QUANTIFYING DANGEROUS SITUATION EXPOSURE FOR BICYCLISTS

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Abstract

This thesis introduces a new method to analyze network-wide bicycle infrastructure to quantify dangerous situation exposure for bicyclists. The method is intended for sketch-level scenario planning. Lack of bicycle volume data is a common impediment to calculating exposure, our method overcomes this by extrapolating short-duration citizen-volunteer count data to estimate community-wide bicycle volumes. First, the count data is extrapolated spatially using an origin-destination centrality technique. Second, the count data is extrapolated temporally using adjustment factors for hour, day, and month. This two-step extrapolation produces a rough estimate of Annual Average Daily Bicyclists (AADB) for streets, trails, and intersections across a community. Next, we propose using public participation to define community-specific "dangerous situation metrics" that can be used to compare AADB exposure for alternative improvement scenarios. We demonstrate the process with a case study by comparing exposure under current conditions and after implementing a proposed bicycle improvement master plan. For example, the case study showed a 5% decrease in AADB exposure to the dangerous right hook situation (bicyclists going straight through an intersection where there is a high volume of vehicles turning right). As another example, the improvement master plan was shown to potentially reduce the need for bicyclists to cross harsh intersections by 7%. The method introduced in this thesis can provide engineers, planners, and other decision-makers a means to compare improvement scenarios for investment decision-making. Furthermore, the literature review and discussion provides a starting point for communities to define their own dangerous situation metrics.

Acknowledgments

This thesis is the result of many individuals and organizations that assisted me throughout my research here at the University of Idaho. I would like to thank Michael Lowry for being an enthusiastic and hard-working major professor and teacher during this process. I would like to thank Michael Dixon and Kevin Chang for serving on my committee and providing valuable input during the research process. I would like to thank PacTrans, the Region X University Transportation Center, for funding this project. The funding was administered by the National Institute for Advanced Transportation Technology (NIATT). I would like to thank Charlotte Claybrooke and Paula Reeves at the Washington State Department of Transportation, and City of Bellingham for sharing their bicycle count and GIS data, including Chris Behee, Kim Brown, and Chris Comeau. Finally, I would like to thank my friends and family for helping me out in so many ways while I was in graduate school.

Dedication

This work is dedicated to Dr. Michael Dixon. The sudden loss of Dr. Dixon came as shock to all who knew him. His enthusiasm for transportation safety accident analysis and teaching was inspiring. There was often a smile on his face, and his lectures usually included a few cheesy jokes that he happily told at his own expense. I am thankful to have had the opportunity to study under him

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Chapter 1 Introduction

1.1 The Need for Bicycle Accident Analysis

Relative to other travel modes, such as traveling by bus or car, cycling is dangerous. In the U.S., bicyclists are 12 times more likely than car occupants to get killed per distance travelled (Pucher and Dijkstra, 2003). The higher risk is likely due to a cyclist having less protection compared with a car driver in the event of an accident, and due to the fact that cyclists tend to do most of their travel in urban areas where the overall risk of accidents is higher (Elvik et al., 2009). There is evidence that cycling can be made safer through a wide range of policies including infrastructure, regulation, and education; cyclists in the U.S. are eight times more likely to get injured than German cyclists and about 30 times more likely than Dutch cyclists (Pucher and Dijkstra, 2003). Cyclist fatalities in the US are double those in Germany and triple those in the Netherlands, both in terms of number of trips and in distance travelled (Pucher and Dijkstra, 2003).

Solutions to reduce cyclist exposure factors are multifaceted, with most studies in North America emphasizing helmet design, regulation and implementation to mitigate the severity of injuries when collisions occur (Reynolds et al., 2009). However, there is evidence that bicycle infrastructure improvements can increase safety. From a preventative measures approach, addressing bicycle infrastructure meets three conditions: 1) it is population based, rather than requiring individual initiatives; 2) it is passive, rather than requiring active participation; and 3) it is accomplished with a single action, rather than requiring repeated reinforcement (Chipman, 2002).

Meanwhile, there is increased interest in cycling and studies suggest citizens are interested in additional bicycle infrastructure (Belden et al., 2011). Nationally, in the 2004 and 2011 Realtor surveys, about 45% of respondents felt that their current communities lack places to bike. The desire for more bicycle facilities is on par with a desire for more shops or restaurants within an easy walk, and about 10% higher than the desire for parks and playgrounds (Belden et al., 2004, and Belden, et al., 2011).

1.2 A New Method for Quantifying Dangerous Situation Exposure

While bicycling is more dangerous than driving a car, it is difficult to quantify exposure faced by cyclists. This thesis introduces a new method which combines bicycle volume estimation tools with a method to quantify exposure to dangerous situations help inform sketch-level scenario planning.

There are two primary impediments to quantifying the exposure face by cyclists. First, there is a lack of bicycle volume data (Elvik et al., 2009; Vandenbulcke et al., 2013), so it is difficult to understand how many people are cycling, how much, and where. Not only is bicycle volume data collection rare, traditional volume estimation methods commonly used for motorized travel such as the four-step model are not well-suited for estimating bicycle volumes (Porter, 1999; Liu et al., 2012). The lack of volume data presents a major challenge for many aspects of bicycle infrastructure planning, such as estimating bicycle accident exposure rates and comparing improvement scenarios for investment decision-making. Second, there is a lack of accident data. While cycling has been found to be more dangerous than driving a car, the mode share is so low that accidents are rare to begin with. Many accidents are not reported, and historically police reports regarding collisions involving a bicycle have suffered from lack of accuracy and detail.

Our work overcomes these impediments through a new four step method. First, data from a citizen-volunteer manual count is used as the basic bicycle volume input (although any bicycle volume data could be used). Second, a technique called observed-demand (OD) centrality is used to extrapolate bicycle volume spatially from count locations to every segment and intersection throughout the transportation network. OD centrality has the ability to estimate volume on each link in the network, and also estimates each turn movement at each intersection. Volumes are then adjusted temporally using adjustment factors. The first two steps overcome the volume data problem and provide an output that is so detailed that maneuvers can be quantified by type and combined with vehicle volume and turn estimations to quantify various types of situations, including potential conflict points.

The third step is aimed at overcoming the lack of accident data. Ideally, bicycle volume would be compared against real accident data, or compared with formulas that predict accident occurrence, called Safety Performance Factors (SPF). However, bicycle accident analysis is in its infancy, accident data is scarce, and often lacks important information. Thus far only one SPF, for use in Boulder, CO, has been created for bicycling (Nordback et al., 2014). Because of data limitations, our method utilizes a literature review to identify dangerous situations, which are situational antecedents that may lead to accidents. The fourth step is to use the volume data and dangerous situation metrics to estimate bicyclist exposure to specific dangerous situations.

1.3 Case Study

To demonstrate our method, we applied it through a case study of the City of Bellingham, WA. Bellingham was selected because it has one of the most robust bicycle volume data sets in the Pacific Northwest, and because it is a relatively isolated urban area rather than a large metropolis with complex travel patterns. We used Bellingham's manual bicycle count data from 2006-2013, and created two scenarios. A current road and trail network was used to create Scenario 1, and Bellingham's draft Bike Master Plan to create Scenario 2. Comparing two scenarios allows us to demonstrate the usefulness of our model as a decision-support tool.

Our model allows practitioners and decision-makers to quantify specific changes in estimated volumes and dangerous movements, and to use this information as a decision-support tool as they craft new scenarios and weigh options.

1.4 Thesis Organization

The next chapter provides an overview of how bicycle volumes are estimated. Chapter 3 describes our method of quantifying bicycle exposure, and will be submitted to an academic journal. Chapter 4 provides additional concluding remarks and recommendations for future work. Finally, the Appendix provides examples of data collection forms.

Chapter 2 Estimating Bicycle Demand

2.1 Citizen Volunteer Manual Count Programs

Bicycle volume data is scarce, but there are efforts underway to increase data collection. The National Bicycle and Pedestrian Documentation Project (NBPD) is a coordinated effort that aims to provide a consistent model of bike and walk data collection methods and ongoing data collection (National Bicycle and Pedestrian Documentation Project, 2014). The Project has been successful at increasing what scarce data is available. Data collection methods consist of two basic types: automatic bicycle counters and manual count programs. Automatic counters provide continuous data but these systems require up front capital outlays of $2,000 to $10,000 (Nordback et al., 2013) and thus are rare and concentrated to main routes. Manual data collection is lower cost and more flexible, and an increasingly popular method is citizen-volunteer manual count programs which typically involve providing citizen-volunteers with clipboards to simultaneously collect data at several locations. The counts are typically conducted one or two times a year during peak travel periods to create a “snapshot” of bicycle and pedestrian travel throughout the community. For example, the NBPD recommends conducting counts four times per year, once for every season, for two hours in the morning (7:00am-9:00am) and two hours in the evening (4:00pm-6:00pm).

Count programs are coordinated and conducted by entities at various levels. For example, the Washington State Department of Transportation (WSDOT) has supervised a citizen-volunteer count program since 2008. The most recent WSDOT count involved 38 jurisdictions and more than 409 observations at intersections (Cascade Bicycle Club, 2013). The California Department of Transportation recently funded an online data-clearinghouse for local communities throughout southern California to upload and share their data from their count programs (Huff, 2014).

Our research was conducted with data from Bellingham, WA, where the city administers a volunteer data collection program as part of a statewide effort coordinated by the Washington State Department of Transportation. Bellingham was selected because it has one of the most robust bicycle volume data sets in the Pacific

Northwest, and because it is a relatively isolated urban area rather than a large metropolis with complex travel patterns. The City of Bellingham has participated in WSDOT's citizen-volunteer count program every year since 2006, when five locations were counted. Over time the count has expanded and by 2013, 18 locations were counted (Cascade Bicycle Club, 2013). Figure 2.1 displays the distribution of the count locations and relative bicycle volumes observed.

Data collection points are located at street intersections and intersections of streets and trails, in several cases the locations have been moved due to construction. Pedestrians and cyclists are counted as they leave the intersection. Each intersection was counted for two hours in the morning (7-9 AM) and evening (4-6 PM), typically in late September or early October. The 18 locations are spread out geographically and fairly diverse in terms of the functional classification of the intersecting streets, such as Arterial/Local or Trail/Arterial. For each collection point, bicycle data from all available years was averaged.

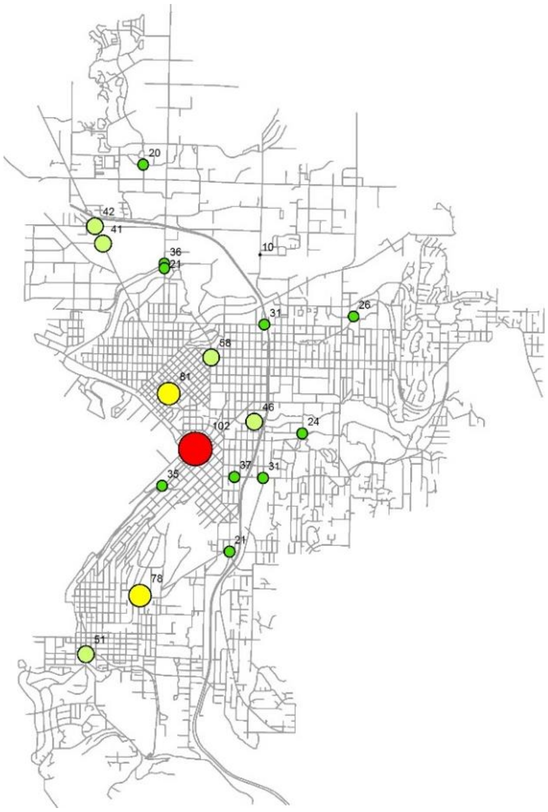


Figure 2.1 Two-hour AM bicycle count average for 2006-2013

2.2 Spatial Extrapolation of Manual Counts

Traffic volume data collected at specific points can be used to estimate network-wide volumes, this is done by spatially extrapolating the data. We use a method called origin-destination (OD) centrality, which is based on a modified form of stress centrality and was successfully utilized by McDaniel et al. (2014) to estimate bicycle volumes throughout Moscow, ID (population 23,800). The method has three basic steps: 1) the transportation network is characterized in terms of preferred bicycle paths between locations, 2) land use information is used to create origins and destinations and respective multipliers that represent a magnitude of "trip potential" between origin-destination pairs, and 3) regression is used to spatially extrapolate count data from the actual count locations to all links and nodes network-wide.

