# Prioritizing Pedestrian Safety Improvement Locations: A Spatial Analytical Approach using Network Kernel Density Estimation

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## Abstract


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Walking for transportation is a critical component of any strategy for smart growth. Regular levels of moderate physical activity have been shown to dramatically reduce many chronic illnesses and replacing automobile trips over short distances preserves scarce resources, reduces carbon dioxide emissions and improves local air quality. One major challenge to expanding the role of walking for transportation is safety. Each year in the U.S. tens of thousands of pedestrians are injured or killed in collisions with automobiles. Identifying areas where pedestrian infrastructure can be improved is therefore an important task for traffic engineers and planners.

This study uses a GIS spatial analysis known as Network Kernel Density Estimation (NetKDE) to highlight areas in the City of Seattle which experienced high densities of pedestrian-vehicle collisions between 2008 and 2012. The results of this spatial analysis are compared with pedestrian demand and a number of high-priority pedestrian safety improvement areas, corridors, and intersections are suggested.

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# 1. Introduction

## 1.1 Background and Context

Pedestrian safety is a major issue in the City of Seattle. Over the decade between 2002 and 2012, there was an annual average of 481 motor vehicle collisions involving pedestrians on Seattle's streets, out of which 423 resulted in injury and nearly 8 a fatality. Although pedestrians were only involved in 3.6% of traffic collisions in Seattle in 2012, they made up over 40% of fatal incidents and 24% of serious injuries(Seattle Department of Transportation 2012a, 2013). Given the vulnerability of pedestrians relative to other modes of travel, it is imperative that the scarce resources devoted to pedestrian-focused capital improvements are distributed efficiently and effectively.

| Pedestrian Collisions | | | |
|---|---|---|---|
| Year | Total Collisions | Injury Collisions | Fatal Collisions |
| 2002 | 486 | 442 | 5 |
| 2003 | 465 | 416 | 11 |
| 2004 | 462 | 357 | 10 |
| 2005 | 486 | 432 | 8 |
| 2006 | 574 | 513 | 9 |
| 2007 | 493 | 448 | 5 |
| 2008 | 471 | 419 | 9 |
| 2009 | 460 | 402 | 11 |
| 2010 | 517 | 442 | 6 |
| 2011 | 398 | 356 | 2 |
| 2012 | 487 | 428 | 8 |

**Table 1- Pedestrian Collisions 2002-2012** **Source- SDOT 2013**

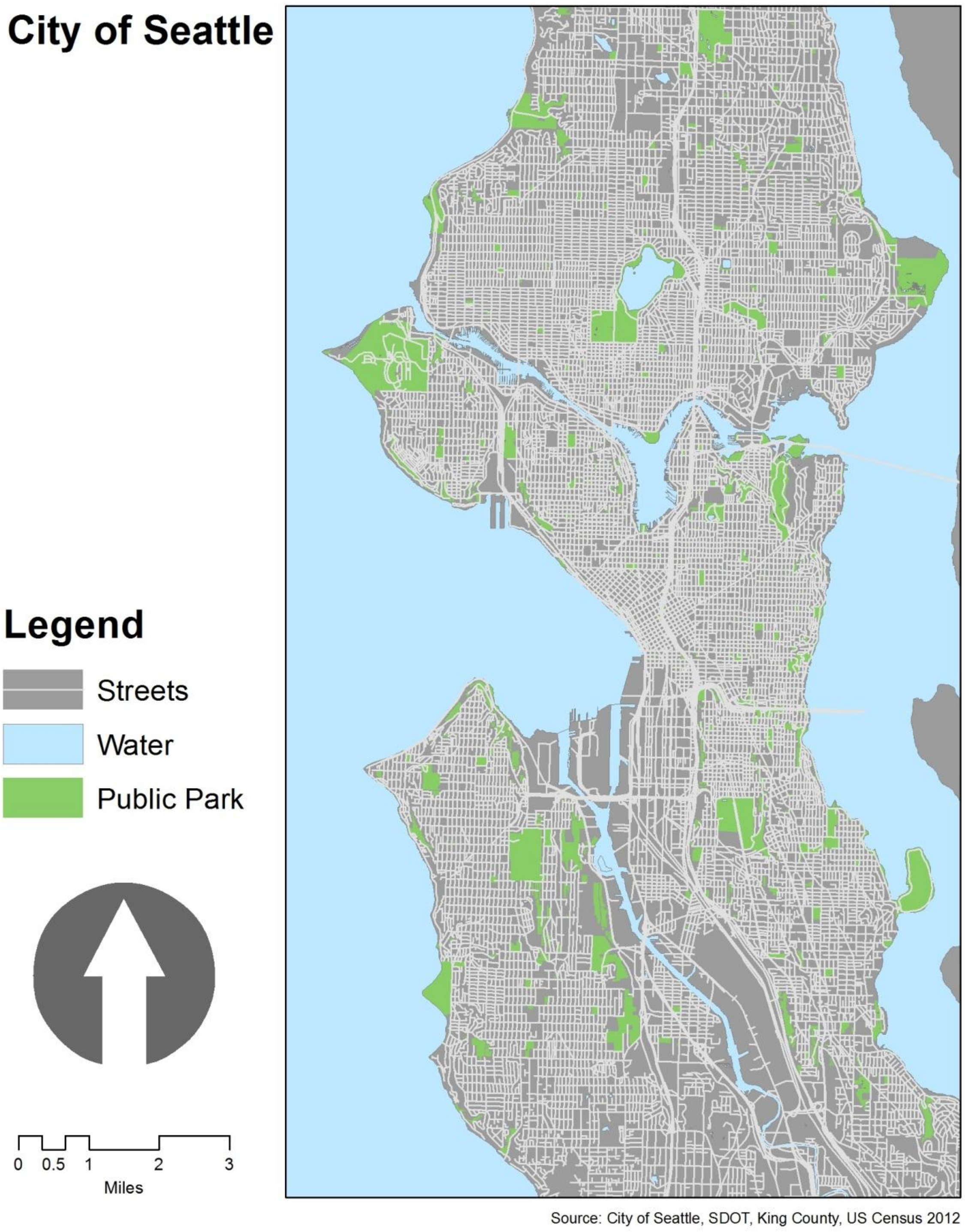


**Figure 1- Seattle Study Area**

The improvement of road safety conditions for pedestrians is a core component of local transportation planning efforts, taking priority in major documents such as the 2009 Pedestrian Master Plan and 2012 Road Safety Summit Action Plan. Each of these plans lay out a long term goal of Vision Zero: a future with no roadway fatalities (Seattle Department of Transportation 2012a, City of Seattle 2009). In addition to the action of local government, the city of Seattle is home to a number of non-profit organizations which advocate for safer streets for non-motorized traffic, such Feet First, Seattle Neighborhood Greenways, and the Cascade Bicycle Club.

In order to prevent pedestrian injury and death, it is necessary to know where collisions occur, the contributing conditions, who is injured, and how severely (Sciortino et al. 2005). It is also important to understand pedestrian demand, or where people are drawn to walk, as greater numbers of pedestrians increase the exposure to potential motor vehicle collisions(Natarajan, Demetsky, and Lantz 2008, City of Seattle 2009).

The use of Geographic Information Systems (GIS) allows for the examination of collision distributions and urban land use and demographic data which is not easily observed directly. Through the integration and manipulation of spatial and statistical data, GIS can be a powerful tool in protecting vulnerable road users by identifying locations which present the highest priority for pedestrian safety improvements.

## 1.2 Research Goals

This research aims to accomplish three major goals. The first goal is to identify street segments, intersections and areas within Seattle which have experienced high numbers of vehicle-pedestrian collisions. The second objective is to reveal streets and areas with high pedestrian demand through the analysis of demographic and land use data. The third and final aim is to suggest high-priority locations for future pedestrian safety infrastructure based on the comparison of the first two results. Walk First, a similar analysis published in late 2011 by the San Francisco Planning Department and Department of Public Health served as a rough template and inspiration for this research methodology (San Francisco Planning Department 2011).

Ultimately, the hope is that this research thesis can provide a methodological framework to help urban planners, engineers and decision makers distribute investments to pedestrian infrastructure where they are most needed. The findings of this analysis have the potential to create a data-based process for the creation and implementation of future Capital Improvements Programs which could contribute to municipal cost savings, efficient project identification, and most importantly, the safety of pedestrians and other vulnerable road users.

## 1.3 Approach

This thesis research is built upon publically available spatial and demographic data from municipal, county, and federal governments. An objective approach in which all results are relative within the study area allows others to more easily employ this analytical framework to their respective local surroundings with a reduced concern for site-specific idiosyncrasies. However, in the discussion and application of research results, local geographic and planning conditions must be taken into account to ensure an appropriate and complete understanding.

After the initial introduction of the research problem and background, this thesis research reviews the existing academic literature concerning walkability, pedestrian traffic safety and public health and their respective relationships to the built environment. In addition, the use of the kernel density estimation as a tool for spatial analysis is discussed and compared with the newer network kernel density tool.

Following the theoretical findings of the literature review, a GIS-based methodology for determining pedestrian collision hotspots and key walking areas is laid out. The results from this method are then compared using a priority matrix to suggest areas which are most suitable for pedestrian safety improvements. The findings are then discussed in both a Seattle-specific and generalized context. Future research paths and methodological improvements are also considered.

## 1.4 Document Organization

This thesis document is divided into six sections. Following the introduction, Section 2 summarizes the existing academic literature and theory upon which this analysis is based with specific attention to the relationships between walking, public health, pedestrian safety and the built environment. Section 3 details the exact methodological approach, including the research dataset and spatial analyses used. Section 4 provides the maps generated through spatial analysis and a succinct overview of the results and findings of the research. These results and their significance relative to both the local conditions in Seattle and in a generalized context are discussed at length in Section 5. Finally, Section 6 discusses possible future uses of this research methodology and means to improve its utility.

# 2. Literature Review

At its essence, the strategy for future growth laid out in *Toward a Sustainable Seattle*, the city's comprehensive plan, is built upon increasing residential and employment density in core nodes located along the regional transportation network. These nodes, known in the plan as urban villages, are intended to become pedestrian and transit-oriented communities (City of Seattle 2005 (updated 2013)). Therefore, understanding the role of walking and pedestrian safety in the built environment is critical to the future development of Seattle and the greater Puget Sound. Moreover, as the goal of this thesis is to suggest a means for more effectively distributing investments to pedestrian safety capital improvements, it is necessary to consider the theoretical underpinnings of the methodology put forth.

This section briefly discusses the academic body of knowledge with respect to walking for transportation and its relationship with the built environment. The two major themes of this research, safety and pedestrian demand, are given special focus. Finally, the spatial analytical method of Kernel Density Estimation (KDE) is explained in the context of traffic safety research and contrasted with the more specialized Network Kernel Density Estimation (NetKDE).

## 2.1 Walking and the Built Environment

The benefits of walking as a form of individual exercise have long been the focus of public health entities, such as the Centers for Disease Control and Prevention and the US Surgeon General's Office. Engaging in moderate intensity physical activity, such as walking, for just two and a half hours per week produces myriad positive impacts on personal health, such as reductions in the risk of serious illnesses like diabetes, obesity, depression, and heart disease, among many others (U.S. Department of Health and Human Services 1999). Until recently, traditional walking behavior research and outreach has been focused on socio-demographic factors and individual attitudes(Sallis and Owen 1999, Saelens and Handy 2008). Over the past decade, however, the relationship between the built environment and physical activity has become the subject of extensive empirical research across a variety of academic disciplines.

Beyond individual determinants of physical activity, such as community walking groups and fitness tracking, the body of academic and institutional research has also shown many variables within the built environment which influence walking behavior, both for leisure and for transportation. Aspects of the physical environment which have been consistently demonstrated to share a positive relationship with walking for transportation include: population and commercial density; accessibility to non-residential destinations; and land use diversity. Other variables such as parks and open space, network connectivity, and perception of personal safety are less decisive in influencing behavior (Cunningham and Michael 2004, Owen et al. 2004, Lee and Vernez Moudon 2006a, b, Saelens and Handy 2008).

Walking as a means of primary transportation holds promise not only in supporting our public health, but also in reducing society's collective environmental impact. By replacing automobile trips, walking has been shown to curb resource and land consumption, air and noise pollution, and greenhouse gas emissions (National Research Council 2009, Ewing et al. 2011). Travel behavior studies indicate that more than three quarters (78%) of all trips made in the United States are by car. On trips between one and two miles in length, this figure jumps all the way to 89%. These short, sub-two mile trips made up 41% of all travel in 2001 (Pucher and Dijkstra 2003, Pooley 2013). As most people are physically capable of walking or cycling these shorter distances, compact, pedestrian friendly built environments hold enormous potential in creating a healthier and more environmentally friendly future.

