub-models. These changes in model specification resulted in sample size increases for two sub-models in comparison to their corresponding parts in the pooled model. For Minneapolis, the number of observations in the pooled sample was only 237, but it increased to 835 in the sub-model that did not have those three variables. For Miami, the exclusion of these variables resulted in a small increase of sample size from 802 to 804. The sample size for Seattle remained the same.

We focused the interpretation of the estimation outcomes of the three sub-models primarily on built environment factors. Among the land-use variables, the percentage of residential land and green space had a negative association with bicyclist injury severity in Seattle and Minneapolis. This relationship was only significant for the last two injury types in Miami. Overall, the modeling outcomes for the percentage of residential land and green space in the three sub-models were highly consistent with those of the pooled model.

For the percentage of commercial land, only the sub-model for Seattle showed a negatively significant relationship. The corresponding coefficients in the sub-models for Miami and Minneapolis were not significant. Only the sub-model for Seattle showed high consistency with the pooled model.

The association between the percentage of office or mixed-use land and bicyclist injury severity was negative in Minneapolis, but the relationship was only significant for the last category in Seattle. In the pooled model, the negative association was only observed for evident injury and severe injury and fatality. Therefore, this relationship was largely consistent with Minneapolis and Seattle. However, such a negative association was not observed in Miami.

Table 4-5: GOL modeling results for Miami (N=804)

Variable	**Threshold between no injury and possible injury**		**Threshold between possible injury and evident injury**		**Threshold between evident injury and severe injury versus fatality**	
	Estimate	P-value	Estimate	P-value	Estimate	P-value
intercept	4.07***	0.00	1.19.	0.08	-2.95***	0.00

population density	0.01	0.46	0.01	0.25	0.00	0.96
residential percentage	-1.45	0.13	-1.30*	0.02	-0.85	0.23
commercial percentage	0.03	0.98	-0.04	0.95	0.36	0.68
office percentage	-0.06	0.96	0.01	0.99	-0.06	0.94
LU mix	-0.97	0.27	-0.96.	0.09	-0.45	0.50
bike lane	-16.31	0.57	4.55	0.84	-0.57	0.98
bus route	-11.52	0.14	-9.01.	0.10	-7.13	0.29
street	-1.74	0.44	1.57	0.30	1.80	0.34
speed limit	0.01	0.22	0.01	0.44	0.04***	0.00
truck	14.62	0.98	0.27	0.49	0.66	0.11
bicyclist age	0.00	0.85	0.00	0.41	0.01*	0.04
bicyclist gender	-0.77*	0.03	-0.22	0.24	0.07	0.78
motorist age	-0.01	0.12	-0.01*	0.03	-0.01**	0.01
motorist gender	-0.12	0.61	0.08	0.61	0.62**	0.00
bike mode	-6.26	0.28	3.90	0.45	0.82	0.90
left turn	-0.10	0.77	-0.15	0.52	0.09	0.75
right turn	0.24	0.35	-0.40*	0.02	-0.77**	0.00

Residual deviance: 1,982.51 on 2,358 d.f.
Log-likelihood: -1,021.17 on 2,358 d.f.
Significance: “***”, 0.001; “**”, 0.01; “*”, 0.05; *italic, 0.10.*

Table 4-6: GOL modeling results for Seattle (N=774)

Variable	**Threshold between no injury and possible injury**		**Threshold between possible injury and evident injury**		**Threshold between evident injury and severe injury versus fatality**	
	Estimate	P-value	Estimate	P-value	Estimate	P-value
intercept	7.41***	0.00	0.78	0.32	-3.25*	0.03
population density	0.01	0.35	0.00	0.92	0.01	0.38
residential percentage	-1.79*	0.02	-0.64.	0.09	-1.79***	0.00
commercial percentage	-1.61*	0.05	-0.74.	0.06	-1.68**	0.00
office percentage	-1.04	0.19	-0.51	0.20	-1.46**	0.01
LU mix	1.06	0.11	-0.26	0.45	-0.72	0.27
bike lane	9.83	0.38	1.64	0.80	11.79	0.33
bus route	-21.3.	0.10	-10.08	0.13	17.84	0.14
street	-1.83.	0.10	-0.81	0.26	0.10	0.93
speed limit	0.09*	0.04	0.01	0.48	0.06	0.14
truck	1.19	0.29	0.9.	0.06	0.60	0.33
bicyclist age	0.00	0.72	0.00	0.81	0.00	0.93
bicyclist gender	-0.70.	0.06	-0.17	0.32	-0.19	0.53
motorist age	0.00	1.00	0.00	0.53	0.00	0.77
motorist gender	-0.59*	0.04	0.04	0.80	-0.13	0.64
bike mode	14.31.	0.07	3.55	0.32	-1.22	0.86
left turn	-0.05	0.87	0.03	0.87	0.32	0.27
right turn	0.01	0.99	0.02	0.93	-1.03*	0.03
slope	11.16.	0.05	5.19*	0.05	6.18	0.14
Residual deviance: 1,803.69 on 2,562 d.f. Log-likelihood: -901.84 on 2,562 d.f. Significance: “***”, 0.001; “**”, 0.01; “*”, 0.05; *italic, 0.10.*						