The use of regression modelling and manual count data to predict bicycle volumes for unobserved locations based on characteristics is not new. Other researchers have used adjacent land use, number of vehicle lanes, vehicle speed limit, and width of the bike lane (Griswold et al., 2011). For example, Jones et al. (2010) developed a regression model ($R^2 = 0.47$) for NBPD data consisting of three explanatory variables: (1) total footage of off-street paths within 0.5 mile, (2) employment density within 0.25 mile, and (3) population density within 0.25 mile.

OD centrality has several features which make it attractive. Compared with other bicycle volume estimation methods it is relatively simple, which allows for the option of modifying the network to create alternative scenarios. It also effectively provides a means to spatially extrapolate count data throughout an entire street and trail network, which provides volume detail on all street and trail segments, as well as individual turn movements, allowing us to analyze specific types of situations.

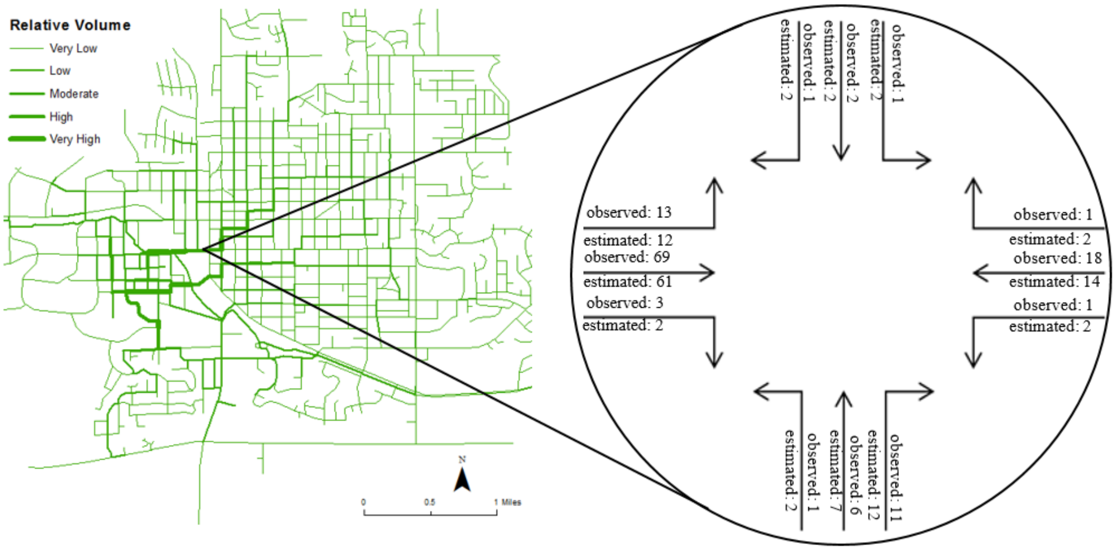


Figure 2.2 Two hour count spatially extrapolated throughout Moscow, ID

Source: McDaniel et al. (2014)

For our case study we utilized GIS parcel, employment and school attendance data provided by the city of Bellingham. For origins, the inputs of residents per parcel were used. For destinations, employees per parcel, employment data, and parcel size were inputs. A limit of 5 miles was placed on bicycle travel. GIS files provided by the City of Bellingham were modified to create the bicycle transportation network, with GIS attributes comprising bicycle impedance inputs. 10% of the citizen count data was withheld and used for calibration. Spatial extrapolation was completed once for 2-hour AM volumes and again for 2-hour PM volumes. The output from this step was a network-wide bicycle 2-hour volume for AM, and another for PM volume.

2.3 Temporal Extrapolation of Network-Wide Two-Hour Volume

While citizen-volunteer counts are short-duration, bicycle traffic fluctuates depending on the time-of-day, day-of-week, and season. Emerging research has demonstrated the possibility of temporally extrapolating short duration count data to estimate average volumes. This research typically relies on automatic bicycle counters

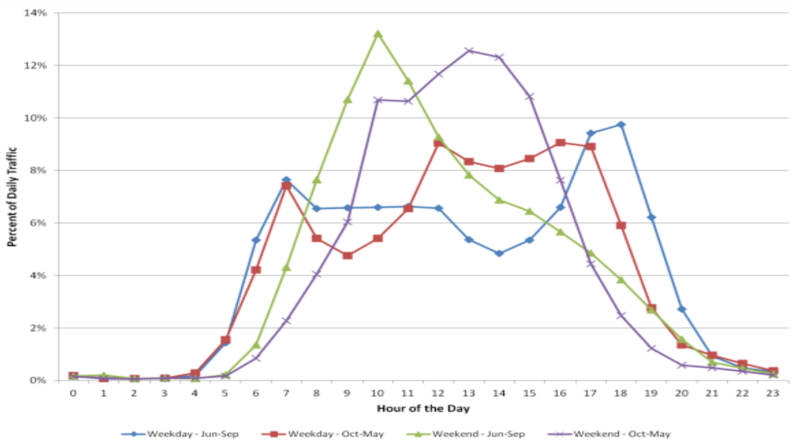


Figure 2.3 Hour of the day patterns on a shared use path in Colorado

Source: Colorado Department of Transportation, cited in the Traffic Monitoring Guide (2013).

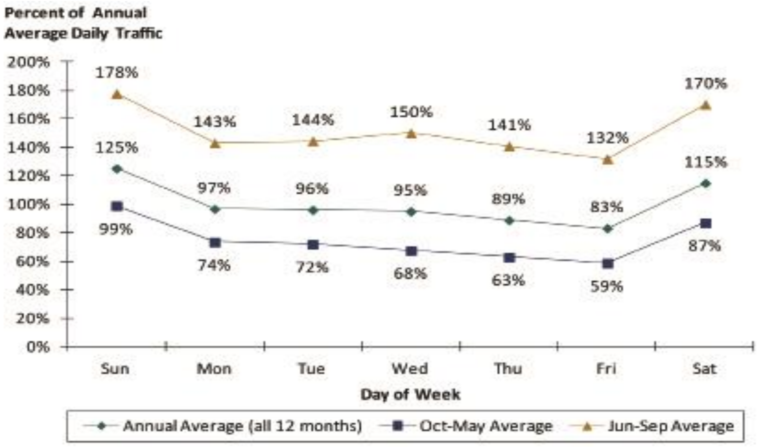


Figure 2.4 Day of the week patterns for a shared use path in Colorado

Source: Colorado Department of Transportation, cited in the Traffic Monitoring Guide (2013).

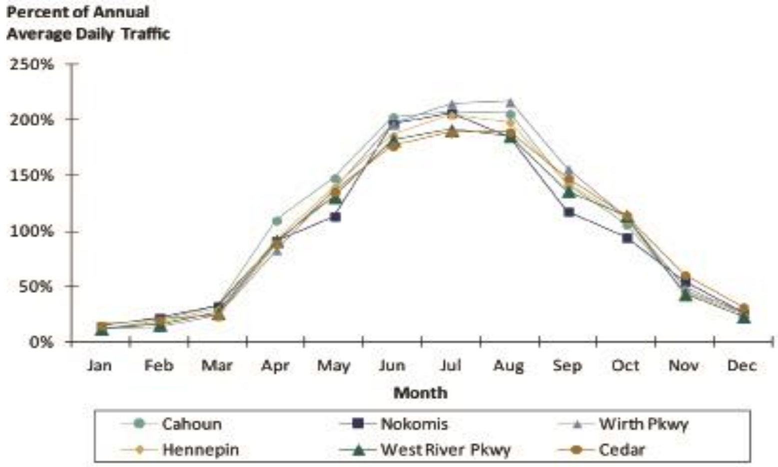


Figure 2.5 Monthly patterns for six shared use paths in Minneapolis, MN

Source: Greg Lindsey, University of Minnesota, cited in the Traffic Monitoring Guide (2013) that can collect continuous data; figures 2.3 through 2.5 depict the findings of how bicycle travel fluctuates over time in various situations.

The goal of temporal extrapolation is to estimate Average Annual Daily Bicyclists (AADB), which represents the total annual number of bicyclists passing a point divided by 365 days. This extrapolation is conducted using adjustment factors that convert short term count data into AADB figures. Adjustment factors for short term counts are an emerging phenomenon, and there are few available to cover diverse climatic zones, facility types, and travel patterns in different cities.

For the case study in this project, off the shelf adjustment factors were not available. Adjustment factors were created for Bellingham, WA by adapting factors available from four sources and local knowledge. The first source, the NBPD, provides adjustment factors for three climatic zones called: Long Winter Short Summer, Moderate Climate, and Very Hot Summer/Mild Winter (NBPD, 2009). The second source is a report prepared by Nordback et al. (2013) for the Colorado Department of Transportation. The report provides a variety of adjustment factors for recreational trails, suburban streets, and urban streets throughout Colorado. The third source of adjustment factors is found in the US DOT's Traffic Monitoring Guide (2013) for Minneapolis, Minnesota. The forth source of adjustment factors is the work by Miranda-Moreno et al., (2013) that included adjustment factors for five North American cities, including Vancouver, B.C. and Portland, OR, but unfortunately did not include a full year. Adjustment factors also vary by facility types (or classes), such as "path" or "pedestrian district" (National Bicycle and Pedestrian Documentation Project, 2009), or "utilitarian", "recreational", or "mixed" (Miranda-Moreno et al., 2013).

The available adjustment factors outlined above were adapted to reflect Bellingham's climate characterized by a rainy fall, winter, and spring, but a dry and mild summer. Table 2.1 summarizes the sources and adaptations, and the adjustment factors used in the case study are listed in table 2.2. The factors were checked against the NBPD factors created with data from Minneapolis, Vancouver and Portland, as well as by the NBPD. For the case study only certain factors are used; the complete list of adjustment factors is shown for illustration.

