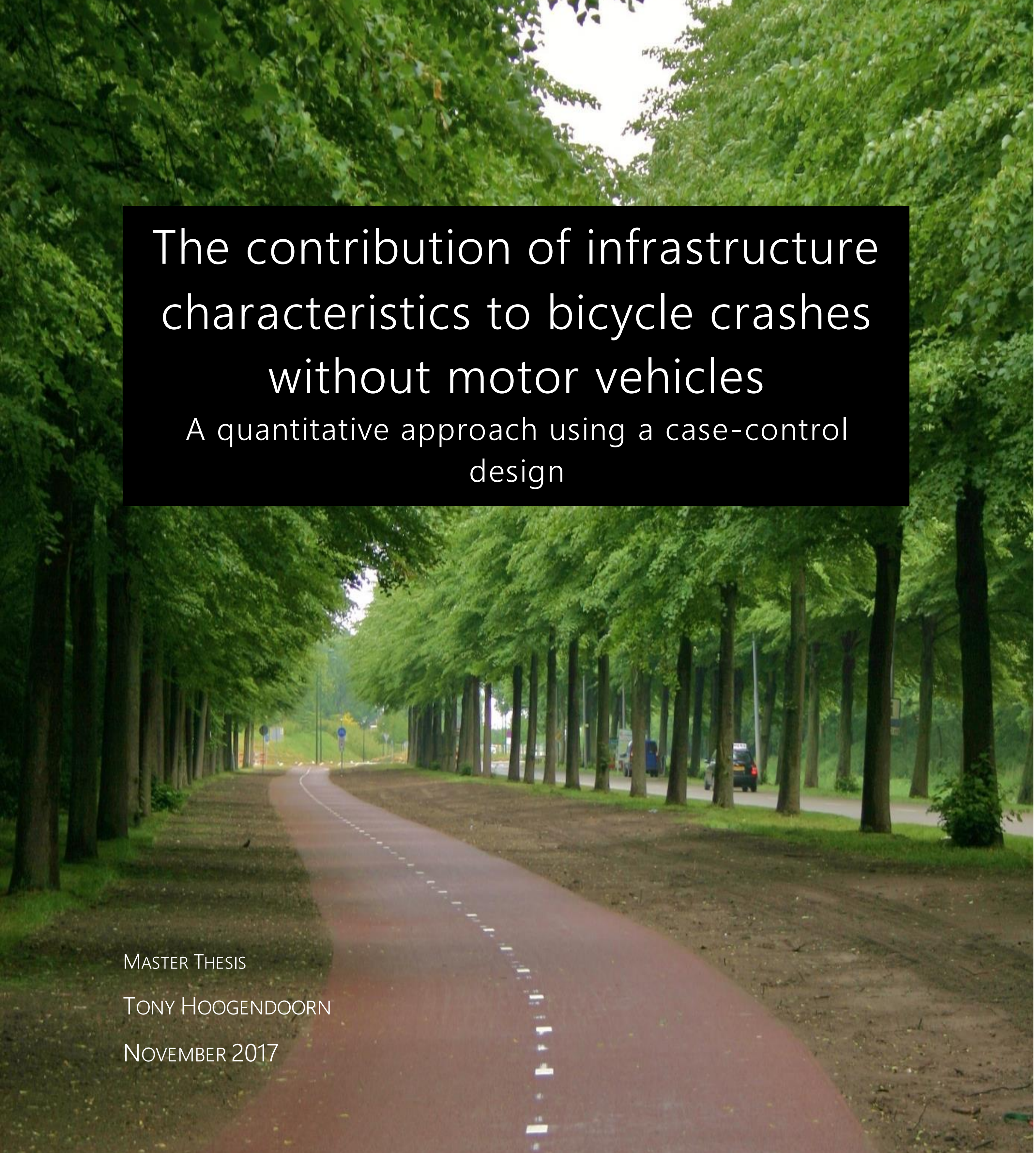

The contribution of infrastructure characteristics to bicycle crashes without motor vehicles

A quantitative approach using a case-control design

MASTER THESIS

TONY HOOGENDOORN

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TU Delft
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Rijkswaterstaat
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veiligheid nl

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A quantitative approach using a case-control design

by

Tony Hoogendoorn

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Thesis committee:

Delft University of Technology	
Prof. dr. M.P. Hagenzieker (Chair)	Faculty of Civil Engineering and geosciences/ Department Transport and Planning
dr. ir. H Farah (Supervisor)	Faculty of Civil Engineering and geosciences/ Department Transport and Planning
dr. S. Sillem	Faculty of Technology, Policy and Management/ Department values, technology and innovation
Rijkswaterstaat	
dr. P. Schepers (External supervisor)	Organizational Unit Water, Traffic and Environment
VeiligheidNL	
H. Valkenberg	Data analyst/ Organisational unit Work and Leisure

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Preface

This thesis contains the investigation of the contribution of infrastructure characteristics to bicycle crashes without motor vehicles. The recent and ongoing growth of the number of injured cyclists cannot be denied and is often recurring in the media. The social relevance and the determination of Rijkswaterstaat to further improve the safety for cyclists got me really enthusiastic on this topic. Contributing to the extension of knowledge on the causes of bicycle crashes can really help improving this safety.

I would like to thank Rijkswaterstaat for the opportunity of doing this thesis within their organization. Specifically, I would like to thank Paul Schepers for being my supervisor at Rijkswaterstaat who provided me help during the research period. Paul provided me with valuable input for this thesis including new ideas for developing the method and insight in specific infrastructure characteristics which were interesting. Moreover, the enthusiastic way in which Paul lend an ear encouraged me to pursue a thorough thesis.

Within the TU Delft, I especially want to thank Haneen Farah for her insightful reviews on the work I performed, on the writing style and report set-up. Moreover, Haneen kept me focussed and because of that, I reconsidered a lot of my work in a positive way. Marjan Hagenzieker as the chair of my thesis committee and Simone Sillem as external supervisor, I want to thank them for their critical point of view on the thesis which they provided during the meetings we had.

The research was not possible without the data and help of VeiligheidNL. Within VeiligheidNL, Huib Valkenberg provided me the data of interest and helped me in understanding the structure of it. Allowing me to several meetings with professionals in the bicycle safety field, provided me with even more insight in this field of practice for better performing this study.

Finally, thanks to my family and friends for their support and encouragement during this project. Especially to my girlfriend Kelly, who was able to support me with a listening ear and provide me with clear input from an outsider. She was also able to get me off of my work when I was stuck on the topic, in order to clear my mind and remain motivated during the whole research time.

Tony Hoogendoorn

Delft, November 2017

Summary

Cycling is one of the main transport modes in the Netherlands. This is due to the fact that the country is flat, has a tempered climate and has long-time cycling supporting policies. Currently, the total number of bicycles and the total cycling distances are still rising. Although this seems a positive development, the number of seriously injured cyclists due to bicycle crashes without motor vehicles also increased rapidly in recent years. These crashes are further divided in single-bicycle, bicycle-bicycle and pedestrian-bicycle crashes (resp. crashes without other road users, with other cyclists and with pedestrians). Because of a low share (2%) of pedestrian-bicycle crashes, these are not in the scope of this study. Within these crashes the infrastructure seems to play an important role and research towards the contribution of infrastructure characteristics is needed.

The current knowledge on the contribution of infrastructure characteristics to bicycle crashes without motor vehicles is limited and especially research on more detailed infrastructure characteristics (e.g. bicycle path width) has not been done yet. Moreover, this knowledge was also obtained from studies with a qualitative nature in which results could be interpreted differently because the judgement whether the infrastructure characteristics contributed to the crash was done by the victim (by reporting the crash characteristics) or the researcher(s) (by making qualitative conclusions). For instance, researchers have suggested that too narrow bicycle paths contribute to bicycle crashes, but quantitative research is needed to study whether there exists an actual correlation.

This research aims to fill in parts of the knowledge gap between the safety problem and the lack of research done on the contribution of infrastructure characteristics. The research question that was answered is: *Which infrastructure characteristics contribute to the occurrence of bicycle crashes without motor vehicles?* For studying these characteristics a case-control method was used, but no suitable method was found for this specific purpose in the available literature. Therefore a second research question was formulated: *Which case-control method design, including a framework for selecting control locations, can be applied when studying bicycle crashes without motor vehicles?*

This study was done by using data from a survey held by VeiligheidNL. This survey was distributed in 13 hospitals in the Netherlands from January until December 2016. In total, 3146 cyclists that were treated at an emergency department (no fatalities) responded to the survey and provided information on the crash location, the crash type, the trip origin and further personal and medical details. In addition, cycling intensities were used and retrieved from the Dutch bicycle counting week held in 2016. This data includes counted cycling intensities of almost all road sections in the Netherlands.

The applied case-control method in this study compares infrastructure characteristics of case (crash) and control locations (no crash). The control locations were selected from the route of a bicycle crash victim. The design of the method included basic steps for the selection of the controls and four extensions (measures) for lowering bias in the method and increasing the statistical power of the results. The bias is lowered by introducing matching, which limits the variability of the confounder (cycling intensity) between the cases and controls. Also, an increased quality of the route reconstruction, in which the route was determined upon the trip purpose, reduced the bias in the method. The statistical power was increased by selecting more controls from a route and by selecting a control from a route of another bicycle crash victim with comparable personal and circumstantial conditions (when information of the route was lacking for the original cyclist).

With the application of the case-control method to the data, the following results were found:

- Collisions with bollards are more likely to occur when the width between the bollard and the edge of the bicycle path is smaller.
- The likelihood of having a handlebar collision (crash in which two cyclists collided into each other with their handlebars) when cycling next to each other increases on narrower streets.

- The likelihood of riding off the road crashes is higher when cycling on narrower streets and bicycle paths.
- Riding off the road crashes occur on narrower streets and bicycle paths as compared to kerb collisions.
- Kerb collisions are less likely to occur at intersections as compared to straight and curved road sections. The likelihood of kerb collisions is even lower when cycling on street intersections as compared to straight and curved streets. All the control locations in this analysis were also exposed to kerbs and therefore this result represents the likelihood of a kerb collision in case these are present.
- Cycling on intersections induces a higher likelihood of having a bicycle crash compared to riding on straight or curved road sections. Especially crashes with motor vehicles (N.B. not in the scope of the study, but an interesting finding) are more likely to occur on intersections than on straight or curved road sections.
- Cycling on two-directional bicycle paths increases the likelihood of having a bicycle crash without motor vehicles in comparison to one-directional bicycle paths. Especially bicycle-bicycle crashes are more likely to occur on two-directional bicycle paths compared to one-directional bicycle paths.
- A collision with a bollard results in more severe injuries compared to other single-bicycle crashes without obstacles.
- Frontal bicycle-bicycle crashes result in more severe injuries than same direction bicycle-bicycle crashes.

The results thus clearly show that some infrastructure characteristics contribute to the occurrence of bicycle crashes without motor vehicles. First, the *width of streets* contributes to riding off the road crashes and handlebar collisions, whereas the *width of bicycle paths* next to bollards contributes to crashes with these objects. Secondly, *the presence of intersections* decreases the likelihood of kerb collisions. Thirdly, *two-directional bicycle paths* are more likely to induce bicycle-bicycle crashes and they possibly induce more severe crashes because frontal collisions are more severe than same direction bicycle-bicycle crashes. And finally, the *placement of bollards* increases the severity of the injuries caused by the corresponding crashes.

Furthermore, the developed case-control method was found effective for the intended purpose, because highly detailed infrastructure characteristics (e.g. road widths) were analysed. On top of that, the number of generated controls was increased with roughly 20% by the two extensions, which was beneficial because otherwise the results were more likely to turn out insignificant, due to a lower amount of analysable data.

Although this study was carried out successfully further research is recommended. The method can mainly be improved by further refining the route reconstruction in the method to retrieve more reliable routes. Moreover, this study adds to the knowledge on bicycle safety but many other infrastructure characteristics that contribute to bicycle crashes without motor vehicles can be studied to further improve the future safety of cycling.

Contents

Chapter 1 Introduction

This research focusses on the contribution of infrastructure characteristics to bicycle crashes without motor vehicles. This introduction chapter is composed of the following sub-sections. The background (section 1.1) provides a short introduction to bicycle safety in the Netherlands and the relevance of studying infrastructure characteristics in relation to bicycle crashes. Following this, the problem definition is introduced in section 1.2 and the research goal is defined in section 1.3. Based on this, the main research questions are formulated (section 1.4) and the research approach is defined (section 1.5).

1.1 Background

In contrast to a lot of other countries in the world, cycling is an important transport mode in the Netherlands. Multiple reasons can explain this (Wardlaw, 2014). First, the history of our spatial planning made the Dutch very devoted to their bicycles. As most of the distances in cities towards services are pretty short, the bicycle is a good alternative for motorized traffic: car and public transport. However the bicycle is also often used in combination with public transport. Second, the policies in the Netherlands supported the growth of the cycling infrastructure which increased the attractiveness of this transport mode. As an example: the main road network (highways) in the Netherlands is 2,500 kilometre long, while our cycling network length is 35,000 kilometre (CBS, 2017).

It is estimated that there are 22 million bicycles and 17 million inhabitants in the Netherlands (KiM, 2015). The Dutch use the bicycle in 27% of the trips they make. In recent years the number of trips and the length per trip have increased, partly as a result of the introduction of the e-bike. The e-bike also led to a higher usage of this transport mode among elderly people (Kruijer et. al, 2012). Moreover, figures from recent years show that also the number of seriously injured cyclists due to bicycle crashes increased rapidly (Weijermans, et al. 2016). Especially the number of injured cyclists in bicycle crashes without motor vehicles in contradiction to injured cyclists in bicycle-motor vehicle crashes (Berveling & Derriks, 2012). Because of this recent development, the focus of this study is on bicycle crashes without motor vehicles.

Kruijer, et al. (2012) showed that in 2012 67% of all bicycle crashes were single-bicycle crashes (bicycle crashes without any other traffic participant). Teschke (2014) confirms this high number of single-bicycle crashes. Moreover, 52% of all injured people in traffic result from single-bicycle crashes (Weijermans, et al, 2016). So, this group is substantial and dedicated research on these crashes can help to find ways to mitigate these types of crashes. The causes of these specific crashes could be related to infrastructure, cycling control, bicycle defects and external forces. The infrastructure contributes to almost half of all single-bicycle crashes (Schepers & Klein Wolt, 2012).

Furthermore, 12% of all emergency department treated cyclists are caused by bicycle-bicycle crashes (crash between two or more bicyclists). The width of bicycle paths and other infrastructural characteristics are suggested to contribute to this type of bicycle crashes (Schepers, 2010). Also, bicycle-pedestrian crashes (crash between bicyclists and pedestrians) are occurring, but according to Schepers (2010) this covers only 2% of all bicycle crashes and are therefore left out of the scope of this study. Nevertheless, part of these crashes could also be related to infrastructure as well.

The infrastructure seems to play an important role in the causation of bicycle crashes without motor vehicles. Improved knowledge on the contribution of infrastructure characteristics can therefore help improve the safety of bicycle infrastructure. According to a literature review done by Schepers (2013), not much research was performed on this specific topic. A first step was made with a detailed empirical research towards infrastructure related bicycle crashes, which was performed by Schepers (2008). This resulted in a list of risky infrastructure characteristics and provides a good overview of the possible contribution of several infrastructure characteristics. Other studies resulted in risks of e.g. cycling on different route types with various infrastructure characteristics (Teschke, 2012) (Vandenbulcke et al., 2014). However, research on a much more detailed level (e.g. influence of bicycle path width) is rarely done.

In order to improve the design of bicycle paths for a safer future, Rijkswaterstaat wants to extend the current knowledge on bicycle crashes. This knowledge can be used for different purposes. Bicycle guidelines (CROW, 2016) which are applied in the infrastructure design can benefit from the increased scientific knowledge resulting from this research. Moreover, the ANWB (Royal Dutch Touring Club) introduced the application CycleRAP for further improving road safety (Wijlhuizen et al., 2016). In this application, a RPS (Road Protection Score) is given to the infrastructure, such that the risk of having a bicycle crash at actual bicycle infrastructure is known. The RPS is based on knowledge on the risks of an extensive set of road factors.

1.2 Problem definition

The current knowledge on the contribution of infrastructure characteristics to bicycle crashes without motor vehicles is limited and partly obtained from studies with a qualitative nature. The results from these qualitative studies could be interpreted differently because the judgement whether the infrastructure characteristics contributed to the crash was done by either the victim (by reporting the crash characteristics) or the researcher(s) (by making qualitative conclusions). For instance, researchers have suggested that too narrow bicycle paths contribute to collisions with kerbs and collisions between cyclists but a quantitative underpinning was missing. Quantitative research is needed to study whether there is a correlation between bicycle path widths and bicycle crashes. Nevertheless, several infrastructure characteristics were analysed quantitatively (e.g. the road type) (Teschke, 2012) (Vandenbulcke, 2014) and provided good insights into the actual risks. However, the number of analysed characteristics was rather limited and many other characteristics can also be examined. Especially research on more detailed infrastructure characteristics, such as bicycle path dimensions (e.g. bicycle path width), had not been done yet.

1.3 Research goals

The primary goal of this research is to provide further insights and identify which infrastructure characteristics contribute to bicycle crashes without motor vehicles. The research will mostly be an extension of the current state of the art of bicycle safety research. Quantitative research is needed to estimate the degree to which infrastructure characteristics play a role in these crashes. With these results, the design guidelines can be improved with respect to the actual risks of infrastructure characteristics. Policy makers can accordingly develop policies to possibly improve the quality (safety) of the infrastructure.

The second aim of the study is to develop a case-control method for analyzing the contribution of specific infrastructure characteristics. VeiligheidNL and Rijkswaterstaat conducted a study on bicycle crashes (Valkenberg et al., 2016). Victims treated at an emergency department of a selection of hospitals received a questionnaire. In contrast to previous studies, victims were asked about the whereabouts of the crash and the origin of the route. The latter allows for reconstructing the most likely route and to select 'control locations' where the same person was cycling under roughly the same circumstances (e.g. weather conditions and alcohol use). Because of the availability of this data, this study will include the development of a case-control method for this specific purpose.

1.4 Research questions

Following the research goals, two main research questions were formulated, which will be answered at the end of the thesis:

MQ-I *Which case-control method design, including a framework for selecting control locations, can be applied when studying bicycle crashes without motor vehicles?*

MQ-II *Which infrastructure characteristics contribute to the occurrence of bicycle crashes without motor vehicles?*

1.5 Research approach

The research approach explains the steps that have been followed in this research in order to provide answers to research questions. The scheme in Figure 1.1 shows the relation between the research questions and the different parts of the research. The scheme also shows the temporal development of the research.

