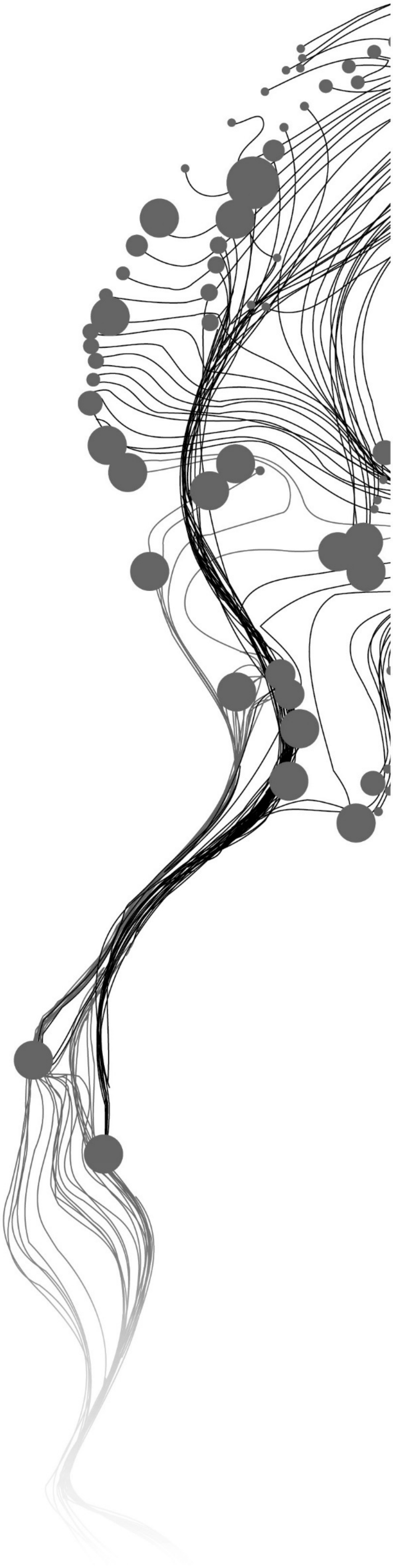
SPATIAL ANALYSIS OF CYCLING ACCIDENTS IN RELATION TO INFRASTRUCTURE DESIGN IN CURITIBA (BRAZIL)

DELIANG GAO
March, 2017

SUPERVISORS:
Dr. A.B. Grigolon (First Supervisor)
Ir. M.J.G. Brussel (Second Supervisor)
Dr. T.M.C. Gadda (Advisor)



SPATIAL ANALYSIS OF CYCLING ACCIDENTS IN RELATION TO INFRASTRUCTURE DESIGN IN CURITIBA (BRAZIL)

DELIANG GAO
Enschede, The Netherlands, March, 2017

Thesis submitted to the Faculty of Geo-Information Science and Earth Observation of the University of Twente in partial fulfilment of the requirements for the degree of Master of Science in Geo-information Science and Earth Observation.
Specialization: Urban Planning and Management

SUPERVISORS:
Dr. A.B. Grigolon (First Supervisor)
Ir. M.J.G. Brussel (Second Supervisor)
Dr. T.M.C. Gadda (Advisor)

THESIS ASSESSMENT BOARD:
Prof.dr. P.Y. Georgiadou (Chair)
Dr. T.M.C. Gadda (External Examiner, Universidade Tecnológica Federal do Paraná)

ABSTRACT

In recent years, cycling accidents in Curitiba has increased. The objectives I am trying to achieve in this thesis are: To analyze the distribution of cycling accidents in Curitiba based on spatial analysis tools; To understand whether cycling safety aspects are linked to cycling infrastructures design characteristics; To identify the gaps between current conditions and standard design guidelines based on the street design aspects.

Spatial analyses of cycling accidents would allow a location analysis and the identification of spatial patterns of cycling accidents. Besides, urban design factors can be assessed with the design guidelines for cycling infrastructure, in order to confirm whether improvements related to safety of cyclists could be realized.

In the first part of analyses in this thesis, number of accidents along the cycling infrastructures and BRT lines were calculated; Number of accidents per neighbourhood derived by spatial joining neighbourhood polygon with cycling accident points; the accident density by area (number per square kilometer), accident density by population (number per 10,000 people), and accident density by road length (number per kilometer) can be calculated. All these processes have been done in ArcGIS. Kernel density estimation can identify the spatial patterns of the cycling accidents. The kernel density estimation for area has been done in ArcGIS. A network based method has been used in SANET. High-density areas of cycling accidents have been identified from the results of this part.

The second part of analyses is cause of accidents detection. A checklist was made to collect street design factors data in high-density areas of cycling accidents in Curitiba. Because of the lack of secondary data, and data collected from the street (primary data) is not much. Qualitative comparison was used to find out the relationship between accidents occurred and street design aspects.

The last part of analyses is about future improvement. Design guidelines from Brazil and other countries were used to do the comparison between cycling infrastructure conditions and guidelines. Gaps can be found from the comparison. Then, the recommendations could be provided to improve the current situations.

The results obtained in this research include: the high-density areas are detected: city center, Sítio Cercado, Avenida Marechal Floriano Peixoto, Portão, Cajuru, and CIC; Street design factors data was collected from some points in high-density areas; The gaps between current conditions in Curitiba and guidelines were identified, etc. Some suggestions of future improvements were given in the last part of the thesis.

One of the impacts of the obtained results is that the result can support the design of new cycling facilities or help the maintenance of the existing facilities to provide a safe environment for cyclists.

ACKNOWLEDGEMENTS

Doing the thesis is not an easy progress. To finish the research needs hard work, besides, helps from other people are essential components. First of all, thanks for the unconditional love and supports from my family.

I sincerely thank the help from my supervisors: Dr. A.B. Grigolon and Ir. M.J.G. Brussel. Thanks to the advisor, data provider and host in Brazil: Dr. T.M.C. Gadda. Thanks to the help of data preparation from B. G. Motta. Thanks to A. Okabe (one of the developers of SANET) for letting me use the software in my thesis for free. The last but not the least, thanks to my friends and colleagues for all the supports and helps.

I am pleasure to be a part of the cooperation between Curitiba and Dutch instructions. Thanks to everyone helped me in the last half year.

The information of that cooperation is: The University of Twente signed a Memorandum of Understanding with 14 parties including the City of Curitiba and four local universities including the public university UFPR. The MoU symbolizes the start of a five-year collaboration consisting of exchange of knowledge and people and joint research projects in order to realize a Smart Curitiba. The MoU offers UT students and researchers a new possibility to work in an international environment on interesting High Tech, Human Touch projects in the field of mobility and innovative city planning. The partners are interested in realizing technological and social innovation in which we combine (civil) engineering technologies with insights from social sciences.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1. INTRODUCTION

1.1. Background and Justification

Cycling is an easy way of transport, especially for poor people. In Rio de Janeiro, for instance, people who live in informal settlements, 57% of all trips are non-motorized (Koch, Lindau, & Nassi, 2013). In addition, the increasing amount of urban cycling makes benefit to the public health (Thomas & De Robertis, 2013), as well as sustainable mobility (Zottis, 2015), making cycling a preferred environmental friendly traffic mode. Shifting the short car trips to cycling can lower the cost more than 80% (from Euro 0.50/km to Euro 0.08/km). And in the future, the difference could be more (Gössling & Choi, 2015).

On the other hand, there are still some barriers to bicycle use: risk exposure to vehicular traffic, streets not conducive to bicycle lanes, lack of traffic control signals at crossings of busy streets (Falcocchio & Levinson, 2015). Also, bicyclists had high rates of both fatal and nonfatal injury in USA (Beck, Dellinger, & O'Neil, 2007). For cyclists in the Netherlands, they had a high risk of being injured (Wegman, Zhang, & Dijkstra, 2012). Dutch governments encouraged people to cycling rather than driving for short trips. However, that change follow by the increased number of serious road injuries (J. P. Schepers & Heinen, 2013). Therefore, it is an essential to improve safety of cyclists. One way to promote cycling safety may be improve cycling infrastructure (bikeways, bike racks, and other trip end facilities) and build up new high quality cycling infrastructure. These efforts can make cycling safer and better for people (Mulvaney et al., 2015).

Curitiba (Brazil) is the capital and largest city of the Brazilian state of Paraná. Curitiba is famous for its Bus Rapid Transit (BRT) system – one of the best bus system in the world (Tschakert, Zimmerer, King, Baum, & Wang, 2016), which plays a big role in making itself a liveable city. Because of its excel performance in sustainable urban development, Curitiba was awarded the Global Sustainable City Award in 2010 (Globe Award, 2010). Specifically, regarding Brazil, the country has never had a comprehensive cycle plan at the national level. Since the 1950s cycling has been associated with sports and leisure activities. In addition, in this scenario, the possession of a car is associated with a high social status, whereas that of a bicycle, often a lower position in society, as a second-class position (Medeiros & Duarte, 2013). Nowadays, the government of Curitiba wants the city to be more sustainable and liveable. One of the solutions for achieving this goal is to extend the bicycle infrastructure to foster the usage of bicycles. By 2015, Curitiba's cycling paths was more than 120km (Welle et al., 2015). And now, Curitiba has a cooperation agreement with Dutch institutions to increase the cycling mobility of the city. The city of Curitiba will invest $90 million to implement hundreds of kilometers of cycling roads by 2016. The target is to increase the integration of the bike to city life through innovative projects in the fields of architecture, urban planning and design, consolidating this mode as a safe and comprehensive mobility option (IGS - University of Twente, 2015).

In recent years, Curitiba is experiencing an increase in the number of fatal and non-fatal accidents involving cyclists. For this reason, the city authorities are analysing the current cycling safety conditions, in order to understand what is lacking and before embarking on new investments. Getting knowledge about the reasons accidents are happening may support on the re-design of existing or on the design of new cycling facilities that are safer for cyclists. For instance, some previous studies found that the design of cycling tracks may decrease the relative risk of cycling-related accidents (Thomas & De Robertis, 2013).

To the best of our knowledge, Curitiba has not yet developed a spatial analysis of cycling accidents, specifically focused on urban design aspects (street design and cycling infrastructure design). However, it is known from the literature that well-designed bicycle facilities, such as physically separated cycling lanes, can lower the risk of accidents involving cyclists (Wegman et al., 2012), and that there is a relationship between accidents severity and urban form (Al-Ghamdi, 2002; Gladhill & Monsere, 2012). Furthermore, it is not certain whether the Brazilian guidelines for cycling infrastructure design (BRASIL, 2007; CET, 2014; CONTRAN, 2007; GEIPOT, 2001) are followed during the design and implementation phases.

Based on the reasons above, a spatial analysis of cycling accidents would allow a location analysis and the identification of spatial patterns. In addition, urban design aspects can be assessed and confronted with the Brazilian guidelines for cycling infrastructure design, in order to confirm whether improvements related to safety could be realized. The results of this research could therefore be useful in future studies on cycling infrastructure planning in Curitiba.

1.2. Research Objectives

The aims of this research is analysing the distribution of cycling accidents in Curitiba based on spatial analysis tools to understand whether cycling safety aspects are linked to cycling infrastructures design characteristics.

In order to understand and solve the research problem, there should be some specific research objectives:

1) Identify the patterns of cycling accidents based on spatial analysis of cycling accidents in city Curitiba;
2) Assessment of the present cycling infrastructure and local street design, which could have influence on the accidents (the selected interesting area will be made by cluster analysis);
3) Identification of gaps between current infrastructure conditions and guidelines for cycling safety design.

1.3. Research Questions

To accomplish these three specific research objectives, research questions are, as follow:

Objective 1: Identify the patterns of cycling accidents based on spatial analysis of cycling accidents in Curitiba.

1) What are the spatial distributions of cycling accidents?

   To understand the spatial distribution of fatal and non-fatal cycling accidents, density analysis could be developed. The high-density areas of cycling accidents would be identified by using kernel density estimation tool based on the spatial data.

Objective 2: Assessment of the present cycling infrastructure and local street design, which could have influence on the accidents.

2) Is there a relationship between urban design and cycling accidents in Curitiba?

   Urban design analysis is about how urban design influences cycling safety. Urban design of cycling infrastructure is therefore an important aspect, not only for improving the safety of existing cycling infrastructure, but also provides insights to urban planning.

   Previous studies suggested that factors such as urban design, human factors, weather conditions, and state of bicycle could be linked to cycling accidents. However, in the present study, the focus will be limited to the urban design aspect, due to lack of data on the other cited factors.

Objective 3: Identification of gaps between current infrastructure conditions and guidelines for cycling safety design.

3) What does the design guidelines have for a safe cycling condition?

   Base on literature review about existing cycling infrastructure guidelines, the standard design for a safe cycling infrastructure conditions will be identified. The most important contents of the guidelines will be figured out, which can be used to guide the future design.

4) Is there a gap between current cycling infrastructure design and the guidelines for cycling infrastructures design in Curitiba?
   The current cycling infrastructure condition of cycling accidents in Curitiba will be assessed in relation to the guidelines. There is a fieldwork to observe the cycling infrastructures quality. The point of fieldwork is whether the cycling infrastructures design followed the guidelines. The analysis was planned on i) the clusters of cycling accidents, and ii) on the main access avenue to the city with its core on the city center, which is known to be dangerous for cyclists.

1.4. Research Design

To achieve the research objectives, the research design of this study will be case study. Because case study is suit to apply theory to new research areas, and that is useful in descriptive or explanatory research (Rowley, 2002). For each specific research objective, there is a corresponding method to do that:

1) To analyze the spatial pattern of cycling accidents, accidents data should be applied. However, the format of accidents data is Excel tables. So, first is the data preprocessing to mapping accident points or segments. And then, doing cluster analysis by applying density calculation tools.
2) To assess the present cycling infrastructure and local street design, urban design factors data should be collected from fieldwork. A checklist will be made for this part of study. During the field work, for each high density of accidents area will be estimated by using checklist.

1.5. Research Matrix

Research design matrix is a method of planning research projects, which uses table to show the research design and what the researcher intends to do in the research (Choguill, 2005). Table 1-1 is the research matrix of this research, with data, methods, and expected results of each research objective and corresponding research questions.

Table 1-1 Research matrix

Research objectives	Research questions	Data	Methods	Expected results
Spatial analysis of cycling accidents in city Curitiba	What are the spatial distributions of cycling accidents?	Cycling accidents records	Mapping accident and density analysis locations in ArcGIS 10.4	Cycling accidents maps, density map of accidents
Assessment of the present cycling infrastructure and local street design	Is there a relation between urban design and cycling accidents in Curitiba?	Literature and urban design guide books	Text analysis	A list of urban design factors (checklist)
Identification of gaps between current infrastructure conditions and guidelines for cycling safety design	What does the design guidelines have for a safe cycling condition?	Cycling lanes design guide books	Literature review	guidelines for cycling safety design
	Is there a gap between current cycling infrastructure design and the guidelines for cycling infrastructures design?	Checklist and photos, urban design guide books	Comparing current conditions with principles in guide book	Identification of improvement.

2. LITERATURE REVIEW

This part is the literature review related to cycling behaviours, cycling safety issue, and previous analyses of cycling accidents worldwide (within recent 30 years). The aims of this literature review are doing an overview of the researches on cycling accidents, analysis of factors on cycling accidents, the characteristics of cycling infrastructure, finding a way to analyse the cycling safety issue in Curitiba and answer the research questions.

Cycling is a kind of physical activity that provides substantial health benefits. In China, commuting by walking and cycling seems to reduce the risk of being overweight by 50% compared to taking public transport (Andegiorgish, Wang, Zhang, Liu, & Zhu, 2012). Nowadays, the role of cycling in big cities is more important. For instance, in Tianjin, China, nearly 78% daily trips are cycling (Peden et al., 2004). Additionally, more and more governments realise the benefits of cycling, policy ways were applied to increase the usage of cycling. Such as, in Singapore, fare card data was used to assess the commuter cycling potential and a data-driven approach was developed to policy making in order to promote the commuter cycling (Kumar, Nguyen, & Teo, 2016).

However, for lots of countries worldwide, cyclists have a relatively high risk compared to car users and pedestrians (Wegman et al., 2012). In Brazil, there are more than 42,291 people killed in traffic accidents every year. Over half of them are vulnerable road users - pedestrians, motorcyclists, and cyclists. The deaths of people per 100k people is 23.4. The deaths of cyclists per 100k people is 0.8 (World Health Organization, 2015).

2.1. Influential Factors on Cycling Safety

There are many factors that influence the cycling accidents, such as, shape of roads, time of day, weather conditions, cyclists characteristics, and traffic facility design (M. Kim, Kim, Oh, & Jun, 2012). Furthermore, there are many natural factors and human behaviour factors that play a role on the rate and severity of cycling accidents. For instance, an analysis of the weather conditions' effect on commuting in northern USA found that the warmer days, absence of wind, rain, and snow promoted bicycle commuting (Flynn, Dana, Sears, & Aultman-Hall, 2012). However, these factors normally are uncontrollable and unpredictable.

Urban design (especially the street design aspect) plays an important role on cycling safety. By implementing well-designed cycling infrastructures, at the city level, the comprehensive planning of bicycle network is necessary for ensuring safe cycling condition. At the street levels, physically segregations of cycling lanes provide a safer condition, because bollards, curbs, or raised tracks can provide buffer to protect the cyclists (Welle, 2015). Furthermore, the design of city traffic lanes also has huge effects on cycling safety, especially for the conditions of intersections. Previous research has proved that improvements on intersections increase the safety of cyclists. Meanwhile, high attention at junctions should be given to differentiate cyclists from motor vehicles, to reduce the risk of turning conflicts. Researchers of "World Resources Institute (WRI) ROSS Center for Sustainable Cities" provided some principles and examples to help planners to improve the traffic safety by optimizing cycling and traffic facilities design (Welle et al., 2015). A research of cyclists' injury severity at unsignalized intersections in Kentucky State, USA suggested that investigating and implementing street lighting could improve bicycle safety; the implementation of traffic calming methods could create a safer traffic environment (C. Wang, Lu, & Lu, 2014). This same study mentioned weather factors as well: worse weather conditions leading to the higher risk of cycling accidents. Furthermore, another study in the Australian Capital region provided an overview of the impact on cycling safety of the riding environment. 39.1% of participants had crashed in traffic, 36.1% on shared paths, 16.8% on footpaths, and 7.9% in cycle lanes. Most accidents (72.8%)

involved vehicle or motor vehicle, while, 18.8% of them with other bicycles, 6.4% with pedestrians, and 2.0% with animals. The finding includes that fewer cyclists were injured in on-road cycle lanes, and a high proportion of injuries were incurred on shared paths (De Rome et al., 2014).