Table 4-7: GOL modeling results for Minneapolis (N=835)

Variable	**Threshold between no injury and possible injury**		**Threshold between possible injury and evident injury**		**Threshold between evident injury and severe injury versus fatality**	
	Estimate	P-value	Estimate	P-value	Estimate	P-value
intercept	6.16**	0.01	-0.10	0.92	-3.79	0.12
population density	0.03	0.19	0.01	0.12	0.00	0.84
residential percentage	-2.36.	0.06	-0.39	0.35	0.74	0.48
commercial percentage	-0.97	0.45	-0.47	0.30	-0.44	0.70
office percentage	-2.78*	0.02	-0.55	0.22	0.78	0.46
LU mix	-0.83	0.30	-0.81*	0.03	-0.68	0.40
bike lane	-7.34	0.49	-5.86	0.30	7.59	0.48
bus route	-11.22	0.44	1.98	0.78	26.94.	0.07
street	-1.00	0.69	-0.79	0.45	-1.50	0.54
speed limit	0.00	0.94	0.01	0.67	0.04	0.44
bicyclist age	-0.01	0.31	0.00	0.62	0.01	0.37
bicyclist gender	-0.47	0.25	0.26	0.15	-0.04	0.91
motorist age	0.00	0.86	0.00	0.31	-0.02.	0.10
motorist gender	-0.32	0.34	0.17	0.27	0.19	0.58
bike mode	12.21	0.15	-3.76	0.27	-21.54*	0.02
left turn	-0.04	0.93	-0.20	0.30	-0.19	0.64
right turn	-0.29	0.47	-0.80***	0.00	-0.68	0.18
Residual deviance: 1,483.39 on 2,454 d.f. Log-likelihood: -741.69 on 2,454 d.f. Significance: "***", 0.001; "**", 0.01; "*", 0.05; *italic, 0.10.*						

Land use mixture hasda negative association with evident injury and severe injury and fatality in Miami and Minneapolis. Such a relationship was consistent with those observed in the pooled model. However, this relationship was not significant for Seattle.

The cumulative length of bus routes had a negative association with bicyclist injury severity in Seattle, consistent with the pooled model. However, for Minneapolis, the cumulative length of bus routes was positively associated with severe injury and fatality at a marginal level of significance. The coefficient for the cumulative length of bus routes in the sub-model for Miami was not significant.

The sub-model for Seattle showed that slope was positively associated with bicyclist injury severity, similar to the pooled model.

Other independent variables showed largely consistent relationships with bicyclist injury severity in the three sub-models. In particular, the variable of speed limit is worth discussing. Speed limit was positively associated with only the most severe category of bicyclist injury in Miami, but this positive relationship was generally observed for all injury categories in Seattle. No such a significantly positive relationship was observed for Minneapolis.

The elasticities of estimated coefficients for built environment variables are presented in table 4-8. Overall, built environment factors had modest effects on bicyclist injury severity. We limit our discussion of the elasticities of "land-use mixture" and "residential percentage," focusing on their effects on severe injury and fatality (SIF). For land-use mixture, the calculated elasticities ranged from 0.16 to 0.27, indicating that the probability of a bicyclist suffering SIF decreased by 0.16 percent to 0.27 percent for a 1 percent increase in land-use mixture. These results were consistent with the results of the pooled model. The percentage of residential land and green space was negatively associated with bicyclist injury severity in Miami and Seattle. The calculated elasticities showed that a 1 percent increase in the percentage of residential land and green space was associated with a 0.26 percent decrease in bicyclist SIF in Miami and a 0.70 percent decrease in Seattle. The result for Minneapolis, however, was not consistent with the last injury category.