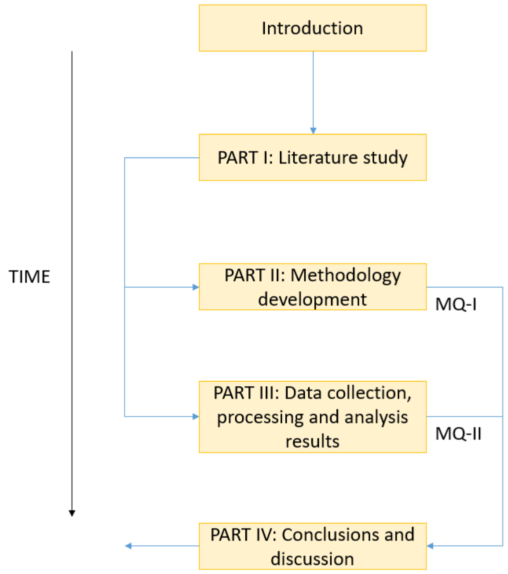


Figure 1.1: Research steps in relation to the main research questions

PART I Literature study

The literature study (Chapter 2) involved a literature review of the most important and relevant infrastructure characteristics which contribute to bicycle crashes without motor vehicles. Some literature concerning more general bicycle safety and guidelines on (bicycle)-infrastructure was reviewed as well. After this more general review, the infrastructure characteristics which contribute to bicycle crashes without motor vehicles were examined more closely. This literature review was expected to result in research hypotheses on the contribution of specific infrastructure characteristics to bicycle crashes without motor vehicles.

The objectives of the literature study were:
- Gain insight into the potentially relevant infrastructure characteristics that contribute to bicycle crashes without motor vehicles
- Formulate hypotheses on relevant infrastructure characteristics

PART II Methodology development

The main focus of this part was to develop a framework for a case-control method which is most applicable to the specific type of data and research questions (Chapter 3). The literature on case-control methods was used to provide insights into the possibilities for designing and using such a method. The aim was to design a framework that could be used for selecting control locations as direct and detailed as possible. First, the method requirements were composed, before designing the basic framework for this method. Second, the effectiveness and ease for determining the control location (how fast?), the data compatibility (how detailed?), the exclusion of bias (how reliable?) were improved by adding quality improving measures (extensions) to the basic framework. After a consideration of different extensions, this part resulted in one generic case-control framework.

Therefore the objectives of the methodology development were:
- Gain insight in case-control methods
- Provide the method requirements
- Provide a basic case-control method framework
- Provide multiple case-control extensions

PART III Data collection, processing and analysis results

The research hypotheses were examined by performing the developed case-control method. The data collection was done by VeiligheidNL and a fully digitalized data set was available for analysis purposes. The dataset, filled out by bicycle crash victims which were treated at an emergency department, contained various types of data:

- Road type
- Medical treatment
- Trip origin
- Cycling activities
- Crash location
- Bicycle type
- Circumstances
- Cyclist experience
- Personal information

The first part of the data analysis is an operationalization of the data in which useful and meaningful data was selected (Chapter 4). Especially three types of data (road type, crash location and trip origin) were useful for applying the case-control method. The information about the crash and departing location made it possible to describe the most likely route which is followed by the cyclist. Also cycling intensity data was included which was retrieved from the Dutch bicycle counting week. These routes were applied to the case-control framework, such that control locations could be selected, leading to results on the different hypotheses (Chapter 5).

The characteristics of the case and control location were gained by using street and aerial photography (which is available at Rijkswaterstaat via Cyclomedia) that contains detailed information/visualization of the infrastructure. With the obtained data from the case and control locations, statistical relations could be found. By using Chi square tests and binary logistic regression, the correlation between case and control locations was calculated. According to the statistical significance of the correlation, the hypotheses on infrastructure characteristics could be supported or rejected.

The objectives of the data collection, processing and results section were:
- Operationalizing of the data to retrieve relevant and meaningful data
- Retrieve statistical results of the relation between infrastructure characteristics and bicycle crashes without motor vehicles
- Support or reject the research hypotheses

PART IV Conclusions

The last part of this thesis consists of an overview of the results and findings in the previous parts. The results and conclusions of this study are presented and the research questions are answered. Furthermore, the discussion includes the interpretation of the results and the limitations of this study. Additionally, recommendations on the application in practice and the possibilities for further research are given.

PART I: Literature study

Chapter 2 Bicycle crash related road factors

This chapter concerns the literature study on relevant infrastructure characteristics which contribute to bicycle crashes without motor vehicles. Section 2.1 concerns a general overview of bicycle safety in which crash factors, crash severity and possible improvements for safer bicycle traffic are discussed briefly. The current scientific knowledge on the contribution of infrastructure characteristics to bicycle crashes without motor vehicles is given in section 2.2. Following from this literature review, research gaps and research hypotheses are formulated in section 2.3.

2.1 General bicycle safety

The Netherlands can be characterized as a country in which the bicycle is highly present and widely used, with a modal share of 27%. Compared to other European countries the Netherlands performs much better with respect to the modal share of bicycles. Only Denmark follows the Netherlands with a bicycle share of 20%. Most other countries have shares lower than 10% (KiM, 2011). However, cycling can also be seen as unsafe due to the vulnerability of cyclists. This is caused by the instability of two wheeled bikes and the highly unprotected appearance of the cyclist itself (Wegman & Aarts, 2005).

According to an extensive literature review on bicycle crashes, several factors were found that contribute to the safety problem of cycling (Reurings et al., 2012). In this section, a brief overview of these factors is given. Three main factors were mentioned by Reurings et al. (2012): the causation of bicycle crashes (section 2.1.1), the injury severity caused by these crashes (section 2.1.2) and the quality of design guidelines (section 2.1.3).

2.1.1 Bicycle crash causation factors

Factors that contribute to bicycle crashes can be identified as direct or latent. The direct factors relate to the primary cause of the crash: the infrastructure, the bicycle itself and the behaviour of the cyclist. Latent factors relate to other influences that affect these direct factors (e.g. different weather conditions) (Wagenaar & Reason, 1990). Schepers & Klein Wolt (2012) suggested a categorization of the direct factors for single-bicycle crashes, resulting in the crash types in Table 2.1. In addition, Schepers & Klein Wolt (2012) mentioned that bicycle crashes are almost always caused by a combination of these factors. Further research on infrastructure related causes can help improve bicycle safety.

Table 2.1: Single-bicycle crash categorization (Schepers & Klein Wolt, 2012)

	Crashes
1	Infrastructure related crashes a. Crash with infrastructure characteristics, preceded by the cyclist inadvertently taking a dangerous riding line b. Crash linked to road surface quality
2	Cyclist related crashes a. Loss of control at low speed when it requires more effort to stabilize the bicycle b. Loss of control due to (moving) baggage, that may have hit the front wheel c. Loss of control due to bad riding behaviour
3	Bicycle malfunction related crashes
4	Other crashes

Crash causation factors for bicycle-bicycle crashes are partly different. According to Schepers (2010), three specific causation categories of bicycle-bicycle crashes can be defined: the infrastructure, behaviour of the cyclist and bicycle related factors. The cyclists' behaviour is an important factor in bicycle-bicycle crashes compared to single-bicycle crashes, as good communication between road users is neccesary to avoid such crashes. For example, clear communication is necessary when crossing each other by giving or taking right of way.

2.1.2 Injury severity of bicycle crashes

The injury severity of bicycle crashes further emphasizes the safety problem caused by cycling. Knowledge on the impact of infrastructure characteristics could be valuable for designing a more forgivable bicycle infrastructure. However, not much research is found on the relation between injury severity and infrastructure characteristics. On the other hand, extensive research is done into the effects of bicycle crashes without motor vehicles to the injury severity.

It was found that part of the seriously injured road users occur in bicycle crashes without motor vehicles: 49% of the total seriously injured people in traffic (Weijermans & Stipdonk, 2015). These crashes also cause around 90% of all seriously injured cyclists. However, bicycle crashes with motor vehicles account for approximately 75% of all cycling fatalities (SWOV, 2013). Therefore bicycle crashes without motor vehicles are less severe but more frequent. Nevertheless, these bicycle crashes are still relevant for research because the number of injured cyclists could have a high influence on the direct and indirect medical costs (Gaither et al., 2017).

In general, bicycle crashes induce injuries categorized by injury to head, body, arms and legs. For crashes with motor vehicles, head injuries are the main category (40%). Crashes without motor vehicles cause injuries to legs (40%) and head (30%). Assuming that injuries to the head are more dangerous to the cyclists, the quantities imply that crashes with motor vehicles are more severe (van Kampen, 2008). Prevention of injuries can be accomplished by wearing protection (helmets), but the risk cannot totally be removed (Rivara et al., 1997).

In addition to this, the inequality factor (ratio of deaths/seriously injured between two different vehicles which crashed into each other) is much higher for crashes with motorized vehicles. For example, a car-bicycle crash is 32 times more lethal for the cyclist than a bicycle-bicycle crash (SWOV, 2012). Also following these factors, it can be concluded that bicycle crashes without motor vehicles are less dangerous than with motor vehicles.

2.1.3 Bicycle design guidelines

For the design of bicycle infrastructure, guidelines are compiled in the CROW Design Manual for Bicycle Traffic (CROW, 2016). The main assumption which is applied in this manual is 'Design for all'. Cyclists cannot be characterized as one general kind, because of high variations in physical condition and experience. Human abilities are most important and also need to be considered. Moreover, bicycle use is different compared to other traffic. A bicycle needs to be in balance when used and the cyclist has no protection against its environment. Therefore consistency and forgivingness of the infrastructure are important factors in the design task (CROW, 2016).

The design guidelines include advice on the design of the most important infrastructure characteristics. For example, design speeds are applied such that cyclists are able to maintain stability. Cyclists riding at low speeds on roads with slopes and high friction (e.g. due to wind) are sensitive for falling off their bikes. Highly related to the design speed is the deviation of cyclists with respect to their riding line which decreases with higher speeds. The standard clearance area obligatory for cyclists is related to the dimensions of the cyclists themselves and the behaviour with respect to obstacles on the road (Figure 2.1). Stability in curves also needs to be guaranteed by obtaining a minimum radius of 4-5 meters (Figure 2.2) (CROW, 2016).

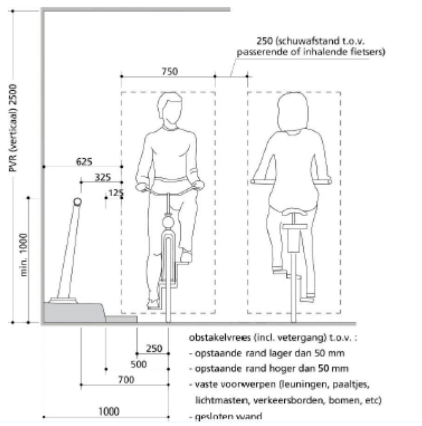


Figure 2.1: Clearance area of cyclists (CROW, 2016)

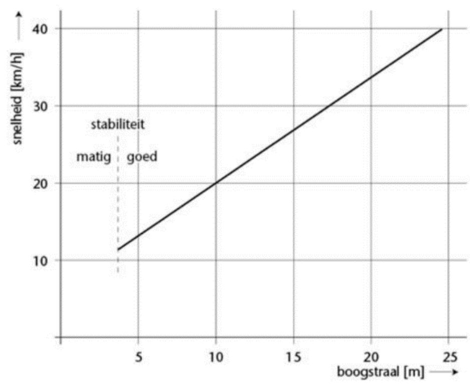


Figure 2.2: Curves and sight (CROW, 2016)

The design guidelines can assist in designing safe bicycle infrastructure. However, a study on the application of the guidelines and the level of compliance resulted in disappointing results. Almost half of all researched municipalities were not able to confirm the quality of their bicycle infrastructure with respect to the guidelines (Figure 2.3) (Bax et al., 2014). The low level of compliance was mainly caused by a limited space in the project area. On the other hand, unfamiliarity with the guidelines and political choices related to infrastructure design were other factors leading to a low compliance. Overall almost half of all road designers do not use the guidelines often, as can be seen in Figure 2.4 (Bax et al., 2014).

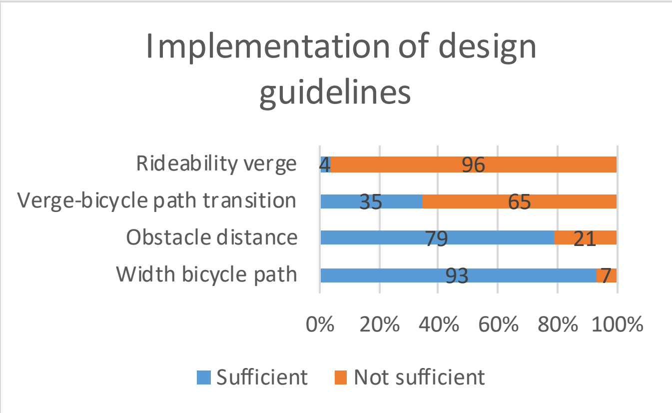


Figure 2.3: Compliance with guidelines on major crash contributing infrastructure characteristics (Bax et al., 2014)

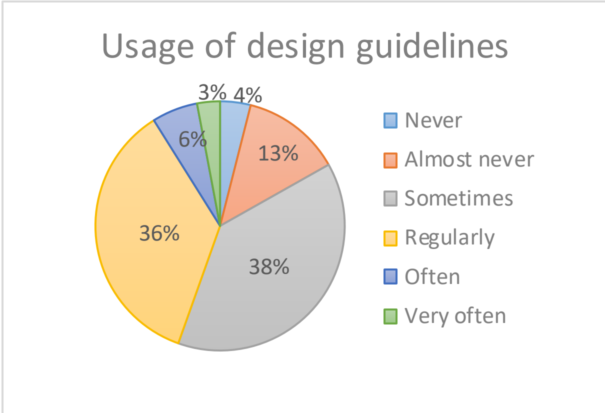


Figure 2.4: Use of design guidelines by road designers (Bax et al., 2014)

2.2 Infrastructural factors of bicycle crashes without motor vehicles

Infrastructural causes suggested in literature are reviewed for single-bicycle (section 2.2.1) and bicycle-bicycle crashes (section 2.2.2). In section 2.2.3 and 2.2.4 a review of spatial and temporal details of bicycle crashes without motor vehicles is given.

2.2.1 Infrastructural factors of single-bicycle crashes

Single-bicycle crashes cover more than two third of all bicycle crashes without motor vehicles. Schepers (2008) and Nyberg et al. (1996) performed studies on the contribution of infrastructure to single-bicycle crashes. In the study of Schepers (2008), bicycle crash victims at emergency departments were asked about the infrastructural cause(s) of their accidents. Only bicycle crashes that occurred on paved infrastructure were accounted for. Parked cars were included as well because they were characterized as objects and not as motor vehicles. This study resulted in the following seven main causes for single-bicycle crashes:

Slippery road surface

Construction materials in the road (metal, wood etc.) can lower the friction between the bicycle tire and the road, resulting in slippery road conditions. Weather related substances (snow and ice) can also increase the risk of having a crash, but this effect can be prevented by taking anti icing measures. Other materials as mud, sand and leaves also increase the risk and are most dangerous in curves (Schepers, 2008).

Although a lot of the single-bicycle crashes are caused by a slippery road surface, not much research is done on this specific topic. On the other hand, it might be questionable if more research into slippery road surfaces is needed, because in case of external materials on roads simply maintaining the infrastructure might be sufficient (Nyberg et al., 1996).

Collisions with kerbs

According to literature, collisions with kerb are a frequent accident type (Schepers, 2008). Most of the cyclists, who crashed into a kerb, had a wrong riding line and collided with the kerb, both on straight and curved road sections. The limited width of the bicycle paths was suggested to be one of the main infrastructural causes for colliding with a kerb. Also, the forgivingness of the drainage along the road and the appearance of the kerb (higher visibility) were suggested to be relevant for the occurrence of these crashes (Schepers, 2008).

Kerbs are mostly applied to separate pedestrians from car and bicycle traffic. However, kerbs were suggested to increase the risk of having a bicycle crash, but the usefulness (do they really separate different road users?) can be questioned (Schoon & Blokpoel, 2000) (Nyberg et al., 1996). A research into the safety of different types of kerbs was done by Janssen (2016). The behaviour of cyclists and pedestrians in relation to right, sloped and levelled kerbs was compared. The results showed that traffic participants (cyclists and pedestrians) mainly used dedicated infrastructure and rarely encroached to the other road users dedicated infrastructure, also in case of levelled kerbs.

Riding off the road

The limited width of bicycle paths limits the possibility of deviations in the riding line of the cyclist and can cause crashes. Also, the road course (e.g. curves) can cause riding off the road crashes. Moreover, the visibility of the edge of the infrastructure was found to be an important factor for riding off the road (Fabriek et al., 2012). Besides the characteristics of the road itself, the characteristics of the verge can also contribute to the crash risk. Too big height differences between the shoulder and the road, a too soft shoulder or infrastructural objects in the verge can lower the chance of returning to the road (Schepers, 2008). The design guidelines (CROW, 2016) suffice in providing good design parameters for safe bicycle infrastructure. (Semi-) hardened shoulders (Figure 2.5), clear edge of track markings (Figure 2.6) and sufficient street lighting can help guide the cyclists safely over the bicycle infrastructure (Schepers & den Brinker, 2011) (Fietsberaad, 2011).

Figure 2.5: Semi-hardened shoulders (Fietsberaad, 2011)

Figure 2.6: Clear edge of track markings (Fietsberaad, 2011)

Collisions with bollards and road narrowings

The main explanations for collisions with bollards are the lowered visibility and the reduced expectation of them on the road. It is suggested that these crashes happen more often within groups of cyclists because it can then happen that bollards are seen too late. Also, the limited space besides bollards can make manoeuvring along the road more difficult and this is suggested as one of the main causes; road narrowings including bollards are expected to be more dangerous (Schepers, 2008).

In recent years a discussion is going on about the usefulness of bollards. Most of the bollards are applied to prevent car traffic from driving on bicycle infrastructure, but it is argued that this goal does not outweigh the number of injured (and death) cyclists as a result of crashes with bollards (Zeegers, 2004). In addition, Zeegers (2004) analysed the design of 800 bollard locations and only one of them met the design guidelines (CROW, 2016). A correct implementation of the guidelines is given in Figure 2.7, including a white introducing marking before the bollard.

Figure 2.7: Implementation of a bollard according to the bicycle design guidelines (Fietsberaad, 2011)

Uneven road surface

An uneven road surface is highly related to a lack of structural maintenance of the infrastructure (presence of potholes and tree root damage). In addition, gaps between tiles and skewed tiles also create an uneven road-surface. Most of the crashes caused by a bad road surface resulted in a direct fall or a collision with a kerb. Cyclists maintaining higher speeds seems to have an increased crash probability due to an uneven road surface (Schepers, 2008).