## 2.2 Relationship between the Built Environment and Pedestrian Traffic Safety

Motor vehicle collisions with pedestrians are a major health and safety concern in the United States. According to the National Highway Traffic Safety Administration (NHTSA), between 4,100 to 5,000 pedestrians are killed each year by motorists and 60,000 to 100,000 injured (US Department of Transportation 2012). Urban areas are often areas of high collision incidence due to the mixing of high density vehicular and pedestrian traffic (Hashimoto 2005, Schuurman et al. 2009, Dai et al. 2010). However, it should be noted that despite the high total number of collisions which occur in dense urban areas, recent study, such as that by Ewing and Dumbaugh (2009), demonstrate that cities tend to be safer on a per-capita and injury severity basis than their suburban or rural counterparts, due in part to slower speeds and lower vehicle miles travelled. Nevertheless, the issue of safety and risk of bodily harm for pedestrians remains significant. Danger for those on foot cuts across the aforementioned public health benefits of walking and thereby warrants greater scrutiny.

In their 2009 literature review of the links between the built environment and traffic safety, Ewing and Dumbaugh revealed two major variables which influence traffic safety outcomes: development patterns and roadway designs. These two variables affect traffic volumes, traffic conflicts, and traffic speed which, in turn, influence collision frequency and crash severity. The diagram in Figure 2 illustrates this relationship. Development pattern characteristics such as density, land use mix, and compact urban form have all been shown to be negatively correlated with the rate of pedestrian fatalities (Siddiqui 2012, Elvik 2001, Dumbaugh and Rae 2009). Roadway design features such as narrower width, greater network density, fewer 4-way intersections, and fewer arterial class streets have been associated with reductions in collision frequency (Ewing and Dumbaugh 2009, Dumbaugh and Rae 2009, Wøhlk Jæger Sørensen and Loftsgarden 2010, Litman 2013).

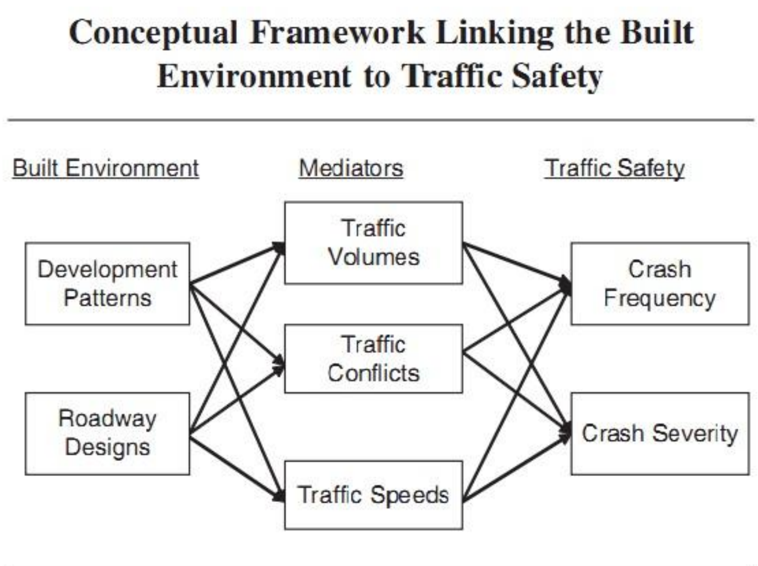


**Figure 2- Ewing and Dumbaugh (2009) Framework of Built Environment and Traffic Safety**

It is important to understand how these built environment variables affect traffic safety on a macroscopic level so that area-wide solutions can be considered. However, the broad scale of these studies is less well suited to traffic safety research at the scale of the individual road segment or intersection. For site specific analysis, the identification of collision clusters or "black spots" through the use of spatial analysis is a useful approach.

## 2.3 Use of Kernel Density Estimation in Traffic Safety

In street segment and intersection level traffic safety analyses the identification of clusters of elevated collision occurrence, known broadly as "black spots" or "hot spots," is common practice in developed countries (Geurts and Wets 2003). The official methods and timeframes for documenting these clusters vary widely from country to country and include a variety of relevant spatial-statistical tools such as sliding window analysis, map study, and Poisson distribution collision probability tests (Sørenson and Elvik 2007). The widespread adoption of GIS and the proliferation of high-quality spatial data has made Kernel Density Estimation (KDE) an increasing popular approach in point pattern analysis hot-spot research (Xie and Yan 2013).

KDE computes the density of an observed point-event distribution in two dimensional Euclidean spaces. In general conceptual terms, the KDE approach calculates the density of nearby point features within an established neighborhood around a given point. Visualized in three dimensions, the KDE neighborhood bandwidth is a bell-shaped curve, symmetrical around the central point feature. The steepness of this curve is regulated by the Kernel (or K) function. A steeper curve will yield a more localized result where a flatter curve produces a smoother density gradient. Neighboring features are given a density score based upon their proximity to the central point which decays as distance increases. Beyond the neighborhood boundary the value is zero. This process is repeated iteratively for each point in the dataset. After all of the density score neighborhoods surrounding each point are calculated, the density scores of the overlapping neighborhoods are summed, producing distinct peaks and valleys (ESRI 2014). When represented in two dimensions the result is a smooth gradient with high and low density values, which can be represented as hotspots. This relationship is illustrated in Figure 3.

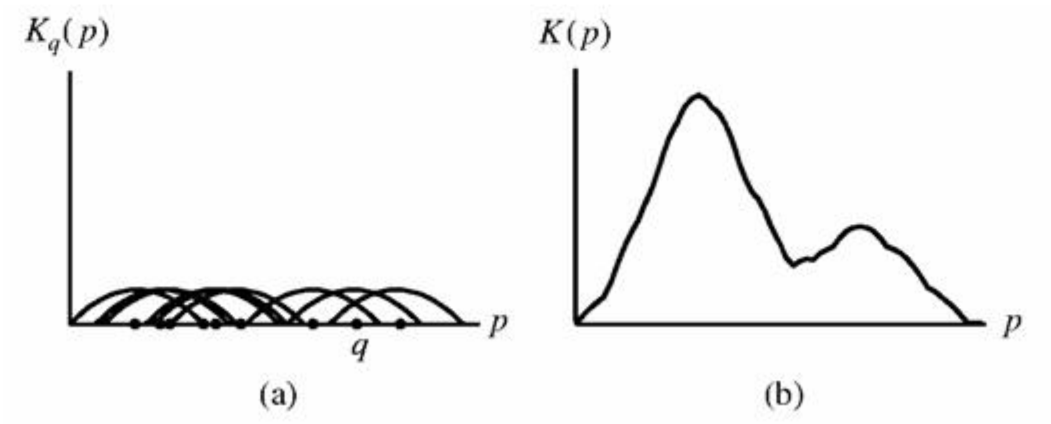


**Figure 3- Kernel Density Estimation (Okabe 2013)**

This two dimensional KDE, also known as planar KDE, has been widely used in fields like geography, epidemiology, criminology, demography, hydrology, and ecology, among others (Produit et al. 2010). In the realm of traffic safety, planar KDE has been used to chart a variety phenomena like hazards for cyclists(Delmelle and Thill 2008), pedestrian collision zones (Schuurman et al. 2009), road traffic accidents (Anderson 2009), and even road kill locations (Gomes et al. 2009).

Although planar KDE has been a useful tool in traffic safety research, it does not reflect the true nature of traffic collisions. The major flaw is that the planar KDE methodology calculates density as though point events are distributed randomly throughout Euclidean space. However, traffic crashes do not occur in open space but are instead bound to the network of roadways and sidewalks upon which traffic flows. This discrepancy leads to an overestimation bias of up to 20% in planar KDE results when used in a network context (Xie and Yan 2008). In response, recent research has focused on the development and use of a kernel density approach which the neighborhood bandwidth is calculated through a network instead of over Euclidean space (Okabe, Okunuki, and Shiode 2006, Xie and Yan 2008, Dai et al. 2010). This novel tool is referred to as Network Kernel Density Estimation, or NetKDE.

## 2.4 Network Kernel Density Estimation

Conceptually, NetKDE is an extension of the KDE process described above. The key difference is that NetKDE computes neighborhood bandwidth distance through the network as opposed to through open space. Like planar KDE, the kernel function which regulates the slope of the bell curve regulating distance decay can be varied to give either a more global or local analysis. However, the literature shows that this is of little practical importance compared to the variation in bandwidth threshold distance(Xie and Yan 2008, 2013). This approach has been shown in a number of instances to correct the inherent bias in planar KDE and give a more accurate depiction of the distribution of network-bound point events (Okabe, Okunuki, and Shiode 2006, Larsen 2010, Produit et al. 2010, Okabe and Kokichi 2012, Xie and Yan 2013). Figure 4 illustrates the difference between the two KDE methods.

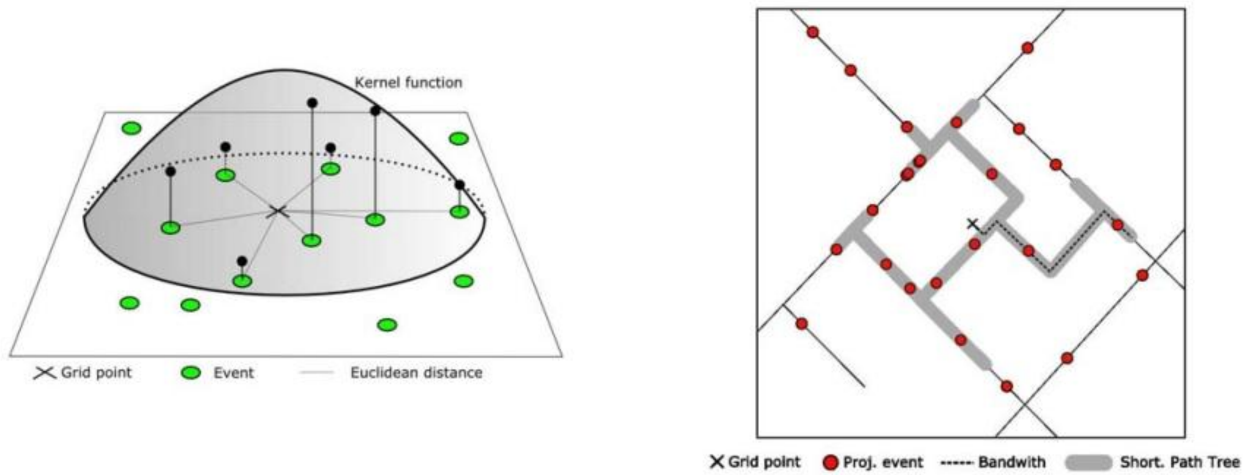


**Figure 4- Planar KDE vs. NetKDE (Xie and Yan 2013)**

## 2.5 Relationship between the Built Environment and Pedestrian Demand

One of the most significant ways in which traffic safety analysis differs between motorists and pedestrians is in the use of traffic volume data to assess collision frequency. For automobile traffic, the standard statistic is Average Annual Daily Traffic (AADT), which is commonly collected for all major intersections and roadways in an urban area, Seattle being no exception (Seattle Department of Transportation 2013). By knowing how many cars cross a given intersection or road segment over a defined time period, crashes can easily be expressed as a rate (number of collisions per 100,000 vehicles, for example). Using rates instead of total number of crashes allows investigators to determine areas which have a higher risk of incident compared to an expected average. This is advantageous because urban areas with the highest number of crashes are often found to be the very same areas with the highest traffic volumes, as well as number of coffee shops, clothing stores, and just about everything else due to the confounding variables of density, risk exposure, and intensity of use (Ewing and Dumbaugh 2009).

Unfortunately, a pedestrian equivalent to AADT is not available for the vast majority of the urban road network. Pedestrian counts that do exist are typically more limited in scope and feature only the busiest of nodes along the network(City of Seattle 2009).   In order to offset this missing data, land use, geographic and demographic information can be used as a surrogate to model pedestrian demand—the expected volume of pedestrians on a network. This stand-in model allows for a partial assessment of pedestrian risk exposure (Lee and Vernez Moudon 2006b, City of Seattle 2009, San Francisco Planning Department 2011).  Perhaps the most visible use of this type of modeling is employed by the popular website Walk Score, which uses network features, parcel-level land use, population, and terrain data to generate pedestrian demand figures (Walk Score 2014). Although pedestrian demand scores are a useful substitute for traffic volume data, the models which generate have been shown to have fairly wide margins of error, depending on local factors such as the quality of urban design(Clifton et al. 2008). Nevertheless, these methods are an important component of assessing risk and priority in pedestrian safety improvement.