The implementation of design guidelines of cycling infrastructures may define the quality of cycling environment. The environments of safe cycling is not only important for safety promoting interventions, but also for informing cyclists about the route options (Yiannakoulias, Bennet, & Scott, 2012). In order to ensure a high-quality and safe cycling infrastructure, several countries developed design guidelines that are specific to the design of cycling infrastructure. For instance, in Australia, the "Cycling Aspects of Austroads Guides" was published by the peak organisation of Australasian road transport and traffic agencies – Austroads (Austroads, 2014).The WRI ROSS Center for Sustainable Cities published a design guideline that includes examples from several countries about how to promote traffic safety through urban and street design (Welle et al., 2015).

Apart from street design aspects, the speed of automobile is an important factor. Speed of vehicles has huge impact on the walking and cycling safety. Data from German In-Depth Accident Study (GIDAS) was used to study the effect of speed on pedestrian safety. The risk of death at 50km/h was more than twice as high as the risk at 40km/h and more than five times higher than the risk at 30km/h. Lower speed of vehicles, especially lower than 35 km/h can drastically decrease the risk of fatalities (Rosén & Sander, 2009). Maintain lower speeds in urban environments helps make living with pedestrians and cyclists better. The implementation of traffic calming, a set of measures for moderation of motorized traffic is an alternative to the streets serve all, it creates movement safe spaces for non-motorized modes. The practice has already been widely adopted in Germany, the United States, Canada, Belgium, the Netherlands and the United Kingdom. In Brazil, Curitiba implemented the calm way – "Traffic calming" as well. In city center of Curitiba, cars and bicycles share the same space. The speed limit for motor vehicles is 30 km/h (Perkons, 2014).

On the other hand, policies play an influential role in cycling safety issue. For instance, analyses of the Philadelphia metropolitan area, USA showed that there were two general approaches that can promote bicycle transportation. Meanwhile, these can increase the cycling safety level of that area as well. One is a set of policies (essentially short-run policies) geared to making bicycling safer and more convenient; The other set is aimed at reducing the convenience of automobile commuting (long-run policies) which is an 'anti-auto' policy (Noland & Kunreuther, 1995). The bicycle safety helmet legislation in California had positive effect on reducing the risk of brain injuries among bicyclists aged 17 years and under (Lee, Schofer, & Koppelman, 2005).

2.2. Analyses of Cycling Accidents

There are several quantitative researches in the field of cycling safety. In recent years, spatial analysis is a popular way to analyze spatial patterns of cycling accidents (Loidl, Traun, & Wallentin, 2016; Loo & Tsui, 2010). In Salzburg, Austria, a spatial analysis has been done in order to reveal and describe patterns of cycling accidents and dynamics on different scale levels and temporal resolutions (Loidl et al., 2016). In Hong Kong, where cycling is a minor way of traffic, spatial analysis of bicycle crash casualties was done through a comprehensive and systematic analysis of injury-inflicting cycling crashes. They found that cycling safety issue has a clear spatial dimension. The suggestion on development of new cycle tracks and to encourage of cycling must be planned carefully with new infrastructures and policies to ensure the safety of cyclists (Loo & Tsui, 2010). In that research, buffer analysis, chi-square tests, analysis-of-variance and binary logistic regression are used to analyze the circumstances leading to bicycle crashes and conduct an epidemiological study on injury patterns of cyclist casualties.

There are already many ways of representing the geographical variations in the risk of cyclist collisions. These can be classified into four categories: collision frequencies, collisions per capita, collision rates per cyclist, and collision rates per distance travelled (Yiannakoulias et al., 2012).

The black spots or hot spots analysis of traffic accidents is quite different from the black spots of crime, because traffic accidents happened along the traffic network, rather than crime hotspots, which can happen anywhere. In other words, the restriction on spatial data of traffic accidents is more than that of crime. A research of comparing three different spatial techniques for quantifying road accident black spots was done by University of Canterbury. These are: kernel density estimation, network analysis and area wide analysis (Anderson, 2007).

Kernel density estimation is a probability density function. One advantage of kernel density estimation is that it can integrate supplementary data into the whole area (Anderson, 2007). Kernel density estimation was applied in researches of street centrality, because that method can transfer all datasets to one continuous data format (Porta et al., 2009; Rui & Ban, 2014). That was widely applied in crime analysis (Brimicombe, 2004). Afterwards, the applications on other fields have been developed because of the development of computer science, which came to overcome several technical difficulties.

A detection of cycling accident trends was done in Melbourne, Australia. By suing a cycling injury database recorded in 2000 and 2011, a kernel density method was applied. Later, the change of cycling accidents density between 2000 and 2011 was calculated in order to identify the absolute change of cycling accidents density in the whole city area (Lawrence, Stevenson, Oxley, & Logan, 2014). However, traffic accidents always happen on the road network, especially when accidents involved vehicles. A Japanese study developed a method based on kernel density estimation in order to measure a network-based density map of accidents. That can be applied to estimate black spots of traffic accidents based on the road network (Atsuyuki Okabe, Satoh, & Sugihara, 2009). Because most GIS software, such as ArcGIS, do not have a specific tool to run network-based kernel density estimation, these Japanese researchers developed an extension toolbox for ArcGIS (Atsuyuki Okabe, Okunuki, & Shiode, 2006). Furthermore, SANET Standalone 1.0 Beta is available for free since October, 2015 (Atsu Okabe, Okunuki, & SANET Team, 2015) , and was experienced on the present study as being a very useful tool to analyse traffic accidents.

In a study in Vancouver, not only the spatial distribution of accidents was analysed, but also combined with environmental factors (Schuurman, Cinnamon, Crooks, & Hameed, 2009). The hotspots of pedestrian injury were identified and mapped. Then, a network based kernel density estimation was applied to create the density map of accidents. The search distance was chosen as 100 meter, as it proved to be the most appropriate distance for highlighting unique incident locations. After that, the characteristics of the built environment of each hotspot location were examined by a team of researchers. 32 pedestrian injury hotspot locations were identified in the city, nearly 97% of them were happened in the downtown major roads. 21 hotspots (66%) were at intersections. About the environment factors of these hotspots, only a few of them have marked and signalized pedestrian crosswalk and/or complex signage. Over half of hotspots had retail establishments and bars nearby.

Qualitative analysis of traffic accidents can also be done through regression models, to estimate relationships among variables. A study in India analysed the traffic accidents per year and its relationship with intersection parameters. They used regression model to do the prediction of future accidents. The relation they found is that number of intersections, major traffic, unpaved shoulder, speed and turning radius had positive impacts on the accidents happened at the intersections. While, the minor traffic was found to have a negative relation with accidents (Murthy & Rao, 2015). Another study applied a binary logistic regression analysis to identify the relation between accident severity levels and other influential factors which affecting the accidents. There are two models in their research: one for inside urban areas, the other for outside urban areas. The result of that research shown as follow: in the inside urban areas, accident severity was effected by age groups 18-30 and older than 60 years old, time and location of the accident; while, in the outside urban area weather conditions, time of accident, age group older than 60 years old had influence on the accident severity (Theofilatos, Graham, & Yannis, 2012). In Riyadh, the capital of Saudi Arabia, some researchers used logistic regression model to analysis the influence of accident factors on accident severity. They applied two different formulas for fatal and non-fatal accidents.

Design variables and age effect were considered in the logistic model. The results show that location (intersection or non-intersection), running red light, and going wrong way have impacts on the accident severity (Al-Ghamdi, 2002).

A spatial Bayesian modelling approach was used in the research of predicting cycling accident risk in Brussels, Belgium (Vandenbulcke, Thomas, & Int Panis, 2014). The network-based kernel density toolbox provided by SANET v.4 (Atsuyuki Okabe et al., 2009), was estimated for 100 m bandwidth, in order to uncover black spots of cycling accidents. The findings of that research suggested that cycling accidents statistically happened with the presence of on-road tram tracks, bridges without cycling facility, complex intersections, proximity to shopping centres or garages, and busy van and truck traffic. The intersections and parked vehicles are then found to have negative effects on the cycling safety.

Cycling accidents can also be analysed qualitatively. For instance, a study explored how the Netherlands reduced 80% of fatal accidents within 30 years. That achieved by establishing a road hierarchy with large traffic-calmed areas, implementing separated bicycle paths and intersection, etc. (P. Schepers, Twisk, Fishman, Fyhri, & Jensen, 2015). Another study in the Netherlands on video-based behavioural observations provided a better understanding of the behaviour between cyclists of separated two-directional bicycle lanes. They found that wider cycling lanes are more efficient to support busy cycling traffic than narrow lanes, and that in many crossings pedestrians and cyclists could have severe conflicts (Van Der Horst, De Goede, De Hair-Buijssen, & Methorst, 2014). A study in Tokyo made a qualitative assessment of the safety conditions of intersections (Y. Wang & Nihan, 2004).

Based on the revised literature, some conclusions can be drawn. There are many advantages of these analysis methods. For instance, network based kernel density estimation can provide the hotspots distribution of cycling accidents. Regression modelling can identify the relations between environmental factors and accidents severity, if we have enough data to do that.

As for the methods to analyse cycling accidents, it can be concluded as follow: To achieve the first objection (Identify the patterns of cycling accidents based on spatial analysis of cycling accidents in city Curitiba), digitizing of the accident points and kernel density estimation are useful. However, considering about the cycling accidents are located on the road network, thus, network based analysis should be done to get the result.

To achieve the second objection (Assessment of the present cycling infrastructure and local street design, which could have influence on the accidents), a fieldwork is good to obtain the data of street design from high-density areas of accidents. A quantitative way (such as regression model) could give a statistical perspective of the design factors' impact on safety. However, when the number of samples is not enough, a qualitative way (text based analysis) could achieve the goal.

2.3. Design Guidelines for Cycling Infrastructures

Cycling infrastructures define the quality of cycling experience. Because of the realization of that, many cycling infrastructures design guidelines were made for a better and safer cycling environment. For instance, in Australia, a cycling guidelines "Cycling Aspects of Austroads Guides", which for engineers, planners and designers involved in the planning, design and construction of cycling facilities, was published by the peak organisation of Australasian road transport and traffic agencies – Austroads (Austroads, 2014). WRI ROSS Center For Sustainable Cities published a design guideline includes examples to promote traffic safety through urban and street design (Welle et al., 2015). They included all kinds of traffic in and between the cities. Certainly, cycling infrastructure is an important component of the guidelines. There are design guiding ideology and principals inside. On the other hand, there are serval specific cycling infrastructure design guidelines which have detailed design standard and cases in different circumstances (Cambridge Cycling Campaign, 2014; Christchurch City Council, 2013; *Cycling by Design 2010*, 2011).

Some big cities in Brazil, such as São Paulo and Rio de Janeiro, have guidelines on their own. However, Curitiba does not have their own design guidelines. When they do the design and implementation, they followed the guidelines of other cities and the national guidelines (BRASIL, 2007; CET, 2014; CONTRAN, 2007; GEIPOT, 2001). However, these guidelines were made over 10 years, which are kinds of out of date and cannot match the current situation.

The implementation of design guidelines of cycling infrastructures may define the quality of cycling environment. The environments of safe cycling is not only important for safety promoting interventions, but also for informing cyclists about the route options (Yiannakoulias et al., 2012).

To achieve the third objection (Identification of gaps between current infrastructure conditions and guidelines for cycling safety design), guidelines of the city and other places should be used. A comparison analysis could show the difference between the conditions in Curitiba and guidelines. Later, the gaps could be found.

3. METHODOLOGY

3.1. Study Area - City Curitiba

The study area of this research is Curitiba, Brazil. Because of some daring policy initiatives taken in the early 1970s, such as creating more pedestrian areas in downtown, introducing a BRT system, encouraging sustainable urban design, today, Curitiba is considered to be one of the most efficient Brazilian cities (Lonelyplanet, 2016).

At the beginning of the 20th century, Curitiba benefited from the wealth of the mills. Later the monoculture of coffee made an evident impact on the economy. In 1970s, Curitiba's Master Plan brought economic changes, with the creation of the Industrial City of Curitiba, in a sparsely populated and humid area in the western part of the city (Prefeitura Municipal de Curitiba, 2013). During the last 50 years, Curitiba metropolitan area has achieved a huge growing. The population was about 400,000 by 1965 (Rabinovitch & Hoehn, 1995). After a rapid population growth, the estimate population is around 1,893,997 by July 1st, 2016 (IBGE, 2016). However, unlike other cities, the repaid growth of Curitiba did not cause problems of quality of life and the quality of transportation. In 1965, Curitiba Research and Urban Planning Institute (IPPUC) was founded, whose job is about implementation of the city master plan. Later, the successful association of land use and streets hierarchy made the city's transport system became famous (Miranda & Rodrigues da Silva, 2012). The benefits of growth obtained by the sustainable planning and advanced public transportation system, which helped the government to control and guide the direction of city expansion (Rabinovitch & Hoehn, 1995). Curitiba has long garnered praise for being one of the world's best models of sustainable urban planning. The government of Curitiba will make large invest on cycling infrastructure construction that will encourage more people to use bicycle to make the city more sustainable.

From 1970s, plenty of cycling infrastructures were implemented in the city. Six types of cycling infrastructures are found (illustrated in Figure 3-1):

- Ciclorrota (shared with cars),
- Ciclovia and Ciclovia_Oficial (segregated cycling lanes),
- Via Calma (traffic calming zone), and
- Passeio Compartilhado (shared with pedestrians)
- Ciclofaixa (on street painted)
- Vias de tráfego geral (roads for motorized transport, with sidewalk only)

Figure 3-2 shows the spatial location of these six types of infrastructure and BRT lines. It is noticeable that the majority of the cycling infrastructure is made up of Ciclovia and Ciclovia_Oficial (segregated cycling lanes). On the contrary, Ciclorrota (shared with cars) is underrepresented, being present only in parts of the city center and in the industrial area. Most BRT lines are from the city center to suburb areas. There are five directions: northeast, northwest, southwest, south, and southeast. Around the city center, BRT lines have overlap with Ciclovia and Ciclovia_Oficial (segregated cycling lanes), Ciclofaixa (on street painted). For the northwest and southwest directions, there is not bike path.

Figure 3-1 Types of cycling lanes

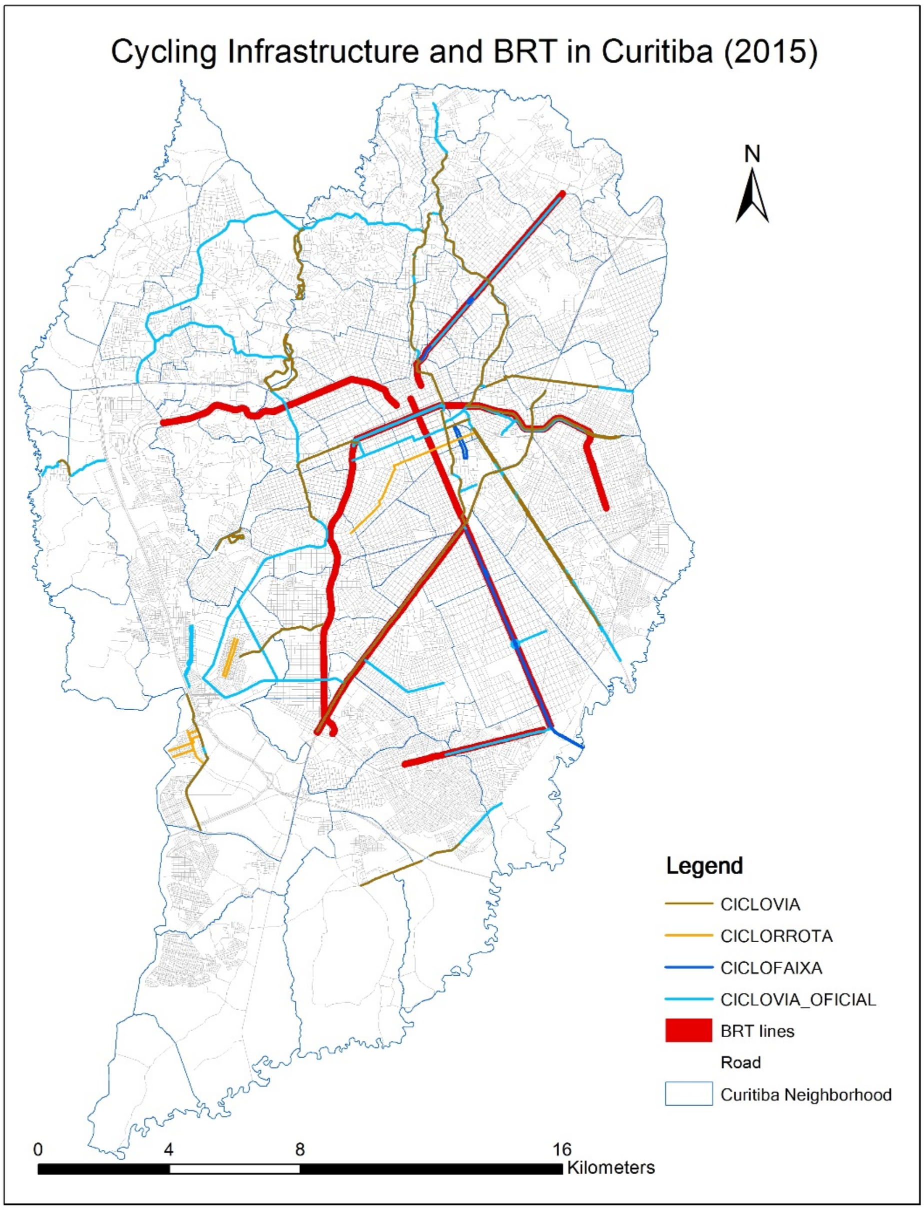


Figure 3-2 Distribution of cycling lanes and BRT lines

3.2. Data Description

The main data for this research are records of cycling accidents in Curitiba between 2013 and 2015. This period was selected because urban design factors were assumed not to change substantially over these three years. Database of cycling accidents was provided by Professor Tatiana Gadda (from Universidade Tecnológica Federal do Paraná, UTFPR) and acquired from local institutions (SAMU, SIATE, and SETRAN, which are the respectively the emergency medical service, the fire brigade, and the municipal traffic office). The following attributes of accidents are recorded: date time, neighbourhood, location, reference point, gender, traffic mode(s) involved and accident severity (3 non-fatal levels and 1 fatal level: 1-3 are non-fatal, and 4 is fatal).