Moreover, tram tracks also contribute to the number of single-bicycle crashes. Crash rates significantly reduce at approach angles higher than 30° (Ling et al., 2017). A possible solution to this problem was an improved route design (separated bicycle and tram infrastructure). However, prevention efforts such as individual knowledge and bicycle tire adaptations were also expected to be effective in solving this problem (Teschke et al., 2016).

Collisions with parked cars

In case parking facilities are missing, car drivers tend to park their cars parallel along the kerbs and road. A conflict will occur with the riding line of cyclists on a bicycle lane. This could induce an increased risk of cycling into a parked car or an opened car door (Schepers, 2008). On the other hand, parking facilities can also be designed next to bicycle infrastructure. Current standards for bicycle lanes insufficiently account for the door zone because cyclists tend to remain on the outer right side of the street even if the bicycle lane is not marked or in a shared space environment (Schimek, 2017). According to a study on German bicycle crashes, no significant difference was found for the severity of injuries on all body parts for car door crashes in comparison to all other bicycle crash victims (Jänsch et al., 2015).

2.2.2 Infrastructural factors of bicycle-bicycle crashes

According to Schepers (2010), bicycle-bicycle crashes can be categorized into three different groups: cyclists in equal cycling directions, crossing directions and opposing directions. Table 2.2 shows the distribution of all bicycle-bicycle crashes over these categories. Cycling in groups (more than one cyclist) contributed to a significant part of the bicycle-bicycle crashes. As a result of narrowing roads, combined with cyclists riding beside each other, crashes occur in which cyclists collide with each other with their handlebar or against each other's front or rear wheel (Schepers, 2010).

Table 2.2: Bicycle-bicycle crashes categorization (Schepers, 2010)

Type	Quantity (#)	Percentage (%)
Same direction crash	113	76
a) Front wheel against another back wheel	30	20
b) Handlebar crash	27	18
c) Side crash	26	18
d) Crash against cyclist in front	24	16
e) Crash when overtaking	6	4
Crossing direction crash	18	12
Opposing direction crash	17	11
Total	148	100

Also, the combination of narrow roads and overtaking or passing each other in opposing directions could increase the risk of cyclists colliding into each other. The relevance of minimum bicycle path widths with respect to bicycle safety is proved by van der Horst et al. (2013). A study using behavioural observations showed that narrower bicycle paths led to more risky situations, but crash risks were not part of their study. Moreover, the likelihood of bicycle-bicycle crashes increases in case the opposing cyclist was riding on the wrong side of a two-directional bicycle path. Especially in curves, cycling on the wrong side of the bicycle paths might be expected for cyclists riding in the outer curve (Bahrololoom et al., 2016).

2.2.3 Spatial details of bicycle crashes without motor vehicles

Road type

An important division which can be made in studying bicycle crashes is the typology of the bicycle infrastructure. The appearance of the road may change from shared space towards dedicated bicycle paths. Table 2.3 shows the shares of crashes per road type found in a study on single-bicycle crashes (Schepers, 2008). The categorisation and description of the infrastructure types as defined in Table 2.3 were also used in this study. For bicycle-bicycle crashes, the distribution of crashes over the road types might differ. For example, bicycle-bicycle crashes do occur more often on dedicated bicycle paths instead of streets with bicycle lanes (Schepers, 2010). No specific information on the occurrence of bicycle-bicycle crashes on different road types was found.

Table 2.3: Road type and single-bicycle crashes (Schepers (2008))

Type	Description	Percentage (%)
Street	Paved infrastructure used by motorized vehicles and bicycles	40
Bicycle path	Paved path dedicated to bicycles only	33
Pedestrian path	Paved path dedicated to pedestrians only	8
Bicycle lane	A red marked or separated by white dots part of a street dedicated for bicycle traffic	7
Unpaved path in park	Unpaved path for bicycle/ pedestrian traffic	6
Parking area	Area in which all riding directions are possible and the parking of cars is the main purpose	4
Other	Examples: bicycle streets or shared space	2
Total		100

A study performed by Moritz (2014), taking commuting distances and crash ratios into account, showed a higher relative risk factor for bicycle paths (0.67) compared to bicycle lanes (0.50). This study also implemented results for cycling on streets where no specific bicycle facility was present and this resulted in a higher relative risk (1.26). Similar studies performed by Teschke (2012), Thisworth et al., (1994), Rodgers (1997) and Harris et al. (2013) resulted in risk factors for the same infrastructure and showed comparable results. In addition, Aultman-Hall & Kaltenecker (1999) collected data from commuter cyclists and found that off-road cycling has a relative risk of 1.8 compared to on-road cycling. Therefore, paved and structured roads which are more in line with the cyclists' expectation are expected to be safer.

The values in these studies include bicycle crashes with motor vehicles. No separate figures for crashes without motor vehicles were found. Besides, the conclusions were based on studies performed in North-America and can therefore not directly be applied to Dutch infrastructure. The Dutch infrastructure typology, the overall road layout and the behaviour of the cyclist are likely to be different and therefore research is needed to understand the safety of bicycle crashes on Dutch road types.

Infrastructure width

Very little research exists on the topic of safe bicycle infrastructure widths. It is widely acknowledged that narrower bicycle paths and lanes contribute to a higher crash risk, but little scientific evidence exists (Schramm & Rakotonirainy, 2009). A study into the safety of cyclists on bicycle lanes showed that the safety was higher safety at larger street widths (Allen-Munley et al., 2004). Most of the conclusions for bicycle paths are based on the cyclists' or researchers' interpretation of the crash site. For example, especially older cyclists (75+) stated in a survey that narrower bicycle paths are related to the crashes they experienced (Boele Vos et al., 2017). Schepers (2008) analysed crash sites and suggested that the width of bicycle infrastructure was not always sufficient according to bicycle design guidelines. Overall the conclusions in these studies do not imply that bicycle path widths at crash sites are indeed smaller than on non-crash sites and further research is needed to confirm this hypothesis.

One- and two-directional bicycle paths

Bicycle safety is not only related to specific infrastructure design variables. Network design can also affect the number of collisions between traffic participants. CROW (2016) makes the recommendation to avoid two-directional bicycle paths because frontal bicycle-bicycle crashes were suggested to induce more severe injuries. However, no studies were found supporting this recommendation. Most studies that were found were related to crashes on two-directional bicycle paths in relation to conflicts with motor vehicles (de Waard & Schepers, 2010) (Allen-Munley et al., 2004) (Methorst et al., 2017).

De Goede et al. (2013) suggested that increased widths of two-directional bicycle paths can decrease the number of crashes because more space is available for cycling next to each other and overtaking manoeuvres. In Dutch guidelines, one-directional bicycle paths are advised to be designed more narrow than two-directional bicycle paths (CROW, 2016), which could be a problem for overtaking manoeuvres on bicycle paths (Schepers, 2010). Cyclists riding in the wrong direction of a one-directional bicycle path increase the possibility of conflicts between two cyclists. This behaviour is observed frequently and the occurrence is also dependent on the intensities on these bicycle paths. Overall, the knowledge on the crash risk on one- and two directional bicycle paths in relation to crashes without motor vehicles is limited (Methorst & Schepers, 2015).

Intersections

Intersections are characterized as a place where traffic streams cross each other. Due to the high severity and better registration of crashes with motor vehicles, these types of crashes on intersections were more frequently researched (de Waard & Schepers, 2010) (Bil et al., 2010) (Asgarzadeh et al., 2017). Meanwhile, single-bicycle and bicycle-bicycle crashes do also happen at intersections. Even crashes occur at intersections which are only suitable for bicycle traffic and pedestrians (VeiligheidNL, 2017). No literature was found including research towards the contribution of infrastructure characteristics to bicycle crashes without motor vehicles on intersections.

2.2.4 Temporal details of bicycle crashes without motor vehicles

The occurrence of bicycle crashes varies over time and therefore a variation over dark and light periods can be made. Schepers (2008) assessed the risk of riding in the dark for multiple age groups. What is clear from his analysis is that older cyclists have a higher risk of having a crash. Cyclists younger than 19 have a relative risk (risk in dark divided by risk in daylight) of 1.4 while cyclists above the age of 60 have an increased risk resulting in a risk factor of 4.1. The visibility of infrastructure is limited in periods of darkness and according to Ormel et al. (2009) poor visibility is considered to be one of the main factors of bicycle crashes. With the appearance of obstacles, road narrowings and curves in bicycle paths a high visibility is desired in order to decrease the number of crashes. The visibility of the infrastructure, in dark and light periods, could be increased by improving the lighting conditions with streetlights. Streetlights can decrease the number of bicycle crashes in urban areas (-13%) and in rural areas (-56%) (Wanvik, 2009).

2.3 Research gaps and hypotheses

The literature review makes clear that bicycle crashes are caused by various infrastructure characteristics. On the other hand, the current knowledge of the contribution of these characteristics to single-bicycle and bicycle-bicycle crashes is rather limited. According to the literature review, the following gaps exist that can be filled and could then contribute to a safer bicycle infrastructure design:

Gap 1: Low street and bicycle path widths are suggested to contribute to single-bicycle and bicycle-bicycle crashes, but these assumptions were not quantitatively supported. The following research hypotheses were defined with regard to widths of streets and bicycle paths:

RH1a/b *The likelihood of collisions with kerbs is related to a) street or b) bicycle path widths*
-> H_0: The likelihood of collisions with kerbs is not related to a) street or b) bicycle path widths

RH2a/b *The likelihood of riding off the road crashes is related to a) street or b) bicycle path widths*
-> H_0: The likelihood of riding off the road crashes is not related to a) street or b) bicycle path widths

RH3 *The likelihood of collisions with bollards is related to the width between the bollard and the edge of the bicycle path*

-> H_0: The likelihood of collisions with bollards is not related to the width between the bollard and the edge of the bicycle path

RH4a/b *The likelihood of handlebar collisions of cyclists cycling together is related to a) street or b) bicycle path widths*

-> H_0: The likelihood of handlebar collisions of cyclists cycling together is not related to a) street or b) bicycle path widths

Gap 2: Quantitative knowledge on the risk of cycling on different road types/sections in relation to single-bicycle and bicycle-bicycle crashes is lacking. Research on different road types so far is mainly focussed on crashes with motor vehicles. The following research hypotheses were defined with regard to different road types/section:

RH5 *The likelihood of collisions with kerbs is related to the presence of different road sections*

-> H_0: The likelihood of collisions with kerbs is not related to the presence of different road sections

RH6 *The likelihood of riding off the road crashes is related to the presence of different road sections*

-> H_0: The likelihood of riding off the road crashes is not related to the presence of different road sections

RH7a/b *The likelihood of a) single-bicycle crashes or b) bicycle-bicycle crashes is related to cycling on intersections*

-> H_0: The likelihood of a) single-bicycle crashes or b) bicycle-bicycle crashes is not related to cycling on intersections

RH8a/b *The likelihood of a) single-bicycle crashes or b) bicycle-bicycle crashes is related to cycling on bicycle paths or bicycle lanes*

-> H_0: The likelihood of a) single-bicycle crashes or b) bicycle-bicycle crashes is not related to cycling on bicycle paths or bicycle lanes

RH9a/b *The likelihood of a) single-bicycle crashes or b) bicycle-bicycle crashes is increased at two-directional bicycle paths*

-> H_0: The likelihood of a) single-bicycle crashes or b) bicycle-bicycle crashes is not increased at two-directional bicycle paths

Gap 3: The current scientific knowledge on the injury severity of bicycle crashes without motor vehicles is not focussed on the contribution of specific infrastructure characteristics. The following research hypotheses were defined with regard to the injury severity:

RH10 *A collision with a bollard results in an increased injury severity*

-> H_0: A collision with a bollard does not result in an increased injury severity

RH11 *A collision with a door of a parked car results in an increased injury severity*

-> H_0: A collision with a door of a parked car does not result in an increased injury severity

RH12 *Frontal bicycle-bicycle crashes are related to an increased injury severity*

-> H_0: Frontal bicycle-bicycle crashes are not related to an increased injury severity

PART II: Methodology development

Chapter 3 Case-control method

This chapter concerns the development of the case-control method which was used for analysing the research hypotheses. This chapter will answer the following research question:

Which case-control method, including a framework for selecting control locations, can be applied when studying bicycle crashes without motor vehicles?

The development of the case-control method reveals the design of the control selection method. For this purpose, background on case-control methods is reviewed. First, a comparison between cohort and case-control studies was made to further emphasize the use of a case-control method (section 3.1). Second, in section 3.2 other (bicycle) traffic safety studies were reviewed that used case-control methods and the research gap is formulated in section 3.3. In section 3.4, the requirements for the case-control method in this study are stated. More detailed specifications are given in section 3.5. In section 3.7 and 3.8 possible functionality improvements (respectively bias exclusion and method optimization) are defined. Section 3.6 represents the criteria for a decision on the use of these possible improvements.

3.1 Control selection in cohort and case-control studies

Analytic studies examining causal relations can be divided into experimental and observational studies. The main dissimilarity between these two types of studies is that in the set-up of experimental studies one or more factors are influenced and that the observational studies are executed without intervention. Cohort, Case-Control and Cross-sectional studies are examples of observational studies. Cohort and Case-Control studies offer the possibility of examining the influence of a certain exposure over a time period, whereas a Cross-sectional study examines it on one specific point in time (Song & Chung, 2010). Cohort and case-control studies are mostly applied in epidemiologic studies and are preferred over Cross-sectional studies because the temporal relationship between e.g. diseases and effects is high and therefore a specific time frame is preferred.

Cohort studies are mainly focused on describing the period before an outcome of interest occurs. From this, the causation can be derived extensively. Therefore, cohort studies most of the time provide the strongest scientific evidence. A disadvantage of this study is the long period in which a follow-up might happen, resulting in long study periods and consequently high costs. A case-control study can be seen as a good alternative, as the study period can be lowered drastically (Everit & Palmer, 2005). These studies are retrospective in which the (e.g. medical) history of a subject (e.g. a person) is assessed by controlling on the presence or absence of an exposure. The effects of the exposure on two groups, defined by the presence or absence of this exposure, are examined by collecting information from the subjects by interviews, records or surveys. This method provides quick detailed conclusions on the exposure, even though this is rarely occurring (Song & Chung, 2010).

The selection of an efficient and representative control group is the most challenging task in the design of a case-control study. In most studies in medical sciences, no perfect control groups exist (Grimes & Schulz, 2005). Therefore it is important to consider the compatibility of the control group and the study goals. Poor choices of controls can consequently lead to incorrect results and possible medical harm (increased crash risk). In order to design effective control groups, these should include the following main attributes for controls in a case-control study (Grimes & Schulz, 2005). The application of these attributes to this study is also given below:

<u>The control is free of the outcome of interest:</u>
On the selected control location in the cyclists' route, no crash is allowed to have occurred.

<u>The control is a representative of the population of risk:</u>
The control location has to be selected from the route of a cyclist that experienced a crash.

<u>The control is selected independently of the exposure of interest:</u>
The exposure of interest (i.e. infrastructure width) is not included in the variables of the control location selection and therefore is included randomly.

Different types of control groups

Different types of control groups are possible to use during a case-control study. A known group (population controls) or an unknown group (neighbourhood, hospital or relative controls) can be used for selecting controls. The main dissimilarity between these groups is that the confounding variables in the known group are already identified (Wacholder et al., 1992), what makes the analysis more effective. A population control group seems to be most applicable to our study because the crash and route information allows for choosing a control location from the same study base (a known group). The main disadvantage of this control group type is the problem of a limited study base size (Grimes & Schulz, 2005). However, the study base in our study seems to be of a sufficient size.

Multiple control groups

Case-control method results can be made more reassuring and trustworthy when concordant results are retrieved from multiple control groups. However, also discordant results can be found. In a study into bicycle safety by using a helmet, two control groups resulted in concordant results which strengthened the conclusions (Rivara et al., 1997). In contrast to this study, other studies resulted in discordant results (Hulka & Grimson, 1980) (Gutensohn et al., 1975). Because of the difficulty of indicating which result should have been discarded, a choice in the design stage is advised (Grimes & Schulz, 2005). However, multiple control groups can as well be used for a sensitivity analysis on the influence of a confounder (e.g. cycling intensities).

3.2 Application of case-control methods in (bicycle) traffic safety studies

Case-control methods are widely applied in traffic safety research. Studies were applied to determine the crash risk of traffic participants by controlling on the presence of a certain exposure in the case and control groups. The risk of riding under the influence of psychoactive substances (Houwing, 2013), the risk of having a crash on different road types (Bhatti et al, 2010) and the safety effects of using helmets on bicycles (Rivara et al., 1997) are examples of these studies. However, only two studies were found in which the risk of bicycle infrastructure was analysed by using a case-control method.

Vandenbulcke et al. (2014) performed a study on bicycle accident risk in the city of Brussels by using a case-control study. Spatial Bayesian modelling with a binary dependent variable (crash/ no crash) was used to compare crash and control locations. Control locations were retrieved from a combination of bicycle infrastructure and traffic intensities according to a traffic model. In this study, the case and control locations were analysed with respect to the occurred crashes and highly crash sensitive locations. The analysis concluded on the contribution of several infrastructure characteristics which were found along the analysed routes.

In addition, Teschke (2014) performed a case-control study regarding the contribution of road types to bicycle crashes, by selecting random controls from the route which was followed by a bicycle crash victim. This study resulted in relative safety rates for fourteen different road types and it also included conclusions on several infrastructure characteristics. The impact of infrastructure characteristics was examined by reviewing the presence of e.g. train tracks in the cases and controls. This study was rather effective on concluding on the contribution infrastructure characteristics but it did not offer the possibility of including all potentially relevant infrastructure characteristics (e.g. bicycle path width could not be analysed).

Overall, these two studies are highly comparable to our study. However, in our study a specific exposure was tested proactively (defined before the analysis) in comparison to the reactive analysis which was done in the reviewed studies (controlling the variables after the analysis was executed). Whereas Vandenbulcke et al. (2014) used a stochastic model, we used individual crash preceding routes to determine the control location. Moreover, for concluding on the contribution of e.g. bicycle path widths, the selection of cases and controls first needs to be restricted to bicycle paths only. For further application of the method, bicycle specific definitions were essential to relate bicycle infrastructure to the case-control method. The relevant definitions which were applied in this study were:

Case	Crash location
Control	Chosen control location from cyclists' route
Population	Routes from cyclists that were treated at an emergency room
Exposure	Infrastructure characteristic

3.3 Research gap

Following from this literature review, the research gap is formulated below:

Gap: Earlier case-control studies on the safety of bicycle infrastructure were not applicable to the purpose of this study because the method for the selection of controls in these studies was not suitable to the available data in our study. Also the level of detail of the infrastructure characteristics obtained in these studies was lower than aimed for in our study.

3.4 Method requirements

The design of the method is the main objective of this section and this process first describes the method requirements, which are described in detail. These requirements are described per individual method step and are listed in Table 3.1. The steps are assigned to the in- and output phase of the data in the method.