A tremendous number of built environment measures exhibit bivariate association with walking (Lee and Vernez Moudon 2006a, b). Of these measures, the following represents a sample of what has been commonly used in pedestrian demand modeling at the municipal level for planning purposes (City of New York 2006, Clifton et al. 2008, City of Seattle 2009, San Francisco Planning Department 2011):

- Access and Need to Walk
    - Percentage of people who walk to work
    - Percentage of people who take transit to work
- Transit Service
- Density of People
    - Population Density
    - Job Density
- Land Use Generators
    - Tourist destinations
    - Colleges and universities
    - Health care services
    - Public and private schools
    - Shopping districts
    - Senior Centers
    - Grocery Stores
- Vulnerable Populations
    - Density of seniors
    - Density of youth
    - Density of disabled people
- Street slope

# 3. Methodology

The overarching purpose of this research thesis is to suggest priority areas for pedestrian safety improvements in the City of Seattle. In order to achieve this goal, the research effort was broken into the following GIS workflows:

- Determining safety needs by mapping the locations of highest collision density through the use of Network Kernel Density Estimation.
- Defining areas of high pedestrian demand through the compilation of land use, demographic, and travel behavior data.
- Prioritizing specific intersections and road segments by comparing the results of the collision density and pedestrian demand analyses.

Walk First, a similar analysis published in late 2011 by the San Francisco Planning Department and Department of Public Health served as a rough template for this approach (San Francisco Planning Department 2011). In addition, variables associated with walking in the literature were considered. All analyses were performed using ArcGIS version 10.1. The NetKDE analysis utilized a third-party toolbar extension called SANET (Spatial Analysis along Networks). This section first describes the study dataset and moves on to discuss the rationale behind and process for completing the aforementioned GIS tasks.

## 3.1 Description of the Dataset

This analysis was completed using publically available data provided by the Seattle Department of Transportation (2012b), the City of Seattle, King County, WA , and the United States Census Bureau. The data utilized was comprised of pedestrian collision point locations, the Seattle street network, King County land use and transportation data, and US Census demographic information.

### *3.1.1 Pedestrian Collision Data*

The pedestrian collision data was collected from police reports and distributed by the Seattle Department of Transportation (SDOT). The SDOT collision records used in this analysis span a 52 month timeframe from January 1$^{st}$, 2008 to April 30$^{th}$, 2012. Each pedestrian collision location is represented as a point shapefile and includes further incident information such as injury severity, number of vehicles involved, and time of day. All collisions within this feature class are joined to the street network at either intersections or mid-block street segments. In total, there are 1,942 separate collision incidents included. Although this dataset is the most comprehensive available, it is unlikely that it is completely inclusive of all incidents, as epidemiological research suggests as many as 20% of pedestrian collisions go unreported to police (Blincoe et al. 2002, Sciortino et al. 2005, Vernez Moudon et al. 2011).

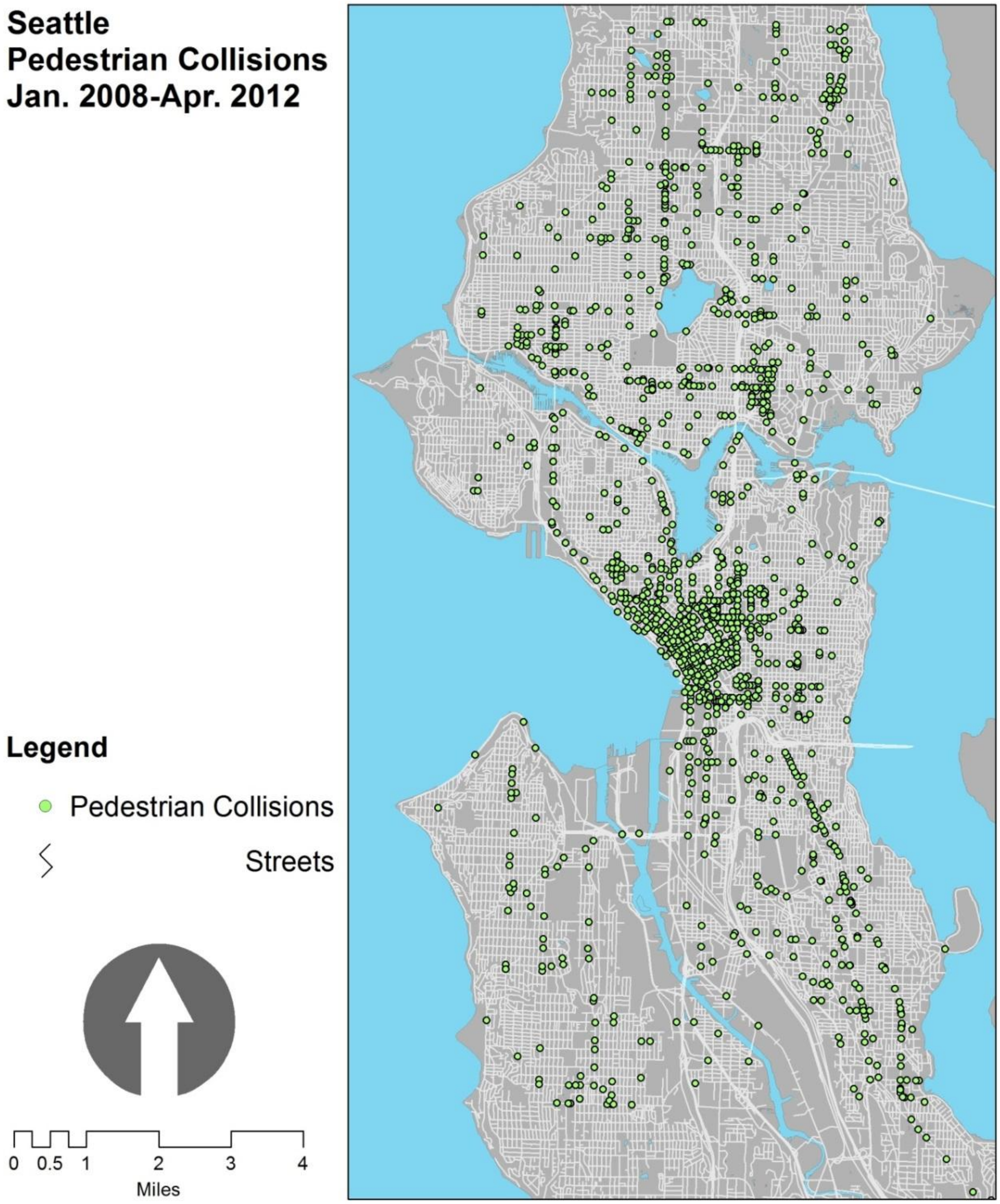


**Figure 5- Pedestrian Collision Shapefile**

In addition to the raw collision data, SDOT has also compiled detailed descriptive statistics of the data on a year-to-year basis. Details include distributions of collision victims by age, sex, clothing and a host of other contributing factors. For a full inclusion of these statistics for 2012, please see Section 8.1 in the Appendix.

### *3.1.2 Streets and Transportation Data*

The Seattle street network and transportation data was provided by the City of Seattle and King County and accessed via the Washington State Geospatial Data Archive (WAGDA). The data includes all city streets and public transportation routes, stored as line shapefiles. In addition to physical location and characteristics, information such as street names and transit route characteristics are also available. Both sets of data were current as of February 2012.

### *3.1.3 Land Use and Administrative Data*

The land use data used in determining pedestrian demand was provided by both the King County Assessor's Office and the City of Seattle and was accessed online via the King County GIS Data Portal and the Washington State Geospatial Data Archive. This data set is comprised of polygon shapefiles at the individual parcel level with information on zoning, present use, and value, among others. In addition, administrative polygons representing parks, special zoning and jurisdictional designations such as Urban Villages (a smart growth zoning designation in the found Puget Sound region) and city limits were included. This data is updated continually by

King County and was current when originally accessed in February 2014.

### *3.1.4 Demographic Data*

Demographic data from the US Census and American Community Survey (2005-2009 5 year estimates) was used in the determination of pedestrian demand. The following data was examined at the block group level: population density, population under 18 or over 65, population walking or taking transit to work, and employment density. All information and block group shapefiles were acquired via the King County GIS Data Portal and were initially released by the US Census Bureau in 2010.

## 3.2 Mapping Collision Hotspots

At first sight, the pedestrian collision points reveal some indication of clustering. However, it is difficult to determine the exact locations and densities of the collision events as many of the over 1,900 points overlap and obscure one another. The first step toward better visualizing the overlapping collision points involves the 'Collect Events' spatial statistics too. Collect events creates a new point layer- with a Z-value for each location. Areas with overlapping points receive the sum of the Z-values for each individual point at that specific location. This process highlights locations with multiple overlying collisions by generating single points with higher Z-values which can be made graphically distinct from points of single collision occurrence. The results of this step can be seen below in Figure 6.

In order to get a clearer picture of collision density values and potential pedestrian safety hotspots, a NetKDE analysis was performed. As mentioned in the literature review, this method was used to avoid the inherent biases of planar KDE in a network context. However, the toolset required to perform NetKDE is not included in the standard ArcGIS toolbox. Therefore, a third-party toolbox extension called SANET was used.

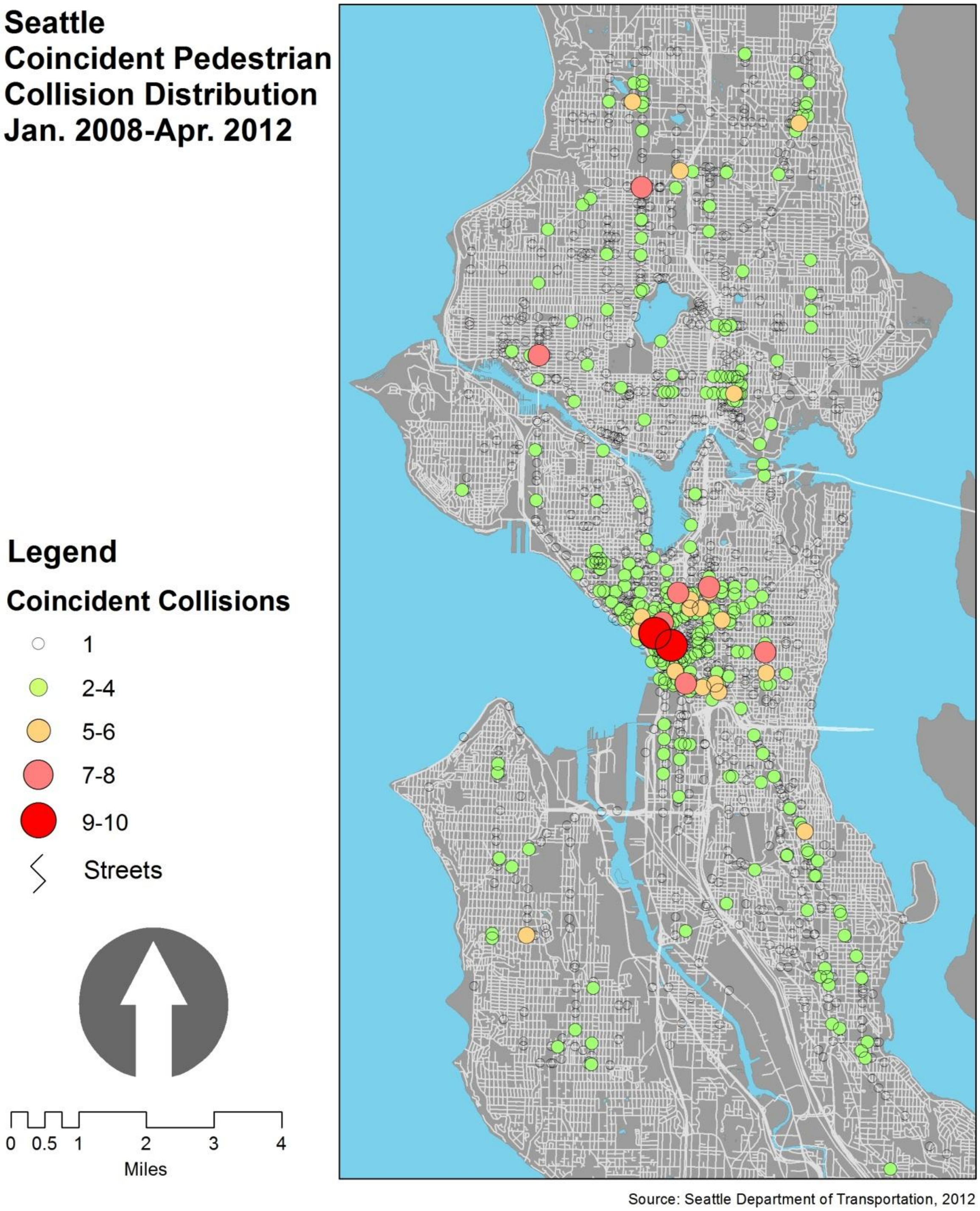


**Figure 6- Collect Events**

### *3.2.1 SANET- Spatial Analysis along Networks and NetKDE*

SANET, or Spatial Analysis along Networks, is an ArcGIS toolbox extension developed by a team led by Japanese researcher Atsuyuki Okabe at the University of Tokyo (Okabe, Okunuki, and Shiode 2006). The toolbox is freely available for non-commercial research at http://sanet.csis.u-tokyo.ac.jp/. While this analysis used only the Network Kernel Density Estimation tool, there are an additional 15 functions which cover all manner of spatial phenomena along network space.