The original data is text-based, there is, accidents were recorded in a spreadsheet. However, issues about data quality were found. Because the information about the accidents were recorded in a tabular form, apart from missing information on attributes of the dataset, 14 records do not indicate the specific location of the accident. The dataset contains 1216 registers in total, however, 99% were complete records, whereas 7% of the records did not contain the exact location. For that reason, these data cannot be used in this research. Because one of this research's aims are analysis the distribution of cycling accidents. However, that data without specific locations cannot be located on the map. Therefore, the rest part of this research is based on the situation that total number of accidents is 1203.

It is important to mention that any details of the data records will not be shown in the thesis, in order to protect the privacy of victims. For data collected in fieldwork, the exact address will not be shown in photos. So, that will not give the related information of accidents directly. All the measures mentioned above are for personal private issue, and also about data privacy.

For the street design analysis part, data was collected from the fieldwork. The aim of the fieldwork were: 1) to collect urban design data from spatially identified high-density areas of cycling accidents; and 2) carry out interviews with local professionals in order to better understand the current situation of cycling infrastructure design and to what extend the cycling accidents are related to certain urban design aspects. A checklist was produced to guide the fieldwork. For all cycling accidents in high-density areas, the same factors were investigated. The aspects of street design were collected for each fatal accident locations, leading to 55 visited locations during fieldwork. For all points, using same factors to check the safety level of each accident location Also, street design information was recorded by photos. Table 3-1 is a brief description of data that used in this research.

Open street map will be used as a base map of Curitiba. That will be used to digitize the road network and mapping accident locations. (Map data copyrighted OpenStreetMap contributors and available from http://www.openstreetmap.org) (OpenStreetMap contributors, 2015).

Table 3-1 Data description of the research

Name	Format	Origin
Accidents data (with specific locations)	Text records	SAMU, SIATE , and SETRAN
Accidents data (without specific locations)	Text records	SAMU, SIATE , and SETRAN
Street design records	Pictures	From fieldwork
Street design factors	Checklist	From fieldwork
Digital map of Curitiba	City map (Vector)	Open Street Map (OSM)

3.2.1. Cycling accident records

The records of cycling accidents are from SAMU and SIATE (first aid organizations). The excel files were provided by Professor Tatiana Gadda. Most records from the datasets have attributes, for instance, time, location, traffic mode involved, and severity level. However, some records do not have specific location or severity level. These data cannot be applied to do the regression analysis due to the missing of severity level attribute. All the data with locations where they happened were in ArcGIS 10.4 (with the help of Bruno Guasti Motta - MSc student from University of Twente), in order to have the shape files of cycling accidents which can be used to do the spatial analysis.

3.2.2. Street design factors

Data of street design factors is needed for the cause of accidents analyses. Therefore, checklists (Table 3-2 and Table 3-3) were produced to collect street design factors for bicycle network and road network respectly. That checklists were used in high-density areas during the fieldwork. There are two main groups in the checklist: bicycle network (Table 3-2) and road network (Table 3-3). Type of lanes, traffic signals, intersections, and speed limitation are important components. The checklist also includes factors of traffic modes, number of lanes, directions, surface material and condition, and how to pass the bus stop.

These factors were selected based on the elements of bicycle infrastructure design in design guidelines: "Making Space for Cycling: A guide for new developments and street renewals" and "Cities safer by design: guidance and examples to promote traffic safety through urban and street design" (Cambridge Cycling Campaign, 2014; Welle et al., 2015). In "Cities safer by design", different types of bicycle infrastructures, bicycle safety at intersections, bike safety at bus stops, and bicycle signals are mentioned as essential elements of bicycle infrastructure design. So that, type of lanes, traffic signals, intersections, and how to pass the bus stop were selected. The previous researches proved the speed of vehicles has relationship with accidents severity (Perkons, 2014; Rosén & Sander, 2009). Other factors were selected based on experience and common sense, such as, traffic modes, number of lanes, surface material and condition.

For each variable in Table 3-2, below is the explanation and hypothesis of these factors:

1) Type of cycling lanes includes almost all common type used nowadays. There are seven types of cycling lanes (shown in Figure 3-1): Ciclovia, Ciclofaixa, Via Calma, Passeio Compartilhado, Ciclorrota, Vias do Tráfego Geral, and Passeio de Pedestres (Prefeitura Municipal de Curitiba, 2015). Here in the checklist, all cycling lanes are reclassified as: Segregated cycling lane (Ciclovia), bike box at the intersections (most appear in the Via Calma), on street painted cycling lanes (Ciclofaixa), shared with pedestrians (Passeio Compartilhado Ciclorrota), and shared with cars (Vias do Tráfego Geral, and Passeio de Pedestres).
2) Surface material includes common materials such as asphalt, bricks, and others. This variable is same in bicycle and road network. Suitable material for cycling or vehicles will provide a high possibility for safe traffic.
3) Surface condition shows how good the surface of cycling lane or road is. Some roads have good conditions with well painted and flat surface; some others have problems of the surface, like not flat surface even with holes, which could be one of the causes of cycling accidents.
4) Traffic signal is an important aspect of traffic safety, especially at junctions. A good visibility of traffic signals and signs has a positive effect on the safety issues.
5) The presence of obstacles can increase the rate of accidents happened. Trees, wheelie bins, utility boxes, or lighting poles may appear in the middle of shared with pedestrians cycling lanes; car parking may be along the shared with cars cycling lanes.
6) Wider cycling lanes can provide more space for cycling that is good for cyclists. In Curitiba, there is a recommend that cars should give cyclists 1.5 meters of space when overtaking.

Table 3-2 Street design checklist for bicycle network

Point： ☐ (Intersection):		☐ (Street):
Date collected:		Time collected:
Group	**Variable**	**Attributes**
Bicycle Network	Type of lanes	☐ Segregated ☐ Bike box ☐ On street painted ☐ Shared with pedestrians ☐ Shared with cars
	Surface material	☐ Asphalt ☐ Bricks ☐ Cement ☐ Stone

		☐ Other:
	Surface condition	☐ Good ☐ Not painted ☐ With holes ☐ Other:
	Traffic signals	☐ Present, which: ☐ Visible <20m ☐ Visible >20m ☐ No signals present
	Obstacles	☐ No obstacles ☐ Car parking Width of parking lanes: ___m ☐ Trees, wheelie bins, utility boxes, or lighting poles ☐ Other:
	Width of cycling lane	________m
Interaction Bicycle and Public Transport	The way of cycling through bus stops/ lanes	☐ Bus stop bypass ☐ Shared bus/bike lanes of normal or minimum width ☐ Shared bus/bike in a wide curb side lane ☐ Separated on-road bicycle lane ☐ Separate off-road bicycle path ☐ No bus stop

Below is the explanation and hypothesis of variable in Table 3-3:

7) Speed of one-way road may be higher than two-way road. So that, direction of vehicle lanes can partly influent the safety. Two-way roads may be safer than one-way roads with other similar conditions.
8) But, if there is a median in the middle of two-way road, which makes the road quite like two separate one-way roads. That can make vehicles faster and more dangerous for cyclists.
9) The more number of lanes means the busier road, which can make effects on the traffic dangerous. Generally, more lanes links to higher speed. That makes the road more dangerous than less lanes.
10) Speed limitation plays an important role in traffic safety issues. The probability of a crash has relationship with the speed. The higher the speed of a vehicle, the higher probability to have a crash involving an injury or fatal accident (Peden et al., 2004).
11) Type of road, similar with hierarchy, can define the grade of road, also determine the speed and number of lanes. That can cover major part of traffic safety issue.

Table 3-3 Street design checklist for road network

Point: ☐ (Intersection): ☐ (Street):
Date collected: Time collected:

Group	Variable	Attributes
Road Network	Direction of lanes	☐ One-way traffic ☐ Two-way traffic
	Number of lanes	_____
	Surface material	☐ Asphalt ☐ Bricks ☐ Cement ☐ Stone ☐ Other:

Surface condition	☐ Good ☐ Not painted ☐ With holes ☐ Other:
Traffic signals	☐ Present, which: ☐ Visible <50m ☐ Visible >50m ☐ No signals present
Type of traffic modes	☐ Bicycle ☐ Motorcycle ☐ Car ☐ Bus ☐ Truck
Speed limitation	_____km/h
Type of road	☐ Highway ☐ "structural corridors" ☐ Main road ☐ Local street
Presence of median	☐ Yes ☐ No

Spatial analysis was developed to identify the areas with the highest density of cycling accidents. The high-density areas of cycling accidents were chosen from the maps. These areas are city center, industrial district, Sítio Cercado, and Avenida Marechal Floriano Peixoto. Data of street design factors of 55 points have been collected from the fieldwork in Curitiba (8 of them do not have data of severity level, so, 47 points are useful). These 47 points' data used to identify the relationship between street design factors and accidents.

3.2.3. Digital Maps of Curitiba

The analysis of accidents' pattern needs data of accident points spatially distributed. However, the records of cycling accidents were recorded in a tabular form. Therefore, digital maps are needed for the digitizing of cycling accident points. In this research, Open Street Map (OSM) data was used to be the reference of cycling accident locations. The digitizing of cycling accident points has been done in ArcGIS 10.4.

3.3. Methods

There are two main parts of this research: spatial analysis of cycling accidents and causes analysis of cycling accidents. Both quantitative and qualitative methods will be used to frame this study.

3.3.1. Spatial Analysis of Cycling Accidents

In the first part, spatial analysis, data of cycling accidents record will be used. In the records of cycling accident data, there are four different categories of severities. For each severity level, the cost is different. Based on the cost of different severity of injurious, they can be weighted as Table 3-4. The data in that table is derived from previous research in Curitiba. In that table, the relative cost means that compare to the slightest accident, how much times of the cost for each severity level. These weights could be used in the analysis which considering about the impacts of different severity level.

Table 3-4 Weighted severity

Severity level	Relative cost	Weight
Code 1 - Small clinical expression	2	0.2
Code 2 - Injuries considered serious without risk to life	3	0.3
Code 3 - Injuries considered serious with risk to life	11	1.1
Code 4 – Death	44	4.4

Quantitative spatial methods will also be used. Before the spatial analysis, data exploration had been done to have an overview of the distribution of cycling accidents from 2013 to 2015. Besides that, in

ArcGIS, number of accidents per neighbourhood can be derived by spatial joining neighbourhood polygon with cycling accident points. After that step, the accident density by area (number per square kilometer), accident density by population (number per 10,000 people), and accident density by road length (number per kilometer) can be calculated.

Referring to previous research in Salzburg (Loidl et al., 2016), cluster analysis and kernel density tools were applied by the software ArcGIS 10.4 to explorer accidents points, to obtain spatial patterns of fatal and nonfatal accidents in Curitiba from 2013 to 2015. This analysis allowed the identification of areas with a high density of accidents. These areas were used in the next part of study (data collection in the fieldwork). However, because of that the spatial analysis is about cycling accidents, a network based method should be used. SANET was used in this part, based on the previous research (Atsuyuki Okabe et al., 2009). The network data is from Open Street Map.

3.3.2. Street Design Factors and Cause of Accidents

In the second part, causes identification analysis, the objective is to find the reasons why cycling accidents happened especially focus on the street design factors. There are many factors that should be considered. For instance, weather conditions, road surface condition, human behavior, and bicycle status; Street design factor plays a big role on cycling safety; Many researches of relations between urban design aspects and cycling accidents were based on qualitative and quantitative approaches (Flynn et al., 2012; J. K. Kim, Kim, Ulfarsson, & Porrello, 2007; Strauss, Miranda-Moreno, & Morency, 2013; Theofilatos et al., 2012; C. Wang et al., 2014; Yan, Ma, Huang, Abdel-Aty, & Wu, 2011). But because of the limited data, qualitative data has been applied in analysis. A checklist was made for collecting primary data.

Based on the data and photos collected from fieldwork, a comparison between current street design of cycling infrastructure and design guidelines would judge whether the implementation followed the standard; and figure out the gaps between current cycling conditions and model conditions. The qualitative analysis has four parts: for major roads (highways), primary and secondary streets, local streets, and cycling parking. For these parts related to the cycling lanes, there are two sub parts: intersections and segments. At the intersections, traffic signal, coloured pavement, markings, bike boxes, and simultaneous green phases for cyclists may be the elements for safer traffic. Bicycle safety at bus stops is another issue. Design for this part should consider about both cyclists and pedestrians (Welle et al., 2015). Also, in this part, there will be specific analysis of accidents. The severity and traffic modes will be considered. So, for this part, there will be analysis of how urban design factors affect cycling accidents of different severity levels and traffic modes.

3.3.3. Design Guidelines Analysis

In the third part, cycling infrastructure design guidelines were used to check whether the cycling infrastructure design followed the guidelines; and find out the gaps between current condition and safe situation. The design of the bicycle infrastructures is divided into three parts in "Making Space for Cycling: A guide for new developments and street renewals": major roads between urban areas, primary and secondary streets, and local streets (Cambridge Cycling Campaign, 2014). These three parts and bicycle parking were evaluated respectively in this research. In each part, data and pictures collected from fieldwork are the representatives of current situation in Curitiba. Design guidelines from Brazil was used to examine whether the implementation followed the guidelines or not. And guidelines from other cycling friendly countries were used to discover the possible improvements.

3.3.4. Future Improvement

The last part is about identification of potential improvement of cycling safety. Because of the excellent design of cycling infrastructure in developed countries, a comparison between cycling infrastructure conditions and guidelines from these cycling friendly countries has been done in this part of analysis. That should base on results of the last part, some planning guide books, for instance, Dutch design manual for bicycle traffic (CROW, 2006), Cities Safer By Design from World Resources Institute (Welle et al., 2015), Cycling Aspects of Austroads Guides (Austroads, 2014), Making Space for Cycling: A guide for new developments and street renewals (Cambridge Cycling Campaign, 2014), Christchurch Cycle Design Guidelines (Christchurch City Council, 2013), and professional knowledge and logical argumentation.

3.4. Flowchart

Figure 3-3 is the flowchart of this research. There are five components of this research: 1) data collection and preparation; 2) spatial pattern analysis of cycling accidents; 3) identify the causes of cycling accidents; 4) comparison between current conditions of cycling infrastructures and standard design guidelines; 5) future suggestions for the improvements based on the design guidelines.

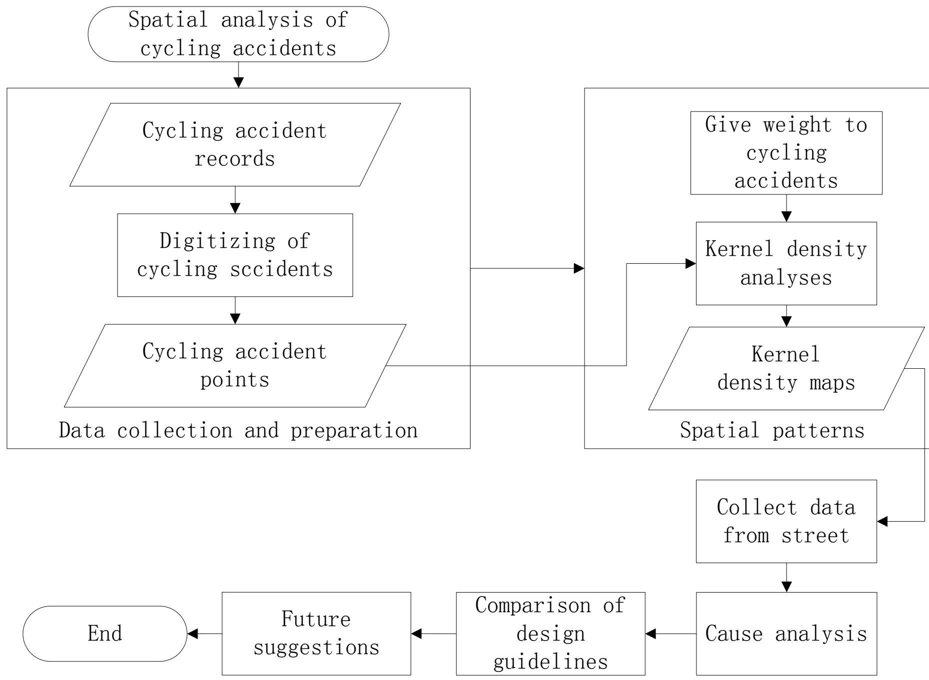


Figure 3-3 Flowchart

4. RESULTS AND DISCUSSIONS

4.1. Descriptive Analysis of Cycling Accidents

Table 4-1 is the description of cycling accidents dataset. Based on the combined information from years 2013, 2014 and 2015, around 3% of accidents were fatal (44). The majority of victims were males (86%). When considering the distribution of accidents in time. There are three categories: morning, afternoon, and evening & night. Nearly two third accidents happened in the day time (61%). The number of accidents in the afternoon is around 1.5 times of that in the morning. The number of fatal accidents is evenly distributed among these three times. All fatal accidents involved motor vehicles. Cars and trucks caused 78% of fatal accidents. The main cause of non-fatal accidents is cars (69%). Conflicts between cars and bicycles is the main cause of the cycling accidents for both fatal and non-fatal accidents.