Table 4-8: Calculated elasticities of built environment factors for bicyclist injury types in three-city sub-models

	No injury		**Possible injury**		**Evident injury**		**Severe injury and fatality**	
	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.
Miami								
population density	-0.16	0.14	-0.13	0.12	0.01	0.00	0.00	0.00
residential percentage	0.44	0.36	0.24	0.17	-0.08	0.10	-0.26	0.21
commercial percentage	-0.01	0.01	0.01	0.01	-0.01	0.01	0.06	0.07
office percentage	0.01	0.01	0.00	0.00	0.00	0.00	-0.01	0.01
LU mix	0.36	0.15	0.24	0.09	-0.04	0.03	-0.17	0.07
bike lane	0.01	0.05	0.00	0.02	0.00	0.00	0.00	0.00
bus route	0.41	0.25	0.12	0.07	-0.08	0.08	0.32	0.19
street	0.33	0.09	-0.34	0.12	-0.02	0.01	0.32	0.09
Seattle								
population density	-0.18	0.14	0.00	0.00	-0.01	0.02	0.17	0.13
residential percentage	0.71	0.72	0.14	0.14	-0.08	0.10	-0.70	0.72
commercial percentage	0.51	0.59	0.13	0.14	-0.07	0.10	-0.53	0.61
office percentage	0.23	0.38	0.07	0.11	-0.03	0.05	-0.32	0.53
LU mix	-0.24	0.24	0.04	0.04	-0.00	0.01	-0.16	0.16
bike lane	-0.17	0.11	-0.02	0.01	-0.01	0.01	0.19	0.13
bus route	0.41	0.25	0.12	0.07	-0.08	0.08	0.32	0.19
street	0.44	0.19	0.12	0.05	-0.05	0.03	0.02	0.01
slope	-0.33	0.33	-0.11	0.12	0.00	0.01	0.17	0.17
Minneapolis								
population density	-0.46	0.29	-0.08	0.06	0.07	0.03	0.00	0.00
residential percentage	1.03	0.88	0.05	0.03	-0.20	0.20	0.32	0.27
commercial percentage	0.20	0.24	0.04	0.05	-0.08	0.11	-0.09	0.11
office percentage	0.57	0.71	0.04	0.04	-0.13	0.19	0.16	0.20
LU mix	0.34	0.21	0.12	0.07	-0.37	0.30	-0.27	0.17
bike lane	0.09	0.10	0.03	0.03	-0.07	0.08	0.09	0.10
bus route	0.20	0.15	-0.02	0.01	-0.03	0.04	0.45	0.35
street	0.22	0.08	0.07	0.02	-0.13	0.07	-0.32	0.12

Chapter 5 Conclusions and Policy Recommendations

5.1 Conclusions

This study addressed the two research questions raised in the introduction chapter. The results indicated that several built environment features and bicyclist injury severitytypes are strongly related. Land-use mixture; the percentages of residential land and green space, commercial land, and office or mixed-use land; slope; and the cumulative lengths of streets and transit routes all showed statistically significant associations with bicyclist injury severity. In particular, land-use mixture and the percentage of residential land and green space were the most important variables that showed negative effects, whereas slope was an important variable that showed a positive effect.

Regression models estimated individually for the three selected cities were broadly consistent with the pooled model. However, some differences are worth noting. The percentage of commercial land and the cumulative length of streets were significant for Seattle, but not for Miami and Minneapolis. The percentage of office or mixed-use land was significant for Seattle and Minneapolis, but insignificant for Miami. Minor discrepancies were also observed with respect to estimated coefficients for the cumulative length of bus routes.

Estimated coefficients for the confounding effects of speed limit, vehicle type, protective equipment, and bicyclist and motorist demographic factors for the pooled model were mostly consistent with findings reported in previous studies. Similar results obtained from the three sub-models were also largely consistent with the existing literature.

The main conclusion drawn from these findings is that, to improve bicycle safety, urban planners and policy makers should encourage mixed land use, promote dense street networks, place new bike lanes in residential neighborhoods, green spaces, commercial areas, and office districts, and avoid steep slopes. In addition, bicycle master plans should incorporate transit routing.

Other desirable complementary efforts would include implementing speed reduction programs, prohibiting large vehicles from entering areas with many bicyclists, and promoting helmet use among bicyclists as a national policy. Furthermore, education programs could be designed to inform bicyclists and motorists that olded and female bicyclists are more vulnerable to severe injuries.

5.2 Limitations and Directions for Future Research

This study had several limitations. First, original data obtained from the comparison cases included items that were coded differently. To facilitate the cross-city comparison, some potentially relevant variables were excluded from the regression models. For example, bicyclists wearing reflective clothing were reported in the data for Seattle, but not reported for the other two cities. Consequently, this interesting variable was dropped. Future research may consider using data coding consistency as a primary criterion for selecting comparison cities to reexamine the research questions.

Secondly, the study period was from 2011 to 2014, but the built environment variables were measured for only one year. Therefore, despite changes in the built environment over the four-year period, the land-use and road network features were treated as if they had remained constant. In the future, frequently updated built environment data should become more accessible to researchers, which will provide a stronger empirical basis for such a study.