The NetKDE analysis was performed on the SDOT pedestrian collision point layer using the Seattle Street Network Database as the network layer. The kernel function type was left at the default (equal split continuous) and the bandwidth for the neighborhood boundary was set at 400feet, based upon what was used in similar studies in the literature(Dai et al. 2010, Larsen 2010). Cell width was set to 40 feet as recommended by the SANET team (Okabe, Okunuki, and Shiode 2006). The resulting shapefile was visualized using a divergent high to low color scale in order to show the calculated density values and hotspots in a heat map fashion.

## 3.3 Mapping Pedestrian Demand

As discussed in the previous section, pedestrian demand is an important factor in assessing walkers' risk exposure in traffic. There are many variables one can choose to include in a pedestrian demand model. In this case of this thesis research, the following five categories were considered after consulting the academic literature and municipal planning documents:

- Access and need to walk
- Transit nodes
- Density of people
- Land Use
- Vulnerable population

The process for calculating each of the five pedestrian demand measures is summarized in their respective subsections below.

### 3.3.1 Access and Need to Walk

The Access and Need to Walk measure reflects locations where people are either dependent on walking or have sufficient accessibility in order to be able to walk regularly. To capture this relationship, journey to work data from the US Census American Community Survey 2005-2009 was used at the block group level. For each block group the percentage of people who walk or take transit to work was calculated and the results displayed as 10 categories via a natural breaks categorization. The resulting shapefile data was then converted to a raster with a 100 foot cell size and each census block group was scored 1-10 based on its natural breaks ranking using the Reclassify tool. This method allowed the percentage total of each census block group to be scored relative to the other block groups in the City of Seattle as a whole, with each natural break receiving a mark of 1 through 10, relative to its respective place among other locations.

### 3.3.2 Transit Priority

Transit Priority stands as a proxy measure for connectivity with the local transportation network. Rather than incorporate transit ridership data, status as an urban village was used as a means to show locations with the highest degree of transit access. Shapefiles representing the urban village classifications Urban Center, Hub Urban Village and Residential Urban Village were used. These were then converted to a raster with a 100 foot cell size and the coverage was scored 7 for Urban Center, 5 for Hub Urban Center and 3 for Residential Urban Village. All areas outside of the urban village zones were scored 0.

### 3.3.3 Density of People

The Density of People measure assesses population both in terms of residential and job density. For each census block group residential and job population was summed and the sum then expressed as number of residents and jobs per acre. These results were scored 1-10 following the same procedure as the Access and Need to Walk measure.

### 3.3.4 Land Use

The land use variable was calculated using parcel level data available from the King County Assessor's office which shows current use in over 120 categories. In order to simplify the number of possible categories, the uses were consolidated into the following categories. Categories were further subdivided based on hypothesized regional, district or local spheres of influence. Uses not represented below were scored 0 in this analysis.

- Tourist attractions and hotels
- Colleges and Universities

- Health care facilities
- Public and private schools
- Parks and playgrounds
- Senior care facilities
- Commercial zoning districts

Each of these identified parcels was then given a ¼ mile buffer and the resulting shapefile was converted to a raster with 100 foot cell size. Using the Reclassify tool, parcel categories were scored 7, 5, and 3 respective of their regional, district or local influence. For example, the University of Washington, being a major regional education center, was given a score of 7 and all public and private schools received a district score of 5.

#### *3.3.5 Vulnerable Population*

The Vulnerable Population category weights census block groups based upon the population percentage of those who are most likely to not have access to an automobile: youth and seniors. To quantify this result, population over the age of 65 and under the age of 18 were summed and then divided by the total population for the census block group. These results were converted to a raster and categorized in the same fashion as the first and third measures presented in this subsection.

#### *3.3.6 Creating the Pedestrian Demand Map*

After the five constituent rasters described above had been created, they were combined to achieve the final Pedestrian Demand map product. Care was taken to ensure that each raster created had a cell size of 100 feet so that combining the results could be done without rescaling.

All rasters were added to one another using the Map Algebra raster tool in ArcGIS. This resulted in a raster with the sum of the pedestrian demand scores calculated in the sections above. The scores in this summary raster were then extracted to points representing every street segment intersection and midpoint using the Raster Value to Point Feature tool. These points containing the raster values were finally associated with the street line segments via a Spatial Join and given a divergent color symbology.

## 3.4 Prioritizing Results

In order to determine street segments and areas of high priority for pedestrian safety improvements, the results of the NetKDE collision location analysis and pedestrian demand mapping were compared. Conceptually, the comparison follows the diagram in Figure 7. Following this matrix, individual street segments are ranked highest through low priority based upon the comparison of safety need and pedestrian demand. Due to the greater personal and societal costs of deficient pedestrian safety conditions, segments are still able to rank as "high" priority, even if their pedestrian demand is low. Although the overall purpose of this study is to improve safety, focusing on locations with high pedestrian demand can create a more widespread sense of security and, therefore, these areas were given the "highest" priority. Locations of severe and fatal collisions were also considered.

| | | Pedestrian Safety | | |
|---|---|---|---|---|
| | | **High:** Ranks top 1/3 of collision kernel density score | **Medium:** Ranks middle 1/3 | **Low:** Ranks bottom 1/3 |
| Pedestrian Demand | **High:** Ranks top 1/3 of pedestrian demand | **Highest** | **High** | **Medium** |
| | **Medium:** Ranks middle 1/3 | **High** | **Medium** | **Low** |
| | **Low:** Ranks bottom 1/3 | **High** | **Low** | **Low** |

**Figure 7- Prioritization Concept Matrix**

In practice, this method was carried out by first dividing the street segments in both the safety and demand maps into high, medium, and low designations, relative to the values generated through the respective analyses. Once this reclassification was complete, each respective designation class (high, medium, low) was selected and exported as its own layer in ArcGIS. After the six new layers were created, the overlapping segments were highlighted using select by location with a 250ft search buffer in order to include adjacent high value segments. These highlighted portions, each of which comprises a "cell" in the concept matrix, were then judged visually and used to create the final map of priority pedestrian safety improvement street segments, intersections and areas.

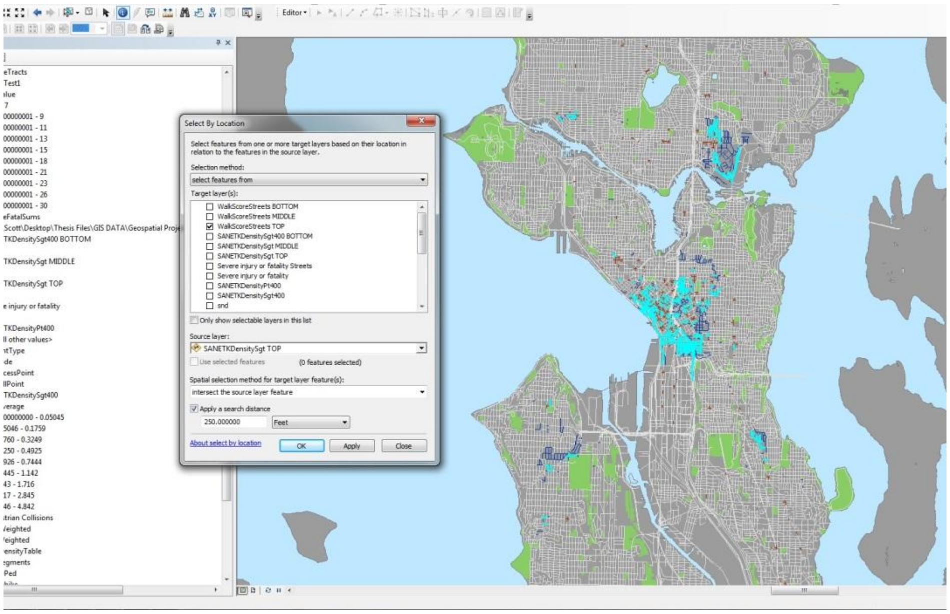

**Figure 8- Selection Process**

# 4. Results

There are three major products that were generated by this research. First, the pedestrian collision hot spot map produced via Network Kernel Density Estimation. Second, the map of pedestrian demand generated through raster analysis. Lastly, a map of priority street segments, intersections, and areas for pedestrian safety investments was created by a visual comparison of the first two results.

## 4.1 Results of Network Kernel Density Estimation for Pedestrian Collisions

The NetKDE analysis revealed several clusters of significant pedestrian collision density. Compared to a planar KDE analysis performed on the same dataset in prior research (see Figure 12 in the appendix), results exhibit a much greater degree of linearity, as expected due to the network-based calculation. There are a number of corridors, areas, and intersections which show elevated levels of collision occurrence. The areas and their context within Seattle are described qualitatively and in no particular order in the subsection below. Streets corridors and intersections with safety concerns are identified in Table 2. The overall collision density map can be seen in Figure 9.

### *4.1.1 High Collision Density Areas*

Broader scale pedestrian collision clusters appear in four areas across Seattle. These areas were identified where collision density values were elevated over several contiguous intersections, as opposed to occurring along a specific street corridor or at an isolated intersection. The areas identified include the following:

**Downtown-** The highest collision densities are found throughout the downtown core. Within this frequent collision area, zones of highest density are oriented along 1$^{st}$ and 2$^{nd}$ Avenue with the peak densities centered on the intersections with Pike and Pine Streets. A smaller sub-peak is located at 5$^{th}$ Ave. and Spring St.

**First Hill/Capitol Hill-** A north to south oriented zone of high crash incidence runs roughly from the intersection of Boren Ave. and Broadway to Broadway and East Olive Way. This area encompasses many important land uses, including three major medical centers and two universities. East Olive Way appears to be involved in several higher density crash locations, possibly as a result of the odd-angle intersections created by its curvilinear shape.

**International District-** A compact zone of high collision incidence stretches from 4$^{th}$ Ave. South to 12$^{th}$ Ave. S and is bounded to the north by S. Jackson St. and S. Dearborn St to the south. This area also contains the nearest major grocery store serving the downtown area.

**University District-** The University District exhibits high levels of crash density between NE 50$^{th}$ St. and NE 40$^{th}$ St. and Interstate Highway 5 and the University of Washington Campus. This area will become increasing important to pedestrians as the UW expands residential options in West Campus and LINK Light Rail is extended north along Brooklyn Ave. NE.