Table 3.1: Method requirement and outcome per step

Phase	Step	Requirement	Outcome
Data input	1	Hypothesis selection	Hypotheses for testing
	2	Data description	Case location
	3	Data generation	Supporting data
Data output	4	Data application	Control location
	5	Control set generation	Set of controls
	6	Statistical analysis	Results

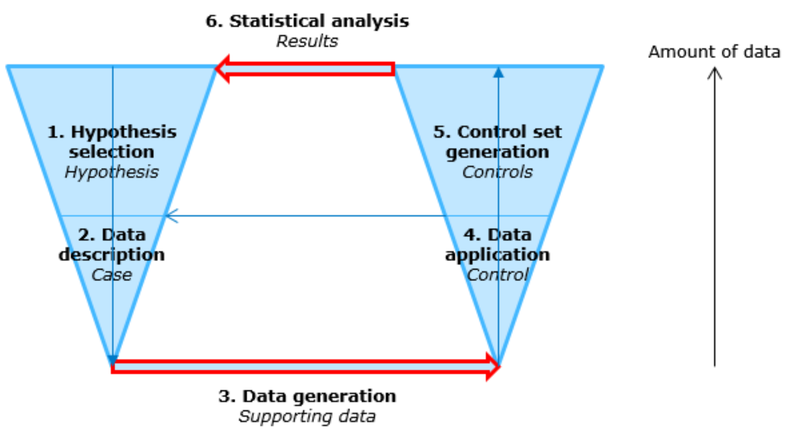


Figure 3.1: Schematization of the relation between the different steps in the method requirements

The schematization in Figure 3.1 shows the process that was followed to conclude on the hypotheses. Data for a specific hypothesis exists out of multiple cases but only individual cases could be used for the generation of controls. When a control was selected, the controls could finally be combined into a control group. The different steps of the method are defined below.

Step 1: Hypothesis selection

The case-control method which was applied in this study had to be applicable to the purpose of the study: supporting or rejecting the research hypothesis. For the right selection of cases and controls the hypothesis functioned as an input to the method.

Step 2: Data description

Following the choice of the hypothesis, the data description step was performed. The main purpose of this step was to select the data in the database related to the chosen hypothesis (research objective). In the data description step, the case location was also characterized, such that accordingly the right control location could be selected.

Step 3: Data generation

The data generation step can be seen as a supportive step. Various data (e.g. the route of a cyclist) which was not yet determined, was generated because this was mandatory for the selection of the control locations.

Step 4: Data application

The data which was available from the dataset and which was created in the data generation step was combined in the data application step. As a result of this application, the control location was selected.

Step 5: Control set generation

Sufficient number of cases and controls had to be selected to retrieve statistical significant results. A higher number of cases and controls could provide a higher statistical power. In order to achieve a certain minimum statistical power, a threshold for the number of controls was needed. In case the threshold was not met yet, more controls were generated. This process was repeated until the threshold was reached.

Step 6: Data analysis

Besides the scope of the actual control location selection, the data analysis step was added which provided results on the hypotheses. The cases and controls were combined and statistical tests were applied to this data. The correlation between bicycle crashes and infrastructure characteristics was the result of this analysis.

These six steps are required for a case-control method. Following from these steps, a flowchart was designed which includes the building blocks (processes). The most essential building blocks for the control selection process together form the main flowchart, called the basic framework. Within the basic framework, the building blocks include the minimum requirements for selecting a control location. In addition, building blocks including functionality improvements were added to the basic framework. Figure A.1 in the Appendix illustrates the building blocks of the final framework.

3.5 Basic framework specifications

The specifications of the building blocks in the basic framework are described in this section.

3.5.1 Hypothesis selection and method choice

In case-control methods a random selection of controls is possible, but the main focus of this study was associated with an exposure-related selection of controls. Nevertheless, for some of the hypotheses in this study a random control selection method satisfied and therefore two selection methods were applied.

The *random control selection* method was related to the comparison of two different types of situations. Since no specific exposure was tested (only the occurrence of two different situations), a random control choice in the cyclists' route was sufficient. The relation between crashes and the road course (intersection/no intersection) is an example. This selection method was called a first order analysis because without any further restrictions (all data can be used), variables could be analysed directly.

The *exposure-related control selection* generated controls, such that crashes were examined with respect to a certain exposure. For this purpose, controls were selected by not taking the exposure of interest (infrastructure characteristic which is examined) into account. This type of selection method was called a second order analysis, because after restricting the data on a specific crash type, a more detailed variable was analysed. An example of this could be the analysis of the infrastructure width in crashes against bollards. In this analysis, the infrastructure width functioned as exposure.

3.5.2 Data description

The hypothesis which was studied could be characterized by a research objective and an exposure. The research objective was related to the crash type, which was included in both the first and second order analysis. Additionally, the second order analysis also included an exposure. The information about the hypothesis was stored as information in the *research objective & exposure* part.

Database

The *database* included variables of the crash location, the trip origin, the causes of the crash, human characteristics and external characteristics (e.g. weather influences) which were used for the control selection process. Therefore, the *database* should include all variables, but according to some data optimization methods (further explanation in section 3.8), not for every crash all variables had to be included. Consequently, a database with lacking information on several variables per crash could be used.

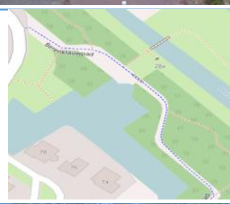
Data filter

The *database* contained data on all kind of crash types which were not of interest for analysing the research objective*.* A dataset related to a specific hypothesis was created by the *data filter*.

Infrastructure characterisation

The description of the crash location was done in the *infrastructure characterisation* part. This was the most extensive part of the method, where the crash location characteristics were described in detail. The level of detail gained in this part was of importance for the final accuracy which was achieved in the control selection process. The detailed description existed out of a top-down infrastructure characteristic description method. The information gained for this characterisation was stored in the *crash location characteristics* part. The *infrastructure characterisation* as executed with input from the *data filter*, which included information on the exact crash location. The individual description steps are stated in Table 3.2. Steps 4 till 6 in Table 3.2 are respectively road course, road dimension and road objects and represent the possible exposures in this study.

Table 3.2: Infrastructure characterisation steps in detail

Step	Description	Choices	Representation
1	Area type	a. Urban b. Rural	
2	Road type	a. Street b. Bicycle path c. Bicycle lane	
3	Amount of directions	a. One-directional b. Two-directional	
4	Road course	a. Intersection b. Straight c. Curve	
5	Road dimensions	a. <1m b. 1-1.5 m c. 1.5-2 m d. 2-2.5 m e. 2.5-3 m f. 3-3.5 m g. 3.5> m h. when exposure: exact dimension	
6	Road objects	a. Bollard b. Kerbs c. Tram tracks d. Parked cars	

3.5.3 Data generation

Route generator

In this case-control method, the control location was selected from the route of the cyclist who was involved in a crash. The *data filter* did not include the exact route which was followed during the trip, but information on the crash location and trip origin was available. This opened the possibility of reconstructing this route.

The route choice of cyclists is affected by criteria such as the distance, turn frequency, slope, intersection control and traffic volumes (Broach et al., 2012). Also the more general level information on safe, fast, simple and attractive routes affects the route choice but is often not included in the trip advice. Current route planners mostly lack the inclusion of all criteria and the shortest route criterion is widely used (Hochmair, 2005). Broach et al. (2012) on the other hand stated that significant route preference differences exist between commuting and utilitarian trips. Covering the distance is the most time-consuming factor in long trips and can be seen as the most relevant choice factor. The route preference differences between commuting and utilitarian trips therefore seem to be related to the distance, as commuting trips are shorter than utilitarian trips (Broach et al., 2012). Because of the high influence of the length of the trip on the route choice, the *route generator* used the shortest route criterion for reconstructing a route.

Random generator

The *random generator* generated random numbers which were used for obtaining a random location on the route. The generated value was between 0 and 1.

3.5.4 Data application

The selection of a control location was done in the *map application* step. In this step, the generated route was combined with the random number or the crash location characteristics. The information about the control location was stored in the *controls* information step. A control location was selected by multiplying a random value between 0 and 1 with the length of the route for the first order analysis. The *crash location characteristics* information was applied to the generated route, in order to select control locations for the second order analysis. This application was done by filtering on the *crash location characteristics* information within the route, such that a control location was retrieved. In case no control location was appointed (e.g. no route available or no comparable infrastructure available in the route), no information was stored in the *controls* information step.

3.6 Method extensions for functionality improvements

The basic framework functions on a normative level and the extensions are extra and not mandatory steps in the control selection process. However, these extensions can improve the quality of the input, output and the processes within the method itself which are indicators of the functionality of the method. Moreover, Wacholder et al. (1992) described four main principles on which the quality of a case-control study can be based. These principles were defined to provide a theoretical framework for the evaluation of advantages and limitations of case-control methods and are given below:

First, the '*study base principle*' concerns the representative nature of the case and control locations. Both have to be a representative of the same study base which is described prior to the actual study. This study base can be seen as the source population of the study and the relevance of obtaining the right study base is critical for choosing the right controls (Mietinnen, 1985). In addition, the amount of data that can be generated with a case-control method depends on the size of this study base.

Secondly, the '*deconfounding principle*' concerns the minimization of the effect of confounders. Confounders are variables that cause unequal initial conditions for the case and control groups (biased factors). In this study, the confounders were related to external (human and environmental) factors which changed during the trip and therefore were different on the case and control locations. However, because of a short time period, it can be assumed that the external factors in this study remain constant over time. Only the cycling intensity is an important confounder. In order to lower the bias in the results, the variability of the confounder needs to be limited. However, the correlation between confounders and the exposure could be high, such that restricting the variability of the confounders will result in a decrease in the variability of the exposure. In this case, the inclusion of variable confounders in the analysis should be considered (Cole, 1979).

Thirdly, the '*comparable accuracy principle*' is related to the accuracy of measuring the exposure of interest. The degree of accuracy in measuring the exposure of interest for the case locations should be equal to the degree of accuracy for the controls unless the effect of the inaccuracy can be controlled for in the analysis. The variability of measuring the exposure in this study was different, related to the infrastructure characteristic taken into account. For example, measuring road dimensions was more straightforward than the inclusion of other more qualitative crash factors (i.e. type of road, curve/straight road).

And finally, the *'the efficiency principle'* is mainly related to a consideration of costs (in time and money) for applying a case-control method. Also the statistical efficiency is relevant in this principle and refers to the amount of data obtained per subject. Consequently, an increase in the amount of data per case can result in lower costs because more controls per case can be selected. This finally results in a faster application of the case-control method.

Following these principles, four corresponding criteria were defined to assess the quality of the method extensions in this study:

- Data generation — Relevant for statistical power
- Bias exclusion — Relevant for examining the bias generated in the method
- Accuracy — Relevant for representative controls
- Speed — Relevant when examining large datasets

A review of the extensions resulted in scores on the four criteria given in Table 3.3. These scores represent a negative (--/-), a marginal (0) or a positive influence (+/++) on the criteria. The scores were determined by testing the extensions in the method or analysing the possible effects. Further clarification of these scores is given in Appendix A (tables A.2-6).

Table 3.3: Review of extensions according to the four criteria

	Data generation	Bias exclusion	Accuracy	Speed	Overall
Extension 1: Bias exclusion Matching confounder	o	+	+	-	+
Extension 2: Bias exclusion Variability between case and control characteristics	-	+	+	-	0
Extension 3: Bias exclusion Route choice bias	o	+	o	o	+
Extension 4: Optimization More controls	++	o	o	-	+
Extension 5: Optimization Replacement of controls	++	-	o	-	0

3.7 Bias exclusion extensions specifications

Bias can be generated in the case-control methods and can be removed by adapting the processes. The main processes in this study in which bias occurred, were the *infrastructure characterisation* (the accurate description of the crash location) and the *route generator* (the reconstruction of the route). As both processes provided input for the *data application* and *control set generation* steps, bad input could result in bad output. The addition of bias excluding extensions to the basic framework was relevant for pursuing higher quality results.

3.7.1 Extension 1: Matching confounder

Expected result: lower bias for bicycle-bicycle crash analysis

Matching is a method in which the variability of the confounder is lowered, in order to not further decrease the efficiency of the method (Wacholder et al., 1992). According to Song & Chung (2010), the method is capable of eliminating the influence of the confounders which are not in the interest of the researcher. With this concept it is easier to select controls. For example, the relevance of cycling intensities in bicycle crashes was associated with this method. The distribution of the intensities could cause an extensive analysis when detailed intensity information was applied.

Individual matching is the most intuitive way of matching, where cases and controls are individually matched according to their confounders. Frequency matching includes the partition of the values of the confounder, such that an equal distribution of categories is developed. The differentiation of the confounder due to this method is significantly lower. However, when no knowledge about the confounder is available, probability matching can be applied. With this method a random selector is used to select a control, utilizing the probabilities of the occurrence of confounders on the subject (Wacholder, et al., 1992).

Frequency matching was the most applicable type of matching for this study because individual matching was still too detailed and probability matching was not necessary because cycling intensities were known in this study (see section 4.1). Frequency matching is more effective when a reasonable balance is found between the number of categories and bias. Intensity categories were included within the *intensity generation* and crash location intensities were provided to the *crash location characteristics*.

According to the review results in Table 3.3 (more detailed review in Table A.2), this extension was included in the method because the accuracy increases and the bias will be significantly lower due to the inclusion of this confounder. The speed of applying the method reduced, but higher quality results were more relevant.

3.7.2 Extension 2: Smaller variability between the case and control characterization

Expected result: more accurate control generation

The exact description of the crash location characteristics is sensitive to the accuracy of the measuring method of infrastructure characteristics (e.g. infrastructure width). Also the projection of the crash location characteristics on the cyclists' route can induce deviations for the exact control location. The variability between the case and control location can be lowered by a higher detailed specification of the infrastructure characteristics. The inclusion of an increased detail level is mentioned in the 'comparable accuracy principle'.

The quality of the creation of controls in the *map application* was highly related to the level of detail of the information in the *crash location characteristics* information step. A higher level of detail in this step could be created by a more detailed version of the *infrastructure characterisation* step (example in Table A.1). The main differences with the detailed information from the basic *infrastructure characterisation* was the more detailed specification of curves, road dimensions, the location of a bollard and the nature of a crash with a parked car.

According to the review results in Table 3.3 (more detailed review in Table A.3), extensions 2 has positive impacts on the accuracy and bias exclusion. However, with a low amount of data, a too high level of detail can prevent the study from being effective because the probability of finding a more detailed control can be lower. Because this study did not include high amounts of data, this extension was left out of this study.

3.7.3 Extension 3: Route choice bias

Expected result: more valid route generation

The control locations were selected from the reconstructed route and the reconstruction could affect the validity of the results. The assumption of a choice for the shortest route for all trips in the basic framework, generates bias towards the analysis results. A further specification on trip purpose in the *route generation* improves the likelihood of approaching the exact followed route. The trip purposes for bicycle traffic (VeiligheidNL, 2017) can roughly be divided into three categories.

The first category is related to the mandatory trip purpose, in which mandatory activities are included. These activities can be related to commuting traffic or other mandatory appointments which are all associated with time pressure. Due to this pressure, the fastest route seems a reasonable choice and this is generally equal to the shortest route on longer trips (Broach et al., 2012), as the distance then becomes are more important criteria.

The second category is related to recreational trip purposes. Trips that are not subject to time pressure are included in this category. Due to the nature of these trips the shortest route does not have to be the most representative route. For recreational trips also other criteria such as the number of turns and the involvement of traffic control measures are involved in the generation of the route (Hochmair, 2005).

The third category is related to round trips and tours. Generating this category is different and less obvious than for the mandatory and recreational categories, while typically no evident route between the crash location and trip origin is followed. Due to this fact, the generation of a route for this category seems not reasonable. For decreasing the bias, the data for round trips and tours have to be excluded.

According to the review results in Table 3.3 (more detailed review in Table A.4), extension 3 has high benefits with respect to lowering bias and has no further impacts on the other criteria. Therefore this extension was included in the method.

3.8 Optimization extensions specifications

The basic case-control method can be improved by optimizing the steps which are related to the *data generation*. The *database* can have the potential of containing a significant amount of data for answering the hypotheses. However, for some individual research objectives the amount of data might not be sufficient but with data optimization this amount can be improved. The optimization can be applied to the steps in which controls are generated.

3.8.1 Extension 4: More controls

Expected result: higher statistical power

The number of cases and controls in other case-control studies are related to the availability of data and the accuracy the researchers want to achieve. From research it is identified, that the effectiveness of a case-control study increase until a case/control ratio of ¼. Above this ratio, the effect of including more controls does not improve the quality of the results any further (Wiebe, 2003) (Song & Chung, 2010). In this study, a ratio with more controls than cases is possible when selecting multiple controls on a cyclists' route.

The amount of data used in the *statistical analysis* is strongly related to the statistical power and representability of the results and conclusions. Increasing the number of selected controls per case is possible and increases the total of analysable data. The *controls* information step in the basic framework includes just one control per case, whereas this extension can improve this ratio to the maximum of 4. For this purpose, the choice for more data is included in the framework, in case the minimum threshold is met. The level of a satisfactory amount of data is a decision that needs to be made by the researcher. More data can be generated by applying the same input from the *route generator* and *crash location characteristics*, but retrieving a new value from the random generator.

According to the review results Table 3.3 (more detailed review in Table A.5), this extension has a highly positive effect on the data generation criteria. Even though the score on the speed criteria was negative, this extension was included due to the beneficial effect of a substantial amount of analysable data.

3.8.2 Extension 5: Replacement of controls

Expected result: more effective use of data

Medical case-control studies often suffer from patients refusing to participate in the study. 'Replacement of a control' can prevent wasting a case, such that valuable information can be used further on. The replaced control should be chosen with care, such that the personal characteristics are equal and the influence of confounders is minimized (Wacholder et al, 1992). In line with this, if for a cyclist in this study no route information or a too short route (further explanation in 4.2.3) is available, it might be possible to use a route of a cyclist with equal characteristics (e.g. personal and circumstantial characteristics). Certainly, for analysis on low frequency crash types (e.g. bollard crashes), replacement could improve the utilization of the data.

The selection of controls from routes of other cyclists can only be achieved when the circumstances (crash, human and external) during the crashes of the two different cyclists were more or less comparable. This assumption is essential for this process, as a low comparability on these characteristics might induce even more biased results because differences in human and external characteristics can encourage different behaviour by the cyclist (Fuller, 2005).

The implementation of the 'replacement of controls' extension is done by a reflection on the availability and length of the route in the *route generator*. When the route is found to be not sufficient, the *confounder control* is used to compare crash, human and external characteristics from all bicycle crash victims in order to select a more or less equal cyclist from which the route can be used.

However the review results in Table 3.3 (more detailed review in Table A.6) shows a marginal overall score, this extension was included in the method. In case valuable conclusions are needed, more time can be invested to generate more data. Due to the low amount of data in some for some of the hypotheses in this study, more time needs to be invested to reach significant results.