Thirdly, this study employed a cross-sectional research design, which limited the ability to establish a causal inference between bicyclist injury severity and the built environment. As longitudinal data on both bicyclist injury severity and the built environment become increasingly available, more sophisticated models can be applied to comprehend causal relationships.

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Appendix

Measuring the Built Environment in ArcGIS

Built environment variables were quantified through spatial overlay.

1) Population density and bicycle mode share were identified through the overlaying of bicycle crash point data and the American Community Survey for 2011.
2) Four land use variables ("LU mix," "residential percentage," "office percentage," and "commercial percentage") were quantified by creating a buffer with a radius of 250 feet at each collision site and overlaying it with the lan- use maps for individual cities.
3) Three roadway design variables were quantified by creating a buffer with a radius of 50 feet ("bike lane" and "bus route") or 250 feet ("street") at each collision site and overlaying it with roadway layers (bike lane, bus route, and street network) for individual cities.
4) The other variables were documented in the collision profiles by using collision ID as the key to join tables. These variables were bicyclist age and gender, motorist age and gender, helmet use, truck involvement, posted speed limit, and motorist momentary behaviors such as turning left or right.
5) The slope as calculated differently in the three cities on the basis of different data (elevation or contour).

Several examples are given here to show how the built environment variables were quantified in ArcGIS:

1) Street Network Variables

Take bike lane as an example. As shown in figure A-1, 50-feet buffers were created around bicycle collision sites. The first step was to overlay these 50-feet buffers and the bike lane layer. Bike lane segments within each buffer were thus identified. The cumulative length of bike lanes was then calculated by aggregating the cumulative length of bike lanes within each buffer.

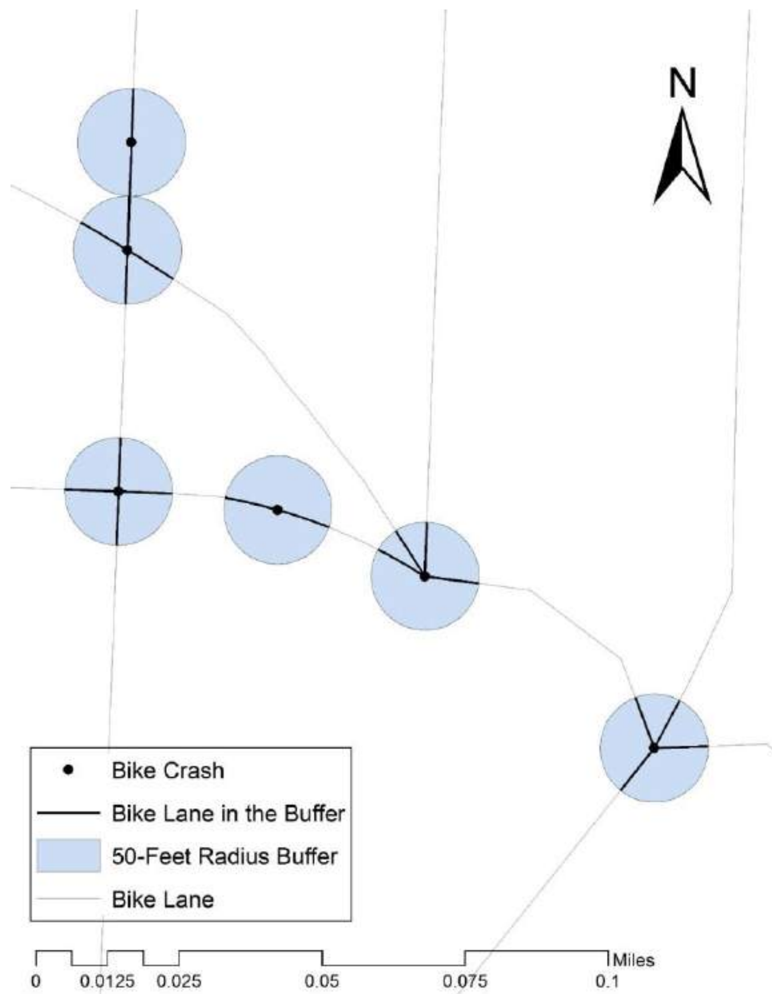


Figure A-1: Measuring the cumulative length of bike lanes around a collision site

The same procedure was applied to identify the cumulative length of bus routes.