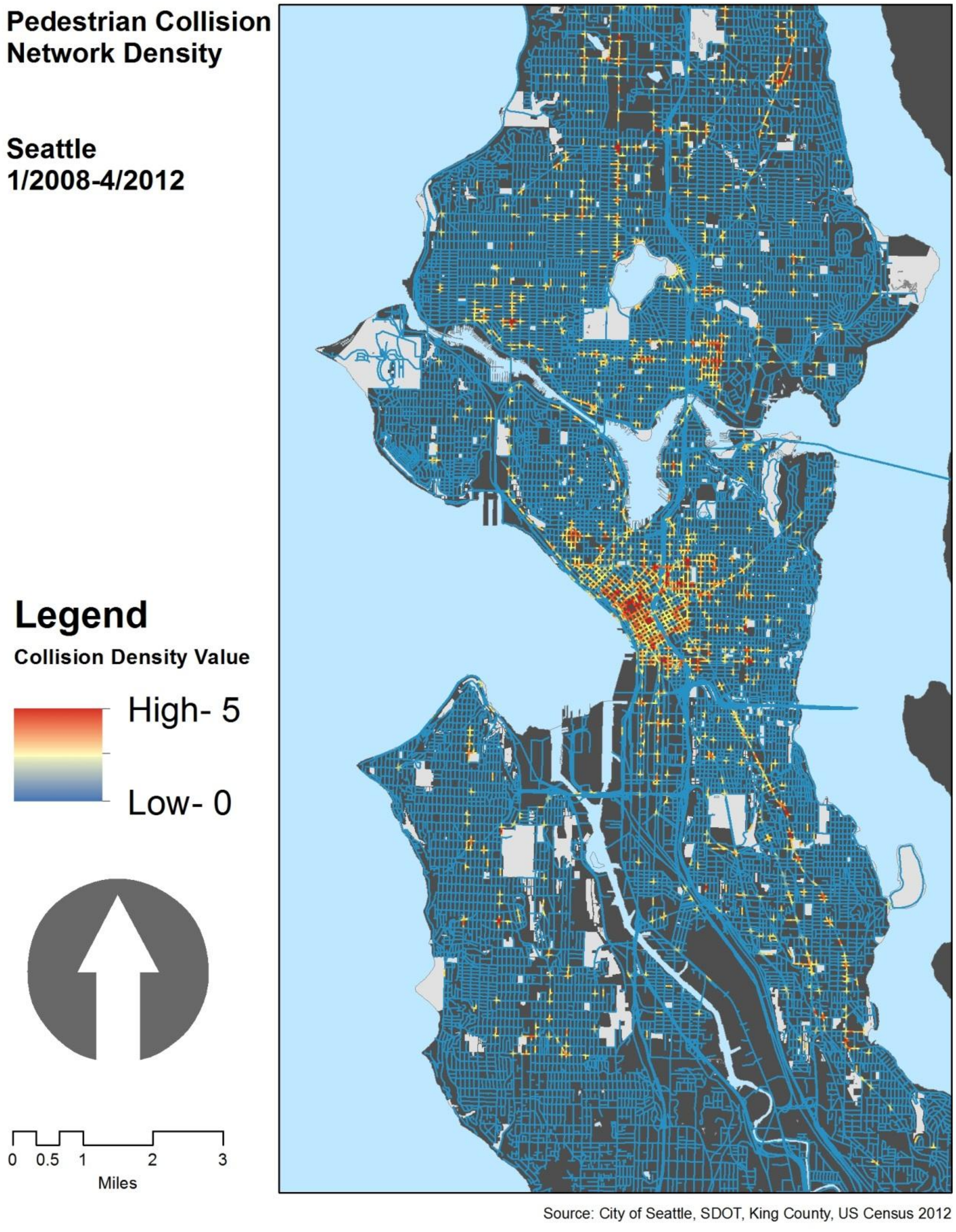


**Figure 9- NetKDE Map of Pedestrian Collisions**

## 4.2 Results of Pedestrian Demand

The results of the pedestrian demand analysis seem to correspond well with "on the ground" observation. This is further verified by comparison with other well-supported pedestrian models, such as Walk Score (Walk Score 2014). Downtown and the University District are the neighborhoods with the greatest potential for pedestrian activities. The inclusion of transit-dependent and vulnerable populations in the analysis is evident in the high values found in neighborhoods like the International District and Columbia City. Oddly, South Lake Union scores fairly low despite being a dense urban area, perhaps as a result of low residential density during both the 2010 Census and 2005-2009 American Community Survey. This calls attention to the fact that all model results should be verified to the best extent possible with real-world conditions. The full overview is shown in the Pedestrian Demand Map found in Figure 10.

## 4.3 High Priority Streets, Intersections, and Areas

Several high priority street corridors, intersections and areas are suggested based on the comparison of the pedestrian collision NetKDE analysis and pedestrian demand map. This selection also took consideration of recently installed or planned pedestrian improvements, such as station improvements in the University District. In total, 22 street corridors, 4 intersections and 4 areas are recommended for prioritization. The results are summarized in the overview map in Figure 11 and in Table 2.

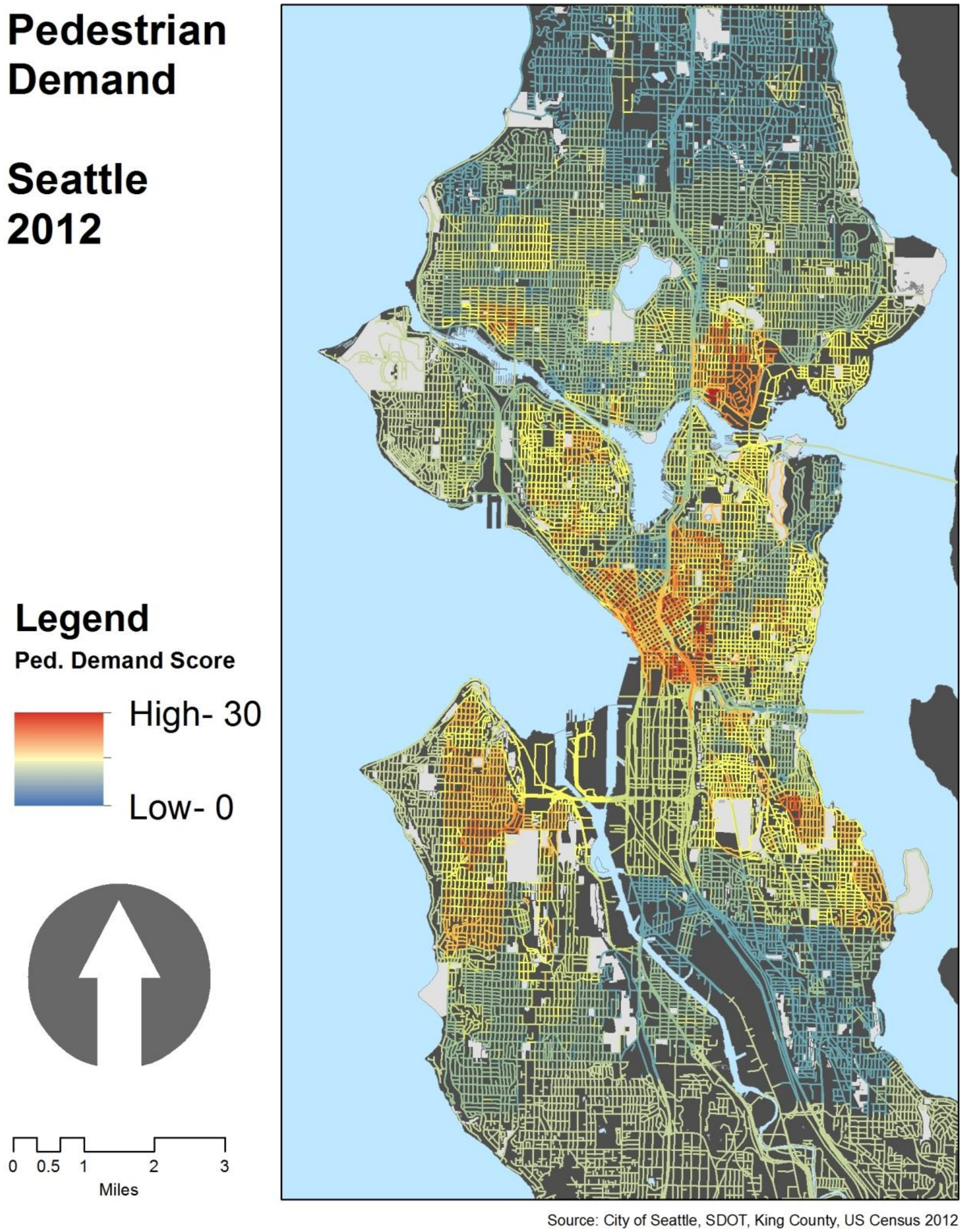


**Figure 10- Pedestrian Demand Map**

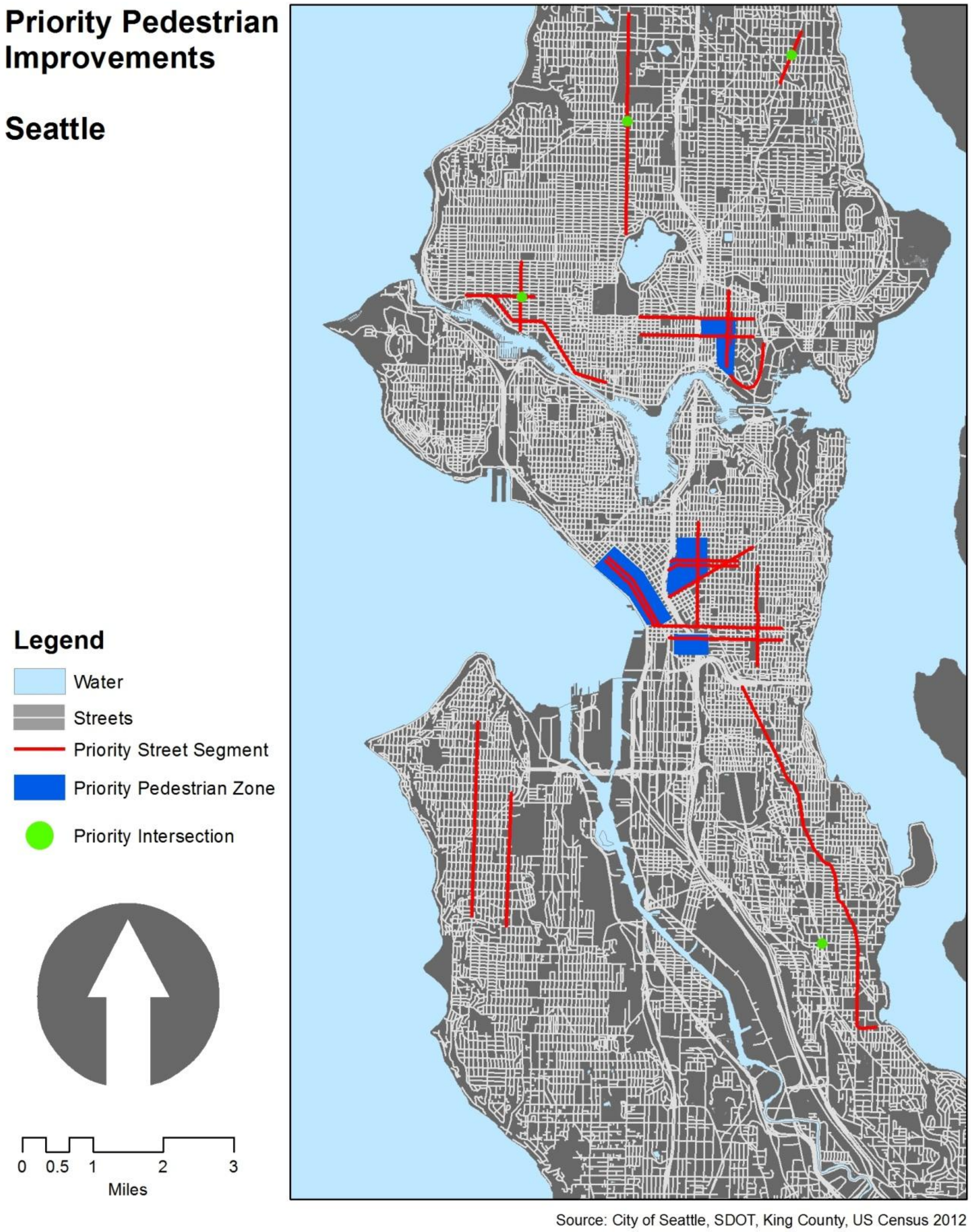


**Figure 11- Suggested Priority Locations Map**

| Prioritized Pedestrian Safety Improvement Locations | | | | |
|---|---|---|---|---|
| Priority Location | Type | Start Intersection | End Intersection | Cross Street |
| Hwy 99/ Aurora Avenue N. | Street corridor | West Green Lake Drive N | NE 135th St. | N/A |
| Lake City Way NE | Street corridor | NE 115th St. | NE 135th St. | N/A |
| 15th Ave. NW | Street corridor | Shilshole Ave NW | NW 65th St. | N/A |
| NW Market St. | Street corridor | 32nd Ave NW | 14th Ave NW | N/A |
| Leary Way NW | Street corridor | NW Market St. | Fremont Ave. N | N/A |
| N/NE 45th St. | Street corridor | Stone Way N. | 17th Ave. NE | N/A |
| N/NE 50th St. | Street corridor | Stone Way N. | 17th Ave. NE | N/A |
| 15th Ave. NE | Street corridor | NE 52nd St. | NE 42nd St. | N/A |
| University Way NE | Street corridor | NE Ravenna Blvd. | NE 40th St. | N/A |
| Burke Gilman Trail | Street corridor (bike path) | 15th Ave NE | Pend Oreille Road NE | N/A |
| Broadway | Street corridor | E. Republican St. | E. Madison St. | N/A |
| E. Pine St. | Street corridor | Interstate 5 | E. Madison St. | N/A |
| E. Pike St. | Street corridor | Interstate 5 | E. Madison St. | N/A |
| E. Madison St. | Street corridor | 7th Ave. | 23rd Ave. E. | N/A |
| 2nd Ave. | Street corridor | Wall St. | Yesler Way | N/A |
| 1st Ave. | Street corridor | Wall St. | Yesler Way | N/A |
| Jackson St. | Street corridor | 1st. Ave | MLK Jr. Way S. | N/A |
| Yesler Way | Street corridor | 1st. Ave | MLK Jr. Way S. | N/A |
| 23rd Ave E | Street corridor | E. Union Street | S. Judkins St. | N/A |
| Rainier Ave S. | Street corridor | Interstate 5 | S. Henderson St. | N/A |
| 35th Ave. SW | Street corridor | SW Avalon St. | SW Holden St. | N/A |
| California Ave. SW | Street corridor | SW Admiral Way | Fauntleroy Way SW | N/A |
| NW Market St. | Intersection | N/A | N/A | 15th Ave NE |
| Lake City Way NE | Intersection | N/A | N/A | NE 125th St. |
| MLK Jr Way S. | Intersection (Light Rail Station) | N/A | N/A | S. Othello St. |
| Hwy 99/ Aurora Avenue N. | Intersection | N/A | N/A | N 105th St. |

**Table 2- Suggested Priority Road Sections and Intersections**

# 5. Discussion

## 5.1 Utility and Application of Analysis

On the whole, this thesis research achieved its purpose: to identify locations along the Seattle street network which showed high densities of pedestrian-vehicle collisions and to use this information to prioritize future pedestrian infrastructure improvements. By better understanding where pedestrian crashes occur, planners and engineers can direct scarce capital improvement funds into areas where they will have the largest impact. Furthermore, as the methodology used publically available collision, land use, and census data, the hope is that other cities can adopt similar analyses to improve their pedestrian safety conditions with a minimal investment of staff time.