PART III: Data collection, processing and analysis results

Chapter 4 Operationalization

This chapter introduces the data which was used for the analysis and the different assumptions which were made for further operationalizing the case-control method. In section 4.1 the structure of the used data is explained. In section 4.2, the assumptions and strategies for the case location description and control location selection are given. The different statistical tests which were used in the analysis are further explained in section 4.3. Finally, the implementation of the case-control method is given in 4.4.

4.1 Data collection

Bicycle crash data was retrieved from a VeiligheidNL dataset. In the year 2016 VeiligheidNL conducted a survey among cyclists treated at an emergency department. In order to further understand the content of the survey the following definition is of importance to understand the final conclusions:

A crash is defined by a crash which resulted in a treatment at an emergency room by the cyclist.

The survey was distributed in 13 hospitals in the Netherlands (Table B.1) from January until December 2016. In total, 3146 cyclists which were treated at an emergency department responded to the survey. Moreover, no fatal crashes were included in the dataset. Within all these responses, information was available on the circumstances during the crash and about the location of the crash. The questionnaire consisted out of 59 questions, but not all of these questions were reasonable to include in this study. The questions of importance to this study and the type of information that could be filtered out of these questions are given in Table 4.1.

Table 4.1: Questions used for this study from the questionnaire

Type	Variable	Survey question	Information
Crash cause	Description of the situation during crash	*[What happened, explain briefly?]*	A brief description of the situation during the crash.
	Crash type	*[What was the type of the crash?]*	Information about the crash type: single-bicycle/related to other traffic participants.
	Collision with a person/infrastructure	*[With what did you collide?]*	Collision with road obstacle/car/cyclist etc.
Trip	Crash/trip origin location information	*[Where did the crash happen?/ Where did your trip start?]*	Information on the location of the crash/trip origin by coordinates or address.
	Trip purpose	*[What was your trip purpose?]*	Information on the purpose of the trip: commuting/recreational trip.
Infrastructure	Infrastructural information	*[On which road type were you cycling?/ What was the road course at the moment of the crash?]*	Information on the infrastructure characteristics on which the crash happened: road type, road course.
Riding behaviour	Age/ gender	*[What is your age?/ What is your gender?]*	Personal information: age, gender
	Alcohol use/ distraction	*[Did you use alcohol before the trip?/ Did you undertake other activities while cycling?]*	Information on the use of alcohol before the trip and information about activities during the trip: use of mobile phone/sound devices or distraction by the environment.
	Riding together	*[Were you cycling alone during the trip?]*	Information on the fact if cyclists were cycling alone.
	Weather/ light conditions	*[What was the weather condition during the crash?]*	Information on the weather conditions and light conditions: [dry, wet][light, dark]
Medical severity	Medical Treatment	*[At which medical department were you treated?]*	Information about the location in which the bicycle crash victim was treated [hospital, physiologist etc.]

Intensity data was used and retrieved from the Dutch bicycle counting week (Bikeprint, 2017). This data included cycling intensities from almost all road sections of the Netherlands (Figure 4.1). The data was collected from cyclists that participated in this week and via a mobile phone application information was collected. Finally, Bikeprint (2017) combined the data of all participants into a structured dataset. The cycling intensity data was made more insightful with a visualization of the intensities on a road map to support the case description and control location processes.

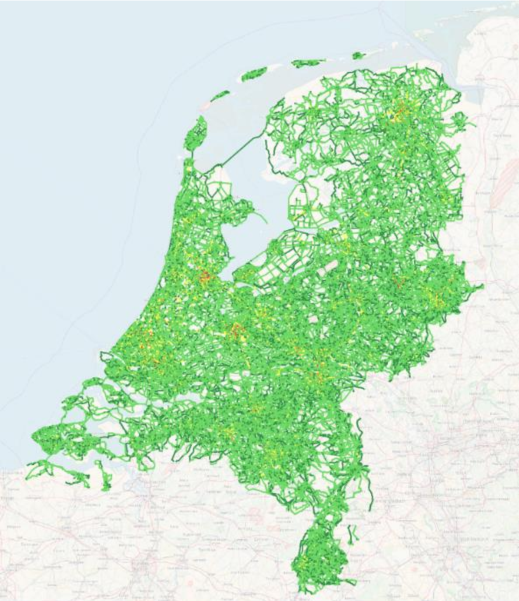


Figure 4.1: Coverage of cycling intensity data in the Netherlands

4.2 Data processing

With the variables gathered from the dataset as described in section 4.1, the case-control method was applied to the data. In order to retrieve data for analysis purposes, the case location was described and the control locations were selected. The specific assumptions and strategies for these two processes are defined below. An overview of the variables used in the data processing is given in Table B.2.

4.2.1 Data set selection

In this study, three different analyses were executed. One analysis was related to analysing all data in which conclusions on the severity of bicycle crashes were made. All available crash data was used for this purpose. The two other analyses were executed by applying the case-control method. For these analyses, a subset of the total dataset was used. For the first order case-control analysis, a random subset of the total dataset was used. The second order analysis included a restricted selection of the data in which one type of crash was included (e.g. kerb or bollard crashes).

4.2.2 Case location description

For the case location description the variables in Table 4.2 were used. These variables were used to select a valid control location, which was comparable to the case location. Further categories per variable are defined in Table B.2.

Table 4.2: Variables for the case location description

Type	Variable	Information
Location	Case location availability	Is it possible to relocate the case location from the information in the dataset?
	Case location	Description of the actual location of the crash, in coordinates
Infrastructure specification	Area	Description of area type
	Road type	Description of road type
	Amount of directions	Description of the amount of riding directions from the case location
	Road dimension	The width of the infrastructure
	Road objects	Description of road objects on case location
	Intensity	The cycling intensity of the case location

Several assumptions were made for the description of the infrastructure characteristics on the case location:

Road type — Road types which were included in the analysis were related to paved and frequently occurring infrastructure. Streets, bicycle paths and lanes were included and a description of these terms is given in Table 2.3. Unpaved infrastructure was excluded because this was not representative, whereas the unpaved infrastructure can temporally be highly different. Also, low occurring road types, such as bicycle streets, were left out. They substantially differ from other used road types and due to the low amount of occurrences, they are less valid for analysis.

Infrastructure width — For measuring the infrastructure width on streets, the width from edge to edge was used. For bicycle paths, the same assumption was made, such that two-directional bicycle paths could also be analysed on the width. For bicycle lanes, the width of the specific lane was used in the analysis.

Width next to bollard — For analysing the relevance of the infrastructure width besides bollards, the width between the bollard and the edge of the road was used. In case of more than two bollards, the widest opening between the bollards was included in the analysis.

Kerbs — For analysing kerb related crashes, only right kerbs were used.

Intensity — Because of a low participation among cyclists during the bicycle counting week, intensities per hour could be created but the accuracy of it was limited. On the other hand, only the equivalence of confounders in the cases and controls needed to be high. Therefore the relative intensity sufficed in the control selection process and more detailed data was not needed. The relative intensity was included in different categories, which are defined in Table B.3. A visualization of these categories is represented in Figure 4.2.

Figure 4.2: Visualization of the cycling intensity data in the Amsterdam area

4.2.3 Control location selection

For the control location selection process the variables in Table 4.3 were used. These variables were described to create valid routes and to further describe the infrastructure characteristics of interest which were found after inspecting the control location.

Table 4.3: Control selection variables

Type	Variable	Information
Route	Route availability	The possibility to describe the route in detail (sufficient information available?)
	Route available length	The route has to have a substantial length in order to use
	External route	The substitute route from another bicycle crash victim
Information	Control location	Description of the actual location of the crash, in coordinates
	Random number	Random number decides on control location on route
Infrastructure specification	Road type	Description of road type
	Road dimension	The width of the infrastructure

For the actual process of the control location selection, several assumptions were made with respect to the choice of the route and the description of the infrastructure.

Length of route — It was assumed that the variation of the infrastructure increases with the length of the route. Control selection in too small routes is sensible for only delivering characteristically equal locations. In order to avoid this, only routes were used which were longer than 500 meters. For selecting more controls on the route, longer routes were needed Table B.4.

External routes — When selecting a usable route from another bicycle crash victim from the dataset (external route), the following human and external factors had to be equal: age, gender, alcohol usage, weather- and light conditions.

Threshold zones — The influence of an infrastructure characteristic is not only experienced at one exact location but also before and afterwards. Therefore, the selection of controls was done by taking a threshold zone into account. The threshold was assumed to be at 10 meters on both sides of the infrastructure characteristic of interest (bollard, intersection etc.), which is a combination of one second reaction time and a small period of time for adaptations to the riding behaviour/line in order to avoid a crash. An example is given in Figure B.1.

Control replacement — For several responses no information was given about the trip. In these cases, a control was selected from the route of another cyclist with characteristically equal conditions. In Table B.5, the factors of the cyclists which needed to be characteristically equal, are given.

4.2.4 Other applied data

Information was needed about the injury severity of the crashes (the severity of all injuries combined). In general, the injury severity can be related to the treatment the cyclists experienced after visiting the emergency room in a hospital. The cyclists were asked to provide information on this topic and two categories were created: severe injuries (hospitalized or treated by a specialist) and moderate injuries (treated by a physiologist or family doctor). It was possible that the cyclist experienced multiple treatments due to the crash which could be categorized in both categories. In this case, the maximum severity (severe) was chosen.

4.3 Statistical analysis

After applying the case-control method, statistical relations between the cases and controls were examined by using different statistical tests depending on the type of variables. Moreover, for statistically analysing the case-control results in this study, two types of statistical analyses were applied.

4.3.1 Choice of statistical test

In the case-control method, the dependent variable is a categorical variable (crash or no crash). The independent variables can differ and are categorical, ordinal or continuous. Depending on the type of variables, respectively the Chi-square test and Binary logistic regression can be applied (Leeper, 2017). In both tests, the significance (p-value) was used to decide on the validity of the results, whereas the statistical significance is the probability that the observed difference was due to chance only. In this study p=0.05 was chosen (95% confidence interval).

Chi-square test

The Chi-square test can be applied to determine differences in proportions using a two-by-two contingency table. This statistical test can only be applied when the dependent variables are uncorrelated and the number of observations in all of the entries in the contingency table are higher than 5 (Laerd Statistics, 2017). The results of the Chi-square test can only be used for the interpretation of a significant relationship between multiple different variables. The strength of the association cannot be concluded on by applying the Chi-square test only. Therefore the Phi (2x2 tables) and Cramer's V (higher order tables) measures of association are introduced. These measures result in a value between 0 and 1, where values closer to 1 have a stronger relationship. Table B.6 shows a more detailed interpretation of these values.

Binary logistic regression

Binary logistic regression can only be applied when four assumptions are met. The dependent variable has to be dichotomous, one or more independent variables are categorical or continuous, there has to be independence of observations and there has to be a linear relationship between continuous variables and the Logit transformation of the dependent variable. The test for linearity was done by applying the Box-Tidwell procedure (Wuensch, 2016).

4.3.2 Odds ratios

To better understand the relationship between variables, odds ratio were used. The odds ratio (OR) is a measure for the association between the independent and dependent variables. The ratio represents the odds that a dependent variable takes a certain value in case the independent variables has a specific value. For binary logistic regression the following equation holds (Szumilas, 2010):

$$\log\left(\frac{P(Y_i=1|X_i)}{P(Y_i=0|X_i)}\right)=\beta_0+\beta_1 X_i$$

In this equation, Y is the binary dependent variable and X the continuous predictor of the independent variable. In order to better interpret the results from this equation, $e^{\beta 1}$ is introduced and represents the odds ratio for one unit change of X. By applying the Chi-square test, the odds ratio is determined manually with the following formula responding to the exposure and outcomes given in the table (Szumilas, 2010):

$$OR=\frac{a/b}{c/d}$$

		Outcome Status +	Outcome Status –
Exposure status	+	a	b
	–	c	d

In case more than two exposures are involved in the analysis, the reference group for the odds ratio of one exposure always consist out of the other exposures. Moreover, when odds ratios are determined for the width of road widths, these ratios represent how the likelihood of a certain crashes changes when one unit (meter) width is applied. Furthermore, the 95% confidence interval (CI) is used to estimate the precision of the OR. In case the interval does not overlap OR=1, the odds ratio reaches statistical significance. The further interpretation of the odds ratio value is defined by Szumilas (2010):

OR<1	An increase of the independent variable results in lower odds of the dependent variable
OR=1	The independent variable does not affect the dependent variable
OR>1	An increase of the independent variable results in higher odds of the dependent variable

4.4 Implementation

Route planner

A usable route was generated with the route planner of the Dutch cycling union (Fietsersbond, 2017). This route generator advices on the route choice by taking the trip purpose into account. The route planner includes options for shortest and most attractive route (low number of traffic lights, low number of turns etc.). These choices are in line with the specification of the route generator in the method.

Location inspection

The control location selection process also included the inspection of the crash and control location. Actually visiting the crash and control locations increases the overall research time radically and therefore the locations were inspected via an application that contains aerial photography and detailed information/visualization of the infrastructure (Cyclomedia, 2017). The application is up-to-date with recent visualizations made in 2016 (equal period as data). The level of detail in this program is sufficient since also dimensions (infrastructure widths) can be determined in detail.

Intensity generator

Cycling intensities from the Dutch bicycle counting week (Bikeprint, 2017) were entered by using a GIS program. For this purpose, QGIS was used in order to visualize and access the available data.

Map application

For the selection of controls in the map application, the OpenStreetMap was used. This open source map was effective for determining a control location. The infrastructure in the OpenStreetMap is characterized in detail, also including bicycle and pedestrian infrastructure. Due to a clear representation of the infrastructure, the OpenStreetMap can provide a fast control selection process.

Statistical analyses

Information from the selected control locations was included in the data file which was retrieved from the data filter. In this file, the information of the cases and controls were combined. By using the statistical functionality of SPSS (Statistical Package for the Social Sciences) results were gathered.

Chapter 5 Results

This chapter concerns the results and will answer the following research question:

Which infrastructure characteristics contribute to the occurrence of bicycle crashes without motor vehicles?

This chapter contains the results of the application of the case-control method to the data per research hypothesis, which are specified in section 2.3. The amount of data and the odds ratios for the analysed crash types are presented. Consequently, conclusions on the hypotheses are drawn. In Table 5.1, an overview of the research hypotheses is given, including the corresponding sections. In addition, section 5.2.3 includes a comparison between kerbs collisions and crashes due to riding off the road. Moreover, the hypothesis test results are presented in section 5.9.

Table 5.1: Content of chapter results

Research hypotheses	Variation of research hypotheses	Section
Collisions with kerbs	Intersections and other road sections	*5.1.1*
	Road and bicycle infrastructure width	*5.1.2*
Crashes due to riding off the road	Intersections and other road sections	*5.2.1*
	Road and bicycle infrastructure width	*5.2.2*
Collisions with bollards		*5.3*
Handlebar collisions of cyclists cycling together		*5.4*
Crashes on intersections		*5.5*
Crashes on bicycle paths and lanes		*5.6*
Crashes on one- and two-directional bicycle paths		*5.7*
Injury severity	Collisions with bollards	*5.8.1*
	Collisions with car doors	*5.8.2*
	Bicycle-bicycle crashes	*5.8.3*

5.1 Collisions with kerbs

The category 'collisions with kerbs' contains 91 cases in which cyclists indicated that they were involved in a kerb collision (Table C.1). This yields 2.9% of all crashes in the dataset. For most of these cases (73.6%), the following reason was given: a loss of balance due to a collision with a kerb happened, without any other noticeable interaction (Table C.2). In 15.4% of the cases, other traffic was specified as the main reason for colliding with a kerb, because the available space for cycling was limited by other traffic. Another 6.6% of the cases was a result of external distractions, in which cyclists were distracted by nature, buildings or other persons around the crash site. 4.4% of the cases were not defined as valid kerb collisions because the kerb in these cases was not directly related to the primary cause of the crash. In these cases, cyclists mostly fell onto the kerb after crashes due to other reasons. In addition, in all the cases cyclists crashed with a right kerb (not levelled or sloped).

5.1.1 Intersections and other road sections

The results for the relation between kerb collisions and the road course are based on 117 data points (cases=48, controls=69). The corresponding tables are given in Appendix C (tables C.3-7). It was found that there exists a (moderately strong) significant relation between kerb collisions and the occurrence of them on intersections. In Figure 5.1 the share of cases and controls distributed over intersections and other road sections (straight and curved) is given. The corresponding odds ratio for kerb collisions on intersections is also defined (OR=0.38; CI=0.17-0.90), which means that kerb collisions are less likely to occur on intersections than on straight and curved road sections. All the control locations in this analysis were also exposed to kerbs and therefore this result represents the likelihood of a kerb collision in case these are present.

In addition, the results were further analysed for different road types. It was found that kerb collisions on street intersections are even less likely to occur compared to kerb collisions on straight and curved streets (OR=0.20; CI=0.05-0.84). The relation between kerb collisions and bicycle paths and lanes on all intersection types were found to be insignificant.

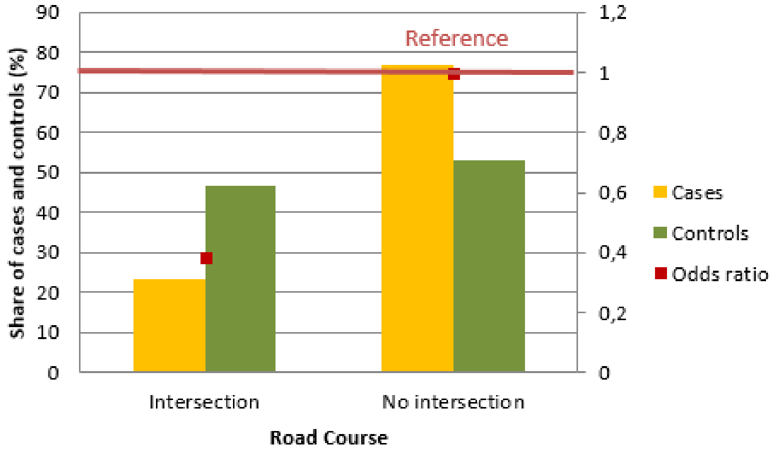


Figure 5.1: Results for the likelihood of having a kerb collision on intersections and straight/curved road sections

5.1.2 Road and bicycle infrastructure width

The results for the relation between kerb collisions and the road and bicycle infrastructure width are based on 82 data points (cases=47, controls=35). The corresponding tables are given in Appendix C (tables C.8-9). The road width distribution per individual road type is schematized in the boxplot in Figure 5.2. The results for the three different road types did not show a significant relation. However, the odds ratio for bicycle lanes (OR=0.37; CI=0.04-3.88) and bicycle paths (OR=0.60; CI=0.23-1.62) are substantially lower than 1. The odds ratio implies how the likelihood of a kerb collision changes when one unit (meter) change of the width is applied. According to these ratios, bicycle lanes are 2.7 (1/0.37) times less likely to induce kerb collisions if the width is increased by one meter. However, because of the lack of significance (resp. p=0.41 and p=0.32) these ratios are only indicative. It should be noted that these analyses are somewhat underpowered which makes it difficult to establish significant relationships.