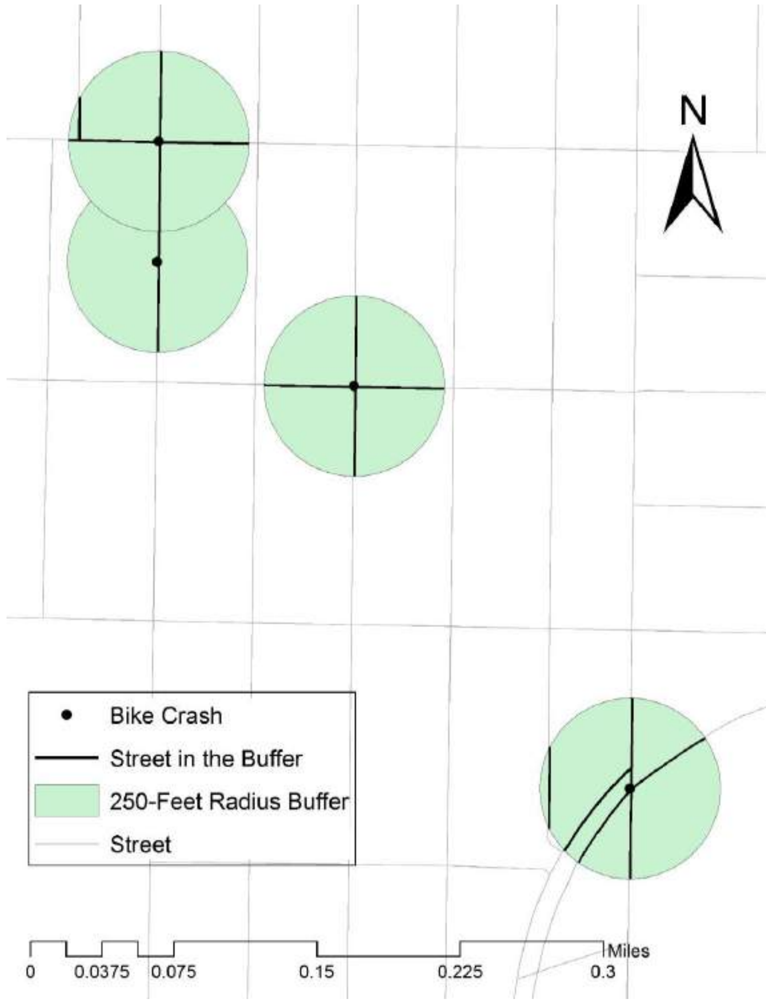


Figure A-2: Measuring the cumulative length of streets surrounding a collision site

As shown in figure A-2, the identification of the cumulative length of streets followed a procedure similar to that of the cumulative length of bike lanes, except that the buffer radius was 250-feet.

2) Land-use variables

Land-use variables ("LU mix," "residential percentage," "commercial percentage," and "office percentage") were measured in 250-feet buffers around bicycle collision sites. By overlaying the buffers and the land use layer, the area of each type of land around each collision site was calculated. Then, the area of each type of land was divided by the total area of a 250-feet buffer to obtain the percentage of the land-use type. Using the following LU mix equation, land-use mixture was measured.

$$LU\ mix=(-\sum Pi\ *ln\ Pi)\ /ln\ n$$

where n is the number of different land-use types and Pi is the proportion of land use in type i. The resulting variable *LU mix* was the land-use mixture index, which varied from 0 (homogeneous land use) to 1 (most mixed land use).