In addition to the robustness and relative ease of the approach, the maps generated serve as a powerful visual aid. Professionals and lay persons alike are able to quickly assess safety concerns without complicated jargon or statistics to obscure the message the map is meant to convey. The result is that interested parties may be more easily able to engage others and create discussion over the importance of pedestrian safety. Moreover, the prioritization method can also be applied at the neighborhood and district scale with only minor modification to the assessment of pedestrian demand. This geographic flexibility increases the utility for smaller organizations, such as school districts, concerned with walking safety.

While this approach was successful in reaching the goal it set out to achieve, it is not meant to be accepted as the only evidence for pedestrian safety conditions. There are many determinants of pedestrian safety; street and sidewalk infrastructure represent only a small fraction of the whole. Individual behavior, traffic speed, clothing, time of day, weather, the quality of urban design, and vehicle design are all factors which can affect the amount of risk a walker faces in traffic (Loukaitou-Sideris 2006, Lee and Vernez Moudon 2006a, Vernez Moudon et al. 2011). In light of this, a holistic approach is recommended when dealing with pedestrian safety issues at the individual project scale. This analysis is best suited for narrowing down candidate locations for improvement which can then investigated in their full context for a better assessment of risk.

## 5.2 Significance of the Result

This analysis was intended to identify areas of collision clustering relative to the local context in Seattle. No attempt was made to ascertain correlation or cause to pedestrian collisions and any aspect of the built environment or behavior. However, a number of studies in the literature demonstrate these types of relationships through statistical means, such as regression analysis (Ewing and Dumbaugh 2009, Vernez Moudon et al. 2011). In the realm of spatial statistics, Xie and Yan (2013) have recently demonstrated a network based use of the Moran's I statistic which can help to demonstrate independence from spatial autocorrelation. Lastly, for a better picture of descriptive statistics of pedestrian collisions in Seattle, please see SDOT's analysis found in Section 8.1 in the appendix.

## 5.3 Methodological Concerns

The largest single methodological concern in this research is a problem faced by many types of "hotspot" density analyses which attempt to assess relative risk or rate of crashes: the confounding factor related to population density. Perhaps stated best by Ewing in his 2009 meta-analysis of the built environment and traffic safety, "Where there are more people and jobs, there tends to be more of everything, from traffic to crime to coffee shops." This methodological concern will remain prevalent in this type of pedestrian safety analysis so long as pedestrian traffic volume statistic is unavailable. Without this AADT type measure, it is not possible to accurately determine risk exposure in the same manner as automobile traffic. With respect to this fact, this thesis makes no claims to exposure or risk evaluation.

# 6. Conclusion

## 6.1 Main Findings and Policy Implications

This research thesis found that Network Kernel Density Estimation can be a powerful GIS workflow in identifying locations with pedestrian safety needs in urban areas. On a policy level, such data-driven analyses can be implemented to effectively schedule Capital Improvement Programs with an emphasis on making the greatest possible safety impact within a limited budget. As similar examples of this analysis have recently been used in cities like San Francisco, the barrier for more widespread municipal adoption should be relatively low, especially considering that in many instances the necessary data already exists and does not need to be generated by planning or engineering departments. This further satisfies the “low cost, high impact” mantra of many cities in the face of challenging financial times.

Beyond the stated goals and utility of this research, the scale of the pedestrian safety issue was brought to light. In the 52 months of this study period, 1,942 pedestrians were struck by motorized traffic in the City of Seattle. Of these victims, 1,435 were injured and 26 lost their lives. This terrible human cost was borne by one of the statistically safest cities for walkers in the United States(Seattle Department of Transportation 2012a). Considered at a global scale, the sheer number of lives to be saved along our streets should make protecting vulnerable road users a priority for all planners, politicians, engineers, public health officials and the general public. It is my hope that this research thesis and others like it will contribute to live-saving decisions in the future.

## 6.2 Future research and improvements

The Network Kernel Density Estimation tool is an exciting development in the field of urban spatial analysis. With greater access to robust computational GIS, it is becoming possible to understand our network based urban world better than ever before. As the NetKDE approach has only been available since 2006 (Okabe, Okunuki, and Shiode), there remains a wealth of opportunities for research within the field of urban and transportation planning. With respect to traffic safety, a similar analysis for bicycle traffic would be useful in many places.

This analysis could also be improved with respect to its depth and findings. Most obviously, follow up with the identified priority locations should be performed. With a complete picture of what might be contributing to pedestrian collisions, site-specific improvements could be developed with a possible economic analysis included. Finally, an attempt to assess collision rate could be made within downtown Seattle, where some limited pedestrian count information exists.

As this report identified four separate zones in Seattle with a high density of pedestrian collisions, it is perhaps most valuable to consider these sites directly in future research. This GIS analysis is adaptable to accommodate many different scales, and a deeper look at the neighborhood level might reveal specific problem areas within these busy zones. For example, the University District or Downtown could be used as a study area and a focus could be given to identifying safety hazards on an intersection or individual crossing level. Furthermore, as limited pedestrian count information exists within these areas, an attempt at a more accurate assessment of risk exposure could be made. With future growth in Seattle planned to occur primarily within these crucial Hub Urban Villages, pedestrian safety will occupy an increasing important role in planning decisions in the coming decade.

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# 8. Appendix

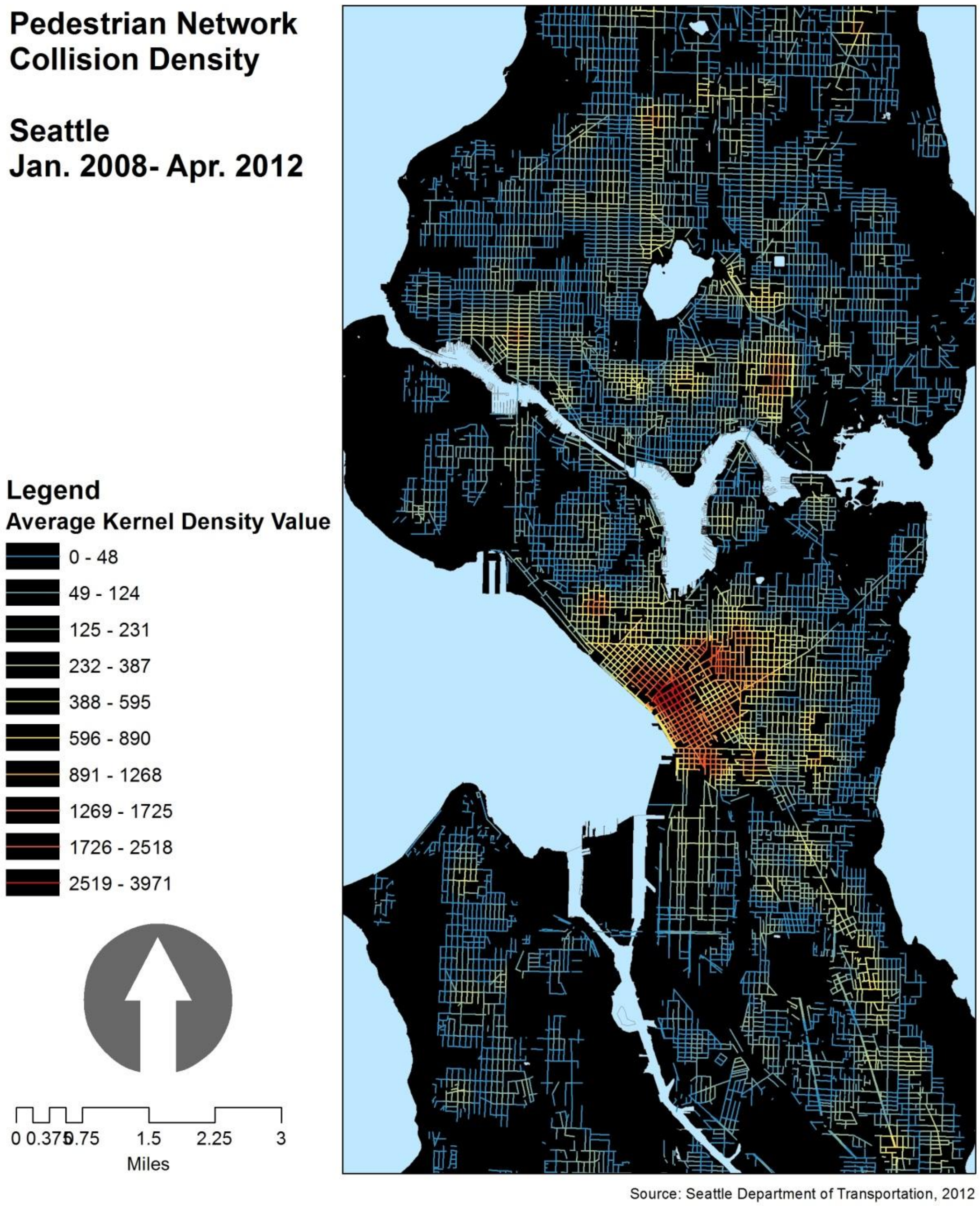



**Figure 12- Planar KDE on Pedestrian Collision Dataset**

## 8.1 Seattle Department of Transportation 2012 Pedestrian Statistics

All of the following data comes from the Seattle Department of Transportation's 2012 City Traffic Report which can be found listed in the bibliography.