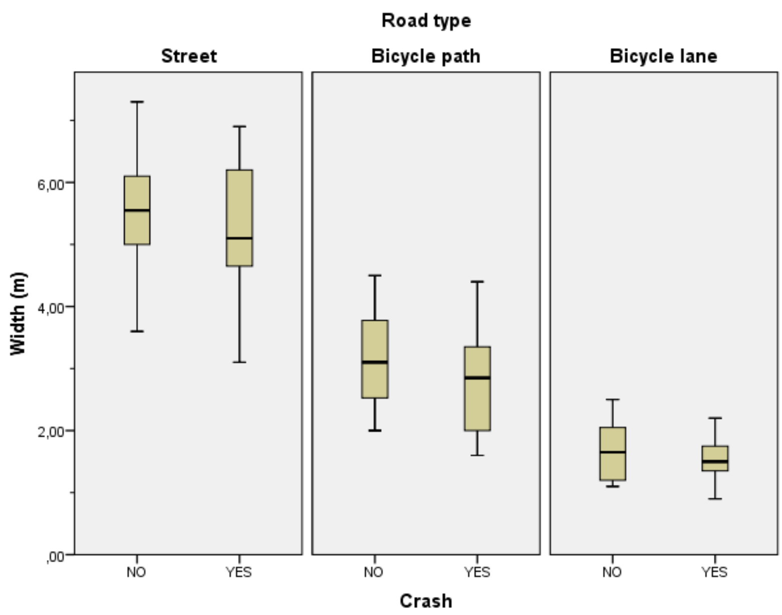


Figure 5.2: Boxplot of street, bicycle path, bicycle lane width distributions in kerb collisions

5.2 Crashes due to riding off the road

The crash category 'riding off the road' contains 139 cases in which cyclists indicated that they were involved in a crash due to riding off the road and riding into the verge (Table C.10). This yields 4.5% of all single-bicycle crashes in the dataset. Most of these crashes (56.1%) are characterized by riding off the road into the verge for which the victims could not mention a specific reason. Moreover, 16.5% of the cyclists who rode off the road, crashed because they weren't able to steer back onto the road. This was mainly caused by a substantial height difference between the road and the verge. In addition, no clear sight on the edge of the road (leaves, waste or water) (5.8%) and give way to other traffic (12.2%) are two reasons for riding off the road. 9.4% of the suggested riding off the road crashes were not included in the analysis because cyclists were not riding on representative infrastructure (e.g. already riding on the verge or on a sidewalk) (an example is given in Figure C.1).

5.2.1 Intersections and other road sections

The results for the relation between riding off the road crashes and the road course are based on 122 data points (cases=69, controls=53). The corresponding tables are given in Appendix C (tables C.11-14). The analysis resulted in a large number of cases and controls for straight road sections (89 data points) in comparison to intersections (17) and curved road sections (16). No significant relation between riding off the road crashes and the road course was found.

Figure 5.3 shows the shares of cases and controls distributed over the different road sections. For curved road sections more cases than controls were found, in comparison to intersections and straight road sections. This fact can also be observed from the (insignificant) odds ratios on intersections (OR=0.49; CI=0.17-1.38), straight (OR=0.94; CI=0.42-2.11) and curved (OR=2.58; CI=0.78-8.51) road sections (the odds ratio represents the odds of one category compared to a combination of the other two). As for intersections and curved infrastructure the p-values are respectively p=0.17 and p=0.12, these values can only be seen as indicative. Moreover, a further distinction was made on bicycle paths and streets, but insignificant results were found.

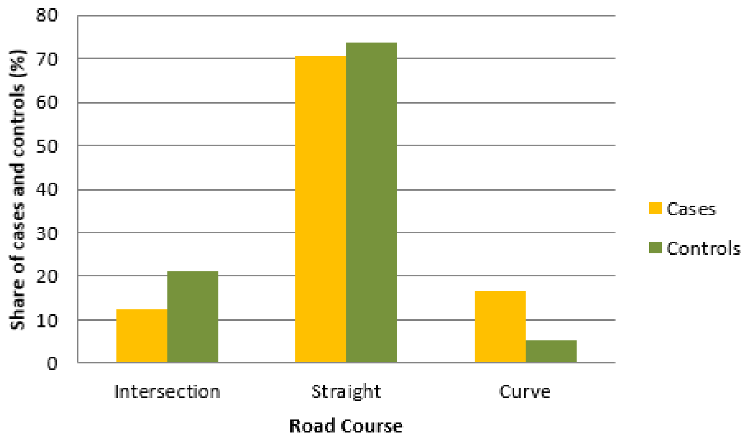


Figure 5.3: Results for the likelihood of having a riding off the road crash on intersections, straight and curved road sections

5.2.2 Road and bicycle infrastructure width

The results for the relation between riding off the road crashes and the road and bicycle infrastructure width are based on 114 data points (cases=67, controls=47). The corresponding tables are given in Appendix C (tables C.15-16). The road width distribution per individual road type is schematized in the boxplot in Figure 5.4. The results show substantial differences for the various road types. Bicycle lanes are not analysed because only two data points were found, which are too few for a sufficient statistical analysis. Therefore only streets and bicycle paths were analysed, both resulting in a significant relation. The odds ratios for streets (OR=0.56; CI=0.32-0.95) and for bicycle paths (OR=0.43; CI=0.19-0.96) represent respectively a moderate and strong relation between riding off the road crashes and the width of these road types. These odds ratios represent a change in the likelihood of having a crash due to one unit (meter) change in width. Therefore, narrower bicycle paths and streets are more likely to induce riding off the road crashes.

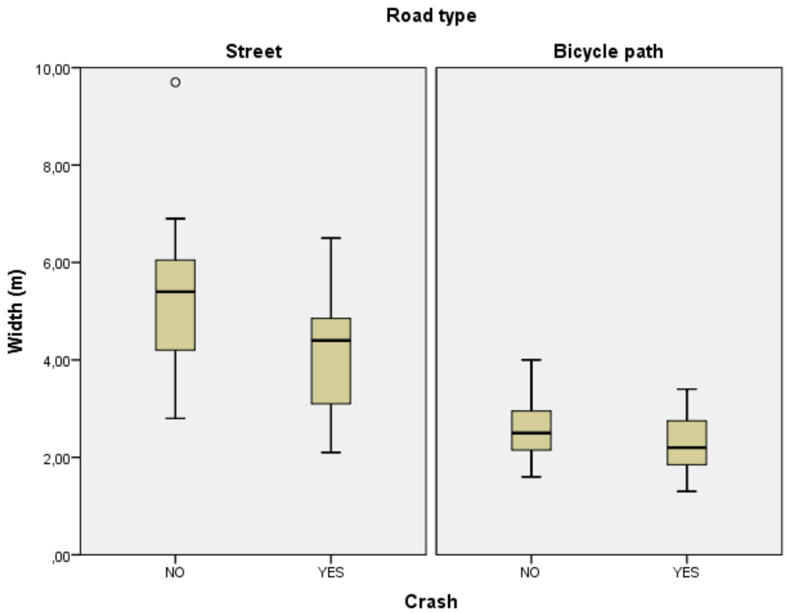


Figure 5.4: Boxplot of street and bicycle width distributions in riding off the road crashes

5.2.3 Kerbs and riding off the road comparison

Collisions against kerbs or crashes due to riding off the road can have comparable causes because only the design of the edge differs. However, a clear difference is that kerb crashes are more frequent in urban areas, whereas riding off the road crashes are more frequent in rural areas (OR=11.55; CI=5.94-22.45) (Table C.17). This finding can logically be explained by the expectation that kerbs are possibly more occurring in urban areas and less in rural areas.

Moreover, no significant difference was found between the likelihood of riding off the road crashes and kerb collisions on different road sections (Table C.18 and Table C.19). Nevertheless, kerb collisions are more frequent on intersections than riding off the road crashes (Table 5.2), but the result was not significant. In addition, riding off the road crashes happen on narrower streets (OR=0.41; CI=0.22-0.79) and bicycle paths (OR=0.30; CI=0.12-0.77) compared to kerb collisions (Table C.20).

Table 5.2: Odds ratios for kerb collisions on different road sections in relation to riding off the road crashes

	OR	Lower	Upper	Significance Level
Intersections	0.5102	0.1528	1.7040	0.2741
Straight and curved road sections	0.9489	0.5141	1.7514	0.8668

5.3 Collisions with bollards

The category 'collisions with bollards' contains 77 cases in which cyclists indicated that they were involved in a crash due to riding against a bollard. A total of 66.2% of the cases was valid for analysing collisions with bollards in relation to the bicycle path width next to bollards. In a practical sense, this width represents the distance between the bollard and the edge of the bicycle path. The bollards which weren't representative for this analysis are presented in Table C.21. For example, 7.8% of the crashes did not happen on representative infrastructure (e.g. on sidewalks, unpaved paths or as in the example in Figure C.2). Moreover, 13.0% existed out of crashes against other objects in the verge (traffic light and signs) and another 6.8% of the cases included no information about the specific bollard. In 5.2% of the cases, a cyclist fell against a bollard but crashed due to other reasons (e.g. slippery roads or a foot in the wheel).

The results for this relation are based on 53 data points (cases=34, controls=19). The corresponding tables are given in Appendix C (tables C.21-24). Almost all crashes did occur on bicycle paths (28 cases), some smaller part occurred on the connection between bicycle paths and streets (5 cases) and only one crash occurred on a bicycle lane (which is not included in the analysis). The width distribution in Figure 5.5 shows the high relative difference in widths between the cases and controls. From this boxplot, it can be seen that almost 75% of the cases had lower widths compared to 75% of the controls (the boxes in the boxplot do not show overlap). Consequently, a very strong significant relation was found between the likelihood of a bollard crash and the bicycle path width next to the bollard. With an odds ratio of 5.54 (CI=1.12-27.45), the likelihood of a bollard crash decreases drastically when the width is increased by one unit (meter).

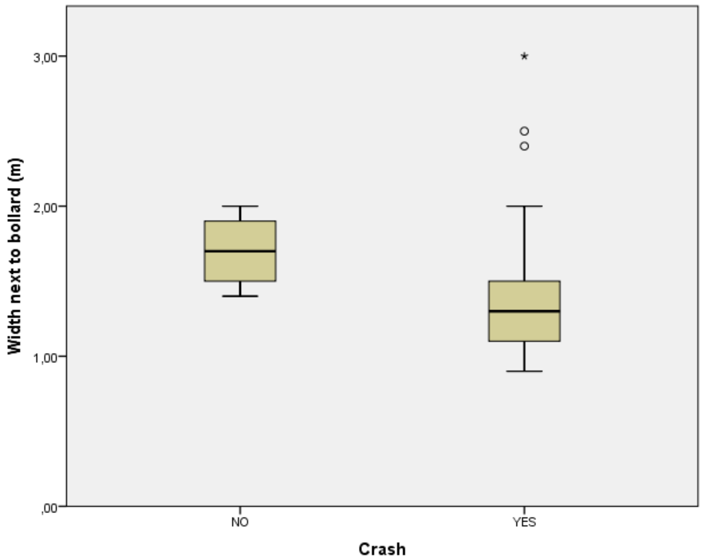


Figure 5.5: Boxplot of the distribution of bicycle path widths next to bollards in bollard collisions

5.4 Handlebar collisions of cyclists cycling together

The category bicycle-bicycle crashes consists out of 14.8% of all cases in the dataset (Table C.25). Moreover, handlebar collisions cover 18.7% of the bicycle-bicycle crashes and are characterized by a collision of the handlebars from different cyclists. 82.9% of these crashes occur when cyclists are cycling together (Table C.26). The other 17.1% of the cyclists that were involved in these crashes, were cycling alone or provided no information on this topic.

The results for the relation between handlebar collisions and the road and bicycle infrastructure width are based on 73 data points (cases=41, controls=32). The corresponding tables are given in Appendix C (tables C.25-28). For all individual road types, lower average widths were found for the cases than for the controls (Figure 5.6). Consequently, handlebar collisions are more likely to occur on narrower streets (OR=2.03; CI=1.02-4.04). The likelihood of a handlebar crashes decreases substantially when the width is increased by one unit (meter). For handlebar collisions on bicycle paths, no significant relation was found with the width. However, the odds ratio for one-directional bicycle paths (OR=2.28; CI=0.47-11.07) is substantially higher than for two- directional bicycle paths (OR=1.47; CI=0.54-3.94), but not significant (resp. p=0.31 and p=0.45).

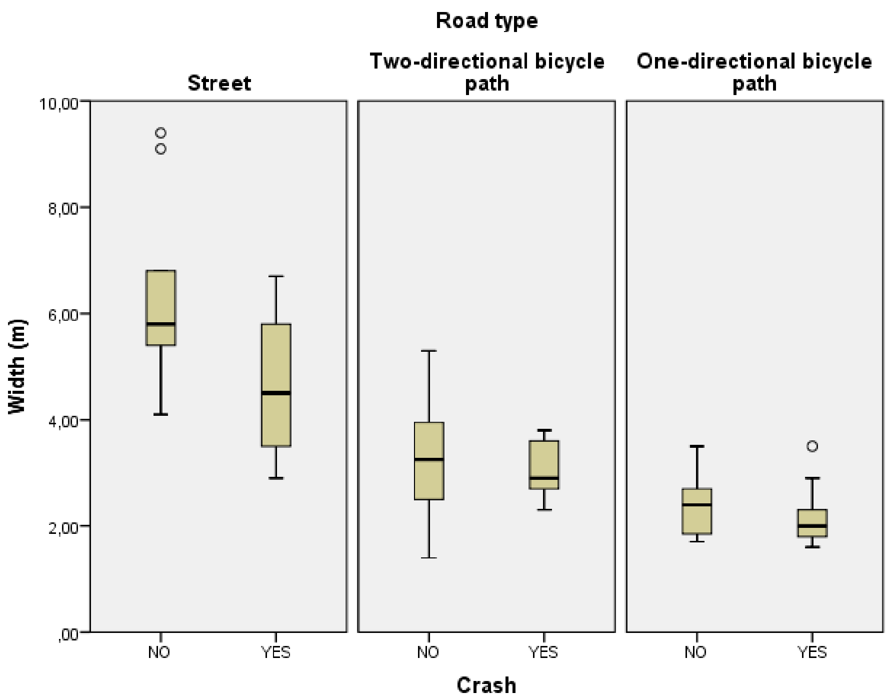


Figure 5.6: Boxplot of street and bicycle path width distributions in handlebar collisions of cyclists cycling together

5.5 Crashes on intersections

Intersections were studied using 223 data points (cases=105, controls=118). The corresponding tables are given in Appendix C (tables C.29-34). It was found that there exists a moderately strong significant relation between bicycle crashes and the presence of intersections. Relatively more cases than controls were located on intersections (Figure 5.7). The odds ratio for having a crash at an intersection (including crashes with motor vehicles) was found to be 2.48 (CI=1.38-4.47), indicative of a substantially increased risk at intersections. However, the results for the likelihood of single-bicycle and bicycle-bicycle crashes on intersections are found to be insignificant. In addition, also motor vehicle-bicycle crashes were examined and it turns out that the likelihood of these crashes is strongly related to cycling on intersections (OR=8.11; CI=2.76-23.92) (Figure C.3). Moreover, for single-bicycle crashes no substantial difference was found between the likelihood of crashes on intersections and other road sections (OR=1.04; CI=0.36-3.06). This relationship was found to be insignificant and this can be related to the fact that this analysis is somewhat underpowered.

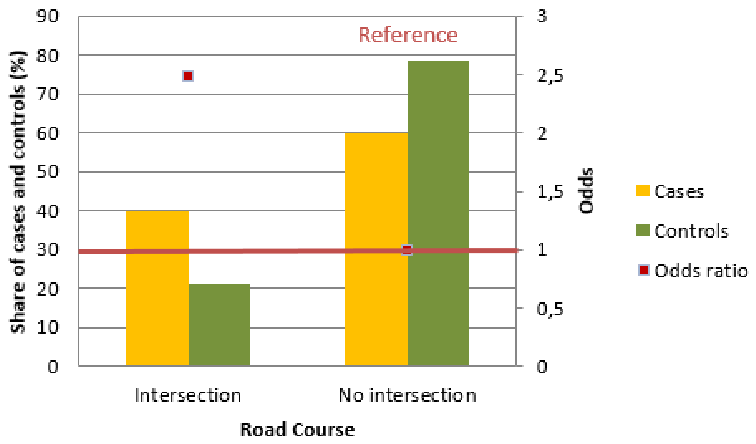


Figure 5.7: Results for the likelihood of crashes on intersections and straight/curved road sections (motor vehicles included)

5.6 Crashes on bicycle paths and lanes

A number of 74 data points (cases=29, controls=45) were used to relate the type of bicycle infrastructure to bicycle crashes without motor vehicles. The corresponding table is given in Appendix C (table C.35). No significant relation was found between bicycle crashes without motor vehicles and the type of bicycle infrastructure. As can be seen in Figure 5.8, the shares of cases and controls hardly differ between bicycle paths and lanes. This implies that there is no substantial difference.

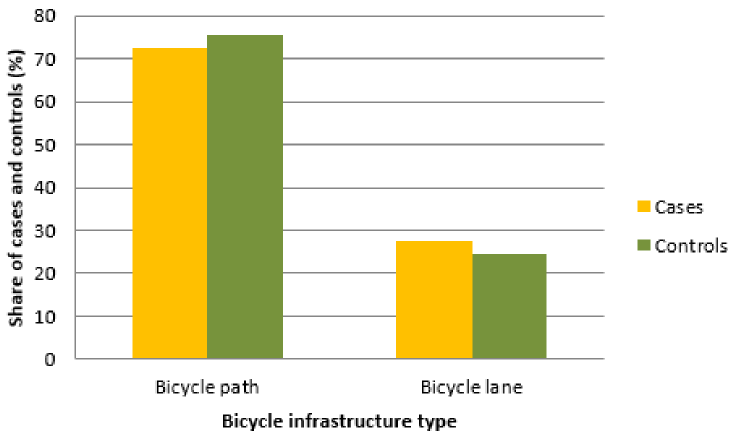


Figure 5.8: Results for the likelihood of having a crash without motor vehicles on bicycle paths and lanes

5.7 Crashes on one- and two-directional bicycle paths

The analysis of the relation between a bicycle crash and allowance of riding in both directions on bicycle paths is based on 213 data points (cases=108, controls=105). The corresponding tables are given in Appendix C (tables C.36-40). The results show that significantly more crashes without motor vehicles occurred on two-directional bicycle paths (Figure 5.9), yielding an odds ratio of 1.90 (CI=1.07-3.41). This suggests that bicycle crashes (motor vehicles included) are more likely on two-directional bicycle paths.