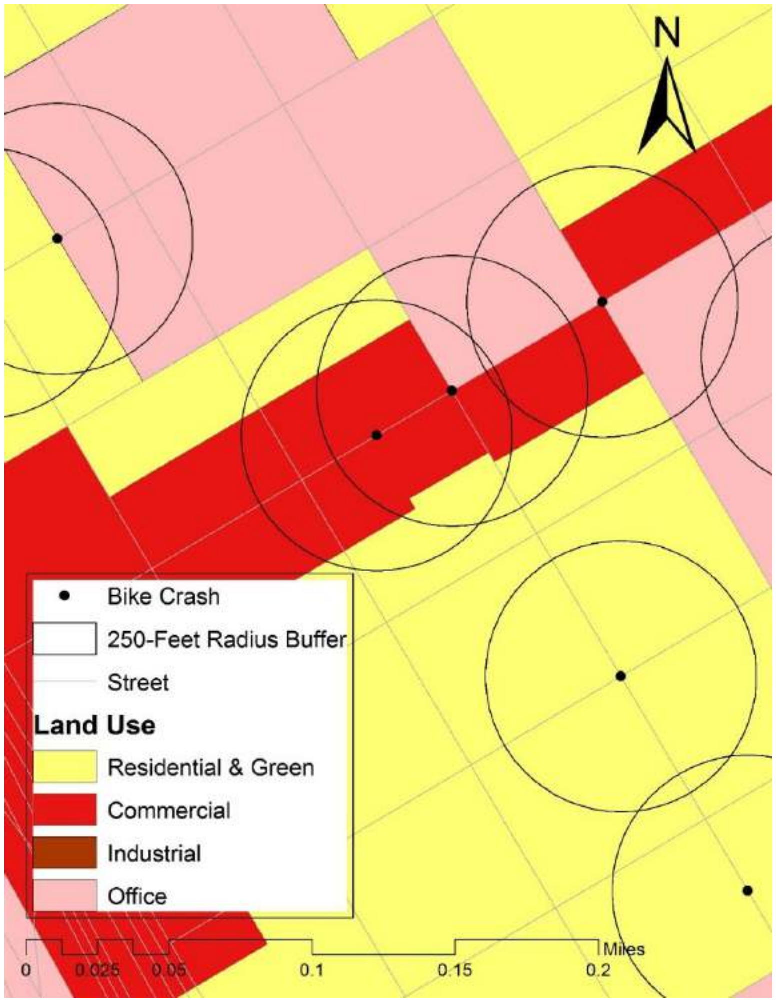


Figure A-3: Measuring land use percentages and mixture around bicycle collision sites

3) Bike Mode and Population Density

Two variables ("population density" and "bike mode share") were obtained by overlaying data obtained from the American Community Survey (ACS) with GIS maps of collision sites. Figure A-4 presents the bike mode share in Seattle as an example.

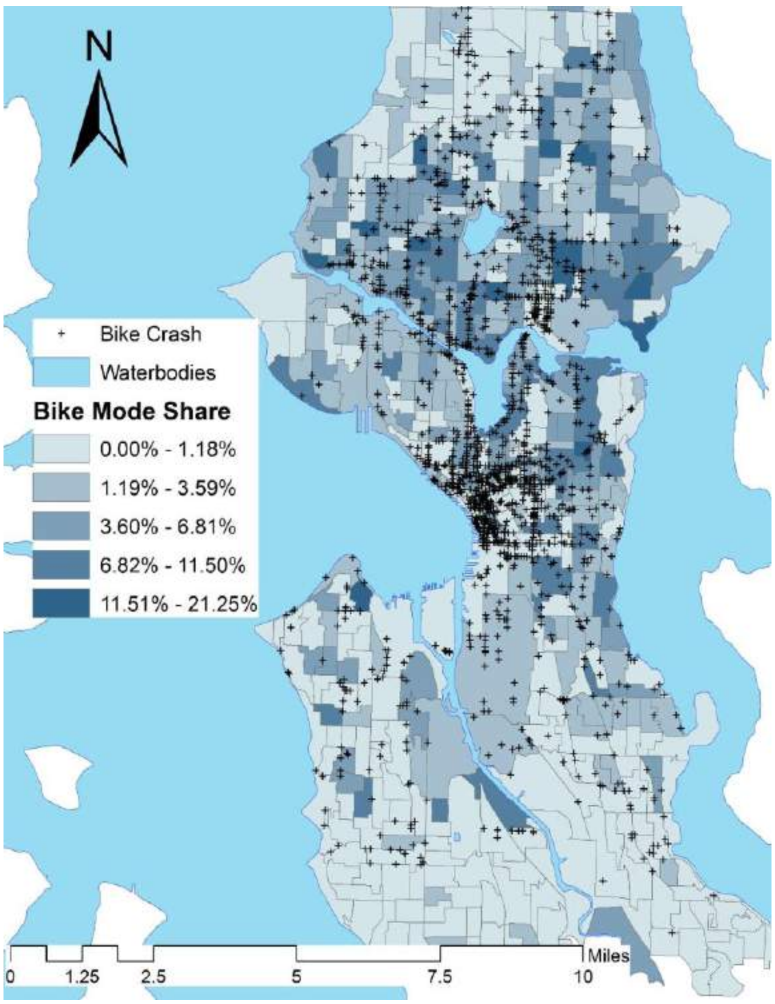
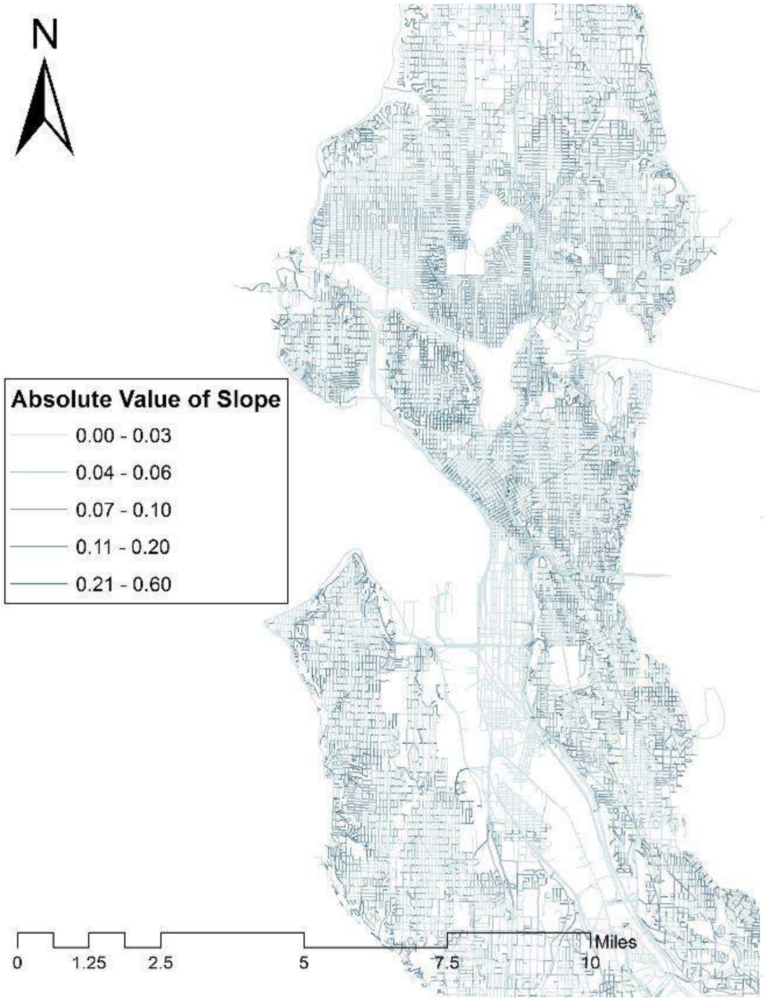