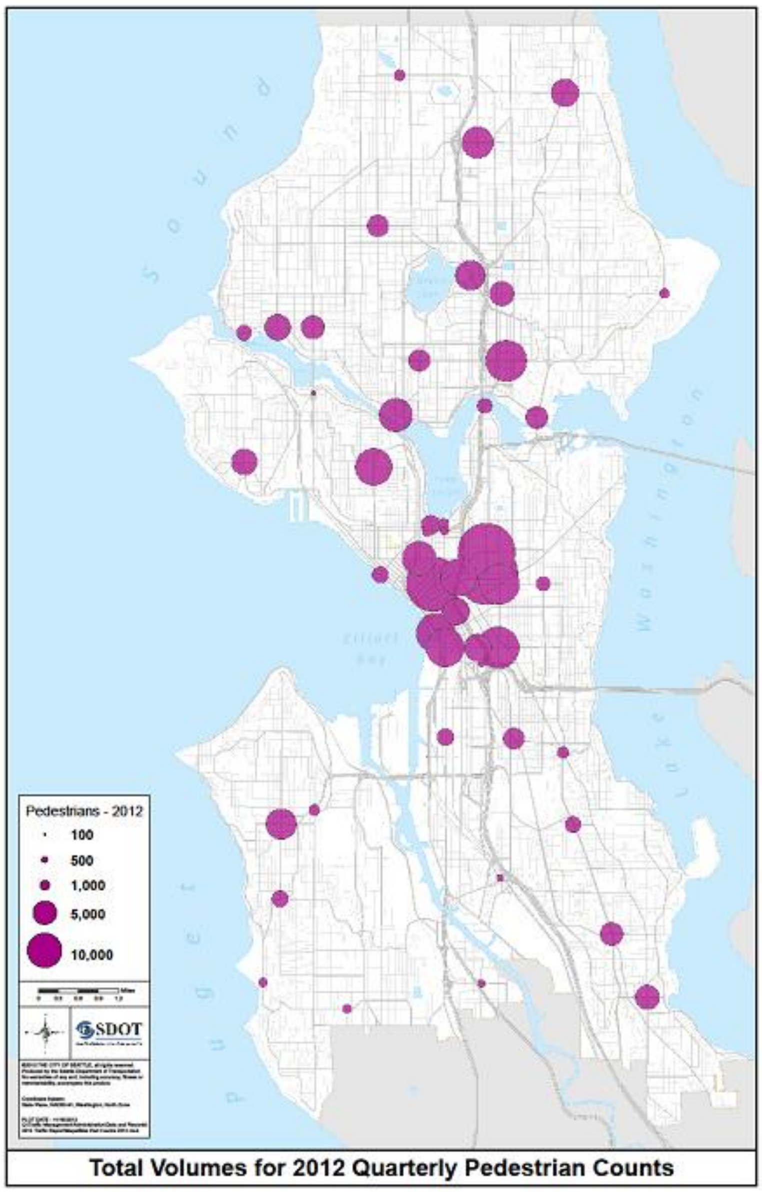
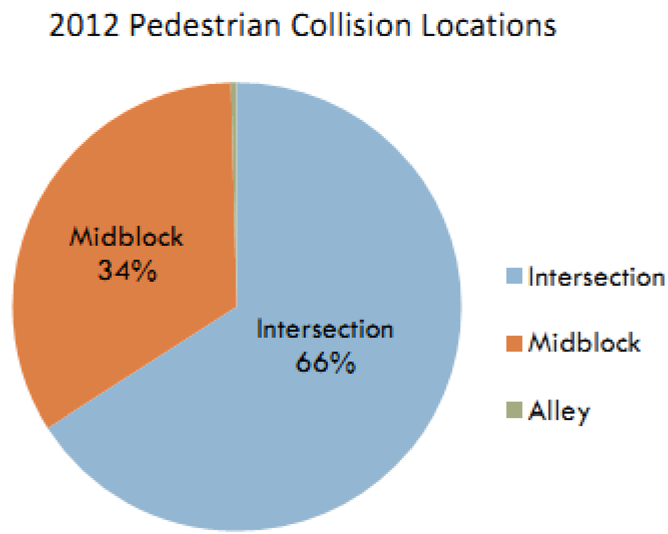



**Figure 13- Single Day Pedestrian Count Locations (SDOT 2012)**




| Collision Location | Count |
|---|---|
| Intersection | 321 |
| Midblock | 164 |
| Alley | 2 |
| **Total** | **487** |

**Figure 14- 2012 Pedestrian Collision Distribution**

**Contributing Circumstances for Drivers in 2012 Pedestrian Collisions**

| Contributing Circumstances | Fatality collision | Serious injury collision | Possible or evident injury collision | Property Damage Only Collision | Total |
|---|---|---|---|---|---|
| Did not Grant Right of Way to Pedestrian | 1 | 29 | 195 | 14 | 239 |
| None | 6 | 23 | 75 | 14 | 118 |
| Other | | 4 | 47 | 3 | 54 |
| Inattention | | 1 | 10 | 2 | 13 |
| Disregard Stop and Go Light | | 2 | 6 | | 8 |
| Improper Backing | | | 5 | 3 | 8 |
| Under the Influence of Alcohol | 1 | 1 | 4 | | 6 |
| Exceeding Reasonable and Safe Speed | | | 3 | 1 | 4 |
| Unknown Driver Distraction | | | 3 | | 3 |
| Disregard Stop Sign/Flashing Red | | | 2 | | 2 |
| Driver Distractions Outside Vehicle | | | 2 | | 2 |
| Exceeding Stated Speed Limit | | | 2 | | 2 |
| Operating Defective Equipment | | | 2 | | 2 |
| Apparently Fatigued | | | 1 | | 1 |
| Apparently Ill | | | 1 | | 1 |
| Did not Grant Right of Way to Vehicle | | | 1 | | 1 |
| Driver Reading or Writing | | | 1 | | 1 |
| Improper Turn | | | 1 | | 1 |
| Improper U-Turn | | | 1 | | 1 |
| Other Driver Distractions Inside Vehicle | | | 1 | | 1 |
| Over Center Line | | | 1 | | 1 |
| **Total** | **8** | **60** | **375** | **37** | **480** |

Not all collisions note contributing circumstances. Some collisions note multiple contributing circumstances.

**Table 3- Contributing Circumstances for Drivers**

| Facility Type | No Injury | Possible Injury | Non Serious Injury | Serious Injury | Fatality | Unknown | Total |
|---|---|---|---|---|---|---|---|
| Marked Cross Walk | 13 | 114 | 94 | 26 | 5 | 5 | 257 |
| Roadway | 6 | 51 | 37 | 19 | 3 | 8 | 124 |
| Unmarked Crosswalk | 4 | 25 | 19 | 10 | | | 58 |
| Sidewalk | 2 | 5 | 5 | 2 | | | 14 |
| Other | | 5 | 2 | 1 | | 1 | 9 |
| Shoulder | | 3 | 5 | | | 2 | 10 |
| Walkway | | 1 | | | | | 1 |
| **Total** | **25** | **204** | **162** | **58** | **8** | **16** | **473** |

Injury Class of Pedestrians Involved in 2012 Collisions by Facility Type

For collisions with State data

**Table 4- Injuries by facility type**

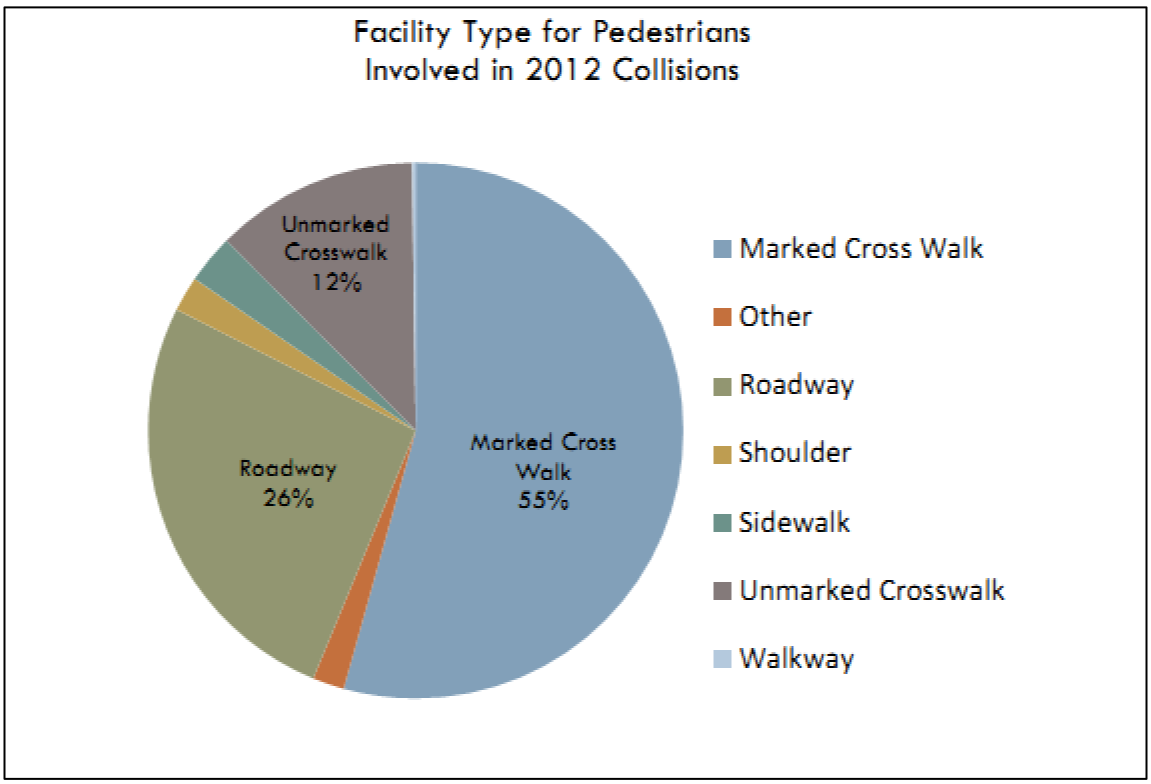



**Figure 15- Facility Type Distribution**

Injury Class of Pedestrians Involved in Collisions in 2012

| Age Group | No Injury | Possible Injury | Non Serious Injury | Serious Injury | Fatality | Unknown | Total | Percent of Total |
|---|---|---|---|---|---|---|---|---|
| 3 to 14 | 2 | 7 | 3 | 2 | 0 | 1 | 15 | 3% |
| 15 to 24 | 5 | 35 | 32 | 12 | 0 | 4 | 88 | 19% |
| 25 to 34 | 5 | 44 | 45 | 11 | 1 | 2 | 108 | 23% |
| 35 to 44 | 3 | 33 | 10 | 7 | 0 | 1 | 54 | 11% |
| 45 to 54 | 2 | 25 | 22 | 13 | 3 | 3 | 68 | 14% |
| 55 to 64 | 3 | 21 | 17 | 4 | 2 | 3 | 50 | 11% |
| 65 and Over | 1 | 16 | 13 | 5 | 2 | 0 | 37 | 8% |
| Missing | 4 | 23 | 20 | 4 | | 2 | 53 | 11% |
| **Total** | **25** | **204** | **162** | **58** | **8** | **16** | **473** | **100%** |