Table 2.1 Summary of adaptations to adjustment factors

Factor	Facility	Source(s)
2 Hour	Street	Adapted from average time of day patterns for bicyclists in Minneapolis MN (Traffic Monitoring Guide p. 4-22, fig. 4-12, 2013) and NBPD count adjustment factors for a pedestrian district 7-9AM and 4-6PM (NBPD 2009)
	Trail	Adapted from hour-of-day factors created for the Colorado's Cherry Creek Trail shared-use path for a weekday October-May (Traffic Monitoring Guide, p. 4-21, fig. 4-11, 2013) and NBPD count adjustment factors for a path 7-9AM and 4-6PM (NBPD 2009)
Day of Week	Street	Adapted from Nordback et al. (p. 107, fig. 56, 2013) commute patterns: low weekend, low monthly variation
	Trail	Adapted from Nordback et al. (p. 107, fig. 56, 2013) front-range non-commute patterns: high weekend, low monthly variation
Month	Street	Adapted from Cherry Creek Trail monthly factors (Traffic Monitoring Guide pp. 4-24 to 4-25, fig. 4-14 and 4-15, 2013). Adjusted similar to monthly trail factors but with increased travel in the winter months and reduced in summer months
	Trail	Adapted from Cherry Creek Trail monthly factors (Traffic Monitoring Guide pp. 4-24 to 4-25, fig. 4-14 and 4-15, 2013). Adjusted to reflect increased winter months due to less snowfall in Bellingham, slower spring increase due to rain, higher peak in late summer due to lack of intense summer heat, rapid drop in fall due to rainy season

Table 2.2 Adjustment factors for AADB used in the case study

	2-Hour		Day of Week							Month											
Class	AM	PM	S	M	T	W	T	F	S	J	F	M	A	M	J	J	A	S	O	N	D
Street	0.1	0.2	0.1	0.2	0.2	0.2	0.2	0.1	0.1	1.4	1.4	1.3	1.1	0.9	0.8	0.7	0.7	0.8	1.0	1.5	1.5
Trail	0.1	0.2	0.2	0.1	0.1	0.1	0.1	0.1	0.2	1.7	1.7	1.5	1.3	1.0	0.8	0.6	0.6	0.7	1.1	1.7	1.7

The adjustment factors are applied to the two-hour volumes to obtain AADB as follows:

$$AADB = \left[\left(\frac{V_{AM}}{k_{AM,C}} + \frac{V_{PM}}{k_{PM,C}}\right)/2\right] * F_{day,C} * F_{month,C}$$

where

V_{AM} = AM 2-hour bicycle volume,

V_{PM} = PM 2-hour bicycle volume,

$k_{AM,C}$ = AM 2-hour adjustment factor for class C,

$k_{PM,C}$ = PM 2-hour adjustment factor for class C,

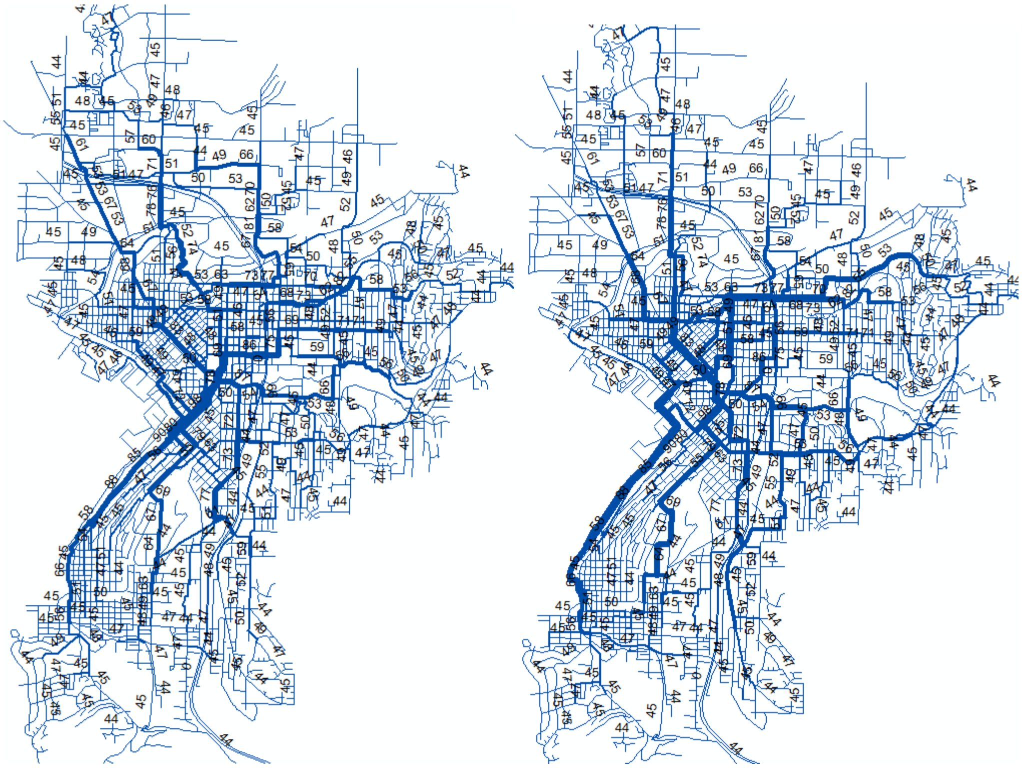
$F_{day,C}$ = day of the week adjustment factor for class C, and

$F_{month,C}$ = month adjustment factor for class C.

2.4 Results

The most important aspect of the OD centrality method is that it produces specific AADB values for every link and every turn movement throughout the network. This can be displayed in map form, as shown in figure 2.6, to depict order-of-magnitude AADB. Practitioners, citizens, and other decision-makers can use maps like these to visualize, discuss, and compare the merits of different proposals.

Origin and destination multipliers were kept fixed, so the total, study-wide bicycle volume is fixed and the change in AADB is merely a shift from travel on certain facilities to other facilities. (Although McDaniel et al. (2014) suggest OD centrality can be used to forecast future growth-scenarios by changing the residential and commercial land use input.)



Scenario 1

Scenario 2

Figure 2.6 Estimated AADB for Scenario 1 and Scenario 2

As an example, Scenario 2 includes extending a shared use path from the south-west into downtown. Not surprisingly, Figure 2.6 shows a decrease in AADB along the parallel arterial because those trips would be shifted to the new shared use path. Practitioners could use maps like these to encourage community dialogue and determine where capital investment funding should be allocated to ensure adequate capacity or improve linkages.

It should be noted that the specific AADB values are rough estimates and the only way to obtain true AADB is by installing and using a continuous counter for the entire year. Consequently, AADB estimation, regardless of the method, can only be roughly validated and the most straight forward method is to simply use local expert knowledge. For the case study, and for scenario planning in general, this level of accuracy is adequate. A potential data collection scenario that could be accomplished within a limited budget would be a manual count program that provides seasonal snapshots at many locations simultaneously, combined with automated counters that provide continuous data collection at key locations and adjustment factors specific to that locale.

2.5 Conclusion

The growing interest in bicycling is spurring additional count efforts such as volunteer programs and automatic counters. The data from these programs can be extrapolated spatially and temporally to estimate bicycle volumes network-wide. The output is data rich in that it provides volume and turn movement estimates for every link and intersection, respectively. This can provide important information for communities that are making infrastructure improvement decisions, establishing a community vision for future capital improvements, and more. The map outputs can be useful in encouraging public dialogue, and for identifying missing links. The next chapter will demonstrate how these results can be used for quantifying dangerous situation exposure in scenario analysis.

Chapter 3 Quantifying Dangerous Situation Exposure[1]

3.1 Introduction

Relative to other travel modes, bicycling is dangerous. In the U.S., cyclists are 12 times more likely than car occupants to be killed per distance travelled (Pucher and Dijkstra, 2003). The higher risk is likely due to a cyclist having more exposure and less physical protection compared with a car occupant, the fact that children cycle, and the fact that cyclists tend to do most of their travel in urban areas where the overall risk of accidents is higher (Elvik et al., 2009). There is evidence that cycling can be made safer; the rate of fatalities from cycling in the U.S. is double that of Germany and triple that of the Netherlands, both in terms of number of trips and in distance travelled (Pucher and Dijkstra, 2003). There is also a discrepancy between countries for non-fatal injury accidents; cyclists in the U.S. are eight times more likely to get injured than German cyclists and about 30 times more likely than Dutch cyclists (Pucher and Dijkstra, 2003).

While bicycling is more dangerous than driving a car, there are two primary impediments to quantify exposure faced by cyclists. A lack of robust accident data makes it difficult to analyze accidents for characteristics, especially at the community scale. This thesis introduces a new method which combines bicycle volume estimation tools with a method to quantify exposure to dangerous situations help inform sketch-level scenario planning. Our method consists of two steps: 1) define exposure metrics, and 2) calculate exposure and compare improvement scenarios. The former overcomes the lack of bicycle accident data, and the latter creates outputs.

Step one is accomplished using the OD centrality method developed by McDaniel et al. (2014) to spatially extrapolate manual count data. Step two goes a step further by temporally extrapolating the data as well; this two-step extrapolation produces an estimate of AADB for every street, trail, and intersection in a community. Although the combination of spatial and temporal extrapolation is a novel use of citizen-volunteer count data, the primary contributions of this thesis are step three and four: the

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[1] This chapter is adapted from a paper submitted to the journal *Accident Analysis and Prevention.*

accompanying analysis of "dangerous situation" exposure and demonstration of a GIS tool through a case study and discuss how the results could be used by engineers, planners, and other community decision-makers to objectively compare proposed improvement plans.

The next section presents the case study scenarios, followed by an explanation of the data sources, the new method, and a discussion of the results from the case study. We conclude with a summary and suggestions for future work.

3.2 Case Study

3.2.1 Volume Data

We demonstrate our method by applying it to the City of Bellingham, WA (2010 population 80,885). Bellingham was selected because it has one of the most robust bicycle volume data sets in the Pacific Northwest, and because it is a relatively isolated urban area rather than a large metropolis with complex travel patterns.

Although any bicycle volume could be used, for our case study, we utilized data collected through the City of Bellingham's volunteer count program. The City has participated in WSDOT's citizen-volunteer count program every year since 2006, when five locations were counted. Over time the count has expanded and by 2013, 18 locations were counted (Cascade Bicycle Club, 2013). The 18 count locations are spread out geographically throughout Bellingham and counted for two hours in the morning (7-9 AM) and evening (4-6 PM), typically in late September or early October.

Spatial extrapolation of the bicycle volume data was accomplished using the OD centrality method developed by Lowry et al. (2014) and applied in Moscow, ID by McDaniel et al. (2014). Temporal extrapolation of bicycle volumes was accomplished using adjustment factors. Several researchers and the NBPD have created adjustment factors for short term bicycle counts, however no year-round factors were available for Bellingham or similar areas. We utilized factors created by the NBPD (2009), Nordback et al. (2013) and the Traffic Monitoring Guide (2013), adapted to fit Bellingham's climate. Vehicle ADT data was provided by the city of Bellingham and spatially extrapolated using OD centrality.

3.2.2 Scenarios

Two scenarios were created, Scenario 1 represents the current road and trail network in Bellingham, and Scenario 2 represents the draft Bike Master Plan (see figure 3.1). Comparing two scenarios allows us to demonstrate the usefulness of our model as a decision-support tool. Practitioners and decision-makers can quantify specific changes in estimated volumes and dangerous movements, and use this information as a decision-support tool as they craft new scenarios and weigh options. For the sake of simplicity, our case study does not account for population or urban growth, or mode shift changes caused by latent demand for facility types.