Table 4-1 Description of cycling accidents dataset

Category		Fatal	Non-fatal
Year	2013	16 1.33%	403 33.50%
	2014	11 0.91%	433 35.99%
	2015	17 1.41%	323 26.85%
Gender	Male	40 3.33%	999 83.04%
	Female	4 0.33%	158 13.13%
Time	Morning	12 1.00%	284 23.61%
	Afternoon	9 0.75%	432 35.91%
	Evening & night	16 1.33%	420 34.91%
Traffic modes	Bicycle fall	0 0.00%	16 1.33%
	Bus & bicycle	4 0.33%	80 6.65%
	Motorcycle & bicycle	1 0.08%	170 14.13%
	Truck & bicycle	12 1.00%	48 3.99%
	Bicycle & bicycle	0 0.00%	20 1.66%
	Rail & bicycle	0 0.00%	2 0.17%
	Car & bicycle	20 1.66%	826 68.66%

Figure 4-1 illustrates the distribution of cycling accidents from 2013 to 2015 which are classified by two different severities: non-fatal – severity code 1 to 3, and fatal – severity code 4. All the cycling accidents happened along the road network. The distribution of very severe accidents (fatal accidents) are mostly located in suburb areas, but not much in the city center. Meanwhile, the high-density area of all accidents seems like is the city center, although the severities of them are not that high (mainly nonfatal accidents). In addition, most fatal accidents happened in the normal road, rather than the cycling lanes. The hypotheses here may be that the appearance of cycling accidents has relations with the population density and the demand of traffic. Because the city center is high population density and highly of traffic area of the city. Besides that, a possible situation that may be the cycling infrastructures can reduce the risk of cycling accidents.

In order to identify the relationships between cycling accidents and cycling infrastructures and BRT, the analysis of overlap of cycling lanes and BRT lines has been done. The result is shown in Table 4-2. Because of the overlap of some types of cycling lanes, the sum of each percentage is more than 100%.

Table 4-2 Cycling infrastructures along the BRT

Type of cycling infrastructure	Length (km)	Percentage (%)
Ciclovia	13.9	17.1
Ciclorrota	0	0
Ciclofaixa	13.7	16.8
Ciclovia_Oficial	46.8	57.5
Cycling infrastructure not present	34.6	42.5

10-meter buffers of each cycling infrastructure, BRT, and road network were applied to derive the number of accidents along each lane. Because the traffic calming area was built in the end of 2015. After the construction, there was not any accident happened over there. So, that type of cycling infrastructure was not considered in this part. Table 4-3 shows the result of that statistic. The accidents happened along Ciclovia_Oficial (0.11 per km) is nearly as twice as accidents along Ciclofaixa (0.06 per km) or BRT (0.07 per km). However, accidents along Ciclorrota (0.09 per km) and Ciclovia (0.08 per km) are just lower than the result of Ciclovia_Oficial. The number per km of accidents happened along the road network without cycling infrastructures was 0.26, which are more than twice of that along any type of cycling lanes. That can be one evidence that cycling lanes can provide safe environment to cyclists and reduce the risk of accidents effectively.

Table 4-3 Cycling accidents along the cycling lanes and BRT

Type of roads	Total number of accidents	Number of fatal accidents	Number of non-fatal accidents	Length of cycling lanes (km)	Density of all accidents (number per km)
Ciclorrota	1	0	1	11.0	0.09
Ciclovia	7	0	7	83.8	0.08
Ciclovia_Oficial	20	1	19	184.8	0.11
Ciclofaixa	1	0	1	18.2	0.06
BRT	6	1	5	81.4	0.07
Roads	1182	43	1139	4464.2	0.26
Total network	1203	44	1159	4685.4	0.26

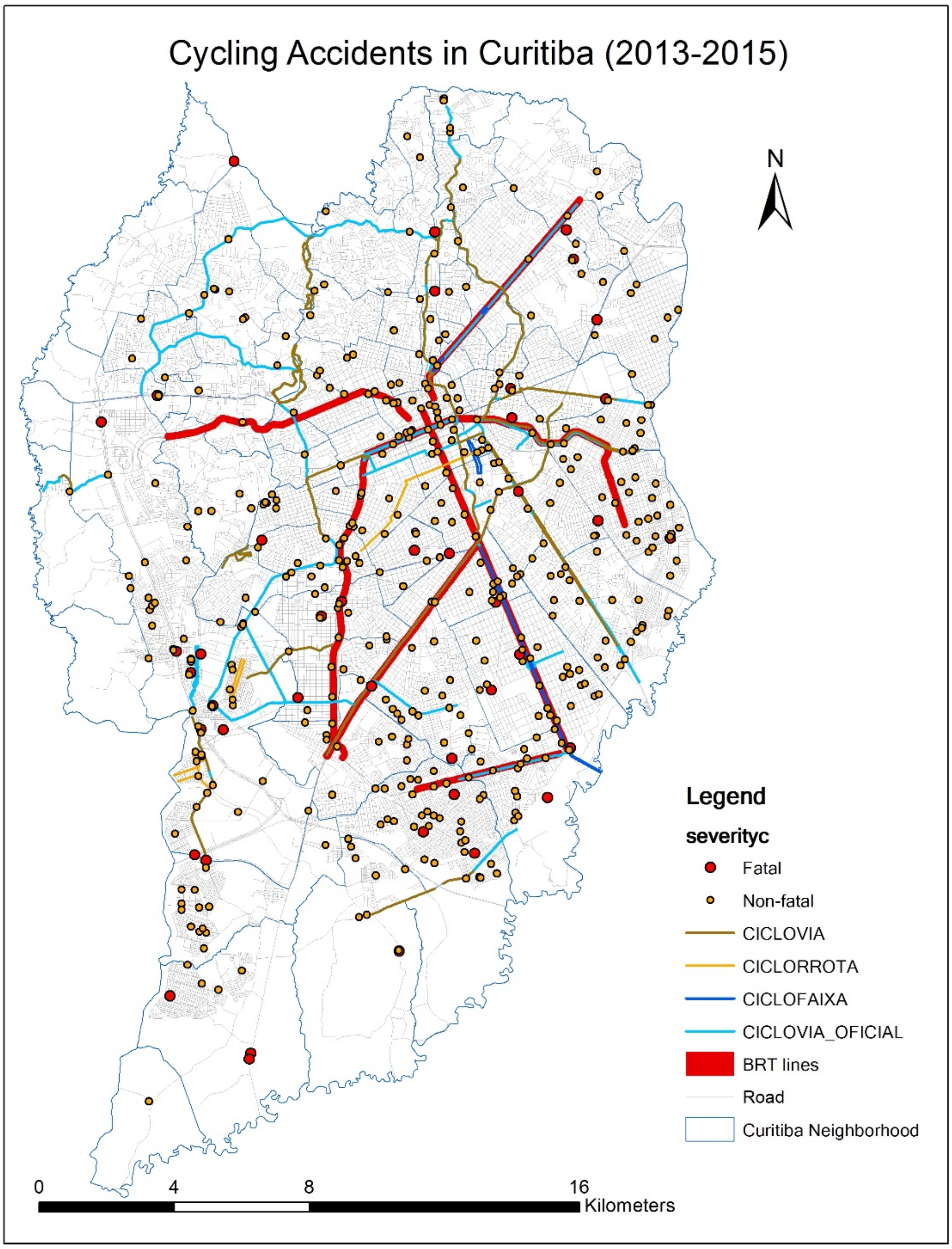


Figure 4-1 Distribution of cycling accidents (2013 - 2015)

4.2. Spatial Patterns of Cycling Accidents

4.2.1. Density of Cycling Accidents by Neighbourhood

Figure 4-2, Figure 4-3 and Figure 4-4 are the accident density maps (number of accidents per square kilometer, number of accidents per 10,000 people, number of accidents per kilometer). Figure 4-2 shows the density of cycling accidents per area. The value of each neighbourhood was calculated by the number of cycling accidents divided by the area of each neighbourhood. The unit of that value is number per square kilometer. That directly displays that high-density (the darkest two areas of the map, whose values are more than 4 per square kilometer) areas are gathered around the city center, in which the area of neighbourhoods are also lower than the area of suburb neighborhoods. And the population around the city center is much more than that of suburb areas. So, high possibility of cycling accidents and small area made city center one of the high-density areas. There is one neighborhood in the east of the city also has a high-density of cycling accidents. The value of that neighborhood is higher than 3. The reason of this circumstance could be that there are many people living in some cities that on the east of Curitiba. They are working in Curitiba, so there are many people cycling every day though that neighborhood. The busy traffic may be the main reason of the cycling accidents.

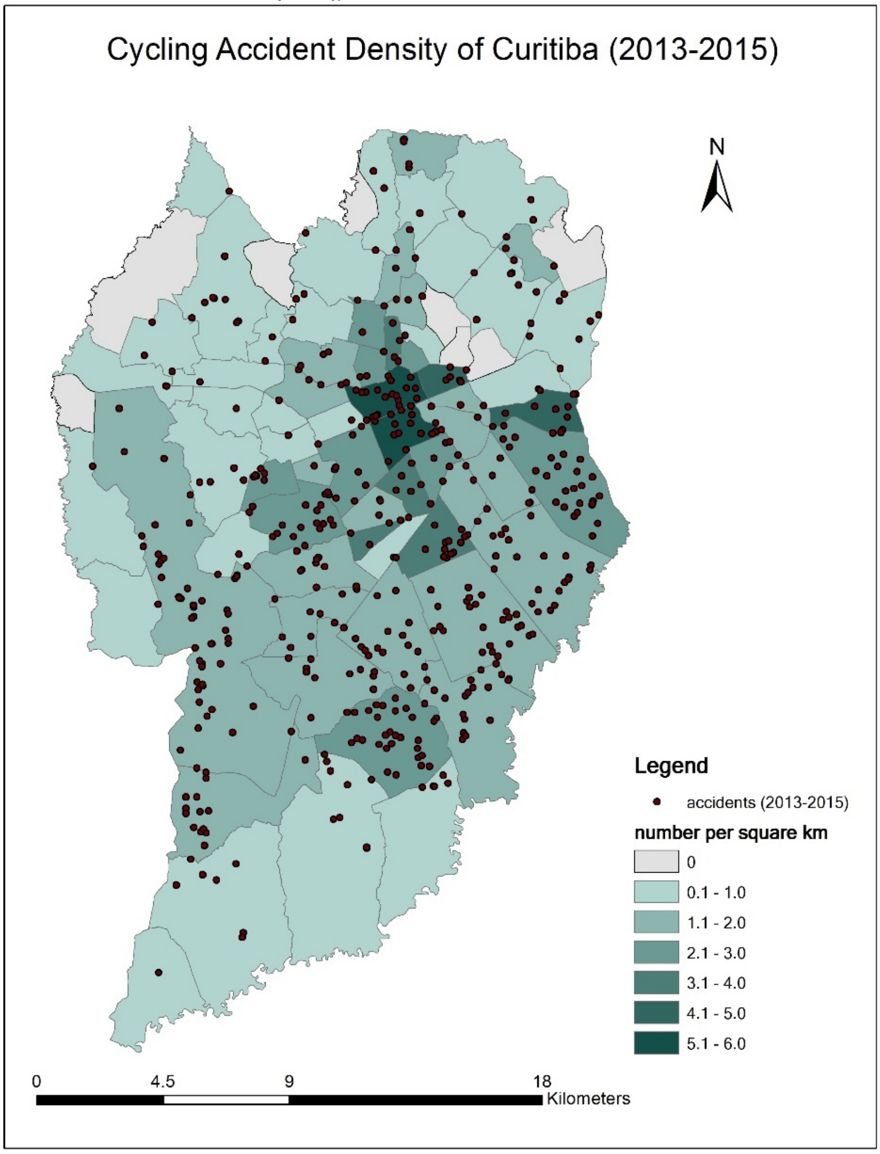


Figure 4-2 Accident density map (per area)

Figure 4-3 is the density map of cycling accidents by population. The value of each neighbourhood was calculated by the number of cycling accidents divided by the population of each neighbourhood. Because of the value could be very low when the number of population is very high. So, the value multiplied by 10,000 became the number of cycling accidents per 10,000 capital. This map shows the highest value is in the city center, and other high-density areas (higher than 6) are close to city center, and another one in the north west edge of the city. Addition, the southern part (two neighborhoods) of city is another relative high-density area with the number higher than 4 but lower than 6. That result mainly based on the population of each neighborhood. The high population areas are mainly around the city center, while, the low population areas are suburb areas. For the distribution of cycling accidents, that is similar as the distribution of population, mainly happened in the city center, not much in the edge of the city. Because of the phenomenon above, the possible explanation of Figure 4-3 may be that in the city center there is high population with high number of cycling accidents, so the density is very high. Although, there is low number of cycling accidents in the subrub areas, however, with relative very low population, the density is very high.

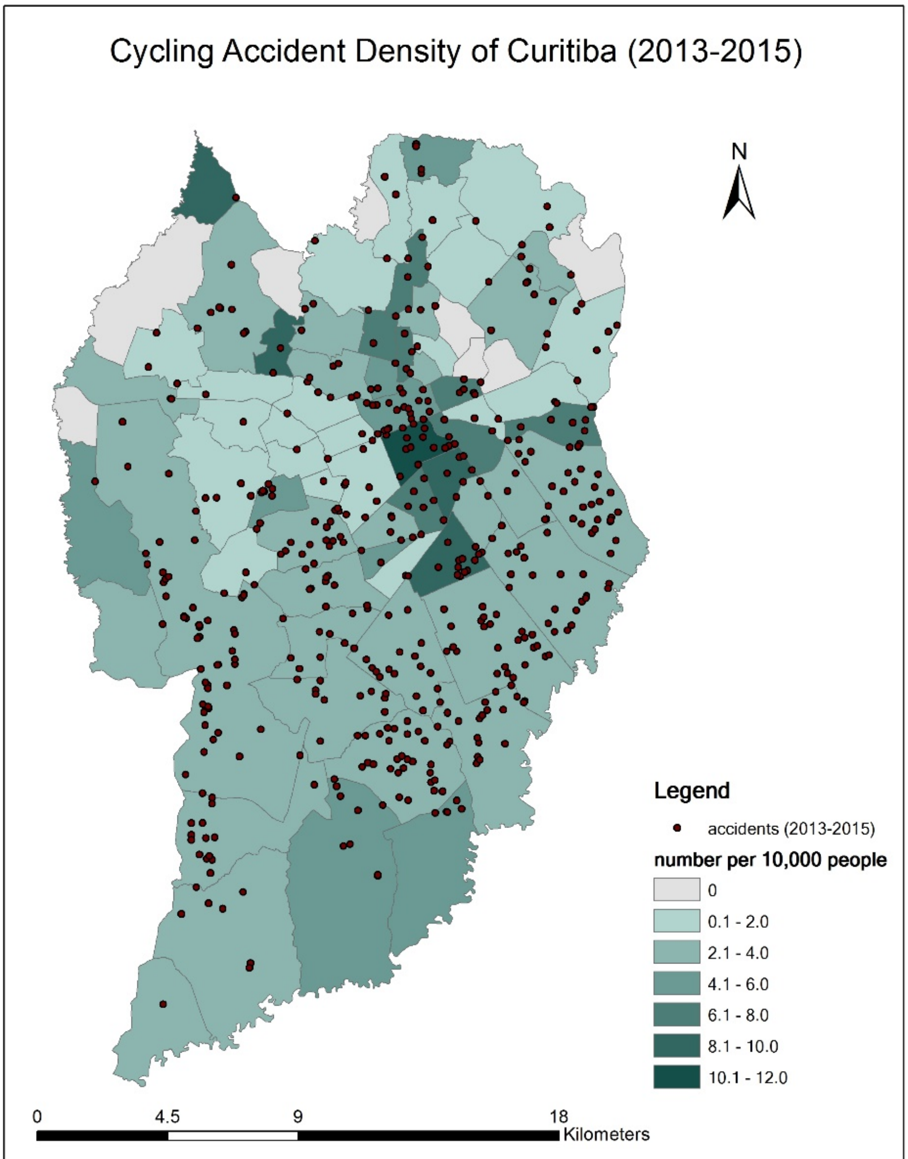


Figure 4-3 Accident density map (per 10,000 capital)

Figure 4-4 is the map of cycling accident density per road network length. The value of each neighbourhood was calculated by the number of cycling accidents divided by the length of road in each neighbourhood, unit in number per kilometer. Because the highest value is 0.36, so higher than 0.18 (over the 50% of the highest value) can be seen as the relative high-density. The high-density areas are around the city center, southern parts of the city, and one neighborhood in north. The road length around the city center is high, because of the heigh-density of population and high-demand of traffic. The road length in suburb areas is much lower than that in city center. So that, some neighborhoods in suburb areas can have high-density per road length (especially in the southern neighborhoods whose total road length is relative low), even although the total numbers of accidents in these neighborhoods are not very high. However, obviously, city center is high-density area because of the high number of cycling accidents, although the total length of road is very high in city center.