For collisions with State data

**Table 5- Injury Class by Age**

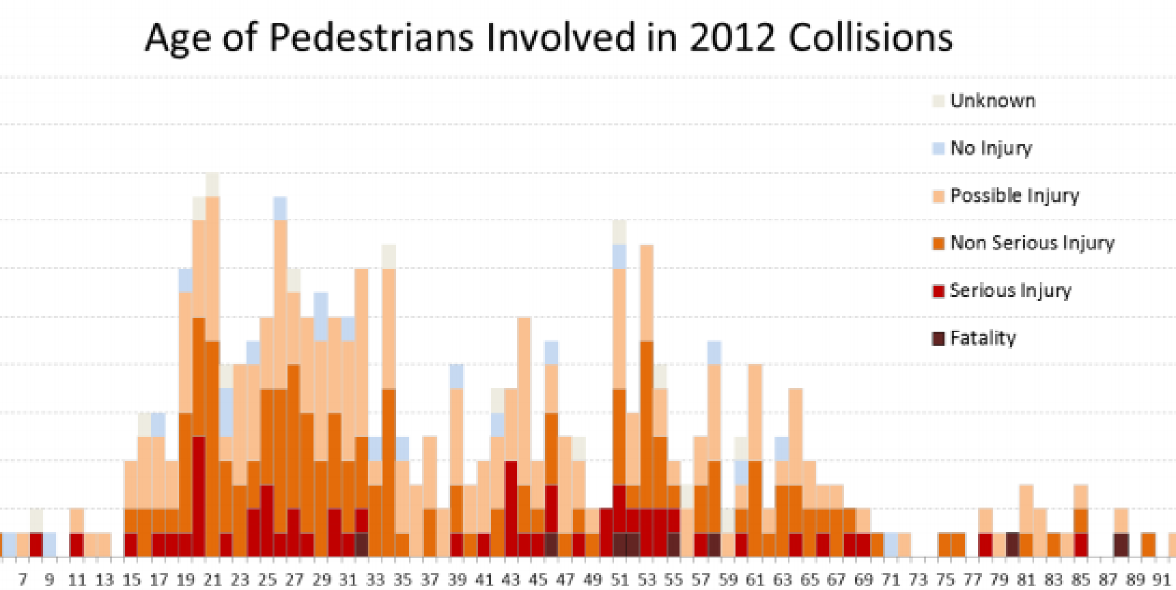



**Figure 16- Age Histogram**

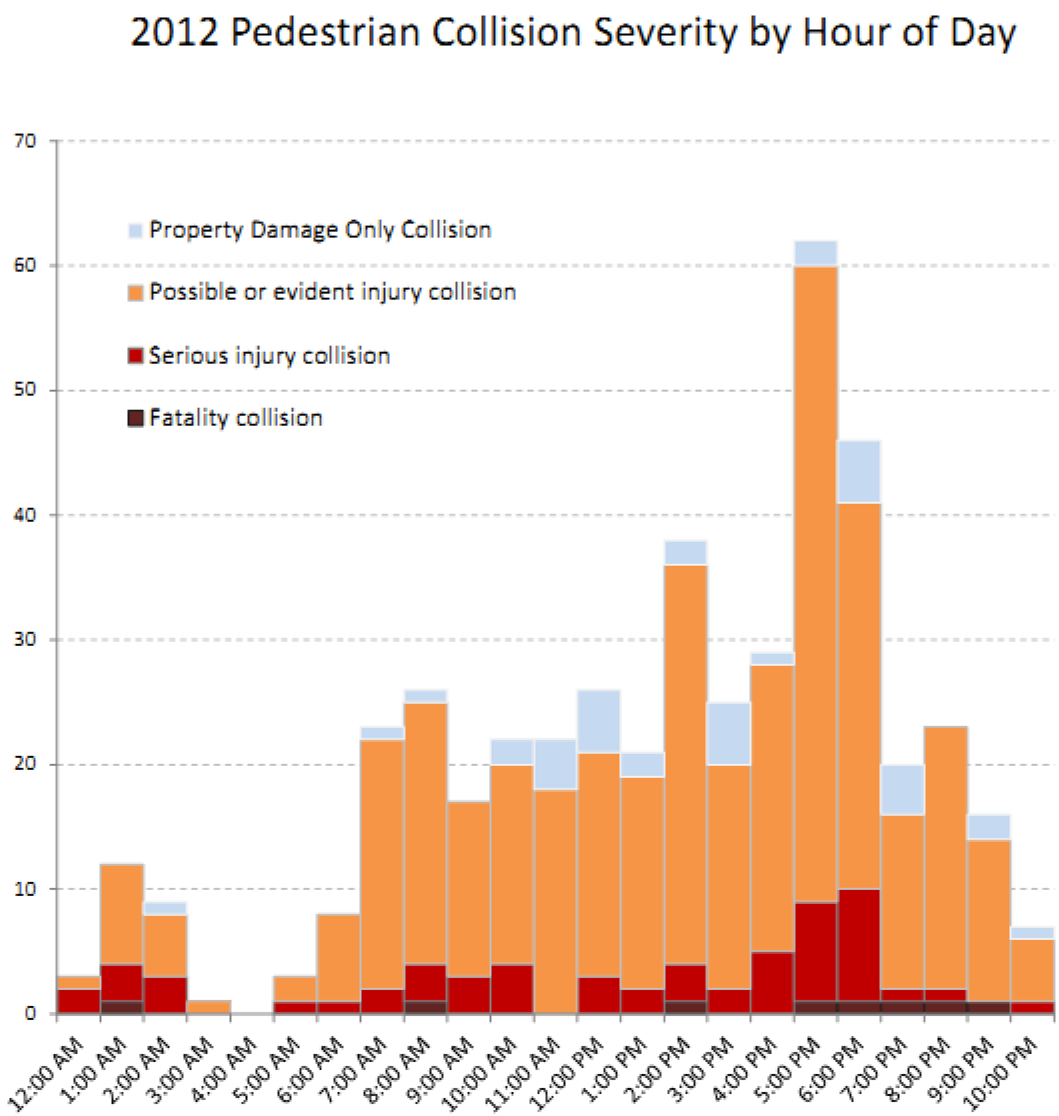



**Figure 17- Hour of Day Histogram**

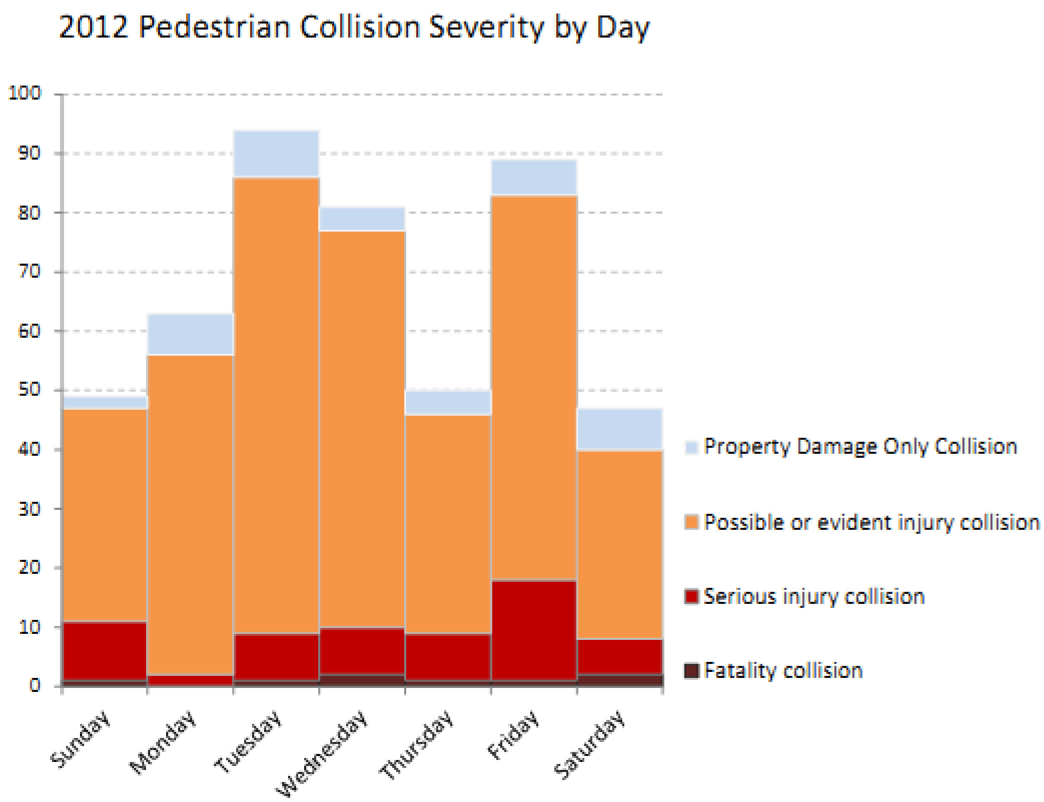



**Figure 18- Day of Week Histogram**

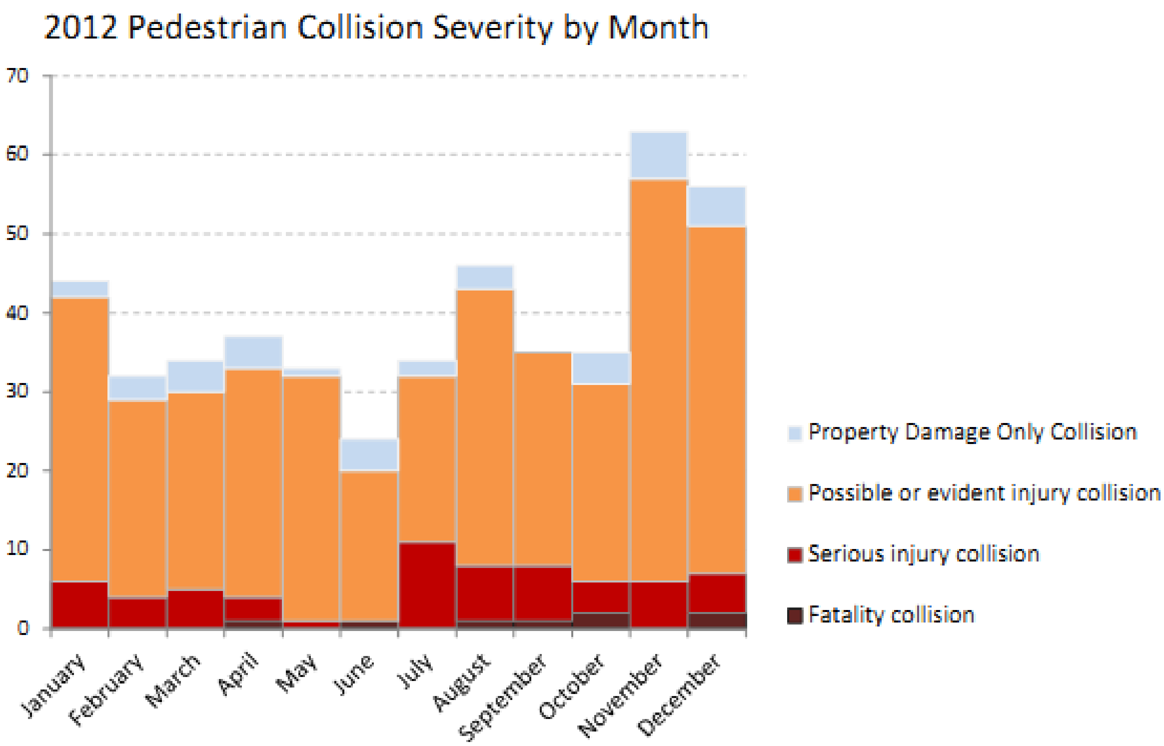



**Figure 19- Month Histogram**

| 2012 Pedestrian Collision Severity by Vehicle Action | Fatality | Serious Injury | Possible or Evident Injury | Property Damage Only | Unknown | Total |
|---|---|---|---|---|---|---|
| Bicycle | | 1 | 12 | | | 13 |
| Entering At Angle | | | 1 | | | 1 |
| Not Stated | | | 1 | | | 1 |
| One Car Entering Parked Position | | | | 1 | | 1 |
| Sideswipe | | 1 | | | | 1 |
| Vehicle Backing Hits Pedestrian | | | 15 | 2 | | 17 |
| Vehicle Going Straight Hits Pedestrian | 6 | 38 | 159 | 18 | | 221 |
| Vehicle Hits Pedestrian - All Other Actions | | 2 | 4 | 1 | | 7 |
| Vehicle Overturned | | | 1 | | | 1 |
| Vehicle Struck Moving Train | 1 | | | | | 1 |
| Vehicle Turning Left Hits Pedestrian | | 14 | 113 | 9 | | 136 |
| Vehicle Turning Right Hits Pedestrian | 1 | 4 | 62 | 7 | | 74 |
| No Data | | | | | 13 | 13 |
| **Total** | **8** | **60** | **368** | **38** | **13** | **487** |

**Table 6- Injury severity by vehicle action**

Injury Class of Pedestrians Involved in 2012 Collisions by Weather

| Weather | No Injury | Possible Injury | Non Serious Injury | Serious Injury | Unknown | Fatality | Total |
|---|---|---|---|---|---|---|---|
| Clear or Partly Cloudy | 19 | 89 | 92 | 34 | 9 | 5 | 248 |
| Overcast | 2 | 30 | 25 | 6 | 2 | | 65 |
| Raining | 4 | 79 | 41 | 17 | 4 | 3 | 148 |
| Sleet/Hail/Freezing Rain | | 1 | | | | | 1 |
| Snowing | | 1 | | | | | 1 |
| Other | | | 1 | | | | 1 |
| Unknown | | 4 | 3 | 1 | 1 | | 9 |
| **Total** | **25** | **204** | **162** | **58** | **16** | **8** | **473** |

For collisions with State data

**Table 7- Injury severity by weather**

| 2012 Pedestrian Collisions by Light Conditions | |
|---|---|
| **Light Condition** | **Total** |
| Daylight | 282 |
| Dark - Street Lights On | 160 |
| Dusk | 14 |
| No Data | 13 |
| Dawn | 7 |
| Unknown | 6 |
| Dark - Street Lights Off | 3 |
| Dark - No Street Lights | 1 |
| Other | 1 |
| **Total** | **487** |

**Table 8- Collisions by light conditions**

| 2012 Pedestrian Collisions by Road Conditions | |
|---|---|
| **Road Condition** | **Total** |
| Dry | 269 |
| Wet | 192 |
| No Data | 13 |
| Unknown | 9 |
| Ice | 2 |
| Snow/Slush | 2 |
| **Total** | **487** |

**Table 9- Collisions by road conditions**

| Injury Class for Pedestrians Involved in 2012 Collisions by Clothing Type | | | | | | | |
|---|---|---|---|---|---|---|---|
| **Clothing** | **No Injury** | **Possible Injury** | **Non Serious Injury** | **Serious Injury** | **Fatality** | **Unknown** | **Total** |
| None Listed | | 1 | | | 2 | | 3 |
| Dark | 9 | 67 | 47 | 18 | 1 | 8 | 150 |
| Light | 2 | 15 | 16 | 2 | | | 35 |
| Mixed | 12 | 119 | 97 | 38 | 5 | 8 | 279 |
| Retro-Reflective | 2 | 2 | 2 | | | | 6 |
| **Total** | **25** | **204** | **162** | **58** | **8** | **16** | **473** |

For collisions with State data

**Table 10- Injury severity by clothing type**