It is also found that bicycle-bicycle crashes are more likely on two-directional bicycle paths. A significant odds ratio of 3.97 (CI=1.22-12.95) was found. Moreover, single-bicycle crashes are equally frequent on one- and two-directional bicycle path, but no significant relation was found. In addition, also the relation with motor vehicle-bicycle crashes was examined. The shares of cases and controls (Table C.40) pointed towards a higher likelihood of these crashes on two-directional bicycle paths. However, an insignificant relation was found (p= 0.27), possibly due to a low number of cases and controls for this analysis.

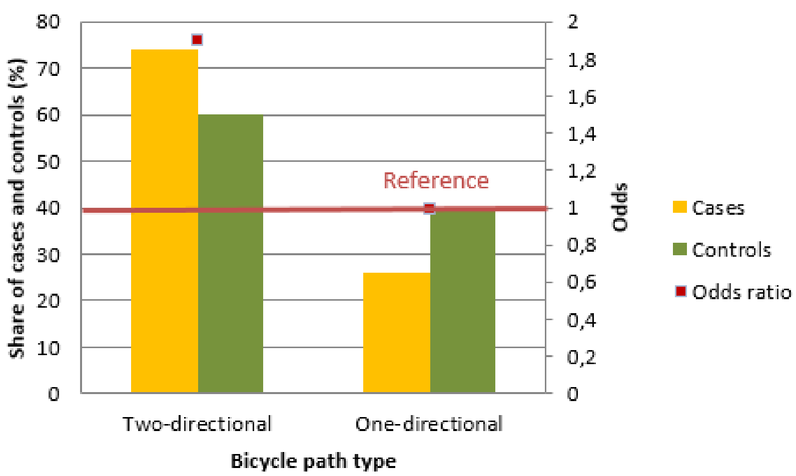


Figure 5.9: Results for the likelihood of having a crash without motor vehicles on one- and two-directional bicycle paths

5.8 Crash injury severity

Half of all bicycle crash victims (49.9%) sustained from severe injuries, i.e. hospitalized or treated by a specialist (severe injuries) after treatment at the emergency room. 24.6% of the victims visited a family doctor or a physiologist (moderate injuries). 25.4% underwent other medical treatment, did not specify the treatment in the survey or did not have any further treatment (unknown severity) (Table C.41). However, between the categories there is also some overlap meaning that some cyclists had multiple medical treatments and therefore selected more than one category in the questionnaire. By taking into account the most severe category, the shares changed to respectively 53.4%, 33.0%, 13.6% (Table C.42). This categorisation (unknown excluded) was further used for the analysis in 5.8.1, 5.8.2 and 5.8.3.

5.8.1 Injury severity due to collisions with bollards

The results for the injury severity of collisions with bollards are based on 1582 data points (bollard=65, single-bicycle crash without obstacle=1517). The corresponding tables are given in Appendix C (tables C.43-44). The results are depicted in Figure 5.10. 75% of the collisions with bollards resulted in severe injuries, whereas only 63% of the crashes without obstacles (Table C.44) and 53.4% of all crashes result in severe injuries. A collision with a bollard induces more severe injuries, compared to single-bicycle crashes without obstacles (OR=1.87; CI=1.05-3.32).

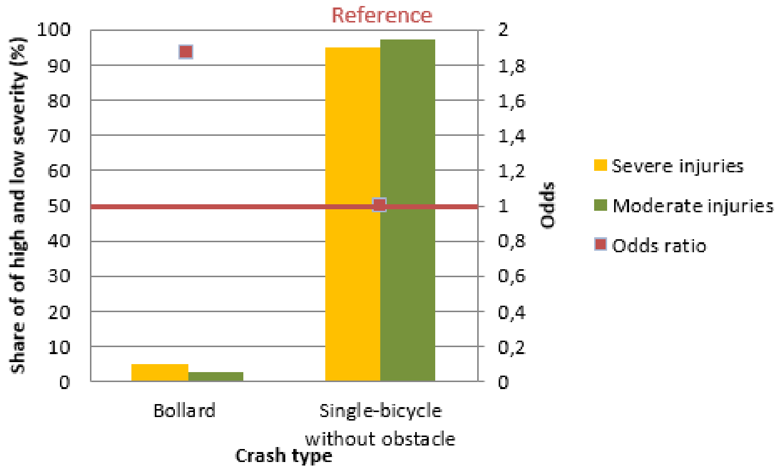


Figure 5.10: Results for collisions with bollards in relation to the injury severity

5.8.2 Injury severity due to collisions with doors of parked cars

The results for the injury severity of collisions with doors of parked cars are based on 1545 data points (car doors=28, single-bicycle crash without obstacle=1517). The corresponding tables are given in Appendix C (tables C.45-46). The results are presented in Figure 5.11. 57% of the collisions with doors of parked cars, 63% of the crashes without obstacles (Table C.46) and 53.4% of all crashes result in severe injuries. Contrary to what was hypothesized, collisions with car doors did not result in more severe injures than single-bicycle crashes without obstacles.

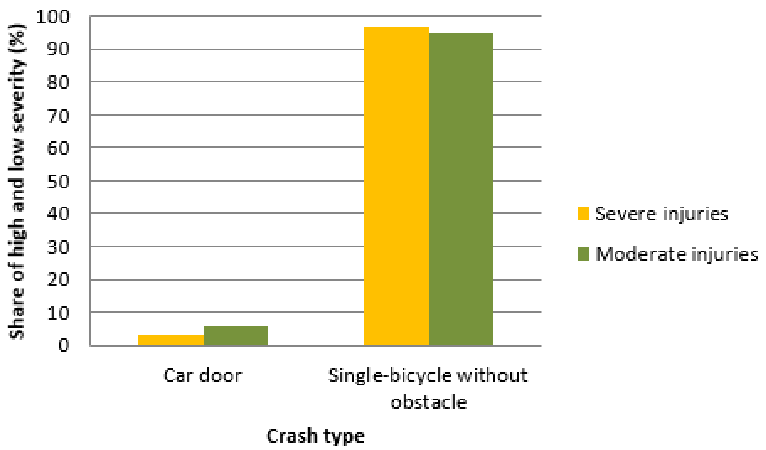


Figure 5.11: Results for collisions with doors of parked cars in relation to the injury severity

5.8.3 Injury severity due to bicycle-bicycle crashes

It was examined whether frontal bicycle-bicycle crashes were more severe than crashes with cyclists riding in the same direction. The analysis was based on 224 data points (same direction=194, opposing direction=30). The corresponding tables are given in Appendix C (tables C.47-49). The results are depicted in Figure 5.12. It was found that opposing direction (frontal) bicycle-bicycle crashes are more likely to induce severe injuries compared to same direction crashes (OR=2.64; CI=1.12-6.22).

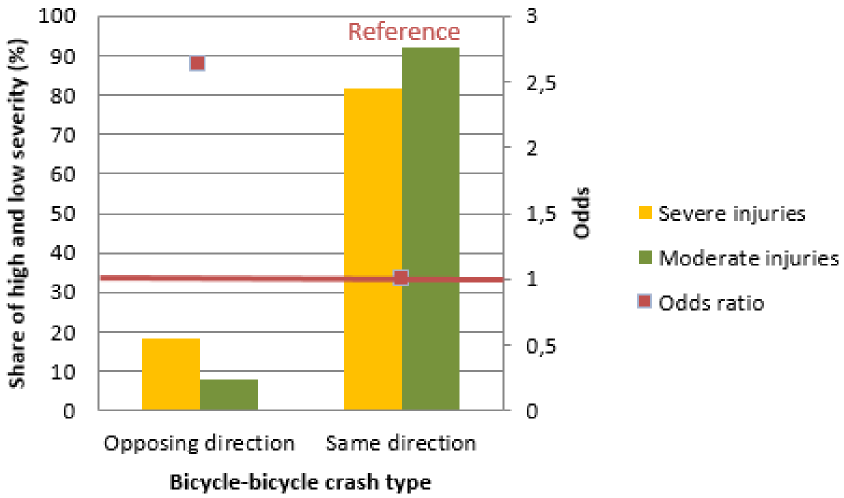


Figure 5.12: Results for bicycle-bicycle crashes in relation to the injury severity

5.9 Hypothesis test results

Following the results, conclusions can be made on the research hypotheses. Sufficient evidence was found to support the following hypotheses:

RH2a/b The likelihood of riding off the road crashes is related to a) street or b) bicycle path widths

RH3 The likelihood of collisions with bollards is related to the width between the bollard and the edge of the bicycle path

RH4a The likelihood of handlebar collisions of cyclists cycling together is related to street widths

RH5 The likelihood of collisions with kerbs is related to the presence of different road sections

RH9b The likelihood of bicycle-bicycle crashes is increased at two-directional bicycle paths

RH10 A collision with a bollard results in an increased injury severity

RH12 Frontal bicycle-bicycle crashes are related to an increased injury severity

Moreover, insufficient evidence was found to support the following research hypotheses:

RH1a/b The likelihood of collisions with kerbs is related to a) street or b) bicycle path widths

RH4b The likelihood of handlebar collisions of cyclists cycling together is related to the bicycle path widths

RH6 The likelihood of riding off the road crashes is related to the presence of different road sections

RH7a/b The likelihood of a) single-bicycle crashes or b) bicycle-bicycle crashes is related to cycling on intersections

RH8a/b The likelihood of a) single-bicycle crashes or b) bicycle-bicycle crashes is related to cycling on bicycle paths or bicycle lanes

RH9a The likelihood of single-bicycle crashes is increased at two-directional bicycle paths

RH11 A collision with a door of a parked car results in an increased injury severity

PART IV: Conclusions and discussion

Chapter 6 Conclusions and discussion

Based on the research conducted and the results obtained, some conclusions can be formulated with respect to the research hypotheses. Consequently, answers can be given to the main research questions. These answers form the conclusion of this thesis which is presented in section 6.1. The findings, the applied method and the used data are further discussed in section 6.2. Several recommendations for further research and practice are made and presented in section 6.3 and 6.4.

6.1 Conclusion

In order to conclude on this thesis, the research gaps that were identified earlier are recalled briefly and the corresponding findings are presented. Then, the final conclusions are given.

6.1.1 Problem definition and research gaps

This first aim of this study was to investigate to what extent infrastructure characteristics contribute to bicycle crashes without motor vehicles. Although infrastructure characteristics is a broad concept, this study aims to fill part of the gap between the safety problem (bicycle crashes without motor vehicles due to infrastructure characteristics) and the lack of research done on this topic.

Multiple studies suggested that the width of road and bicycle paths contributes to the occurrence of bicycle crashes without motor vehicles, but no quantitative background supporting these findings was found. When this knowledge is further refined, this can be implemented in the guidelines, resulting in a possible safer bicycle infrastructure design. Also, extensive knowledge was found on bicycle crashes with motor vehicles on different road sections, resulting in different crash risks. However, we also want to understand the relationship between cycling on different types of road sections and crashes without motor vehicles, which is hardly researched. Also the injury severity of bicycle crashes is suggested to be related to the different types of crashes, but little knowledge was found on the contribution of specific infrastructure characteristics to the severity of single-bicycle and bicycle-bicycle crashes.

The second aim of this study was to determine the influence of a small group of infrastructure characteristics by using a case-control method. The methodology used to fulfil this objective was based on a case-control method which includes the selection of controls on the route of bicycle crash victims that were treated at emergency departments in 13 hospitals in the Netherlands. The design allows for analysing differences between infrastructure characteristics on crash and control locations. However, no directly applicable method for this purpose was found in the literature and therefore the aim of this study was to find a suitable method.

6.1.2 Main findings

The application of the developed case-control method was done for the different research hypotheses defined in section 2.3. This resulted in the following significant findings per research gap:

Gap 1: The risk of street and bicycle path widths in bicycle crashes without motor vehicles

- Collisions with bollards are more likely when the width between the bollard and the edge of the bicycle path is smaller.
- The likelihood of having a handlebar collision when cycling next to each other is increased on narrower streets.
- The likelihood of riding off the road crashes is higher when cycling on narrower streets and bicycle paths.
- Riding off the road crashes occur more often on narrower streets and bicycle paths as compared to kerb collisions.

Gap 2: The risk of different road types/sections in bicycle crashes without motor vehicles

- Cycling on intersections induces a higher likelihood of having a bicycle crash compared to riding on straight or curved road sections. Especially crashes with motor vehicles are more likely to occur on intersections than on straight or curved road sections.

- Cycling on two-directional bicycle paths increases the likelihood of having a bicycle crash without a motor vehicle in comparison to one-directional bicycle paths. Especially bicycle-bicycle crashes are more likely to occur on two-directional bicycle paths compared to one-directional bicycle paths.

- Kerb collisions are less likely to occur at intersections as compared to straight and curved road sections. The likelihood of kerb collisions is even lower when cycling on street intersections as compared to straight and curved streets. All the control locations in this analysis were also exposed to kerbs and therefore this result represents the likelihood of a kerb collision in case these are present.

Gap 3: The contribution of infrastructure characteristics to the injury severity of bicycle crashes without motor vehicles

- A collision with a bollard results in more severe injuries compared to other single-bicycle crashes without obstacles.

- Frontal bicycle-bicycle crashes result in more severe injuries than same direction bicycle-bicycle crashes.

6.1.3 Conclusions

Following from the research done, the research questions can be answered.

MQ-I Which case-control method design, including a framework for selecting control locations, can be applied when studying bicycle crashes without motor vehicles?

The case-control method as applied in this study focusses on selecting controls from the routes of bicycle crash victims. In the literature it is often acknowledged that case-control studies can be very effective with respect to the study period, in contradiction to cohort studies (i.e. reviewing an extensive cycling history).

A process that enables statistical analyses on the data for the research hypotheses, was designed for this specific study. This process included 6 steps: the hypothesis selection, the data description (description of crash locations), the data generation (reconstruction of the route), the data application (selection of control locations), the control set generation (set of controls per hypothesis) and the statistical analysis. The different steps in the method are incorporated in a framework which provides a clarification of the mutual relations between the steps.

In addition to these six basic steps in the case-control method, four extensions were designed to further improve the quality of the results. First, a reduction of the influence of the confounding variable (cycling intensity in this study) was achieved by matching. This measure limits the variability of the confounder between the cases and controls. Secondly, the quality of the route reconstruction was improved by using more detailed trip purpose categories, such that the routes were generated accordingly (e.g. shortest route or most attractive route). Thirdly, an increase in the statistical power of the final results was realised by generating more data. This was done by selecting more controls from a route of a bicycle crash victim. And finally, a control location was selected from the route of another bicycle crash victim (with comparable personal and circumstantial conditions) when limited trip information was available for the original cyclist (replacement of controls process). This increased the amount of data.

This design served the purpose of this study. Namely, due to the highly detailed case location description, detailed infrastructure characteristics (e.g. road width) could also be analysed. By first filtering the data on a specific crash type (e.g. bollard crash), research could be done on the role of detailed infrastructure characteristics in relation to those crash types. On top of that, the amount of data (controls) generated with the method was sufficient for retrieving a substantial number of significant results. Despite the fact that a lot of questionnaires were not fully filled out (resulting in difficulties to reconstruct the route and consequently select the control location), the 'replacement of controls' extension improved the number of generated controls with roughly 20%. Without this extension, the statistical power would have been lower.

MQ-II Which infrastructure characteristics contribute to the occurrence of bicycle crashes without motor vehicles?

The results show that a few infrastructure characteristics contribute to the occurrence of bicycle crashes without motor vehicles.

First of all, for a number of crash types it was found that street and bicycle path widths contribute to a higher likelihood of bicycle crashes without motor vehicles. More specifically, cyclists more often ride off the road on narrower streets and bicycle paths (mostly in rural areas). Lower widths between bollards and the edge of the bicycle path also contribute to a higher likelihood of colliding with a bollard. Moreover, handlebar collisions between two cyclists riding next to each other are more frequent on narrower streets.

Furthermore, it was found that the presence of intersections is an important factor for the occurrence of kerb collisions because these crashes are less likely to occur on intersections than on straight and curved road sections. Especially on street intersections, cyclists are less likely to be involved in a kerb collision.

In addition, the occurrence of two-directional bicycle paths in a cyclist's route influences the likelihood of bicycle-bicycle crashes. It was found that cycling on two-directional bicycle paths induces a higher likelihood of having a bicycle-bicycle crash, compared to one-directional bicycle paths. Moreover, it was found that especially frontal bicycle-bicycle crashes result in more severe injuries (compared to crashes when riding in the same direction).

Finally, the placement of infrastructural objects can influence injury severity because crashes with bollards induce more severe injuries than single-bicycle crashes without objects.

6.2 Discussion

This section includes a discussion of the results in this thesis. They are put in a wider context to show the possibilities for a safer design of the bicycle infrastructure. Finally, the limitations of the method and data are discussed to assess the validity of the results.

6.2.1 Interpretation of results

Eighteen hypotheses were examined in this study, resulting in both significant and insignificant results. Besides the results discussed below, some infrastructure characteristics were analysed but these relations were found to be insignificant.

Street and bicycle paths widths

Riding off the road crashes, bollard collisions and handlebar collisions were found to be related to the width of streets or bicycle path widths. These findings agree with the suggestion from qualitative studies that narrower streets and bicycle paths contribute to a higher crash risk (Schepers, 2008, 2010). And because no other related studies were found, these findings extend the scientific knowledge on the contribution of road widths to bicycle crashes without motor vehicles and can be used to refine the guidelines.

More specifically, the average width of bicycle paths in riding off the road crashes (mainly occurring in rural areas) is 2.28 meter (cases). For the controls an average of 2.58 meter was found and CROW (2016) prescribes bicycle path widths of >2.50 meter on low-intensity bicycle paths. Although the suggestion of CROW (2016) is closer to the controls than to the cases, this value suffices on average. In addition, in 16.5% of these crashes, the height difference between the road and verge was too big for re-entering the road. Sufficient (semi-)hardened shoulders, as advised by Fietsberaad (2011), can suffice for both appointed problems.

For the design of bollards, CROW (2016) recommends a width of 1.60 meters next to a bollard whereas in the crashes in our study an average of 1.43 meter was found. In three crashes the width was found greater than 2.40 meter. Bollards are placed to prevent car traffic from entering a certain area or road stretch, but with a car width of 1.85 meter (85% percentile) (Eger, 2013), the three found bollards do not seem to be sufficient. The finding that few bollards are in line with the design rules, is in agreement with the finding of Zeegers (2004) that only one out of 800 bollards was designed correctly.