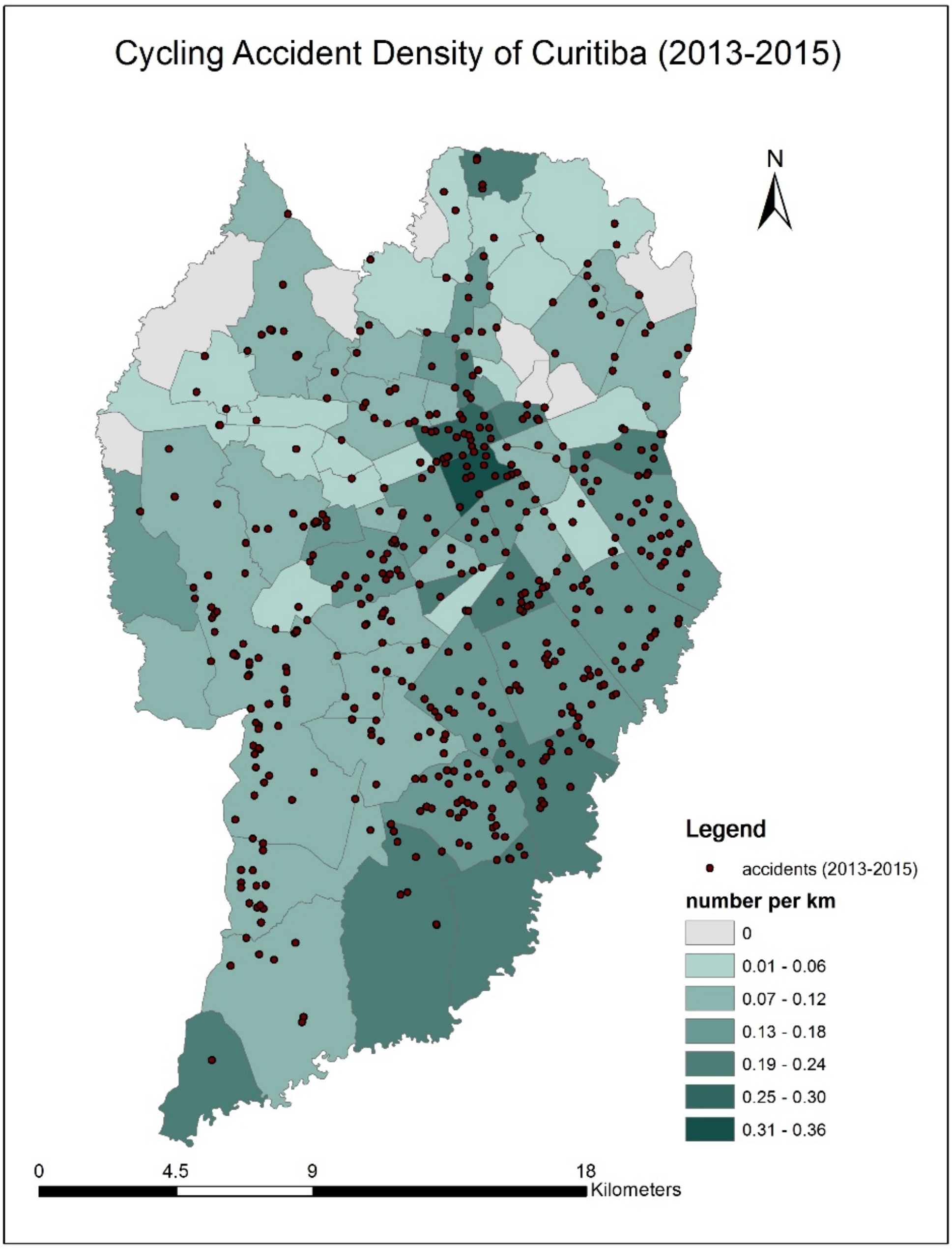


Figure 4-4 Accident density map (per road length)

4.2.2. Density of Cycling Accidents by Area

In this part of the thesis, kernel density tool was applied to obtain the spatial patterns of cycling accidents. There were two analyses, one was calculated by same weight of all cycling accidents, and the other one was calculated by different weights based on the cost of each severity level (as shown in Table 3-4). These processes were done in ArcGIS 10.4 by the kernel density tool. The size of result raster is 10 meters. The value of each raster means how many accidents happened in the neighborhood area of that raster. For the analysis with different weights, the value can reflect the rate of cycling accidents happening. After this part of analysis, the result maps used to choose the high-density areas of cycling accidents in order to collect street design data in the fieldwork.

As the results of these analyses, Figure 4-5 shows the density map of same weight for all cycling accidents from 2013 to 2015. There are some high-density areas in this map, for instance, the city center, Sítio Cercado (a neighbourhood in the south part of the city), Avenida Marechal Floriano Peixoto (an avenue connects the city center and the airport), Portão (a neighbourhood in the middle of the city), and Cajuru (a neighbourhood in the east part of the city).

For these results, possible explanations could be: (1) There are many people living and working in the city center, so it is easy to understand that many cycling accidents in the city center due to the high-demand of the traffic and there are lots of people cycling over there. (2) There are some neighbour cities on the east of the city. So, there are many people cycling every day through the neighbourhoods in the east part of the city. So, that is possible to be the reason why there are high-density areas in the east part of the city. (3) For the whole city, rich people normally living in the north part of the city, while the poor people living in the south. Comparing to the rich people who usually driving, cycling is an easy way for poor people to travel every day. As a result, there are many people cycling in the southern city. However, the cycling infrastructures over there are not with good quality. So that, there are some high-density areas in the south part of the city.

There is another map (Figure 4-6) shows the result of cycling accidents density with considering about the weight of severity from Table 3-4. In this map, the highest density area is Cidade Industrial de Curitiba (the industrial area of the city). As well, Sítio Cercado is another high-density area. The patterns are changed because of the weight of different severities are changed. Based on the weights in Table 3-4, fatal accidents have much more impact than without weight (four times as non-fatal with risk of life cycling accidents, and nearly fifteen times as non-fatal without risk of life cycling accidents). There are some fatal accidents happened in Cidade Industrial de Curitiba (CIC), Sítio Cercado, and other southern neighborhoods. So the result shows that high-density areas are close to these fatal accidents. In Figure 4-6, city center is not the highest density area anymore, because most accidents in the city center are with low severity level.

Sítio Cercado is the only one area with high density of cycling accidents in both density maps. That area can be seen as an unsafe area for cyclists, because of the high-density of cycling accidents and there are many fatal accidents. One possible reason is that there are so many low income people living in Sítio Cercado, because of the low living cost. Additional, the terrain surface over there is relative flat (comparing to the northern city). However, the cycling infrastructures there with bad quality. The combination of these factors may be one of the reason. That seems like a combined effect of social-economic, environment, and urban design factors. For the detailed analysis of urban design (cycling infrastructures design) factors will be shown in the Section 4.3.

The results of this part are density maps of whole city. There are still some limitations of this method. One major limitation is that cycling accidents only appeared along the road network. They cannot happen in the middle of blocks. These maps above cannot match the reality. However, these results can provide a direct view of the distribution of cycling accidents. So, for this part of analysis, the results just show the high-density areas which can be used to identify the patterns of cycling accidents. That helps us to know where the clusters of cycling accidents are. These high-density areas of two maps were used as sample areas of the fieldwork. The data of fieldwork was collected from the city center, Sítio Cercado, Cidade Industrial de Curitiba, and Avenida Marechal Floriano Peixoto (all of them are high-density areas of two maps).

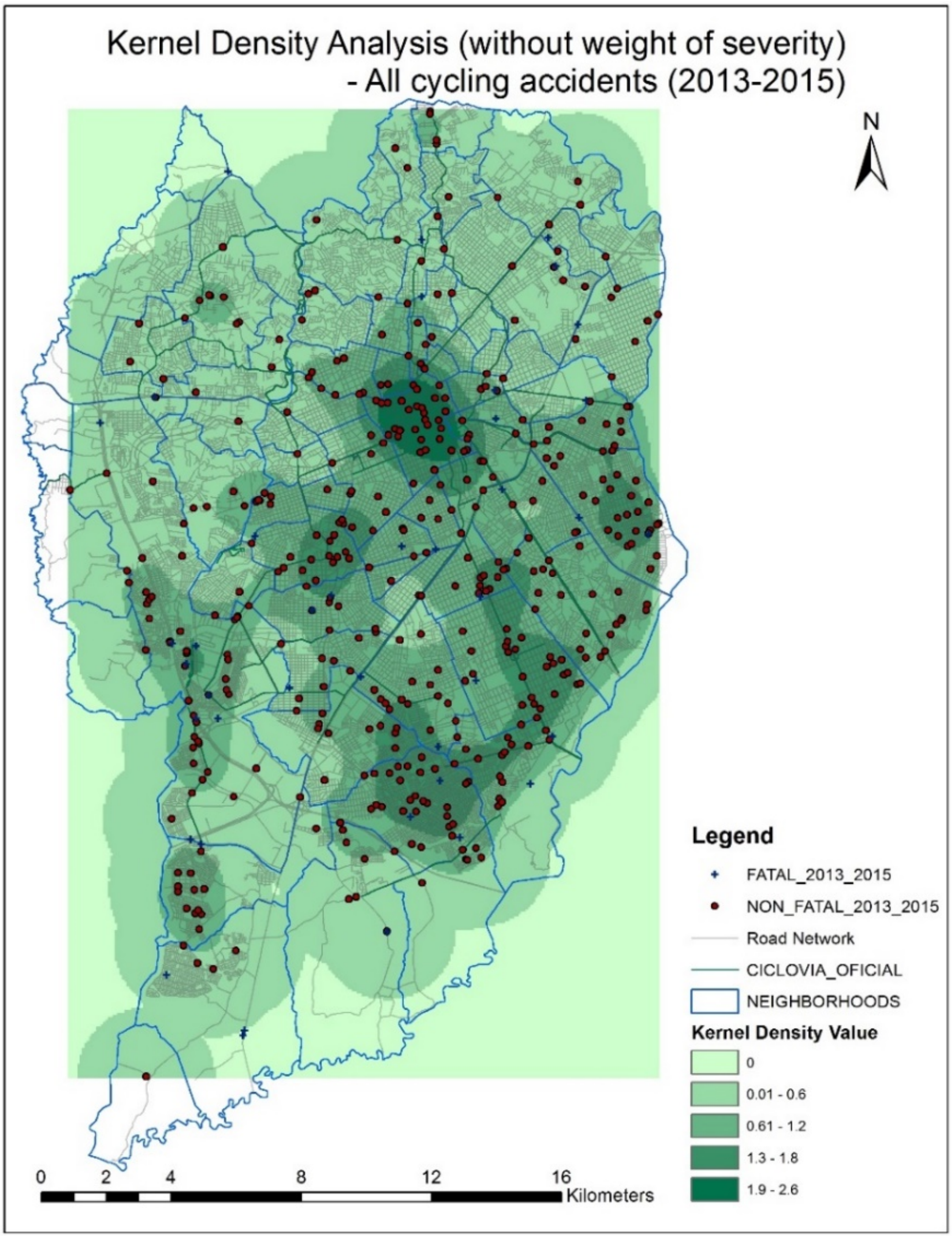


Figure 4-5 Kernel density of cycling accidents (without weight)

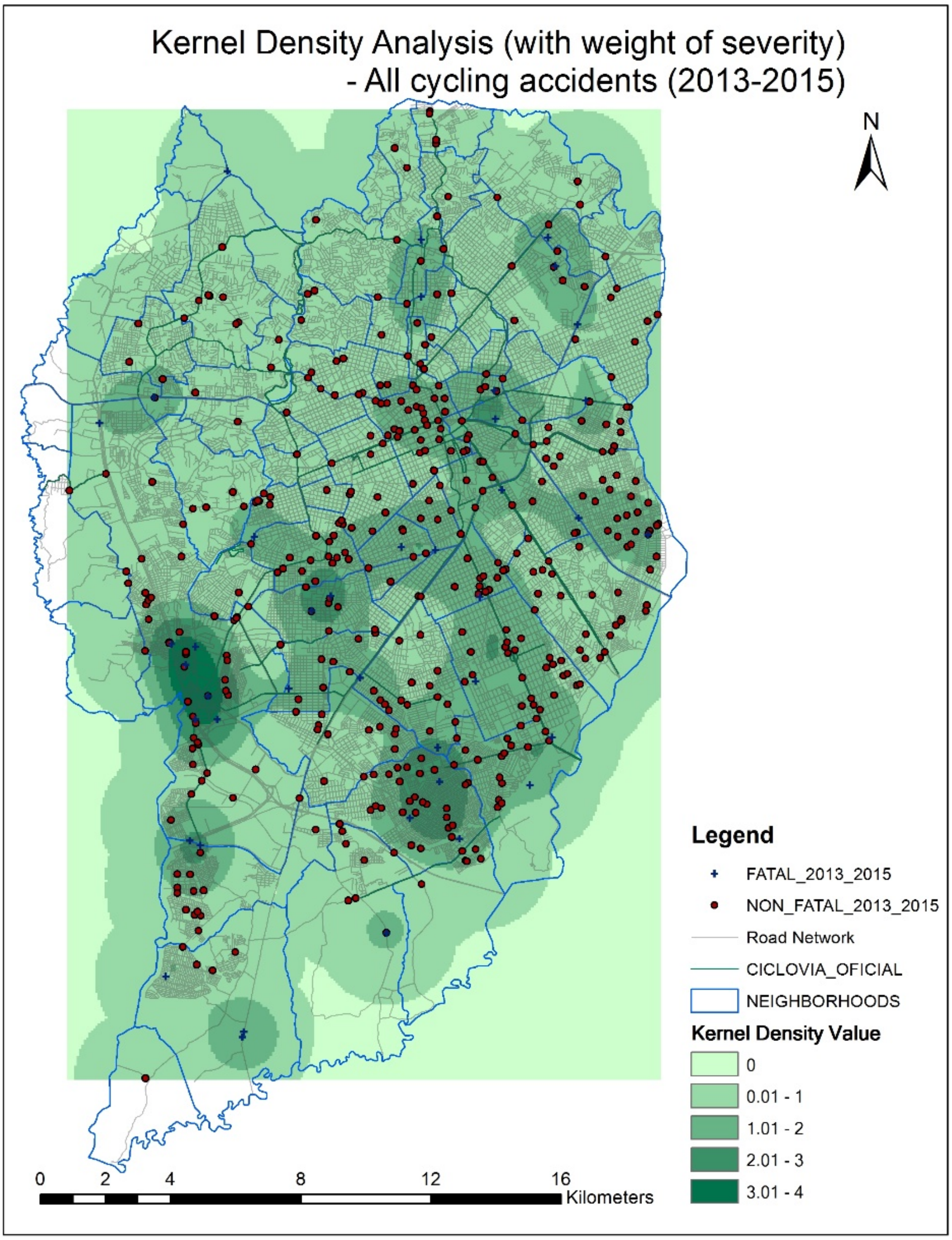


Figure 4-6 Kernel density of cycling accidents (with weight)

4.2.3. Density of Cycling Accidents by Road Network

In this part, kernel density estimation was applied based on the road network of Curitiba. This analysis was done by the software SANET. Figure 4-7 shows the map of result. All cycling accidents from 2013 to 2016 were used in that analysis. The weight was set by the length of each road in the traffic network. For each accident, there was nothing considering about the severity, which means in this part of analysis all accidents have same weight. The value on the road network means how many accidents happened along the road per 100 m from 2013 to 2015. From the map, there are lots of high-density spots can be identified. Some high-density areas can be found along the Avenida Marechal Floriano Peixoto, somewhere in city center, Sítio Cercado, Cidade Industrial de Curitiba, and some areas in the northern city. The result quite similar like the results of density by area. However, the result of this network based is more like the reality, and easy for people to know where the specific high density areas are. Although this method is quite good, there is still something can be improved. One limitation is that there is not difference for these accidents with different severities. If the software can set weights for the point data, it is easy to assess the impact of serious accidents.

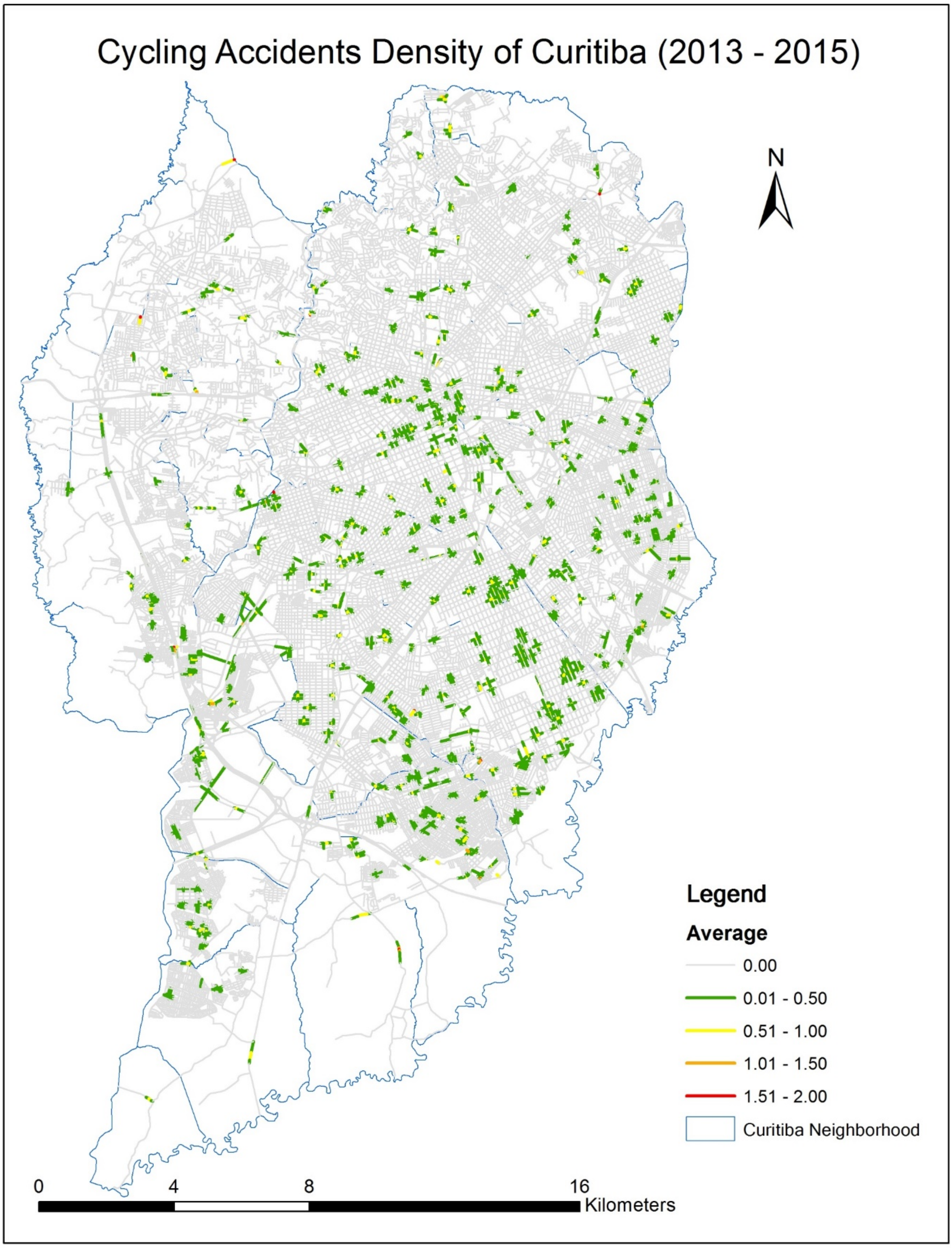
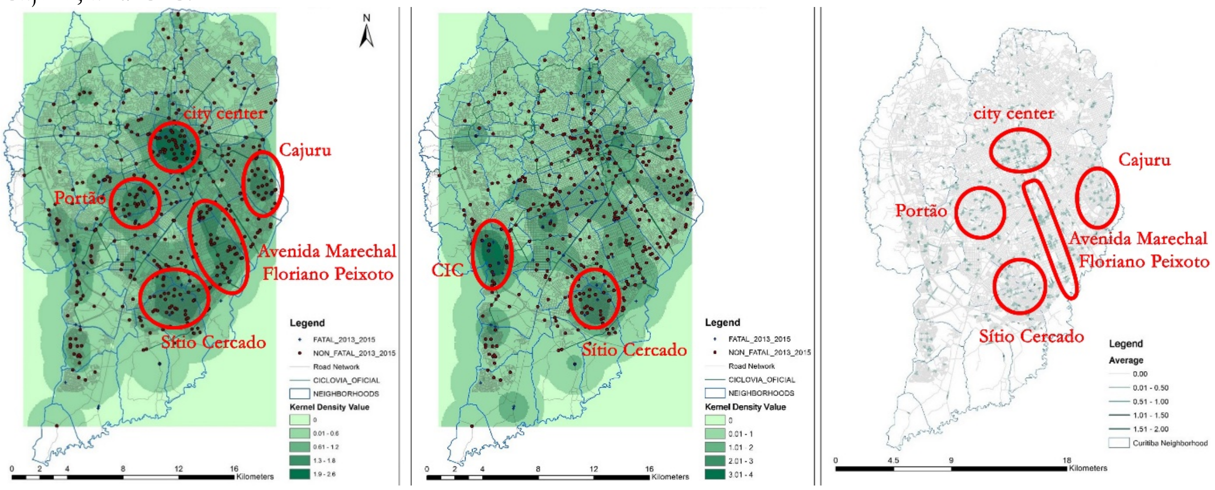


Figure 4-7 Network based kernel density estimation

Based on these three density analyses, high-density areas were detected from these maps. Figure 4-8 illustrates the high-density areas: city center, Sítio Cercado, Avenida Marechal Floriano Peixoto, Portão, Cajuru, and CIC.