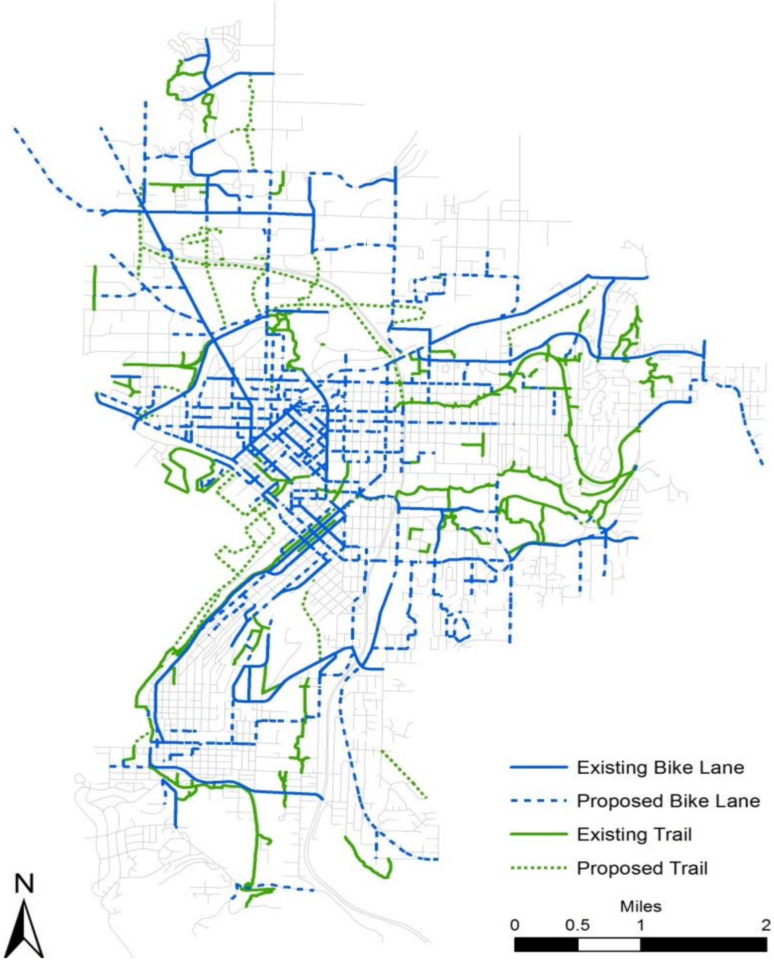


Figure 3.1 Existing and proposed bike network for Scenario 1 and Scenario 2

3.3 Method

3.3.1 Dangerous Situation Typology

Lack of bicycle accident data is an impediment to understanding bicycle exposure, and there are various reasons for limited bicycle accident data. Low numbers of bicyclists lead to few bicycle accidents and relative to car accidents, which often incur high costs and insurance claims, bicycle accidents are less likely to be reported. Schimek (2014) suggests that as many as 89% of bicycle accidents go unreported and he further notes that even if reported, the police documentation concerning bicyclists often lacks the details necessary to analyze collision factors. Ideally, bicycle accident analysis would involve the development of a Safety Performance Function (SPF), an equation used to predict the expected number of crashes per year at a location as a function of exposure and location characteristics. Creating a statistically sound SPF requires a very large set of accident data. Recently, Nordback et al. (2014) created what is apparently the first and only SPF for bicycles in a US city. Their work is an important step forward for bicycle accident analysis; however, their SPF is specific to signalized intersections and not intended to be transferred to other cities. It is unclear when an adequate number of bicycle-specific SPFs will be developed to accomplish large-scale scenario planning.

To overcome the lack of accident data, a literature review was used to identify dangerous situations. Our intent is to enumerate common situational antecedents of bicycle accidents. Different bicyclists, with different levels of skill and experience, would certainly have their own definition of “dangerous” for each situation. In fact, for a few of the dangerous situations there is substantial debate and disagreement on what is ideal. Some bicyclists have enormous tolerance for vehicle traffic while others, especially young children, have little or none. Geller (2007) suggested there are four types of bicyclists: (1) “Strong and Fearless”, (2) “Enthused and Confident”, (3) “Interested but Concerned”, (4) “No Way No How.” He further postulates that the majority (60%) of bicyclists are Interested but Concerned; a community might want to define their metrics for this type of bicyclist. Furthermore, some of the dangerous situations have overlapping issues which can be mitigated simultaneously; for others, mitigation would require choosing between trade-offs.

Public input is an important step in identifying community wants and needs in crafting a dangerous situation metric. If done with care, this step can ensure that the outputs created accurately reflect the wants and needs of the community. Public input, local experience, and findings from research should be used.

We organized concepts into 24 dangerous situations. Table 3.1 lists the dangerous situations for bicyclists we identified in the literature. The dangerous situations are organized into five categories: (1) traffic conditions along street segments, (2) physical conditions along street segments, (3) intersection and network movement, (4) cyclist behavior, and (5) environmental factors.

The remainder of this section summarizes key aspects for each dangerous situation with an emphasis on thresholds and design recommendations from the literature. We also identified specific volumes and thresholds that we utilized to create metrics to apply to our model to quantify the number of bicyclists exposed to dangerous situations.

Table 3.1 Dangerous situations for bicyclists

	Dangerous Situation	Description	References
1	Mixed cycling in harsh traffic	Cycling in the vehicle travel lane on a road with high vehicle volume, speed, and/or percent heavy vehicle	Teschke, 2012; Harkey and Stewart, 1997; Elvik et al., 2009; Moritz 1997; Tinsworth et al., 1994; Allen-Munley et al., 2004; Klop and Khattak, 1999; Vandenbulcke 2013; Schepers et al., 2011; CROW 2007; Kim et al., 2007; Stone and Broughton, 2003; Carter et al., 2007; McCarthy and Gilbert, 1996
2	Dedicated ROW in harsh traffic	Cycling in a dedicated right-of-way adjacent to high vehicle volume, speed, and/or percent heavy vehicle	Reynolds et al., 2009; Furth, 2012.
3	Separated cycling	Physically separated on-street cycling, such as cycle tracks	Lusk et al., 2011; Lusk et al., 2013; Kim et al., 2007; Wachtel and Lewiston, 1994; Schepers et al., 2011
4	Cramped Space	Roads without a bike lane or shoulder, narrow travel lanes	McCarthy and Gilbert, 1996; Vandenbulcke 2011; Allen-Munley et al., 2004; Klop and Khattak, 1999; Harkey and Stewart, 1997
5	Excessive space	Roads with wide travel lanes, no bike lane, and at least moderate speed	Allen-Munley et al., 2004; Hunter et al., 1999
6	Dooring and vehicle parking	Areas with on-street parking and high parking turnover	Vandenbulcke et al., 2013; Tilahun et al., 2007
7	Frequent access points	High frequency of driveways	Allen-Munley et al., 2004; Emery and Crump, 2003
8	Crossing railroad tracks	Crossing or riding alongside in-road rail tracks.	Vandenbulcke et al., 2013; Teschke et al. 2012
9	Poor pavement	Low quality pavement	Callister and Lowry, 2013
10	Frequent or sharp curves	Thoroughfare with high frequency of curves or curves that have low angles	Kim et al., 2007
11	Steep grade	Grades more than 4%	Allen-Munley et al., 2004; Klop and Khattak, 1999; Teschke et al., 2012
12	Crossing harsh traffic	Crossing a road with high vehicle volume, speed, and/or percent heavy vehicle	Summala et al., 1996; CROW, 2007; Schepers et al., 2011
13	Complicated intersections	Navigating; e.g. five point intersections or roundabouts	Daniels et al., 2009; Brüde and Larsson, 2000; Schoon and Van Minnen, 1994; Vandenbulcke et al., 2013
14	Right hook	Right-turning cars conflicting with through cyclist	McCarthy and Gilbert, 1996; Räsänen and Summala, 1998; Schimek, 2014; Weigand, 2008; Schepers et al., 2011; Furth et al., 2014

Table 3.1 (continued)

	Dangerous Situation	Description	References
15	Left sneak	Cyclist sneaking across travel lanes to complete a left turn	Hunter et al., 1999
16	Through clip	Left turning vehicles conflict with through cyclist	Summala et al., 1996; Räsänen and Summala, 1998; Schimek, 2014; Shepers et al., 2014
17	Gaps in bicycle network	Discontinuity of bicycle the network	Krizek and Roland, 2005; Mekuria et al., 2012
18	Wrong-way riding	Cycling the wrong-way on a one-way street.	Wachtel and Lewiston, 1994; Räsänen and Summala, 1998; Schimek, 2014; Summala et al., 1996; Hunter et al., 1999;
19	Sidewalk riding	Cyclist utilizing sidewalks	Schimek, 2014; Wachtel and Lewiston 1994;
20	Infrequent cyclers	Low cyclist volume	Elvik et al., 2009; Jacobsen, 2003; Nordback et al., 2014; Brüde and Larsson, 1993; CROW 2007
21	Crowded shared-use paths	Major paths where cyclist volume is high	Teschke et al., 2012; CROW 2007
22	Reckless riding	Riding behavior that is unsafe	Wegman et al., 2012; Minikel 2012; Schimek, 2014; Kim et al., 2007
23	Inclement weather	Weather that decreases visibility and control	Kim et al., 2007
24	Darkness	Low light or hours of darkness	Tinsworth et al., 1994; Schimek, 2014; Reynolds et al., 2009; Kim et al., 2007

3.3.1.1 Traffic Conditions Along Street Segments

The first dangerous situation listed in Table 3.1 is **mixed cycling in harsh traffic**. Mixed cycling is defined as cycling on a roadway along with motorized vehicles without a painted or physical separation. For the past thirty years there has been ongoing, and often polarizing, debate about the advantages and disadvantages of mixed cycling (Mapes, 2009). Nevertheless, both sides would agree that traffic can be deemed harsh, undesirable, and unsafe at *some* threshold of vehicle volume, speed, and percent heavy vehicle.

Traffic volume is an important predictor of all types of collisions, with some researchers suggesting it is the single most important factor (Elvik et al., 2009). For adult cyclists, major roads or thoroughfares have a higher relative danger index than minor or neighborhood streets (Moritz, 1997; Tinsworth et al., 1994). High traffic volume is significantly associated with increased injury severity in the event of a crash

(Allen-Munley et al., 2004; Klop and Khattak, 1999). Some researchers use the road type, such as “arterial” or “collector” to identify high volume roads (Teschke et al., 2012). Schepers et al. (2011) set the “busy arterial road” threshold at an ADT of 8,000 and higher. The Dutch CROW Design Manual for Bicycle Traffic (2007), sets infrastructure thresholds using a combination of road type, speed and volume, with the latter set at 4,000 to 5,000 vehicles per day.

High vehicle speeds significantly increase the severity of injury and fatality rates for cyclists, and some researchers have found cyclist fatality rates to be directly related to vehicle speed (Kim et al., 2007; Klop and Khattak, 1999; Stone and Broughton, 2003). There appears to be a threshold effect at about 20 mph (32 km/h), above which there is a greater probability of injury or fatality. For example, if vehicle speeds exceed 50 mph (80 km/h), the death rate increases sixteen-fold (Kim et al., 2007). In their work to create bicycle safety indices, Carter et al. (2007) suggested considering two basic categories of vehicle speed: speed limits of 35 mph (56 km/h) or higher. Kim et al. (2007) suggested considering separate bicycle paths on roadways that have a speed limit of 30 mph (50 km/h) or over, and a 20 mph (30 km/h) speed limit in residential neighborhoods with significant pedestrian and bicycle traffic.

Increased heavy vehicle traffic is correlated with higher cyclist accident risk, injury severity, and fatal injury (Kim et al., 2007; Allen-Munley et al., 2004; Vandenbulcke, 2013). The weight and size of trucks, vans, and busses reduces maneuverability, and heavy vehicles may block sight lines for operators, other drivers, and cyclists. A London study found that trucks and vans were involved in 14 out of 15 fatal vehicle-bicycle left turn collisions (with vehicles driving on the left in Great Britain this is equivalent to a right hook), (McCarthy and Gilbert, 1996). Kim et al. (2007) suggest special precautions in the design of bicycle facilities or when selecting arterials for bicycle lanes to decrease the chance of conflict with heavy vehicles. Harkey and Stewart (1997) recommend wider bicycle lanes on roads with increased percent heavy vehicles, specifically widths greater than 4 ft (1.22m). The CROW manual (2007) recommends separated facilities for bicycles when rapid bus service is desired, but if busses are limited to 20 mph (30 km/h) then shared roads or bus ways are acceptable.