Figure A-4: Measuring bike mode share at bicycle collision sites

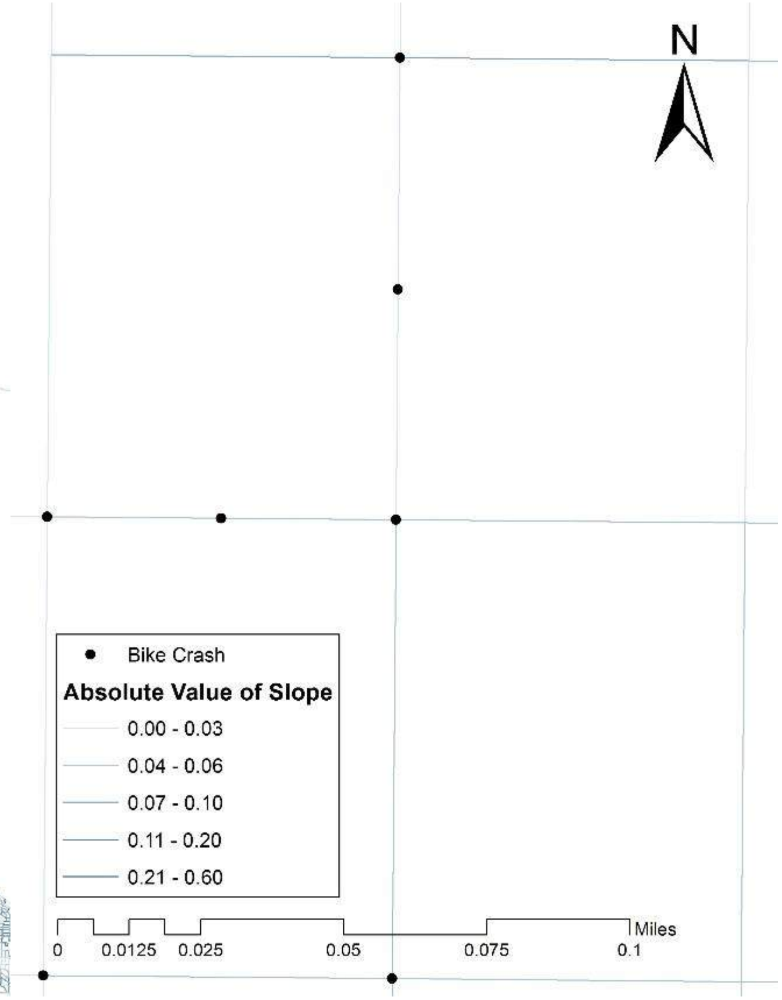
4) Slope

Seattle's street network has recorded the elevation of each road intersection, and the slope was calculated by the difference of elevation divided by the length of the road segment. Figure A-5 displays the calculated slopes in Seattle.