(a) (b) (c)

Figure 4-8 High-density areas of cycling accidents

4.3. Street Design Factors of High-density Areas

A fieldwork aimed to collect the urban design factor data from these six high-density areas has been done in September 2016. During the fieldwork in Curitiba, street design factors of 55 cycling accident points in the high-density areas were collected. Table 4-4 and Table 4-5 show the collected street design factors data. There are percentage value in the table, which calculated by the number of accidents divided by the total number of sample data (the number is 55).

Table 4-4 is about the bicycle infrastructures factors. Regarding the severity level, more than 82% of them are non-fatal accidents. Nearly half of all then accidents happened at intersections (49%).

In the type of bicycle lanes part, over half of the bicycle lanes are shared with pedestrians (55%). There is less than 2% of accidents happened on the segregated cycling lanes. And the rates of on street painted cycling lanes and shared with cars road are same (22%). These rates show that shared with pedestrians cycling lane is the most dangers type of bicycle lanes. Correspondingly, segregated cycling lanes is the safest type based on the lowest rate (2%). The reason of that result may be that segregated cycling lanes can keep cyclists, pedestrians, and vehicles separate can keep them safe. On street painted cycling lanes and shared with cars roads give the space to cyclists, but no effective protection for cyclists. For the shared with pedestrians street, there are many chances to have a conflict between cyclists and pedestrians. So, the risk of accidents on that street is much higher than others'.

Over 90% accidents happened on the asphalt road. Two third accidents happened on the bad conditions, such as without painted color or symbols, or not a flat surface. That can reflect that surface condition may have influence on the accidents happening.

The data reflection of traffic lights is different from the expected situation. The hypothesis about the traffic lights is that when there is a good visibility of traffic lights, the probability of accidents could be lower than the conditions without traffic light. However, the result is that over two third accidents happened when there is a good visibility of the traffic lights (69%). One possible reason could be that people be more careful when the environment is not safe for instance, have traffic lights at the intersection.

Most accidents located on a road without any obstacle (78%). Therefore, the obstacle (such as street lights, road signs) may be not a reason of the accidents. In addition, maybe people could be more careful on the road with obstacles: with a lower speed and more attention on the cycling and other people.

Most accidents happened on a narrow cycling lanes or even no specific cycling lanes (38% with the width is 1 meter and another 38% without cycling lanes). Looking at the wider cycling lanes, the rate decreased a lot. Especially for the width more than 1.5 meter, the risk is lower than 2%. That is a safe condition for cyclists. Fatal accidents happened when there is not cycling path or the cycling infrastructures are the shared lanes of normal and minimum width and separated off-road lane. Conclusions can be got is that wider shared cycling lanes and segregated cycling lanes can provide safer environment for cyclists.

The way pass the bus stop also has effects on the cycling safety. There is only 2% accidents happened when the cycling shared lanes of wide lane. Meanwhile, shared lanes of normal or minimum width, separated on-road lane, and separated off-road lane have similar rate of accidents happened (24% for each). Here the separated cycling lanes did not meet the expectations. One possible reason could be that when cyclists passing the stops, pedestrians may cross the cycling lanes. If the speed of cyclists is fast, they do not have enough time to stop, and the conflict may happen.

Table 4-4 Street design factors for cycling network (%)

		category	explanation	severity			total
				Non-fatal	Fatal	Null	
	intersection	0	No	36.4	9.1	5.5	50.9
		1	Yes	30.9	9.1	9.1	49.1
bicycle	type	1	segregated	1.8	0	0	1.8
		3	on street painted	16.4	0	5.5	21.8
		4	shared with pedestrians	38.2	10.9	5.5	54.6
		5	shared with cars	10.9	7.3	3.6	21.8
	surface material	1	asphalt	61.8	14.6	14.6	90.9
		2	bricks	5.5	3.6	0	9.1
	surface condition	1	good	23.6	5.5	5.5	34.6
		2	not painted	43.6	12.7	9.1	65.5
	traffic signals	2	Visible >20m	50.9	5.5	12.7	69.1
		0	No	16.4	12.7	1.8	30.9
	obstacles	0	No	54.5	12.7	10.9	78.2
		1	Yes	12.7	5.5	3.6	21.8
	width	0	No cycling lanes	18.2	16.4	3.6	38.2
		1		30.9	1.8	5.5	38.2
		1.5		16.4	0.00	5.5	21.8
		2		1.8	0	0	1.8
	bus	0	No bus stop	10.9	10.9	1.8	23.6
		2	shared lanes of normal or minimum width	14.6	3.6	5.5	23.6
		3	shared lanes of wide lane	0	0	1.8	1.8
		4	separated on-road lane	18.2	0	5.5	23.6
		5	separated off-road lane	23.6	3.6	0	27.3

Table 4-5 is about the road network infrastructures factors. 20% accidents happened along the one way roads. Another 80% is along the two way roads. Nearly half of accidents happened on the segments (45.45%). The surface material of all accidents locations is asphalt. 93% of them with good conditions of surface. So, the conditions of surface may not be a decisive factor for the cycling accidents.

Considering about the role of traffic lights, 67.27% of them with very good visibility of traffic lights. One third of them without any traffic light. There are six different composition of the traffic modes. The group of bikes with motorcycles, cars, and buses is the most common one (72.73%). There are 58.18% accidents happened on the roads have speed limitation of 40 km/h. 14.55% and 20% for 50 km/h and 60 km/h. Comparing with that, the speed limitation of 30 km/h is a relative safe condition (only 7.27%). Most accidents happened on the roads with lanes less than three (80%: 21.82% on one-lane road, 58.18% on two-lane road). That reflects that wider road for vehicles can reduce the risk of cycling accidents as well. The rates of accidents on highways and local streets are much lower than that of other types of roads. There are similar rates for highways and local streets. The rate of accidents on the roads with "median" is a little higher than that without "median". That means "median" does not have strong impact on the emergence of accidents.

Table 4-5 Street design factors for road network (%)

		category	explanation	severity			total
				Non-fatal	Fatal	Null	
road	directions	1	one-way	14.6	1.8	3.6	20.0
		2	two-way	52.7	16.4	10.9	80.0
	surface material	1	asphalt	67.3	18.2	14.6	100
	surface condition	1	good	63.6	16.4	12.7	92.7
		4	not flat	3.6	1.8	1.8	7.3
	traffic signals	1	<50m	0	1.8	0	1.8
		2	>50m	50.9	3.6	12.7	67.3
		0	no	16.4	12.7	1.8	30.9
	traffic modes	1 2 3	bike motorcycle car	1.8	3.6	1.8	7.3
		1 2 3 4	bike motorcycle car bus	54.6	5.5	12.7	72.7
		1 2 3 5	bike motorcycle car truck	3.6	0	0	3.6
		1 2 3 4 5	bike motorcycle car bus truck	1.8	1.8	0	3.6
		1 3 4	bike car bus	0	1.8	0	1.8
		2 3 5	motorcycle car truck	5.5	5.5	0	10.9
	speed	30		5.5	1.8	0	7.3
		40		41.8	5.5	10.9	58.2
		50		7.3	5.5	1.8	14.6
		60		12.7	5.5	1.8	20.0
	lanes	1	Number of lanes	10.9	3.6	7.3	21.8
		2		40.0	12.7	5.5	58.2
		3		12.7	1.8	0	14.6
		4		3.6	0	1.8	5.5
	type	1	high way	5.5	5.5	0	10.9
		2	" structural corridors "	29.1	0	7.3	36.4
		3	main road	25.5	7.3	3.6	36.4

	4	local street	7.3	5.5	3.6	16.4
median	0	no	29.1	7.3	7.3	43.6
	1	yes	38.2	10.9	7.3	56.4

4.4. Analysis of Street Design in Relation to Cycling Accidents

The results of this part include current conditions of cycling infrastructure in Curitiba and samples in standard design guidelines. There are three types of road hierarchies: major roads (highways), primary and secondary streets, local streets; and one related infrastructure: cycling parking. All roads include factors of intersection and segment (the two units of the network analysis of cycling accidents). Pictures of cycling infrastructures for each type of road in city Curitiba were taken during the fieldwork.

4.4.1. Design Factors of Major Roads

Figure 4-9 illustrates examples of the cycling conditions of major roads in Curitiba. They were taken at "Avenida Marechal Floriano Peixoto" that connects the city center with the airport region (about 7 km from city center to airport). There is a painted cycling lane along the road without solid isolation. However, there are some problems, for instance, the cycling lane sometimes is on the right side (picture a & d), and others are on the left side (picture c). The change happens at the intersection, where the cyclists can cross the road using zebra crossing (picture b). Additionally, the width also changes "randomly". In picture a, the width can allows two cyclists side by side. However, in picture c, the width is only enough for one cyclist.

Figure 4-9 Cycling lanes along major road

Figure 4-10 are two pictures of cycling lanes along the highway - BR-376 that is a city highway through neighborhood CIC. There are roads for vehicles and narrow paved street for pedestrians along the parallel secondary road. But no separate space for cycling. Generally speaking, people should ride bikes on the roads for vehicles. However, considering about the safety conditions, it is better to do that on the sidewalk, although the surface condition of the sidewalk is not good enough for cycling. Some Local people would like to choose the sidewalk rather than the roads based on the traffic safety issue. For that condition, the sidewalk should be wider and better surface to make safe environment for cyclists and pedestrians.

Figure 4-10 Cycling lanes along highway

Cycling lanes along the major road often is a connection between urban areas. These cycling ways must be fully separated from vehicle road (Cambridge Cycling Campaign, 2014). However, there is not cycling lane along the city highways in Curitiba, but some parallel secondary roads have cycling lanes shared with vehicles or pedestrians (Figure 4-10). For other major roads connecting the city center to suburb areas and other nearby cities or the major roads parallel to the highways, there are painted or segregated cycling lanes (Figure 4-9). The width of them is 0.5 to 1 meter. The speed limitation of the highway is 60 km/h. However, some vehicles were over speed. In the Brazilian guidelines, the minimum width adopted for the unidirectional track (one way) is 2 meters, which corresponds to the effective width of the bike lane. When the lanes have uneven edges in more than 10 cm, there is a need to add 0.50 m on the bike path. (BRASIL, 2007). Comparing the width of cycling lanes along the highway in Curitiba and the suggestions in guidelines, the difference is that the current cycling infrastructures cannot provide enough space for cyclists to have safe cycling environment.

On the highway, the cyclist's conviviality with traffic is much more dangerous, mainly due to the vehicles' speed. Even if the cyclists are sheltered in an exclusive cycling space, they may have to face serious risk situations, such as: 1) strong displacement of air through the side passage of heavy-duty vehicle at high speed; 2) solid deformation of the pavement of the bicycle lane, as a result of the deformation of the lane through which motor vehicles circulate; 3) presence of debris on the bicycle lane, left by trucks providing removal services in urban areas; 4) slippage due to accumulation of dirt, sand and water in the cycle track (BRASIL, 2007).

The intersections of the major roads play a role on the cycling safety as well. When the cyclists passing the intersections, the design should make sure they have ample lateral space (BRASIL, 2007). The Scottish guidelines suggested that cycling lanes should be highlighted by colored combine with cycling symbol markings. High friction surface should be laid over the full width of the carriageway for a distance of 50m in advance of and through the intersection (*Cycling by Design 2010*, 2011).

Based on the current condition of cycling infrastructure on major roads in Curitiba and the guidelines, the flaws are as below:

1) There is not cycling lanes along the city highways;
2) The width and continuity of cycling lanes on some major roads are not good enough.

4.4.2. Design Factors of Primary and Secondary Roads

There are several cycling infrastructures applied along the primary and secondary streets. Primary streets carry the most traffic. Cycle traffic will be high on these routes as these will also be the most direct routes between areas. Secondary streets connect the primary streets to local streets. Because of the lower speed and traffic volume, less infrastructure is required (Cambridge Cycling Campaign, 2014).

In a traffic calming zone, specific cycling infrastructures (like bike boxes) have been placed to lower the speed of vehicles, show the priority of cyclists and provide safe environment for cycling (Figure 4-11 are pictures taken from Avenida Sete de Setembro). For normal primary and secondary streets, there are painted cycling lanes along the streets. Some of them are segregated (Figure 4-13), while others are shared with pedestrians (Figure 4-14).

The speed limitation of vehicles in traffic calming zone is 30 km/h which is safer than the normal primary and secondary streets. In addition, the roadside parking nearby the cycling lanes is not a common phenomenon, which can also improve the safety. Figure 4-12 is roadside car parking for taxi in front of a shopping mall. The car parking could block the line of sight. That would be a cause of the accidents at some narrow intersections.

(a) (b)

Figure 4-11 Traffic calming zone

Figure 4-12 Roadside car parking

Figure 4-13 is segregated off road cycling lane along the primary and secondary street (Rua Mariano Torres). There is a difference of the level between vehicles and cyclists to keep the safety of cyclists. However, there is not clear distinction between the cycling lanes and the sidewalk. Sometimes, people just walk on the painted cycling lanes while cyclists are passing by, which may cause conflicts. It is surprising to observe that there is a traffic jam during the morning peak hours, while the parallel cycling lane is empty. It reflects that the usage of cycling lanes is still at a low level, and combined with the poor conditions of the sidewalks (shown on the right side of the picture).

Figure 4-13 Painted cycling lanes (ciclovia)

Figure 4-14 shows the pictures of shared with pedestrians cycling lanes along the primary and secondary street (Avenida Presidente Affonso Camargo). Some cycling lanes are painted with symbols of pedestrians and bicycles to distinguish the space dedicated for each. Conversely, some of them do not have symbols or color to distinguish the space of cyclists and pedestrians.

(a) (b)

Figure 4-14 Cycling lanes share with pedestrians

The speed limitation of some primary roads is 60 km/h, (some) secondary roads in Curitiba are 40 km/h, while in traffic calming zone it is 30 km/h. However, in the guideline "Making Space for Cycling: A guide for new developments and street renewals", the speed limitation of primary and secondary roads is 30 km/h (Cambridge Cycling Campaign, 2014). For the situation in the Netherlands, the speed limitation of vehicles is 50 km/h in the city area. For the mopeds on bicycle path, the maximum speed is 40 km/h (Ministerie van Infrastructuur en Milieu, 1990). These situations in cycling friendly countries can prove that the planning strategy of traffic calming is appropriate for the safety of cyclists. And the maximum speed of Curitiba's primary and secondary streets should be lower to match the planning standards.

For the width of cycling lanes, the Brazilian guidelines for cycling infrastructure design suggest that the minimum width should be 1.2 meters. If there is an uneven edge, the width should be increased to 1.7 meters (BRASIL, 2007). The current condition is that the width of primary and secondary roads is from 1.5 to 2 meters in Curitiba, which matched the suggested by the Brazilian guidelines. However, the guidelines for Cambridge (UK), for instance, suggested that the cycling lanes should be segregated lanes with the width no less than 2.1 meters.

Another issue of the space is that the on-street car parking could be a problem for the cycling safety. If the car parking is on the right side of the road, the implementation of a 0.5-2.5 m buffer zone should be provided in order to avoid the problem of 'dooring' of cyclists by parking cars and reduce the risk of cyclists' injury (Cambridge Cycling Campaign, 2014). Another solution could be that implemented the car parking on the left side of the road. That makes the car parking between the vehicle road and "median". The cyclists would not be bothered by the car parking. In the traffic calming zone of Curitiba, the car parking is on the left side to make a safe space for cyclists. However, the traffic calming zone was built at the end of 2015. Based on the available data, before that, there were some accidents happened. After that, there was not any serious accident. In the future, new updated data should be used to assess the consequent of traffic calming zone.