A common strategy to mitigate the severity of harsh traffic is to provide a dedicated right of way (ROW) for bicyclists in the form of a bike lane or a buffered bike lane. In a review of the literature, Reynolds et al. (2009) reports that "bike lanes were found to have a positive safety effect in five studies, consistently reducing injury rate, collision frequency or crash rates by about 50% compared to unmodified roadways." Nevertheless, as with mixed cycling, at a certain threshold of vehicle volumes, speeds, and percent heavy vehicle, bicycling in a **dedicated ROW in harsh traffic** can still be a dangerous situation. While painted bike lanes provide cyclists and vehicle drivers with clarity on how to share available space and thus reduce conflict, a painted line does not prevent cars from intruding. Illegally parked cars, risk of dooring (being struck by a car door), lack of clarity on how to negotiate a left sneak (left turn maneuver), conflict at pocket turn lanes and through intersections remain flaws. Dutch standards suggest bicycle lanes only for urban roads with two lanes and no parking, and speeds under 30 mph (50km/h), in higher intensity traffic, alternative routes or cycle tracks are recommended (Furth, 2012).

Another strategy to mitigate harsh traffic is to physically separate bicycle travel from vehicle travel, these facilities are often referred to as "cycle tracks." Separation might be accomplished by placing the bike lane between the curb and parallel parking or with a vertical median such a concrete barrier, bollards, or fencing. Research concludes cycle tracks are safer than similar conditions otherwise (Lusk et al. 2011; Lusk et al. 2013) and Kim et al. (2007) suggest cycle tracks should be installed when vehicle speeds exceed 31 mph (50km/h). The danger of **separated cycling facilities** is largely limited to conflict with vehicles at intersections. Conflict may arise due to cyclists gaining a false sense of security, or when vehicle drivers who are making a turn fail to see the cyclists as they cross the cycle path. The latter seems to be particularly problematic when cyclists approach intersections while riding on the left side of the street, which occurs on two-way cycle paths (Schepers et al., 2011) or when cyclists ride the wrong way (Wachtel and Lewiston, 1994). Drivers have a tendency to fail to look in the "wrong direction" when pulling out to make a right turn.

3.3.1.2 Physical Conditions Along Street Segments

Cramped space is a dangerous situation when motorists are inclined to overtake cyclists even though there is insufficient space. McCarthy and Gilbert (1996) found overtaking to be the most common vehicle maneuver associated with vehicle-bicycle accidents and Vandenbulcke et al., (2013) suggest cramped space is likely the primary factor for increased accidents on bridges. Klop and Khattak (1999) found cramped space increases injury severity when coupled with high vehicle speeds. Harkey and Stewart (1997, p. 116) note that "paved shoulders and bike lanes essentially produce similar operations with respect to motor vehicle-bicycle interactions, and supporting that theory, Allen-Munley (2004) found that no shoulders were reported in 75% of the locations where vehicle-bicycle collisions occurred. Harkey and Stewart (1997) recommend a bicycle lane of 4 feet (1.22m) to optimize operating conditions for motorists and bicyclists and minimize paved surface, but found that widths ranging from 3.5 to 5 feet (1.07-1.53m) result in similar vehicle-bicycle interactions. Where there is insufficient space, sharrows are a solution that can help move cyclists further away from parked cars, and help drivers move to the left of the outside travel lane (Alta Planning + Design, 2004).

On the other hand, **excessive space** may also be unsafe. Allen-Munley et al. (2004) found that on roads without bike lanes, while crashes were evenly distributed across lane widths, more severe injuries were associated with wider lanes. They point out that wider streets may produce higher operating speeds, cyclists believing they have ample space, and motorists potentially using single lanes as multiple lanes. These conclusions are supported by Hunter et al. (1999, p.2) who write: "Lanes wider than 4.6 m [15 ft] sometimes result in the [dangerous situation] of two motor vehicles side by side". In many states, wide outside lanes have been abandoned as a bicycle facility in favor of bicycle lanes Furth (2012), while in other cases practitioners are utilizing sharrows in favor of excessive lane width (Alta Planning + Design, 2004).

Dangerous situation number six is **dooring and vehicle parking**. Most cyclists dread the prospect of being hit by a car door that is quickly opened after a motorist finishes parallel parking, or worse, to be hit by the vehicle as the motorist leaves their parking space. Tilahun et al. (2007) found that cyclists are willing to add more than 9 minutes to a 20 minute commute to switch from a facility with parking to one without. Parked vehicles may also restrict sight distances for cyclists and drivers (Vandenbulcke et al., 2013).

Dangerous situation number seven is **frequent access points.** Allen-Munley et al. (2004) found that 20% of collisions occurred at driveways. Driveways increase the opportunity for right hook, through clip, and conflicts caused by sidewalk and wrong-way riding. One of the most dangerous vehicle-bicycle conflicts involves vehicles entering onto a main roadway from a side road and turning right while a cyclist riding on the left side of the road approaches from the right (Rasanen and Summala 1998). The danger from frequent access points is exacerbated when combined with wrong-way riding and sidewalk riding (see dangerous situations 18 and 19, respectively).

Crossing railroad tracks can result in falls due to tire slippage along the track or the bike tire being lodged in the tracks, and riders may change course and swerve into traffic in an effort to cross tracks at a safe angle. Teschke et al. (2012, p. 2341) found that streetcar or train tracks are particularly hazardous to cyclists; they note that this is “a finding that does not appear to have been reported elsewhere” and given the renewed interest in streetcars “this result deserves consideration in broader transportation planning.” Vandenbulcke et al., (2013) also found increased risk directly around areas with tram tracks that were on-road and crossable.

Poor pavement quality is often a consideration in methods to assess bicycle suitability, however there are very few studies that look at how pavement quality impacts bicycle safety (Callister and Lowry, 2013). Presumably uneven pavement surfaces would contribute to sidewalk riding, shift to other routes and accident potential.

Frequent or sharp curves may have traffic calming benefits in residential areas, but they also reduce sight distance and maneuverability. Kim et al. (2007) found vehicle-bicycle accidents involving curving roads tend to be more severe.

Hilly terrain is not only a deterrent to cyclists, but also affects the speed differential of vehicles and cyclists, as well as braking efficiency, and sight distance.

Allen-Munley et al. (2004) and Klop and Khattak (1999) found that hilly terrain is associated with increased injury severity, on both straight and curved sections of roadway. The same finding was reported by Teschke et al. (2012) for downhill grades, but their results were not statistically significant for uphill grades.

3.3.1.3 Intersection and Network Movement

Intersections are the greatest point of vehicle-bicycle interaction and the primary location where collisions occur (Korve and Niemeier, 2002; Wachtel and Lewiston, 1994; Wang and Nihan, 2004). Wachtel and Lewiston (1994) found that 74% of vehicle-bicycle collisions occur at intersections, while a more recent study by Schimek (2014) found that 81% of vehicle-bicycle collisions occur at intersections.

The first dangerous situation that we identify for an intersection is simply the act of crossing it. Summala et al. (1996) found that **crossing streets with harsh traffic** is more demanding mentally and physically than crossing a minor road. Once again, “harsh” is subjective and can be defined based on vehicle volume, vehicle speed, and percent heavy vehicle (Schepers et al., 2011). The CROW manual (2007) defines the following thresholds for bicycle crossings: up to 800 passenger car equivalent per hour (pcu/h), crossability is considered “reasonable without a central traffic island” for refuge; from 800 to 1,600 pcu/h, crossability is “reasonable provided crossings can be made in two stages” with a central traffic island for refuge; from 1,600 to 2,000 pcu/h, crossability is “moderate to poor”; and above 2,000 pcu/h, crossability is “poor”. The CROW manual (2007) also recommends cross street vehicle speed limits should not exceed 20 mph (30 km/h) for uncontrolled intersections with a high volume of bicyclists.

Navigating **complicated intersections** is dangerous even if traffic is not harsh. Complicated intersections might involve 5 legs or more, a combination of one-way and two-way streets, or roundabouts. Reynolds et al. (2009) write that “findings of roundabout studies show some consistency, with elevated risks for cyclists after installation of roundabouts with multiple traffic lanes or with marked bike lanes, whereas there were risk reductions or no apparent increase in risk at roundabouts with separated cycle tracks.” Vandenbulcke et al. (2013) confirmed high accident risk associated with marked cycle lanes in roundabouts. Brude and Larsson (2000) suggest that it is safer for cyclists to bypass the roundabout on a bicycle crossing than to ride in the roadway of the roundabout. They found roundabouts with a speed limit of 30 mph (50km/h) were found to be safer than 45 mph (70 km/h) and recommended a central island radius of 30 to 80 feet (10-25m) to keep vehicle speeds low.

Another dangerous intersection situation is the **right hook**, i.e. the situation in which there is a high volume of right-turning vehicles and straight moving bicyclists. In a London study a third of fatal vehicle-bicycle collisions occurred because of this situation (vehicles in Great Britain drive on the left side of the road, so it is actually a "left hook") and a vast majority of the vehicles were trucks or vans (McCarthy and Gilbert, 1996). In a Finland study, the right hook was far less prevalent, accounting for only 8% of collisions (Räsänen and Summala, 1998). In a study of bicycle collisions from 2008-2009 in the U.S., 6% of vehicle-bicycle collisions were right hook collisions (Schimek, 2014). There are several strategies to reduce right hook danger, including advanced stop lines, signal treatments that either provide an early start for cyclists or prevent conflicting vehicle right turns, spacing cycle tracks (2-5m) from the roadway, and raised crossings (Weigland, 2008; Schepers et al. 2011). While some states have guidelines that recommend protected crossings for pedestrians when the number of right-turning vehicles reaches a threshold (i.e., 250 veh/hr in Massachusetts), there are no national guidelines for permitted conflicts at bike crossings (Furth et al., 2014). They note that guidelines in the Netherlands stipulate that up to 150 right turning vehicles per hour is acceptable for one-way cycle tracks, and that two-way cycle tracks should avoid all permitted conflicts.

Left hand turns can be dangerous for cyclists, especially when the bicyclist needs to sneak through a gap during heavy traffic. This is called a **left sneak** and is dangerous for three reasons: first, the risk of sneaking across travel lanes in order to be in position to turn; second, avoiding being rear-ended while waiting to turn; and third, sneaking through a gap in oncoming traffic. Hunter et al. (1999) found that 6% of bicycle collisions in Austin, TX involved cyclists attempting to turn left. At some locations with several lanes of high vehicle flows, cyclists made "advanced crossover" movements (crossing multiple lanes at once) prior to the intersection, and, although data was sparse, this seemed to be more dangerous than other maneuvers. Their study summarized the manner in which cyclists made left turns: 44% "did so like a motor vehicle with proper lane destination positioning," another 8% in the same manner but "with improper lane destination positioning", almost 17% "made pedestrian style left turns, where the cyclist would ride all the way to the intersection and then use the crosswalk to get across the street like a pedestrian" (Hunter et al., 1999).

In a **through clip**, oncoming left-turning vehicles cut in front of bicyclists who are going straight through the intersection. In a study in Finland it was found that 12% of vehicle-bicycle collisions involved a through clip movement (Räsänen and Summala, 1998). In the U.S., Schimek (2014) found that 9% of vehicle-bicycle collisions were involved in a through clip, the highest of any specific movement. One remedy offered by Shepers et al. (2011) when there is a high volume of straight moving bicyclists is to provide a vehicle left-turn lane in the opposite oncoming direction, even if not warranted for vehicle needs, to give oncoming drivers "extra time to slow down and notice cyclists".