Minneapolis and Miami are two flat cities, and they did not have elevation identified for each intersection but contours at the resolution of 2-feet and 5-feet, accordingly. We used the "Near" command provided by ArcGIS to estimate the elevation of each intersection and then followed the same steps that we took for Seattle. Figure A-6 shows the contour data and the calculation of slopes for Minneapolis.

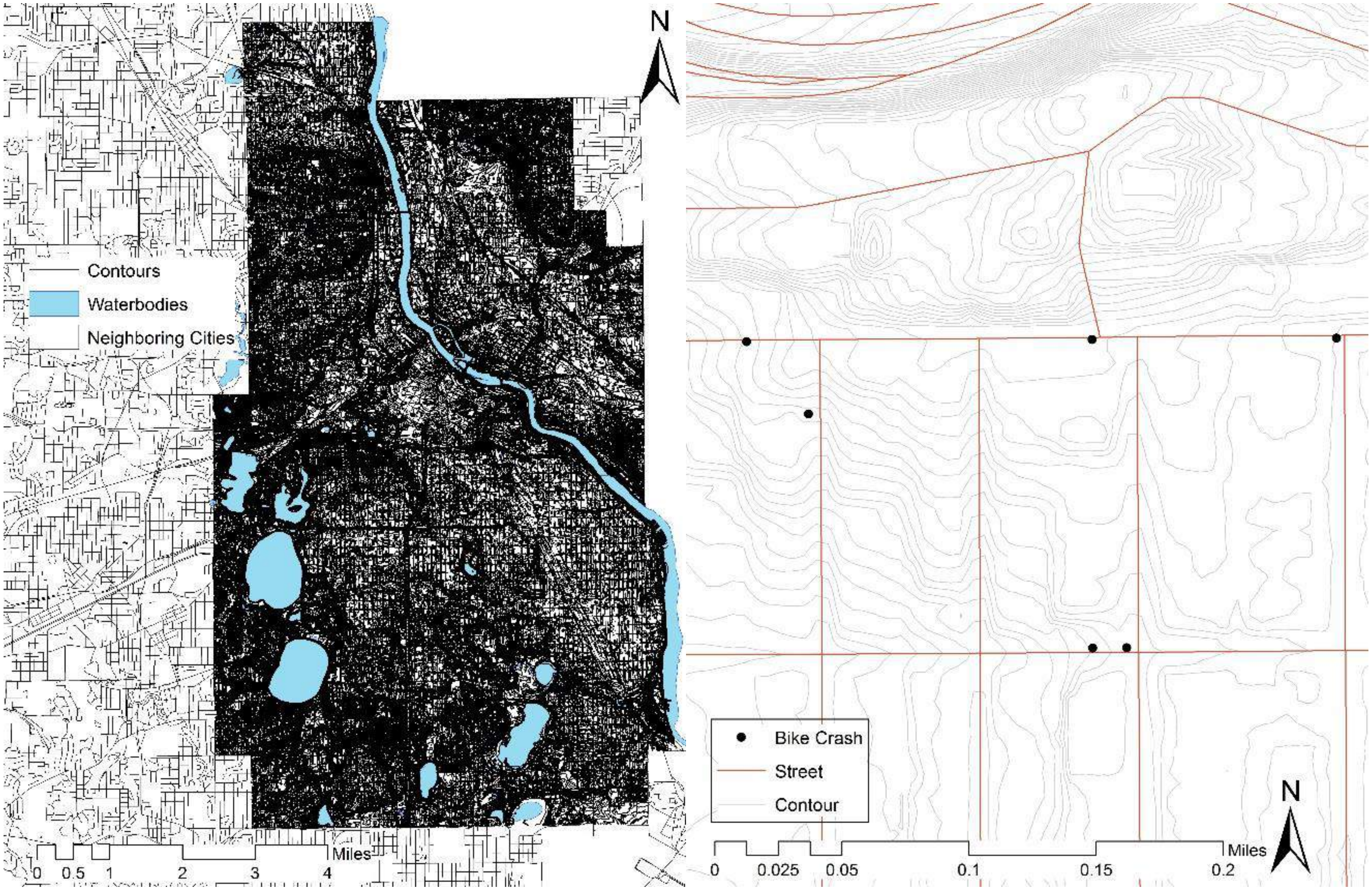


(a) Street slopes in Seattle



(b) Overlaying streets and bicycle collision sites

Figure A-5: Measuring slope at bike collision sites for Seattle



(a) Contours in Minneapolis (b) Overlaying streets, contours and bike crashes

Figure A-6: Measuring slope at bike collision sites for Minneapolis