Safety issues at intersections are different from the safety conditions along the road. At primary and secondary streets' intersections, the priority rights of cyclists should be respected. In Curitiba's traffic calming area, "Bike box" was applied to show the priority and advanced rights when waiting for the traffic lights. Similar ideas are included in guidelines as well (Cambridge Cycling Campaign, 2014). Note the adoption of advanced cyclist retention, ahead of motorized traffic. Another important point in the arrangement are the different marks on the pavement, especially those facing the bicycle. In addition to painting the bike, there are arrow markings indicating paths, the advanced retention bands, as well as the bounding paint of the bicycle space near the edge of the cycle path (BRASIL, 2007). In Scotland, simple priority crossings and Advanced Stop Lines (ASLs) applied to ensure the safety of cyclists at the intersections (Cycling by Design 2010, 2011).

About the way passing the bus stops, in the guidelines of Brazil, the idea is that keep wide separated cycling lanes (at least 2 meters) to avoid the crash of cyclists with people going up and down the collective. In cases of very busy stops, the route may not be adequate for the deployment of a cycle path. Due to this volume of traffic, it is suggested to opt for the implantation of a bicycle path or leave the bicycle free to share with other vehicles the same road space (BRASIL, 2007). Other guidelines suggested that cycling lanes should be continuous, away from the pedestrians waiting area or behind bus stops (Cambridge Cycling Campaign, 2014; Welle et al., 2015). The current conditions in Curitiba is separated bicycle lanes. Figure 4-15 shows one of the ways to pass the ordinary bus stop along the primary and secondary streets. The painted cycling lanes passing the bus stop. That is not the best choice to keep the safety of pedestrians. A better way could be that cycling lanes passing the bus stop behind the waiting area. For the famous BRT lines. Because of there are special bus roads for BRT, no bus stop passing problem for them.

Figure 4-15 Cycling lane passing bus stop

Signals is important for the safety at intersections. In Curitiba, no specific cycling signals over there. There are traffic signals for vehicles and cyclists when the cycling lanes along the roads. If there is not painted cycling lanes or the cycling lanes are shared with pedestrians, the traffic signals are for the pedestrians and cyclists together. Many guidelines suggested a good visibility of traffic light for cyclists. Different signals for vehicles, pedestrians, and cyclists should be separate, and easy to be distinguished (Welle et al., 2015). In addition, it is recommended to place lower light poles to ensure good visibility for cyclists (BRASIL, 2007). So that, one improvement could be that place cycling traffic signals to determine the respective order and rights at the intersections.

The disadvantages of cycling infrastructure in primary and secondary roads are:

1) Speed limitation is higher than the suggestions from guidelines, except the traffic calming zone;
2) The width of cycling lanes could be better;
3) Car parking along the cycling lanes;
4) No specific traffic signals for cyclists.

4.4.3. Design Factors of Local Streets

Figure 4-16 shows pictures of the local streets in Curitiba (R. Des. Cid Campêlo). These local streets are mostly distributed in the suburb areas. There are not specific cycling lanes for cyclists. Therefore, people ride bikes on the street with vehicles.

(a) (b)

Figure 4-16 Cycling on local street

When there are the low volumes of motorized traffic. However, some special arrangements may be adopted, within what is conventionally called traffic calming (even though Traffic Moderation, see concept in this chapter).

Among the most common solutions are:

1) narrowing of the motorway traffic lane, approaching crossings with bicycle lanes;

2) elevation of the runway to create transversal ripple, in neighborhoods with low traffic, before crossings with bicycle lanes;

3) closing of direct passage to the automotive traffic (BRASIL, 2007).

Local streets are majority of streets within an area where people live or work, shop or enjoy themselves. Ideally with children able to play in the street, as well as being quiet and safe for cycling. Car traffic should be minimized in this area (Cambridge Cycling Campaign, 2014).

There are cars, buses, and motorcycles with the speed limitation of 40 km/h on the local streets (R. Des. Cid Campêlo). There is not specific speed limitation in the Brazilian guidelines. However, that speed (40 km/h) is much faster than 20 km/h (the suggested speed in other guidelines) (BRASIL, 2007; Cambridge Cycling Campaign, 2014). Moreover, encourage walking, cycling and active shop frontages such as cafes and seating areas. The designs may seek to discourage unnecessary through-traffic to improve the safety and comfort of walking and cycling (Christchurch City Council, 2013).

Because of the local streets are relative small streets, some local streets do not have cycling lanes, while others only have narrow cycling lanes (the width less than 2 meters). In many guidelines, they suggested cyclists should share the local street with cars or pedestrians (BRASIL, 2007; Cambridge Cycling Campaign, 2014). However, it must be observed carefully, especially by the cyclists. This is because, in most Brazilian cities, the lateral strip near the edge of the road presents precarious traffic conditions. The different one is "Christchurch Cycle Design Guidelines". In that guidelines, at least a separated cycle paths with a separation (0.6-1 m) should be provided between cars and pedestrians by kerbs or painted separation (Christchurch City Council, 2013).

The traffic volume of the local streets is lower than that of major roads (highways), primary and secondary streets. So, in the Brazilian guidelines, mini roundabout is a good choice for local street intersections (BRASIL, 2007). Besides, there are not many traffic lights at the local street intersection in Curitiba, which once again meet the design guidelines. The current condition is that there is not many traffic signals at local street intersections.

The car parking on the local streets is very common in Curitiba. Figure 4-17 is a picture of car parking in CIC. These car parking take up space of cycling. The on-road car parking is not safe for cyclists. For instance, if the driver open the door without looking back, cyclist who just passing the car may get hurt. In addition, cycling between vehicles and car parking is dangerous.

Figure 4-17 Car parking in local streets

About the way of bus stops passing, street design should force cyclists slow down to make sure the safety of pedestrians. There are cycling lanes shared with bus in Curitiba, which with the width less than normal width. When the bus stop, cyclists cannot pass on the right side. That can make sure the safety of pedestrians and passengers. However, if cyclists want to try the left side to pass the bus, maybe that is not a good choice. Because of the one lane road and "high" speed traffic. So, that is better that cyclists stop to wait till the bus leaving. On the other hand, some guidelines suggested that design should slow down the speed of cyclists to make sure the safety of pedestrian (Welle et al., 2015). So, shared with vehicles cycling lanes with signs of bus stop or other symbols to remind the cyclists be aware of the buses and pedestrians could be a solution to the way passing bus stops.

The shortages of cycling environment in local streets are:

1) Speed limitation is higher than the suggestions from guidelines;
2) Not many traffic signals at local street intersections;
3) Car parking is common along the streets.

4.4.4. Design Factors of Cycling Parking

In Curitiba, the infrastructures for bicycle parking is very simple and limited. The solid infrastructures are painted (red color) metal frames (for instance, two red stands in Figure 4-18). Cyclists can lock their bikes leaning against the red frames. There are not many parking infrastructures (like the one in Figure 4-18) in Curitiba. The infrastructures are evenly distributed in the city center. However, there is demand of parking infrastructures. During the fieldwork, it is not easy for me to find a parking infrastructure. Sometimes, I just parked bike to a pillar or iron fence.

Figure 4-18 Cycling parking infrastructures

For the parking infrastructures, there are two main parts: locations and space of them, and the type of infrastructures. Because of the lack of cycling parking infrastructures, local situation is that there are many bikes stand randomly in front of some buildings. However, maybe 30 meters away, there are some red metal frames used to park bikes, but no one used them. On the other hand, security of parking bikes is another part need attention. The parking infrastructures should be firmly fixed on the ground.

The Brazilian guidelines suggested that the care for the implantation of urban furniture for bicycles should take into account the accessibility of people with disabilities to urban spaces, especially those with visual impairment. (BRASIL, 2007).

Type of cycling infrastructures in that guidelines are as follow:

1) Without supports or coats
2) With special supports
3) Brackets that hold the two wheels and the frame
4) Brackets with attachment to one of the wheels
5) Concrete blocks and metal blocks
6) Brackets with two-wheel socket
7) Trestle support
8) Hook type bracket
9) Stake support
10) Pedal mount

Other guidelines suggested that a convenient and secure location is good for people to use bikes regularly. Cycling parking should be easier to access than car parking that encourage people to cycle. Cycle parking stand (an immovable object) used for securely store the bikes (Cambridge Cycling Campaign, 2014).

The deficiencies of cycling parking are:

1) Lack of sufficient quantity of parking infrastructure;
2) Not enough space for parking lots.

5. CONCLUSIONS AND RECOMMENDATIONS

This research aims on analysing the distribution of cycling accidents; understanding links between cycling safety aspects and cycling infrastructures design characteristics; identifying the gaps between current conditions and standard design guidelines. Kernel density estimation was applied to derive the high-density areas of cycling accidents. Street design factors data and pictures were collected in these areas to understand the current environment of cycling in Curitiba. Then the gaps between current situation and design guidelines were detected.

5.1. Spatial Patterns of Cycling Accidents

Maps of the density analyses by neighbourhood show the non-spatial calculation results. These maps show that the city center is one of the high-density areas, and that is one of the highest density of accidents as well. Besides that, one neighbourhood in the east (Capão da Imbuia) and some neighbourhoods in the south (Sítio Cercado, Umbará, Alto Boqueirão, and Ganchinho) are also relative high-density areas. The results of kernel density estimation show that city center, Sítio Cercado, CIC, Portão, Novo Mundo, and Cajuru are high-density areas. The network based kernel density estimation shows that city center, Sítio Cercado, CIC, Avenida Marechal Floriano Peixoto, and some areas in the northern city are high-density areas.

Based on the results of density analyses, there are six high-density areas: city center, Sítio Cercado, Avenida Marechal Floriano Peixoto, Portão, Cajuru, and CIC. Because of the relative small area, high population, and compact road network, city center became one of the high-density area. Due to the absolute high numbers of cycling accidents in city center, Sítio Cercado, Avenida Marechal Floriano Peixoto, Portão, and Cajuru, these areas became high-density areas detected by using kernel density estimation. Based on the different severity levels have different impact. The weight given to accident points. The pattern of accidents changed. Because of the fatal accidents have huge effect, some areas nearby the fatal accidents became the high-density areas. For instance, because of there were many fatal accidents in Sítio Cercado, CIC, Portão, Avenida Marechal Floriano Peixoto, as a result, these areas were high-density areas.

5.2. Causes of Cycling Accidents

Based on the bicycle infrastructures factors data, some relationships between cycling accidents and design factors can be concluded as fellow:

Traffic model is an influential element of the cycling safety. From the data exploration, there are 69% accidents is bicycle with car. That means vehicles is very dangerous for cyclists. Especially, cycling accidents with cars may happen in the narrow streets, or at the intersections where the line of sight easily to be blocked.

Different type of cycling lanes could make various effects on the cycling safety. Because of that 55% of the accidents happened on the shared with pedestrians cycling lanes. 44% is on street cycling lanes without isolation from the vehicle. One conclusion can be found is that segregated cycling lanes is much safer than other types cycling lanes. Moreover, serious accidents easily take place on the shared with pedestrians cycling lanes.

The data for width of cycling lanes shows that wider lanes have lower risk of accidents. Especially, when the width is higher than 1.5 meter, the rate is very low (less than 2%). So that, the width of cycling lanes could be an important factor of the cycling safety issue. When the cycling lanes wider than 1.5 meter, the cyclists could have a safe environment.

The way passing the bus stops has effect on the cyclists and pedestrians' safety. The "shared lanes of wide lane" has the lowest rate of accidents. That type of cycling infrastructure maybe the best choice in Curitiba.

Then, considering about the traffic models. Motorcycles may play a rule to the accidents. There is 72.73% of accidents happened in where has the traffic model of "bike motorcycle car bus". While, there is only 1.82% of accidents happened in where has the traffic model of "bike car bus". There is a huge difference between the traffic model with and without motorcycle.

Speed of vehicles may be another reason of the cycling accidents. There is 7% of accidents happened in the roads with speed limitation of 30 km/h. When the speed faster than 40 km/h, the rate is more than eight times higher (58% of accidents happened). That can reflect that speed at 30 km/h is much safer than speed over or equal to 40 km/h. In other words, lower the speed can improve the safety of cyclists significantly.

5.3. Future Improvement

Learning from other successful designs and policies is an efficient way to improve current conditions. Based on the guidelines and other good samples of cycling safety, there are some suggestions for the future improvement as follow.

5.3.1. Suggestions for Major Roads

For the major roads, if some cycling infrastructures have already existed for a while. These infrastructures should be well maintained. Many design guidelines suggest that cycling lanes should be at least 2 meters wide and the surface should be flat (BRASIL, 2007; Cambridge Cycling Campaign, 2014). Furthermore, painted or have symbols to distinguish the space for cycling is better for cyclists and pedestrians distinguishing the space for them. If there are not cycling lanes along the road and there is much demand of cycling traffic, new cycling infrastructures should be implemented in these areas. If the demand of cycling traffic is not much. Considering about the limited budget, no need to build up new cycling infrastructures. But, some maintenance should be done to improve the quality of cycling lanes. Based on the guidelines "Programa Brasileiro de Mobilidade por Bicicleta" and "Cycling by Design 2010", the improvement could be wider the width of cycling lanes and improve the surface conditions (BRASIL, 2007; *Cycling by Design 2010*, 2011). Such as, implement coloured high friction material especially at the intersections to improve security of cyclists; make the cycling lanes wider than 2 meters.

For the road likes Avenida Marechal Floriano Peixoto which has painted cycling lanes, but still has some shortages, for instance, the width of cycling lanes changed after the intersections. The improvements could be that keep the width of cycling lanes at least 2 meters, and keep the continuity of the cycling lanes, based on same guidelines above. That means keep the cycling lanes on one side of the road, do not change that from right to left, and vice versa. However, considering about the convenience and the suggestions in design guidelines, I would like to suggest the cycling lanes on the right of the road, just between the motorway and sidewalk. About the way passing intersections, painted cycling lanes and traffic signs should be provided to remind drivers keeping the low speed and high awareness of cyclists when they driving pass the intersections. The priority and respect should be given to the cyclists.

5.3.2. Suggestions for Primary and Secondary Roads

For the primary roads, traffic calming areas should be promoted. Because lower speed of vehicles is safer for cyclists (Perkons, 2014; Rosén & Sander, 2009). Reduce or even prohibit the car parking near the cycling lanes can reduce the risk of conflicts between cars and cyclists. One solution could be move the car parking from the right side of the roads to the left side.

The segregated or shared with pedestrians cycling lanes should be applied along the primary roads, and ban the painted or shared with cars cycling lanes. Because the risk of cycling accidents for segregated cycling lanes is the lowest; and the on-road cycling lanes remain the chance of conflicts between cars and cyclists. The off-road cycling lanes along the primary roads should be different from sidewalk, distinguished by the symbols of "bike" or "people". Rather than the current situation (no symbols to distinguish the corresponding space). The painted and flat surface should be applied on these cycling lanes. The manhole covers or poles should not be on the cycling lanes to keep the flat surface and the continuity of cycling lanes. For the purpose to reduce the conflicts between cyclists and pedestrians, some solid isolation could be put between cycling lanes and sidewalk. For instance, give different level for cycling lanes and sidewalk. Hard shoulder could be one kind of the solid isolation.

For the secondary roads, forbid the car parking near the intersections is a way to avoid the block of line of sight. Because of the traffic volume of secondary roads is lower than the volume of primary roads. The shared with cars or pedestrians cycling lanes seems enough for secondary roads. Adding buffer zone to cycling infrastructures can provide space for cyclists (Tony, 2016). That also can match the "vehicles should be 1.5 meter away from cyclists" criterial. So that, possible solutions could be that implement shared with cars cycling lanes (with a 0.5 m buffer between cars and cyclists) on the secondary roads. Or, implement shared with pedestrians cycling lanes with the coloured sidewalk or symbols to distinguish each space for cyclists and pedestrians.

Speed of vehicles also has impacts on the cycling safety, which cannot be ignored. The speed limit for busy primary and secondary roads should be relative low. For the primary roads, because of the suggestion of segregated cycling lanes have already been given. The speed limitation can be a little higher. However, at the intersections, the speed limitation should remain 30 km/h to keep the safety of cyclists, especially when the cars make turns at the intersection. For the secondary roads, speed of cars should be lower than 40 km/h or even 30 km/h in some narrow roads to ensure safety of cyclists. The ideas above can also be found in the master plan of Curitiba (IPPUC, 2010). That suggested that the bike paths should with a segregated place for cyclists and a maximum speed of 30 km/h for vehicles. In the central region of the city, where the vehicles with a maximum speed of 40 km/h to increase the safety in the traffic.

For the way passing bus stops, segregated off-road cycling lane is highly recommended. That can keep cyclists continue to go even though there are buses stop for people in and out. They just need to slower the speed when passing the stops to ensure the safety of passengers. The curved route near the stops can slow down cyclists as well. If there is not enough space for off-road cycling lanes, on-road painted cycling lanes can be used. Bus drivers should pay more attention on cyclists when the buses stop or forward.

5.3.3. Suggestions for Local Streets

Local streets have buses, cars, motorcycles, bicycles, and car parking in s tinny space. Therefore, lower the speed of vehicles is essential to the safety of cyclists. For instance, lower the speed limitation from 40 km/h to 30 km/h can lower the risk of accidents. Because of the previous researches show that higher speed will cause higher risk of accidents and serious accidents(Roads and Traffic Authority of New South Wales, 2008). Research of relations between speed and the risk of fatality for all people in Ashton shows that when the impact speed is 50 mph (nearly 80 km/h), the risk of pedestrian fatality is 90%; when the speed is 40 mph (nearly 64 km/h), the risk of pedestrian fatality is 50%; when the speed is 30 mph (nearly 48 km/h), the risk of pedestrian fatality is 10% (Richards, 2010). So that, lower the speed of local streets can reduce the risk of cycling accidents efficiently, and accidents with pedestrians as well. The ways to lower the speed could be make lower speed limitation, or make the roads narrow for vehicles, or change the road become traffic calming zone, or put some solid speed humps to force the vehicles slow down, or use mini roundabout to reduce the speed at some busy intersections.