Gaps in the bicycle network often occur at intersections where bike lanes terminate on one side of the intersection and do not continue on the other side. Although little research has investigated the safety issues associated with gaps in the bicycle network, Krizek and Roland (2005) found discontinuities introduce high levels of discomfort. Mekuria et al. (2012) argue the stress associated with bicycling from origin to destination is determined by the most stressful link along the route, not the average of stress across the route. They suggest providing continuity across a network should be a key consideration for bicycle planning.

3.3.1.4 Cyclist Behavior

Wrong-way riding is a dangerous situation for at least two reasons; first, it increases the possibility of head-on collisions, which are usually more severe, and second because motorists often fail to look where they do not expect oncoming cars or cyclists (Wachtel and Lewiston, 1994) Drivers entering from a side road and turning right often fail to scan to the right, thus cyclists coming from that direction are less likely to be detected (Summala et al., 1996). In a study in Finland, wrong way riding was the most frequent accident type among collisions between cyclists and cars at intersections (Räsänen and Summala, 1998). A similar study in the US reported that cyclists facing traffic accounted for at least 39% of all bicyclist injuries (Schimek, 2014). Hunter et al. (1999) found that wrong-way riding was more prevalent on streets with wide lanes and without a bike lane, suggesting bike lanes provide the added value of encouraging proper riding. Alta Planning + Design (2004) found that sharrows reduced wrong-way riding by 80%.

It is important to note that unpermitted wrong-way riding is distinct from "contraflow" or "facing traffic cycling", where bicycling against the direction of vehicle traffic is permitted and intentional. Typically contraflow bike lanes are placed on low volume and low speed roads. Kim et al. (2007) found contraflow riding reduces the probability of injuries, but that the effects on fatalities was unclear due to statistical issues likely associated with greater severity from head-on collisions. Vandenbulcke et al. (2013) found low accident rates for contraflow bike lanes. These results are probably due to increased opportunity for cyclists and motorists to see each other and react as needed (Kim et al., 2007). In the Netherlands contraflow bike lanes are frequently installed to preempt wrong-way riding and other undesirable detour behavior (CROW 2007).

Sidewalk riding poses a risk for conflict with pedestrians, but perhaps more important is the increased risk of conflict with motor vehicles at intersections and driveways. Similar to wrong-way riding, sidewalk cycling places which is that motorists often neglect to check for cyclists coming from unexpected directions. This is especially true for motorists entering the roadway from a driveway or side road and failing to look upstream (Wachtel and Lewiston, 1994, Summala et al., 1995). Schimek (2014) found 77% of sidewalk bicyclists injured were riding facing traffic. He also notes that "wrong-way and sidewalk riding is disproportionately represented among crashes where the motorist failed to yield . . . suggesting that the bicyclist's unexpected position was the key factor leading to the crash" (Schimek, p. 11, 2014).

Locations where there are **infrequent cyclers** are a dangerous situation because the likelihood of a cyclist being struck by a motorist reduces as cycling increase, termed the “safety in numbers” effect (Jacobsen, 2003). For all types of traffic, the correlation between volume and collisions is not linear; the percentage increase in accidents is less than that of traffic volume (Elvik et al., 2009). The effect is the same for bicycling. Both the Brüde and Larsson (1993) cyclist accident prediction model and Nordback et al. (2014) model SPF for bicycles predict that per-cyclist accident rates decrease as the number of cyclists increase. Brüde and Larsson (1993) suggest that additional motor vehicles increases the potential for conflict, while an increase in pedestrians or cyclists increases the “number of ‘living warning signs’”. Jacobsen (2003) found that the number of motorists colliding with people walking or bicycling will increase at roughly 0.4 power of the number of people walking or bicycling; a doubling of active travel modes is expected to result in a 32% increase in injuries.

Brüde and Larsson (1993) suggest it may be desirable to concentrate pedestrians and cyclists at intersections with high quality facilities for them and little motor-vehicle traffic. In terms of efficient infrastructure investment, concentrating users at crossings could expand options such as installing a higher quality facility or separating the crossing altogether with a bridge or tunnel, as long as a sufficient density of cycling facilities is provided. The CROW manual (2007) suggests 1,000 cyclists per day as a minimum for cycling streets. Nordback et al. (2014) found that signalized intersections with fewer than 200 AADB have substantially higher collisions per cyclist, while those with cyclist volumes greater than 600 per day have relatively low risk.

On the other hand, cycling on **crowded shared-use paths** is a dangerous situation for bicyclists and pedestrians. Teschke et al. (2012) point out that several safety studies have failed to distinguish shared-use paths from cycle tracks. In their case-crossover study in Vancouver and Toronto, Canada, it was found that although muli-use paths rank high in terms of preference and are safer than a major street with parking and no bike infrastructure, they present higher risks than bike-only paths and cycle tracks (Teschke et al., 2012). The CROW manual (2007) suggests mitigating this dangerous situation by separating bicyclists and pedestrians with paint markings if the pedestrian flow rate is greater than 100 pedestrians per hour and separating with a physical barrier or space if the pedestrian flow rate is greater than 200 pedestrians per hour.

Very little research is available about the effects of **reckless riding** (Wegman et al., 2012). In this category, we include things such as alcohol consumption, aggressive behavior and the like. Minikel (2012) reports that in a dataset of Berkeley vehicle-bicycle collisions, police found 41% cyclist at fault, 54% motorist at fault, and the remaining 5% no-fault. While only 4% of police-reported bicyclist collisions involve alcohol, serious or fatal injuries are correlated with alcohol, with 22% of fatalities involving motorist or bicyclist alcohol use (Kim et al., 2007; Schimek, 2014).

3.3.1.5 Environmental Factors

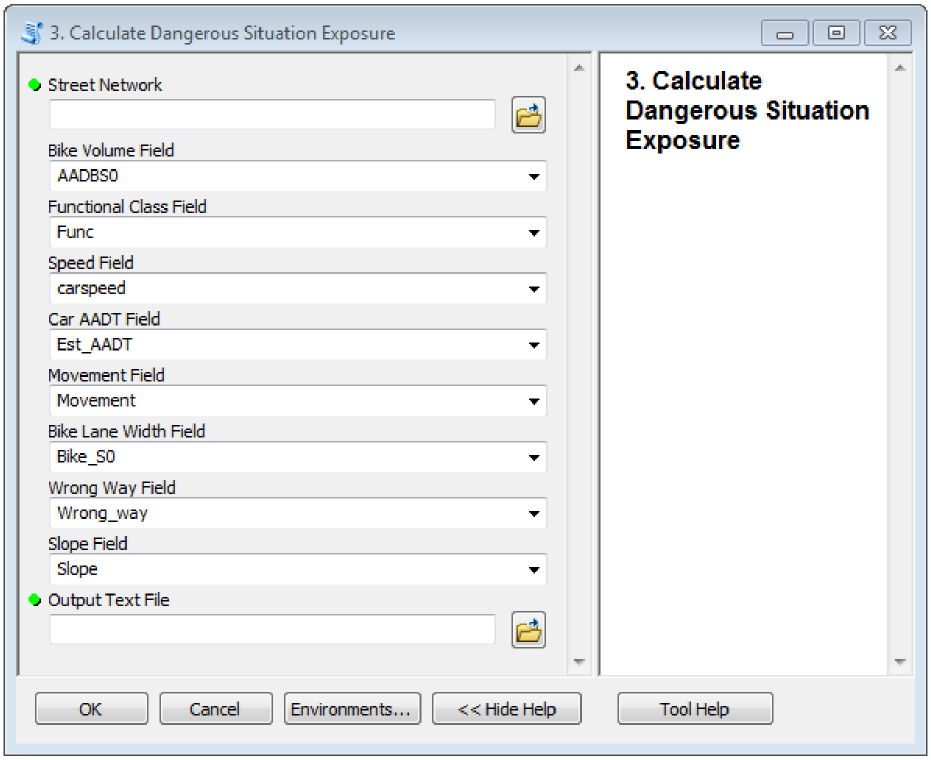
Kim et al. (2007) found that **inclement weather** conditions, defined as "rain, snow, fog, etc.," were significantly associated with bicyclist injury severity and increased probability of fatal injury in an accident by 128%. They suggest reduced visibility and traction are to blame.

Darkness poses a dangerous situation for bicycling. Tinsworth et al., (1994) found that 21% of bicycle injuries occurred during dusk, dawn or darkness. Vehicle-bicycle crashes in low-light conditions account for 20% of injuries and 47% of fatalities in the U.S. (Schimek, 2014). Kim et al. (2007) report that darkness without streetlights increases the probability of fatal injury by 110% compared to accidents occurring in daylight or darkness with streetlights. Reynolds et al. (2009) report that the presence of street lighting on rural roads reduced the rate of cyclists' injuries by half.

3.3.2 Using Metrics to Calculate Dangerous Situation Exposure in GIS

The final step of our method is to compare the volumes on the network to the dangerous situation typology. To do so, metrics were created that identify specific dangerous situations. For our case scenario we were able to create twelve dangerous situation metrics. Eight metrics are for dangerous situations that occur on street segments, and 4 are at intersections.

We created a GIS tool using open-source Python programming for ArcGIS to calculate dangerous situation exposure (see figure 3.2); the user provides the network file for streets and trails with the estimated AADB and also automobile AADT. The AADT can be obtained through any means, such as a travel demand forecasting model. For the case study, we applied the tool to the Bellingham bicycle travel network that included bicycle and vehicle volume attributes (calculated as described in sections 3.3.1). Section 3.4 discusses the results.


3. Calculate Dangerous Situation Exposure

Street Network

Bike Volume Field: AADBS0

Functional Class Field: Func

Speed Field: carspeed

Car AADT Field: Est_AADT

Movement Field: Movement

Bike Lane Width Field: Bike_S0

Wrong Way Field: Wrong_way

Slope Field: Slope

Output Text File

3. Calculate Dangerous Situation Exposure

Figure 3.2 User Interface for the "Calculate Dangerous Situation" GIS Tool

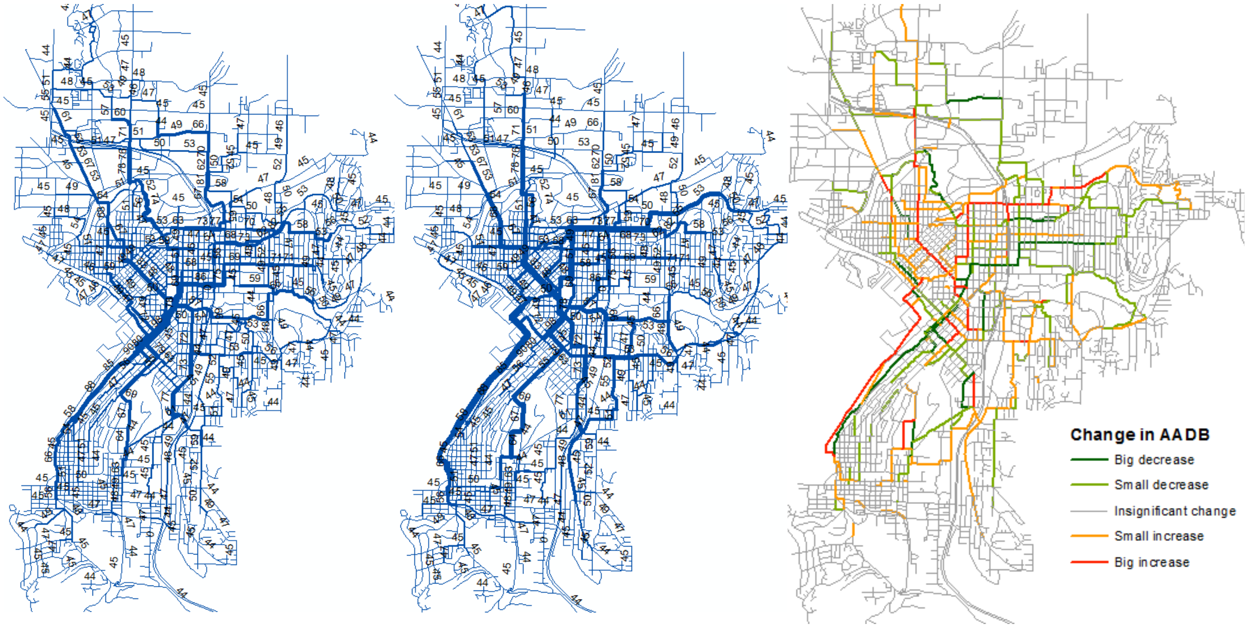
For example, the metric for the dangerous situation "cramped space" is a street segment with a vehicle lane width of less than 12 feet, vehicle volume of greater than 1,000 AADT on roads with speed limit of greater than 20 mph. Tables 3.3 and 3.4 list the metrics created and the thresholds that trigger quantification.

We encourage communities to tailor the metrics to their own specific needs and desires. Public input, local experience and ongoing literature review are all recommended to ensure that the metrics are providing the specific information that individual communities need to make decisions about bicycle infrastructure.

3.4 Case Study Results

3.4.1 BMT Categorized by Facility Types

The spatial and temporal extrapolation of bicycle volumes outputs network-wide bicycle volumes that can be analyzed in several ways. The change in volumes can be analyzed and depicted in map form (shown in figure 3.3) that, among other things, can encourage community discussion to inform infrastructure planning efforts.



(a) (b) (c)

Figure 3.3 Estimated AADB for (a) Scenario 1 (b) Scenario 2 (c) change between Scenarios 1 and 2

The outputs also enable the calculation of Bicycle Miles Traveled (BMT) by multiplying link length times AADB. Table 3.2 compares the BMT on various types of facilities under each scenario. In Scenario 2, estimated trail use would increase by more than a quarter, which is not a surprising given that the trail network in Scenario 2 would increase 50%, by about 34 miles, and adding important connections in the network. On the other hand, Scenario 2 exhibits a decrease in cycling on arterials and collectors. The biggest change would be an increase in travel on local roads with bicycle facilities.

Cycling on non-improved collectors decreased slightly, while it increased slightly on collectors with bike lanes. Improving minor arterials shifted travel quite a bit, but the net cycling on minor arterials was the same, with cyclists shifting from minor arterials without facilities to those with them. Cycling on arterials without bike lanes fell by more than 50%, and cycling on arterials with bike lanes doubled. The latter condition makes sense given that Scenario 2 would add 55 miles of bike lanes to minor and major arterials, more than doubling them. The total amount of cycling on arterials with or without facilities fell by about 30%.

Table 3.2 Comparison of BMT for Scenarios 1 and 2

Facility	Scenario 1: Existing Conditions	Scenario 2: w/Proposed Improvements	Change
Trail	15%	20%	6
Local			
standard	46%	33%	-14
bike boulevard	0%	12%	11
Collector			
no bike lane	8%	6%	-3
bike lane	2%	4%	2
Minor Arterial			
no bike lane	12%	5%	-7
bike lane	5%	12%	7
Arterial			
no bike lane	9%	4%	-5
bike lane	2%	4%	2
Total	100%	100%	

3.4.2 Dangerous Situation Exposure

Exposure to dangerous situations along street segments is summarized in Table 3.3 in terms of annual BMT, and Table 3.4 summarizes exposure to dangerous situations at intersections in terms of “annual bicyclists” (AADB times 365 days). The conditions for each metric were defined for case study illustration. We recommend that a community define their own metrics through some public involvement process (see Section 3.4). The values in Table 3.3 and Table 3.4 are summed across the whole network. It should be noted that the units for each metric do not imply an estimated number of accidents or conflict occurrences, but rather the metrics are *indicators of the extent of exposure* to certain conditions. For example, Table 3.4 reports “605,000 annual bicyclists" for the right hook situation for Scenario 1. This does not imply that 605,000 bicyclists experienced a right hook conflict; instead, the metric indicates that across the whole network an estimated 605,000 bicyclists (based on estimated AADB) go straight through intersections that exhibit a high volume of vehicles turning right (based on AADT).

Table 3.3 Annual BMT exposed to dangerous situations along street segments

Dangerous Situation	Metric Conditions	Scenario 1: Existing Conditions (Annual BMT)	Scenario 2: w/Proposed Improvements (Annual BMT)	Change (Annual BMT)	Percent Change
Mixed cycling in harsh traffic	No bike lane Vehicle volume > 3,000 AADT	666,000	272,000	-394,000	-59%
Dedicated ROW in harsh traffic	Bike lane Vehicle volume > 8,000 AADT	97,000	250,000	+153,000	+158%
Cramped space	Veh. lane width < 12 ft Vehicle volume > 1,000 AADT Vehicle speed limit > 20 mph	307,000	180,000	-127,000	-41%
Dooring and vehicle parking	Vehicle parking turnover > 4 per hr	2,646,000	2,746,000	+100,000	+4%
Frequent access points	Access points > 30 per mile	3,923,000	3,847,000	-76,000	-2%
Steep grade	Grade > 4%	197,000	197,000	0	0%
Wrong-way riding	Wrong-way riding occurrence	134,000	145,000	+11,000	+8%
Infrequent cyclers	Cyclist volume < 15 AADB	1,151,000	1,096,000	-55,000	-5%

Table 3.3 shows a significant decrease (59%) in exposure to mixed cycling in harsh traffic. This is accompanied, however, by a much larger increase (158%) in exposure to cycling with a dedicated ROW in harsh traffic. Overall, cycling in harsh traffic (the sum of both conditions) decreased by about 241,000 annual BMT. Essentially, under existing conditions much of the cycling on arterials occurs on those

without bike lanes. Scenario 2 moves cyclists off arterials to some extent, while also adding bike lanes, resulting in about half of bicycle travel on arterials with bike lanes. On one hand, the results indicate that investment in new bike lanes would result in travel shifting onto these new facilitates, and may provide cyclists with more direct routes; on the other hand, some cyclists who will not tolerate cycling on relatively busy roads, albeit on a bike lane, may require less stressful routes. Perhaps alternatives to bike lanes on arterials, such as bike boulevards along parallel routes may be a solution that the community would prefer.

There are other insightful findings in Table 3.3. There is an unfavorable increase (4% or 100,000 annual BMT) in exposure to dooring and parking. This is also most likely due to an expected shift in cycling to roadways that would have new bike lanes, but also have considerable parallel parking. Cycling on facilities with cramped space would decrease significantly, about 41%. Wrong-way riding would increase by 8%, perhaps due to the increased attractiveness of one-way streets in the historic core of the city. There are concentrations of wrong-way riding in one particular neighborhood, suggesting contraflow bike lanes might make a lot of sense. Currently, many streets throughout the study area have infrequent cyclist. Scenario 2 provides a 5% decrease to this dangerous situation by concentrating cyclists. This result is presumably safer and also presents the opportunity to more efficiently allocate infrastructure improvements.

Table 3.4 Annual Bicyclists exposed to dangerous situations at intersections

Dangerous Situation	Metric Conditions	Scenario 1: Existing Conditions (Annual Bicyclists)	Scenario 2: w/Proposed Improvements (Annual Bicyclists)	Change (Annual Bicyclists)	Percent Change
Crossing harsh intersections	Cross street vehicle volume > 2,000 AADT	7,114,000	6,647,000	-467,000	-7%
Right hook	Vehicle right turns > 1,000 AADT	605,000	577,000	-28,000	-5%
Left sneak	Oncoming through vehicle volume > 2,000 AADT	7,516,000	7,523,000	+7,000	0%
Through clip	Oncoming left-turn vehicle volume > 1,000 AADT	615,000	613,000	-2,000	0%

Table 3.4 shows that at intersections, exposure to a few dangerous situations would be reduced, but for others the exposure would not change. Crossing streets with harsh traffic is reduced by 7%. Exposure to the right hook situation is reduced by 5%. There was no significant change in the exposure to the left sneak and through clip.

Hot spot maps can be created to explore the location of certain dangerous situations in greater detail. Figure 3.4 is offered as an example. The map shows locations throughout the area where there is a high number of bicyclists going straight and vehicles turning right, i.e. the right hook dangerous situation. Our process and tools can quickly provide citizens and decision-makers with maps and metrics to support the decision-making process.

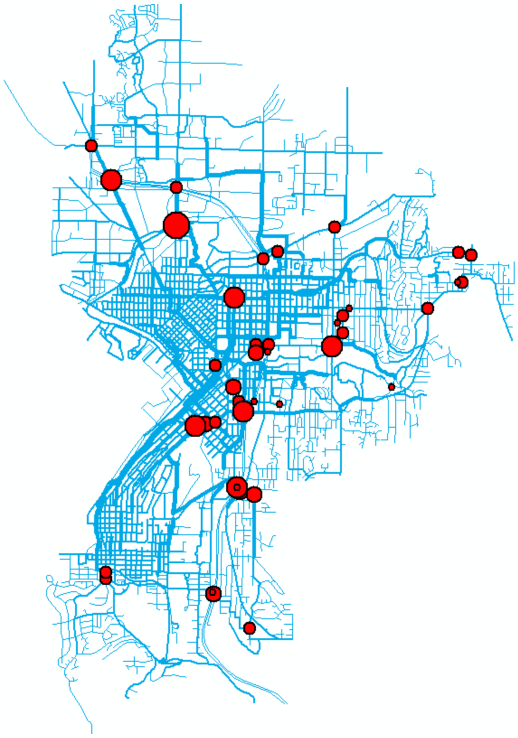


Figure 3.4 Example map of concentrations of the right hook dangerous situation

3.5 Conclusion

This section demonstrates, through a case study, how citizen-volunteer count data and OD centrality can be used to estimate network-wide bicycle volumes, quantify dangerous situation exposure, and compare scenarios. Network-wide volume information can provide decision-makers with information necessary to make infrastructure improvement decisions. In particular, demand for proposed facilities can be estimated and used to focus improvements that are tailored to community preferences. Vehicle volumes can be estimated and used to identify potential conflict areas and can inform bicycle infrastructure improvement location and design.

For example, the case study showed a 5% decrease in AADB exposure to the dangerous right hook situation and to potentially reduce the need for bicyclists to cross harsh intersections by 7%. The method introduced in this thesis can provide engineers, planners, and other decision-makers a means to compare improvement scenarios for investment decision-making.

We suggest several areas for future work. First, the data from two-hour volunteer count programs are an important resource, but it is not robust and could be complimented by continuous count data. Improving and expanding data collection should be a priority, both in terms of collecting more two-hour counts, but also in terms of setting up continuous count collection programs that can be used to adjust the two-hour data. Second, adjustment factors need to be developed for additional climatic zones across the country to assist planners in temporally interpolating extrapolated count data. Third, our model can be improved to provide practitioners with more direct solutions, perhaps it could even create prescriptive outputs. For example, it is very useful to understand specifically where additional bicycle infrastructure, such as bike lanes or separated paths could be added to improve the network in terms of connectivity. Experience in using our model can lead to refinement and adjustments that produce specific types of outputs that are useful to practitioners and decision-makers. The tool could be expanded to output recommended route locations which minimize dangerous situations. Our tool provides practitioners with a tool that they can utilize to help decision-makers understand the benefits and drawbacks of various network scenarios.