5.3.4. Suggestions for Cycling Parking

To improve the service level of bike parking infrastructures, new infrastructures should be evenly distributed throughout the city, especially for the areas with high demand of cycling traffic. Near the entrances of shopping malls, office buildings should have more parking infrastructures to make the bikes placed in an orderly manner.

5.4. Limitations and Recommendations

Because of the quality of cycling accidents data, the lack of design factor data, and the limited spatial analysis tools, there are many limitations of this research.

Some records' attributes in accidents data are missing. Such as, some accidents do not have severity level; some do not have traffic models involved in the accidents; some data do not have records of severity class. The design factors data used in this research was all collected from the fieldwork. There is not dataset about design factors for each road in Curitiba. Besides that, there are also some problems of the cycling accident locations. For instance, some records of location just have a name of the street, without building number or the description of specific reference of the location; some data records just has name of road and neighborhood but no specific locations. For these accidents, they cannot be digitized. These data missing cause that some analysis cannot be done properly. Although, for some of them, the approximate locations could be found by using the name of roads. Because of that, for the analyses of numbers of accidents happened along different types of cycling lanes and BRT lines, the result could have some deviation compared with the actual.

For the future research, more design factor data should be collected. For instance, based on the result from my research, type of cycling lanes, width of cycling lanes, and speed of vehicles are crucial factors. These factors data should be collected by the police or first aid organizations when the accidents happening. In addition, if the time was plenty, design factor data for other accident points should be collected, in order to have a comprehensive understanding of the accidents. After that, quantitative analysis could be done to find out the relationship between the accidents severity and street design factors. Besides that, some evaluation of cycling safety in other places can be done as well. The cause analysis of accidents in other high-density areas or other places should be done at the same time to have a perspective of the reasons of accidents happening. After that, improvement and new implementations could be done to provide a safer environment for cyclists.

Functions of spatial analysis tools are limited. In the spatial pattern detection part, kernel density estimation was applied. However, the kernel density tool in ArcGIS is not a network based tool. For the cycling accidents, which indeed just can happen in the roads, that tool is not suitable. SANET is a network based analysis tool boxes. But SANET has another limitation. Users cannot set weight of points in SANET. This is different from the tool in ArcGIS. In ArcGIS, the tool can be set different weight to consider about the impact of different level of points data. For instance, using the weight of points based on the cost of different severities. That way can give fatal accidents much more impact than non-fatal accidents. And then the black spots may be found in different areas.

Because of that, one future improvement can be doing a network based kernel density estimation based on different weight of accident points' severities.

LIST OF REFERENCES

Al-Ghamdi, A. S. (2002). Using logistic regression to estimate the influence of accident factors on accident severity. *Accident Analysis and Prevention*, *34*(6), 729–741. http://doi.org/10.1016/S0001-4575(01)00073-2

Andegiorgish, A. K., Wang, J., Zhang, X., Liu, X., & Zhu, H. (2012). Prevalence of overweight, obesity, and associated risk factors among school children and adolescents in Tianjin, China. *European Journal of Pediatrics*, *171*(4), 697–703. http://doi.org/10.1007/s00431-011-1636-x

Anderson, T. K. (2007). Comparison of spatial methods for measuring road accident "hotspots": a case study of London. *Journal of Maps*, *3*(1), 55–63. http://doi.org/10.1080/jom.2007.9710827

Austroads. (2014). *Cycling Aspects of Austroads Guides Quick Reference*.

Beck, L. F., Dellinger, A. M., & O'Neil, M. E. (2007). Motor vehicle crash injury rates by mode of travel, United States: using exposure-based methods to quantify differences. *American Journal of Epidemiology*, *166*(2), 212–8. http://doi.org/10.1093/aje/kwm064

BRASIL. (2007). *Programa Brasileiro de Mobilidade por Bicicleta-Bicicleta Brasil Caderno de Referência para elaboração de: Plano de Mobilidade por Bicicleta nas Cidades*. Retrieved from http://www.cidades.gov.br/images/stories/ArquivosSEMOB/Biblioteca/LivroPlanoMobilidade.pdf

Brimicombe, A. J. (2004). On Being More Robust About " Hot Spots ." *Analyst, The*.

Cambridge Cycling Campaign. (2014). Making Space for Cycling: A guide for new developments and street renewals.

CET. (2014). Espaço Cicloviário (Vol. 13).

Christchurch City Council. (2013). *Christchurch Cycle Design Guidelines*.

CONTRAN. (2007). VOLUME IV Sinalização Horizontal (Vol. IV, p. 128).

CROW. (2006). *Ontwerpwijzer fietsverkeer [Design guide for cycling facilities]*. CROW publication 230, Ede.

Cycling by Design 2010. (2011). Retrieved from www.transportscotland.gov.uk

De Rome, L., Boufous, S., Georgeson, T., Senserrick, T., Richardson, D., & Ivers, R. (2014). Bicycle crashes in different riding environments in the Australian capital territory. *Traffic Injury Prevention*, *15*(1), 81–8. http://doi.org/10.1080/15389588.2013.781591

Falcocchio, J. C., & Levinson, H. S. (2015). *Road Traffic Congestion□ : A Concise Guide*. Retrieved from http://www.eblib.com

Flynn, B. S., Dana, G. S., Sears, J., & Aultman-Hall, L. (2012). Weather factor impacts on commuting to work by bicycle. *Preventive Medicine*, *54*(2), 122–124. http://doi.org/10.1016/j.ypmed.2011.11.002

GEIPOT. (2001). *Planejamento Cicloviário: Diagnóstico Nacional*.

Gladhill, K., & Monsere, C. M. (2012). Exploring Traffic Safety and Urban Form in Portland, Oregon. *Transportation Research Record: Journal of the Transportation Research Board*, *2318*(1), 63–74. http://doi.org/10.3141/2318-08

Globe Award. (2010). The Brazilian city Curitiba awarded the Globe Sustainable City Award 2010. Retrieved January 1, 2016, from http://globeaward.org/winner-city-2010.html

Gössling, S., & Choi, A. S. (2015). Transport transitions in Copenhagen: Comparing the cost of cars and bicycles. *Ecological Economics*, *113*, 106–113. http://doi.org/10.1016/j.ecolecon.2015.03.006

IBGE. (2016). Population estimate - 2016. Retrieved November 7, 2016, from http://cidades.ibge.gov.br/xtras/temas.php?lang=_EN&codmun=410690&idtema=130&search=parana%257Ccuritiba%257Cpopulation-estimate-2016-

IGS - University of Twente. (2015). University of Twente's Research Institute IGS Signs Memorandum of Understanding with Curitiba, Brazil. Retrieved August 23, 2016, from https://www.utwente.nl/igs/archive/!/2015/10/291834/university-of-twentes-research-institute-igs-signs-memorandum-of-understanding-with-curitiba-brazil

IPPUC. (2010). 2010 a 2015 - A revisão do Plano Diretor. Retrieved February 12, 2017, from http://www.ippuc.org.br/mostrarlinhadotempo.php?pagina=17&idioma=1&tipo=&posicao=0&titulo=2010 a 2015&ampliar=sim

Kim, J. K., Kim, S., Ulfarsson, G. F., & Porrello, L. A. (2007). Bicyclist injury severities in bicycle-motor vehicle accidents. *Accident Analysis and Prevention*, *39*(2), 238–251. http://doi.org/10.1016/j.aap.2006.07.002

Kim, M., Kim, E., Oh, J., & Jun, J. (2012). Critical factors associated with bicycle accidents at 4-legged signalized urban intersections in South Korea. *KSCE Journal of Civil Engineering*, *16*(4), 627–632. http://doi.org/10.1007/s12205-012-1055-1

Koch, J., Lindau, L. A., & Nassi, C. D. (2013). Transportation in the Favelas of Rio de Janeiro (Working Paper). *Lincoln Institute of Land Policy*, 97.

Kumar, A., Nguyen, V. A., & Teo, K. M. (2016). Commuter cycling policy in Singapore: a farecard data analytics based approach. *Annals of Operations Research*, *236*(1), 57–73. http://doi.org/10.1007/s10479-014-1585-7

Lawrence, B. M., Stevenson, M. R., Oxley, J. A., & Logan, D. B. (2014). Geospatial Analysis of Cyclist Injury Trends: An Investigation in Melbourne, Australia. *Traffic Injury Prevention*, *16*(5), 513–518. http://doi.org/10.1080/15389588.2014.973947

Lee, B. H. Y., Schofer, J. L., & Koppelman, F. S. (2005). Bicycle safety helmet legislation and bicycle-related non-fatal injuries in California. *Accident Analysis and Prevention*, *37*(1), 93–102. http://doi.org/10.1016/j.aap.2004.07.001

Loidl, M., Traun, C., & Wallentin, G. (2016). Spatial patterns and temporal dynamics of urban bicycle crashes-A case study from Salzburg (Austria). *Journal of Transport Geography*, *52*, 38–50. http://doi.org/10.1016/j.jtrangeo.2016.02.008

Lonelyplanet. (2016). Curitiba. Retrieved August 23, 2016, from https://www.lonelyplanet.com/brazil/the-south/curitiba

Loo, B. P. Y., & Tsui, K. L. (2010). Bicycle crash casualties in a highly motorized city. *Accident Analysis and Prevention*, *42*(6), 1902–1907. http://doi.org/10.1016/j.aap.2010.05.011

Medeiros, R. M., & Duarte, F. (2013). Policy to promote bicycle use or bicycle to promote politicians? Bicycles in the imagery of urban mobility in Brazil. *Urban, Planning and Transport Research*, *1*(1), 28–39. http://doi.org/10.1080/21650020.2013.866875

Ministerie van Infrastructuur en Milieu. (1990). *Road Traffic Signs and Regulations in the Netherlands*.

Miranda, H. de F., & Rodrigues da Silva, A. N. (2012). Benchmarking sustainable urban mobility: The case of Curitiba, Brazil. *Transport Policy*, *21*, 141–151. http://doi.org/10.1016/j.tranpol.2012.03.009

Mulvaney, C. A., Smith, S., Watson, M. C., Parkin, J., Coupland, C., Miller, P., … McClintock, H. (2015). Cycling infrastructure for reducing cycling injuries in cyclists. *The Cochrane Database of Systematic Reviews*, *12*(12), CD010415. http://doi.org/10.1002/14651858.CD010415.pub2

Murthy, N., & Rao, R. S. (2015). Development of model for road accidents based on intersection parameters using regression models. *International Journal of Scientific and Research Publications*, *5*(1), 1–8.

Noland, R. B., & Kunreuther, H. (1995). Short-run and long-run policies for increasing bicycle transportation for daily commuter trips. *Transport Policy*, *2*(1), 67–79. http://doi.org/10.1016/0967-070X(95)93248-W

Okabe, A., Okunuki, K. I., & Shiode, S. (2006). SANET: A toolbox for spatial analysis on a network. *Geographical Analysis*, *38*(1), 57–66. http://doi.org/10.1111/j.0016-7363.2005.00674.x

Okabe, A., Okunuki, K., & SANET Team. (2015). SANET. Retrieved November 18, 2016, from http://sanet.csis.u-tokyo.ac.jp/index.html

Okabe, A., Satoh, T., & Sugihara, K. (2009). A kernel density estimation method for networks, its computational method and a GIS-based tool. *International Journal of Geographical Information Science*, *23*(1), 7–32. http://doi.org/10.1080/13658810802475491

OpenStreetMap contributors. (2015). Planet dump. Retrieved from http://planet.openstreetmap.org

Peden, M., Schurfield, R., Sleet, D., Mohan, D., Hyder, A. A., Jarawan, E., & Mathers, C. (2004). *World report road traffic injury prevention*. *Public Health* (Vol. 120). Retrieved from http://linkinghub.elsevier.com/retrieve/pii/S003335060500212X

Perkons. (2014). Traffic calming. Retrieved August 23, 2016, from http://www.transitoideal.com/pt/artigo/4/educador/100/traffic-calming

Porta, S., Strano, E., Iacoviello, V., Messora, R., Latora, V., Cardillo, A., … Scellato, S. (2009). Street centrality and densities of retail and services in Bologna, Italy. *Environment and Planning B: Planning and Design*, *36*(3), 450–465. http://doi.org/10.1068/b34098

Prefeitura Municipal de Curitiba. (2013). History of the City. Retrieved October 26, 2016, from http://www.curitiba.pr.gov.br/idioma/ingles/historia

Prefeitura Municipal de Curitiba. (2015). Estrutura Cicloviária. Retrieved November 4, 2016, from http://www.curitiba.pr.gov.br/conteudo/mais-bici-estrutura-cicloviaria/2221

Rabinovitch, J., & Hoehn, J. (1995). A Sustainable Urban Transportation System: The "Surface Metro" In Curitiba, Brazil, (608). Retrieved from http://purl.umn.edu/11886

Richards, D. . (2010). *Relationship between Speed and Risk of Fatal Injury: Pedestrians and Car Occupants*. *Road Safety Web Publication*. Retrieved from http://www.dft.gov.uk/pgr/roadsafety/research/rsrr/theme5/researchreport16/doc/rswp16.doc

Roads and Traffic Authority of New South Wales. (2008). Speeding Fact Sheet 4 - How does speeding increase the severity of a crash? (pp. 11–14).

Rosén, E., & Sander, U. (2009). Pedestrian fatality risk as a function of car impact speed. *Accident Analysis & Prevention*, *41*(3), 536–542. http://doi.org/10.1016/j.aap.2009.02.002

Rowley, J. (2002). Using case studies in research. *Management Research News*, *25*(1), 16–27. http://doi.org/10.1108/01409170210782990

Rui, Y., & Ban, Y. (2014). Exploring the relationship between street centrality and land use in Stockholm. *International Journal of Geographical Information Science*, *28*(7), 1425–1438. http://doi.org/10.1080/13658816.2014.893347

Schepers, J. P., & Heinen, E. (2013). How does a modal shift from short car trips to cycling affect road safety? *Accident Analysis & Prevention*, *50*, 1118–1127. http://doi.org/10.1016/j.aap.2012.09.004

Schepers, P., Twisk, D., Fishman, E., Fyhri, A., & Jensen, A. (2015). The Dutch road to a high level of cycling safety. *Safety Science*. http://doi.org/10.1016/j.ssci.2015.06.005

Schuurman, N., Cinnamon, J., Crooks, V. A., & Hameed, S. M. (2009). Pedestrian injury and the built environment: an environmental scan of hotspots. *BMC Public Health*, *9*(1), 233. http://doi.org/10.1186/1471-2458-9-233

Strauss, J., Miranda-Moreno, L. F., & Morency, P. (2013). Cyclist activity and injury risk analysis at signalized intersections: A Bayesian modelling approach. *Accident Analysis and Prevention*, *59*, 9–17. http://doi.org/10.1016/j.aap.2013.04.037

Theofilatos, A., Graham, D., & Yannis, G. (2012). Factors affecting accident severity inside and outside urban areas in Greece. *Traffic Injury Prevention*, *13*(5), 458–67. http://doi.org/10.1080/15389588.2012.661110

Thomas, B., & De Robertis, M. (2013). The safety of urban cycle tracks: A review of the literature. *Accident Analysis and Prevention*, *52*, 219–227. http://doi.org/10.1016/j.aap.2012.12.017

Tony, C. (2016). Fortunately We Are Still Learning. Retrieved January 31, 2017, from http://allfamoustogether.blogspot.nl/2016/04/fortunately-we-are-still-learning.html

Tschakert, P., Zimmerer, K., King, B., Baum, S., & Wang, C. (2016). Sustainable Urban Development and Urban Farming. Retrieved August 23, 2016, from https://www.e-education.psu.edu/geog030/node/371

Van Der Horst, A. R. A., De Goede, M., De Hair-Buijssen, S., & Methorst, R. (2014). Traffic conflicts on bicycle paths: A systematic observation of behaviour from video. *Accident Analysis and Prevention*, *62*, 358–368. http://doi.org/10.1016/j.aap.2013.04.005

Vandenbulcke, G., Thomas, I., & Int Panis, L. (2014). Predicting cycling accident risk in Brussels: A spatial case–control approach. *Accident Analysis & Prevention*, *62*, 341–357. http://doi.org/10.1016/j.aap.2013.07.001

Wang, C., Lu, L., & Lu, J. (2014). Statistical Analysis of Bicyclists' Injury Severity at Unsignalized Intersections. *Traffic Injury Prevention*, *9588*(October 2014), 37–41. http://doi.org/10.1080/15389588.2014.969802

Wang, Y., & Nihan, N. L. (2004). Estimating the risk of collisions between bicycles and motor vehicles at signalized intersections. *Accident Analysis and Prevention*, *36*(3), 313–321. http://doi.org/10.1016/S0001-4575(03)00009-5

Wegman, F., Zhang, F., & Dijkstra, A. (2012). How to make more cycling good for road safety? *Accident Analysis and Prevention*, *44*(1), 19–29. http://doi.org/10.1016/j.aap.2010.11.010

Welle, B. (2015). Want a cycling city? Design for traffic safety. Retrieved June 1, 2016, from http://thecityfix.com/blog/world-bicycle-forum-2015-medellin-colombia-safe-urban-cycling-street-design-ben-welle/

Welle, B., Li, W., Adriazola, C., King, R., Obelheiro, M., Sarmiento, C., & Liu, Q. (2015). *Cities safer by design: guidance and examples to promote traffic safety through urban and street design*.

World Health Organization. (2015). *Global Status Report on Road*. Retrieved from www. who.int

Yan, X., Ma, M., Huang, H., Abdel-Aty, M., & Wu, C. (2011). Motor vehicle-bicycle crashes in Beijing: Irregular maneuvers, crash patterns, and injury severity. *Accident Analysis and Prevention*, *43*(5), 1751–1758. http://doi.org/10.1016/j.aap.2011.04.006

Yiannakoulias, N., Bennet, S. A., & Scott, D. M. (2012). Mapping commuter cycling risk in urban areas. *Accident Analysis and Prevention*, *45*, 164–172.

Zottis, L. (2015). Using Bikes to Improve Mobility in Rio de Janeiro's Favelas. Retrieved August 17, 2016, from http://thecityfix.com/blog/using-bikes-improving-mobility-rio-de-janeiro-favelas-luisa-zottis/