Chapter 4 Thesis Conclusion

4.1 Summary

This thesis introduces a new method to quantify exposure to dangerous situations for bicyclists for scenario planning and investment decision-making. The work is novel in that it combines four steps to create a new method that provides solutions for analyzing bicycle exposure. The first step is to spatially extrapolate bicycle volumes using OD centrality and regression. The second step is to temporally extrapolate two-hour count data into AADB volume by utilizing adjustment factors. The third step is to define dangerous situations through a literature review in an effort to provide communities a reference point from which to craft their own definitions. The fourth step is to compare two scenarios through calculated metrics such as BMT, AADB, and estimated bicyclist exposure to specific dangerous situations.

4.2 Implications

The method is useful in that it can provide bicycle volume estimates throughout a network that can be used for various purposes, including network improvements, reduction in dangerous situation exposure, and informed community discussion. The outputs consist of: 1) AADB estimated for each individual link and turn movement, which is not only data rich but can provide a visual and numerical display of bicycle volumes throughout the network, 2) BMT categorized by facility types, and 3) Quantified exposure information for specific types of dangerous situations.

4.3 Method Limitations

The method presented in this thesis has limitations. A crux of volume estimation is the underlying volume data. The two-hour manual counts must be extrapolated both spatially and temporally. Compared with electronic continuous counters, a benefit of volunteer manual counts is that they can be at more locations that can be well-distributed and representative of the network. However, bicycle volume data collection is an emerging field, as the data is utilized collection methods ought to be refined. For example, our method would benefit from collection sites that are representative of all portions of the travel network. In addition, the OD centrality model is designed to be used with count data that includes all turn movements at each intersection (12 movements for a standard 4-way intersection). A full movement count makes it possible to input intersection arrival and departure information into the model, which increases accuracy. However, Bellingham data includes only information on intersection departure directions (4 movements for a standard 4-way intersection); the arrival link is unknown and thus accuracy is reduced.

A limitation of short duration manual count data is that it requires temporal extrapolation to extend it throughout the day, week, and year. Each step utilizes a different adjustment factor and the creation of these factors is an emerging field. Continuous count data from the same locality can be used to create adjustment factors, but these counters are costly and few jurisdictions have invested in this technology. As more jurisdictions install continuous counters and more researchers work with the data the adjustment factors will likely become more reliable.

The vehicle volumes are daily averages and it is unclear how volumes are effected by time, and this unknown could be problematic when analyzing the interaction between vehicles and cyclists. For example, it might be the case that the right hook situation is actually not a problem for a particular intersection, because it might be the case that bicyclists are using the intersection at different times of day than the motorists who are turning right.

With the use of GIS, the calculation and comparison of dangerous situation exposure can be quite precise in terms of computation. However, the volume figures are estimated and depending on the quality of the GIS files, which tend to have generic facility classification and attributes are generic. For example, when analyzing right hooks, there may be some reason why a particular intersection does not actually pose right hook danger despite having a high volume of right turning vehicles. Some dangerous situations, such as wrong-way and sidewalk riding may be difficult to predict without more data collection efforts. The dangerous situation metrics are not intended to be predictors of accidents, exhaustive nor applied as-is to all jurisdictions, rather, the primary usefulness of the metrics is to compare the difference across scenarios. The dangerous situation metrics are an indicator of the types of situations that may be undesirable and highlight areas that should be investigated further. With this tool, individual communities can explore and prioritize their own wants and needs and craft their own dangerous situation metrics.

4.4 Future Work

Bicycle volume data collection is an emerging field, data is scarce and much of the current collection efforts are accomplished with very small budgets. The National Bicycle and Pedestrian Documentation Project, the Washington State Department of Transportation's Bicycle and Pedestrian Documentation Project, and the City of Bellingham's count program are efforts to provide consistent bike and pedestrian data.

In order to provide more robust data for spatial extrapolation, data collection sites should be well distributed in terms of infrastructure type and bicyclist volumes. While the tradition has been to focus on high-volume locations, a model such as ours which extrapolates counts would benefit from data from diverse locations that represent other areas of the network. Forms should be standardized to reduce data collection error. Furthermore, to increase accuracy, data collection should include individual turn movement details. Manual count programs should be expanded and research efforts to refine methods should be supported.

Temporal extrapolation of bicycle count data is also an emerging area. The two hour counts are remarkable in that they are conducted throughout a city simultaneously, however, resources are so minimal that many municipalities such as Bellingham only collect data for two two-hour counts one day a year. Research to create adjustment factors for expanding the data into AADB is emerging and should be supported. Automated counters, used in combination with manual counts could help provide additional clarity. Nordback et al. (2013) suggest that 7-days of counts is desirable, pointing out that one week of counts can create an average AADB absolute percent difference error range of between 15%-30%, which is near the range observed for AADT. They also note that when 4 weeks of bicycle counts are available for each location the average error is 15%, which is very close to the average error reported for AADT.

While automatic bicycle counters require significant capital outlay, they are becoming increasingly common. A potential data collection scenario that could be accomplished within a limited budget would be a manual count program that provides seasonal snapshots at many locations simultaneously, combined with automated counters providing continuous data collection at key locations and for the creation of adjustment factors.

As bicycle volumes increase, as more volume data are collected, and as collision reports include more details it will be possible to more accurately estimate bicycle risk, especially if there were sufficiently robust collision data.

This is the first application of OD centrality outside Moscow, ID where it was created. Both Moscow and Bellingham, WA are smaller cities with centralized services and gridded street networks. Additional larger cities should be explored to determine how transferrable this method is to other locations.

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Appendix

City of Bellingham, WA 2013 Manual

Count Instructions and Data Collection Form

2013 Volunteer Instructions and Count Form

Bicycle and Pedestrian Count Volunteer Instructions

Dates:

Volunteers can choose to conduct the count on Tuesday, Wednesday, **or** Thursday, October 1, 2, or 3

Time(s):

7:00-9:00am or 4:00-6:00pm

Count Coordinator:

Kim Brown, Transportation Options, City of Bellingham
Office #: 360-778-7950, Cell #: 360-927-4129 E-mail: kimbrown@cob.org

Please print out the attached 'Pedestrian and Bicyclist Count Form' and bring it and the following items with you to your count location:

1. pen/pencil (2)
2. something to write on (clipboard, portfolio)
3. timekeeping device (cell phone, watch)
4. weather-appropriate clothing, umbrella?, water

Introduction:

This is an annual bicycle and pedestrian count taken at locations throughout Washington State in nearly 40 jurisdictions. We have 19 count locations in Bellingham. Data collected from these counts will be used to monitor success in increasing bicycle and pedestrian travel as identified in the Washington State Bicycle Facilities and Pedestrian Walkways Plan while also providing critical data to support improvements to bicycle and pedestrian facilities.

Conducting the Count:

Each location will have at least one counter. Depending on the number of volunteers, some locations may have more than one counter. In these cases, please use only one count form per location. Since the locations with multiple counters are expected to be busier, it will work best if one person counts and the other person fills out the form.

You have been provided with one copy of the count form. Please make sure to write your name and location on the form and indicate the correct time period (either 7-9am or 4-6pm).

The count itself is very simple: place a hatch mark on the form for each passing cyclist, pedestrian, or other non-motorized transit. People in wheelchairs are to be counted as pedestrians, as should children in strollers. People walking their bicycles count as bicyclists. People on rollerblades, skateboards, scooters, and other non-motorized transport devices are to be counted as “Other”. A person who passes by a point more than once is counted each time they pass by the point.

Whom do you count? Only count those pedestrians and cyclists passing through your post (intersection). This includes anyone who is walking their bicycle past your post. Do not count passersby on nearby streets unless specifically instructed to do so, as this could result in double-counting.

Other Information: The accuracy of the count depends largely on the coverage of all points during the entire morning and evening commute. **Please make sure to get to your location 15 minutes ahead of count time!** Use that time to practice how you will record people passing through your intersection once the actual count begins.

Returning the Count Forms:

Data can be submitted online via WSDOT's website:
http://www.wsdot.wa.gov/bike/Count.htm

In addition, please submit hardcopy count forms to:

Kim Brown, Public Works Engineering, City of Bellingham, 210 Lottie Street, Bellingham, WA, 98225.
You can also e-mail or fax forms to: Email: kimbrown@cob.org
Fax: 360.778.7901

If you are unable to make your assigned shift:

Please call Kim Brown at 360-778-7950 (office), or 360-927-4129 (cell) ASAP.

Thanks to everyone involved in this important data collection effort. This would not be possible without your help!

Pedestrian and Bicyclist Count Form (page 1 of 2 – please return both pages)

Name :_______City: __Date__

Location: ____Time slot:____

Weather:_____

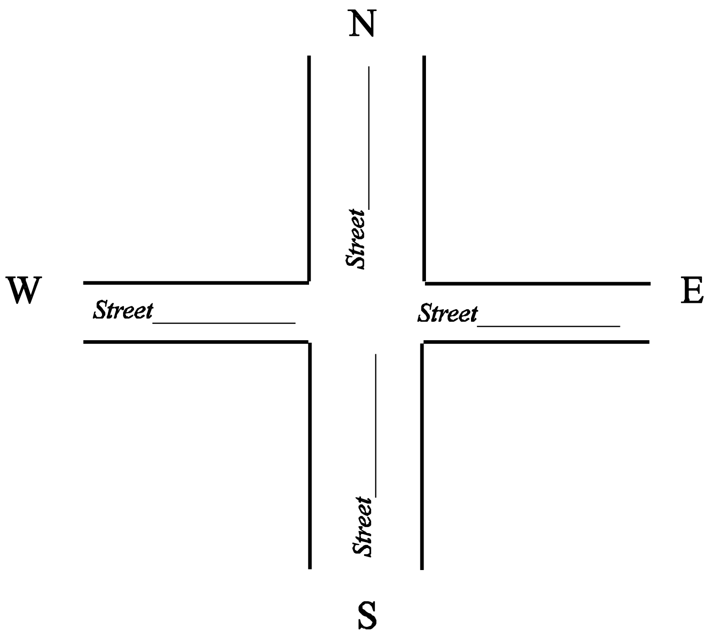
Directions: Please place a hatch mark on the form for each passing cyclist, pedestrian, or other non-motorized transit. People in wheelchairs are to be counted as pedestrians. People walking their bicycles count as bicyclists. People on rollerblades, skateboards, scooters, and other non- motorized transport devices are to be counted as "Other".

Have your bearings and ensure that the hatch mark is placed in the direction of travel. If you are located at an intersection, the direction of travel when leaving the intersection should be recorded. For example, a cyclist starting northbound and then turning right at your location should be noted as traveling eastbound.

Gender and Helmet Use: Depending on the volume of travelers at your location, you may be able to collect additional information, such as gender and helmet usage. If you are able to collect this information, please do so in the appropriate box on the following page. Some intersections may be too busy to capture this information – if this is the case, please focus on the direction and mode of travel.

For day of count questions, contact Kim Brown at 360-927-4129 or
`email kimbrown@cob.org`

Please indicate each leg of the intersection:



		NORTHBOUND	SOUTHBOUND	EASTBOUND	WESTBOUND	**TOTAL**
User	Gender					
Bicyclist	**Male** with helmet					
	Male without helmet					
	Female with helmet					
	Female without helmet					
Pedestrian	Male					
	Female					
Other (rollerblade, etc.)						

☐ Please check this box if you entered this data into WSDOT's data entry website here: http://www.wsdot.wa.gov/bike/Count.htm