Handlebar collisions are more frequent on narrower streets and can possibly be attributed to avoiding manoeuvres that can be expected more frequently on narrower streets. However, further increasing the street width can initiate other behaviour by car drivers. Allen-Munley et al. (2004) found that at higher street widths more space is available for cyclists, which results in a higher safety for the cyclist. We can now extend this finding with a more detailed knowledge on bicycle-bicycle crashes. In addition, an indication of a higher likelihood of handlebar collisions on narrower bicycle paths was found. This quantifies the knowledge of Schepers (2010) but our results were statistically insignificant due to a low amount of data.

Road types and sections

An increased likelihood of kerb collisions on straight and curved road sections was suggested by Schepers (2008). The present study confirms and quantifies this suggestion and it also extends the current, limited, knowledge on kerb collisions. In addition, it was found that this relation was even stronger on streets. A reason for this can be that in various cases it was found that the cyclists' riding line on streets was influenced by other traffic (overtaking manoeuvres). Moreover, all kerbs in the analysis were right kerbs and as Janssen (2016) found that cyclists tend to use their own dedicated bicycle infrastructure (even in case of levelled kerbs), implementation of levelled kerbs might reduce the number of crashes on straight and curved bicycle paths.

Crashes on one- and two-directional bicycle paths were mainly studied with respect to motor vehicles. In our study it was found that cycling on two-directional bicycle paths increases the likelihood of having a bicycle crash without motor vehicles. Single-bicycle crashes were found equally frequent on one- and two directional bicycle crashes. On the other hand, bicycle-bicycle crashes were found to be substantially more likely to occur on two-directional bicycle paths. These results extend the current knowledge on the risk of cycling on two-directional bicycle paths. Additionally, de Waard & Schepers (2010) found that two-directional bicycle paths are riskier in relation to motor vehicle-bicycle crashes on intersection and crossings. Our results show an indication of a higher likelihood of motor vehicle-bicycle crashes on two-directional bicycle paths. Whereas all of these crashes occurred on intersections this seems in line with what de Waard & Schepers (2010) found. However, we cannot confirm this because our results were insignificant.

CROW (2016) already advised against the use of two-directional bicycle paths and provided guidelines to benefit safety on these bicycle paths. A width of 3 meter per direction in combination with a separating verge in the middle is recommended. Nevertheless, for several cases in our study a limited space was found for the bicycle infrastructure which further confirms one of the reasons for not complying with the guidelines, as Bax et al. (2014) found.

Cycling on intersections was found to increase the likelihood of having a crash in general. Crashes with motor vehicles were more frequent on intersections than on other road sections and this outcome corresponds with the risks found in other studies by Bil et al. (2010) and Asgarzadeh et al. (2017). With respect to crashes without motor vehicles, no significant results were found. It was observed that single-bicycle crashes were equally frequent on intersections as on road sections.

Crash injury severity

It was attempted to quantify relations of injury severity due to collisions with bollards. More severe injuries were found for collisions with bollards in comparison to single-bicycle crashes without obstacles. According to Schepers (2008), almost half of such crashes are caused by elderly cyclists (65+yr). Therefore, this result might be somewhat biased because elderly people are more vulnerable road users (Reurings et al., 2012) and the share of elderly cyclists in the group without obstacles might be lower. Nevertheless, this finding can definitely support for lowering the number of bollards on bicycle paths, as the discussion on the usefulness of bollards is still ongoing. Nonetheless, these results only relate to the injury severity (and not to the crash risk) and therefore the design of more forgiving bollards can also be advised.

Furthermore, frontal bicycle-bicycle crashes were found to induce more severe injuries in comparison to same direction bicycle-bicycle crashes. This result can logically be explained by a higher relative speed in frontal crashes and consequently a higher energy dissipation. CROW (2016) already advises against the use of two-directional bicycle paths because of more severe injuries. This advice was so far not underpinned by quantitative scientific knowledge and the result from this study helps to fill this gap.

Collisions with doors of parked cars seem to be associated with more severe injuries compared to all other crashes, but this relation was found to be statistically insignificant. Moreover, Jänsch (2015) also studied these collisions and similarly found no significant difference between the injury severity of collisions with doors of parked cars and all other crashes.

6.2.2 Limitations

Although this study have led to interesting and new insights, it is important to mention that various limitations were found during this study:

- Since only the crash location and the trip origin was specified, uncertainty exists on the actual followed route in-between. By including information on the trip purpose, the route generation process was partly improved. Moreover, the uncertainty becomes higher at longer trips, as more route choices exist. However, in this data mostly short trips were included. On the other hand, the assumption can be made that due to a constant design policy within individual municipalities the infrastructure design might spatially be comparable. However, still uncertainty exists which affects the results. This can possibly be resolved by contacting the victim, but recalling the route after a long period could be difficult.
- Originally, MAIS (Maximum Abbreviated Injury Scale) categories were present in the dataset but they were not available for this study due to privacy restrictions. Therefore severity categories were created, but these were less accurate compared to the MAIS categories. However, the type of treatment largely represents the injury severity.
- The intensity data from the Dutch bicycle counting week was not accurate. However, due to the application of matching, categories were created and accurate values became less important. Also, in rural areas low intensities were frequent and in urban areas, high intensity differences were observed. Whether this was related to the measuring method was not clear, but consequently only cycling intensities in urban areas were used in this study.
- Street and aerial photography was used to inspect the case and control locations. In a few cases, the street photography showed recent road works in which infrastructure characteristics (e.g. road width or objects) might have changed. Because the actual crash might have happened before these images were taken, these cases were omitted. Older photography would have sufficed for these cases but this was not available.
- The quality of the answers in the questionnaire was not always good enough. For instance, some of the cases were omitted because of inaccurate descriptions of the crash location. Although a satisfying number of statistically significant results was found in this study, the amount of analysable data was seriously affected by this low-quality information. Further contacting the bicycle crash victims can further increase the amount of analysable data.
- The formulation of some of the questions in the survey was sometimes ambiguous, resulting in misinterpretation of terms by the crash victim. For instance, the victims were regularly confused about the terms bicycle paths and lanes. However, this was solved in this study because the case location was inspected and provided additional information. Better explaining the terms in the survey seems necessary to improve the reliability of the data.
- The case-control method in this study was not suitable to examine the crash risk of e.g. kerbs, bollards or tram tracks crashes in general. With the method only analysis was possible on more detailed variables (e.g. road/bicycle paths width) in relation to those crash types. Furthermore, road maintenance was also not examined because the temporal nature of dirt on the road makes the case location description impossible after a certain time.
- The selection of control locations was done manually and because many variables were considered this resulted in an increase of time needed to perform this study. Moreover, when applying the method manually this can also induce errors made by the researcher. Improving the method with an automated control selection process can therefore reduce the research time and accuracy.

- The questionnaire was handed out by VeiligheidNL in 13 hospitals in the Netherlands. Panneman & Blatter (2016) studied the representativeness of these hospitals to all hospitals in the Netherlands. The population (age and gender) in the sample hospitals was a good representative of the Dutch population. However, older cyclists filled out the questionnaire more often, leading to an overrepresentation in the dataset for this study. Consequently, the conclusions on the injury severity might be biased because older cyclists might generally experience more severe injuries. This can be resolved by applying weight factors in the analysis.

- The conclusions were rather generic because e.g. age, alcohol usage and weather conditions can also affect the likelihood of crashes but these were not included in the analysis. By restricting the results on a variable (only include data for e.g. older cyclists), the influence could be examined. However, a small number of cases in this study did not allow these levels of detail.

- Several results indicated a possible relation but were found statistically insignificant which was partly related to small number of cases.

6.3 Recommendations for further research

Due to the aforementioned limitations, the following recommendations can be formulated to improve the applicability of the method and the used data:

- It is recommended to improve the quality of the reconstruction of the routes in the method. This can be done by contacting the victim to retrieve information on the actual followed route. Also a random test can be done on a sample of routes, such that further insight into the quality of the route reconstruction is gathered.

- An increase of the amount of data, could increase the number of statistically significant results and conclusions. Combining data from multiple years or also including crashes from cyclists which were not treated at an emergency room could be relevant.

- The implementation of the method is mainly done manually and the control selection can possibly be better done by applying e.g. the Google Terrapattern application. This application uses satellite imagery in which the user selects a location. The application delivers comparable aerial images from the same specified area, by controlling on the same characteristics within the image. However, specific maps of the Netherlands are not yet available.

Moreover, the following recommendations with respect to further research on the contribution of other relevant infrastructure characteristics are mentioned:

- In other studies, bollards or tram tracks on the roads are suggested to induce a substantial amount of crashes. Further research on the quantitative risk of these infrastructure characteristics is advised. Comparing the exposure (e.g. bollard/km) of bollards or tram tracks to cyclists with the relative amount of bollard crashes (e.g. bollard crash/km) is proposed.

- Crashes due to riding off the road are related to the street and bicycle path widths. It was also found that the height difference between the road and verge affects the crash occurrence. Further research on this topic can provide insight on the actual risk of various heights and the possible relation to the subsoil of the verge.

- Since temporal (e.g. leaves and dirt on the road) or structural maintenance (e.g. cracks and bumps) is found to be a main cause of single-bicycle crashes, further quantitative research seems advisable.

- Because of a high efficiency of the case-control method with respect to the study time, it is recommended to also apply the case-control method to other transport modes (e.g. motor vehicles on highways). In case this is applied in other fields, only the infrastructure description in the method should be adjusted to the specific field of research.

6.4 Recommendations for practice

As a result of this study the following recommendations for practice are formulated. Some results show that by more strictly following the guidelines in the design process (CROW, 2016), the safety of the bicycle infrastructure can be improved:

- Apply a width of 2.50 meter for low-intensity bicycle paths, as prescribed by CROW (2016), because this suffices on average for preventing riding off the road crashes.
- Apply a width of 1.60 meter next to bollards on bicycle paths (recommendation of CROW (2016)), which results in safer bicycle infrastructure. Reconsidering the placement of bollards in case in which the width next to the bollard is higher than 1.85 is advised because then the bollards lose their purpose.
- Apply a safe design of bollards as prescribed by CROW (2016) or reconsider the placement of them because these objects increase the injury severity.

In addition, the following recommendations are made to improve the safety of bicycle infrastructure:

- Apply levelled kerbs on straight and curved bicycle paths.
- The application of semi-hardened shoulders as advised by Fietsberaad (2011) improves the safety of bicycle paths (for preventing riding off the road crashes and better re-entering the bicycle path).
- The application of one-directional bicycle paths is preferred over two-directional bicycle paths.

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PART V: Appendices

Appendix A Methodology

Table A.1: Infrastructure characterisation steps in detail

Step	Description	Choices		Representation
4	Road course?	a. Intersection b. Straight	c1. Strong curve 90^0 c2. Normal curve 45^0-90^0 c3. Soft curve 0^0-45^0	
5	Road dimensions?	a. <0.5m b. 0.5-0.75 m c. 0.75-1m d. 1-1.25 m e. 1.25-1.5 m f. 1.5-1.75 m g. 1.75-2 m h. 2-2.25 m	i. 2.25-2.5 m j. 2.5-2.75 m k. 2.75-3 m l. 3-3.25 m m. 3.25-3.5 m n. >3.5 m o. when exposure: exact dimension	
6	Road objects?	a. Bollard b1. Hardened shoulders: Equal to infrastructure b2. Semi-hardened shoulders	b3. Soft shoulders (grass etc.) c. Kerbs d. Tram tracks e. Parked cars	

Table A.2: Review for extension 1: Bias exclusion – Matching confounder

Criteria	Extension effect	Effect
Data generation	No effect. The amount of data is not changed by this measure.	o
Bias exclusion	The assumption of equal intensities in the basic framework is changed into a variable intensity over the network.	+
Accuracy	The accuracy increases because the controls can be made more characteristically equal to the cases, because also the intensity is taken into account.	+
Speed	The intensity is accounted for in the case description step and the control location step. The overall speed of determining a control therefore is lowered.	-

Table A.3: Review for extension 2: Bias exclusion – Variability between case and control characteristics

Criteria	Extension effect	Effect
Data generation	A too high level of detail can prevent the study from being effective because the probability of finding a more detailed control can be lower, resulting is less generated data	-
Bias exclusion	The assumptions within the *infrastructure characterisation* step are changed and more differentiated input can be given. The increased level of detail decreases the bias in this part.	+
Accuracy	The accuracy increases because the controls can be made more equal to the cases, because the detail level in the *infrastructure characterisation* step is increased.	+
Speed	A more detailed description of the variables needs a more accurate measuring method, which increases the process time of the method.	-

Table A.4: Review for extension 3: Bias exclusion – Route choice bias

Criteria	Extension effect	Effect
Data generation	No effect. The amount of data is not changed by this measure.	o
Bias exclusion	The assumptions within the *route generation* step are changed and more differentiated input can be given. The increased level of detail decreases the bias in this part.	+
Accuracy	No effect. The cases are not made more equal to the controls by this measure.	o
Speed	No effect. The application of this measure does not influence the speed of using the method.	o

Table A.5: Review for extension 4: Optimization – More controls

Criteria	Extension effect	Effect
Data generation	A maximum of four controls per case can be selected by applying this extension. This can result in an advantageous amount of data, which can result in a considerably higher statistical power.	++
Bias exclusion	No effect. No bias is generated when selecting more than one control for one case.	o
Accuracy	No effect. This measure does not affect the equality between the cases and controls.	o
Speed	Because the maximum achievable number of controls is increased more control locations can be analysed, resulting in a higher overall process time.	-

Table A.6: Review for extension 5: Optimization – Replacement of controls

Criteria	Extension effect	Effect
Data generation	This optimization step can generate routes for cyclists with lacking route information. Therefore valuable data can be generated to re-use parts of the dataset.	++
Bias exclusion	The *confounder control* compares a selection of crash inducing factors. As not all factors can be included in this step, bias is generated. The level of bias is related to the choice of the set of comparable factors.	-
Accuracy	No effect. This measure does not affect the accurate selection of controls in comparison to the cases.	o
Speed	Because the possibility of examining the route from other bicycle crash victims, more controls can be analysed by using this extension. This can result in a higher overall process time. Also the confounder control step itself increases the process time	-

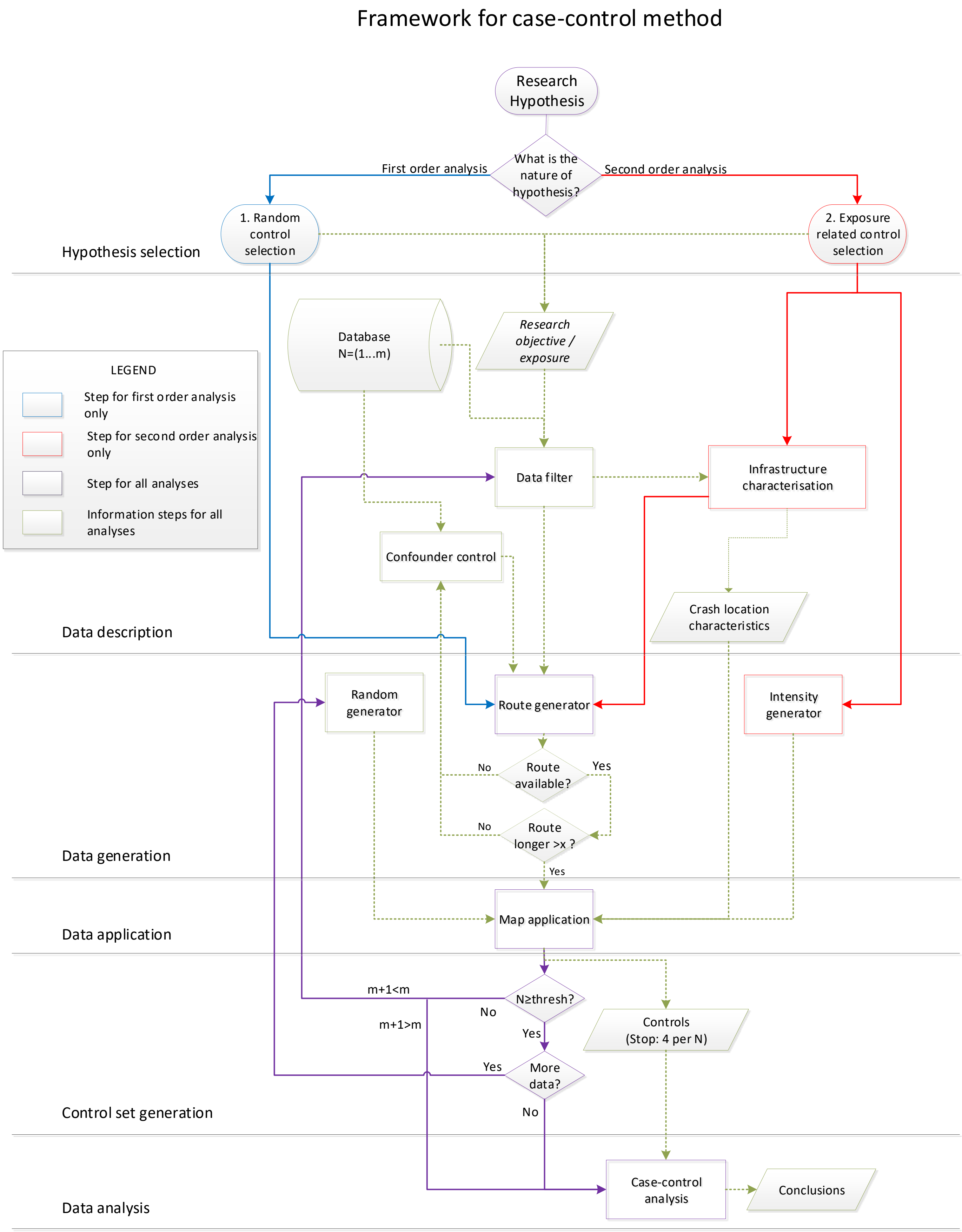

Figure A. 1: Framework for the case-control method

Appendix B Operationalization

Table B.1: Hospitals which handed out questionnaires for the survey conducted by VeiligheidNL

Hospital	Location
VUmc*	Amsterdam
AMC	Amsterdam
Bravis ziekenhuis	Bergen op Zoom
Maasziekenhuis Pantein	Boxmeer
Reinier de Graaf Gasthuis	Delft
De Gelderse Vallei	Ede
Admiraal De Ruyter Ziekenhuis	Goes
MC Groep Zuiderzee	Lelystad
Isala Diaconessenhuis	Meppel
Radboudumc	Nijmegen
Sint Jans Gasthuis	Weert
Ommelander Ziekenhuis Groep	Winschoten
Streekziekenhuis Koningin Beatrix	Winterswijk

Table B.2: Applied variables with specific categories

Type	Variable	Categories
Location	Case location availability	Yes No
	Case location	Latitude coordinate ; Longitude coordinate
Infrastructure specification	Area	Urban Rural
	Road type	Street Bicycle path Bicycle lane
	Amount of directions	One-directional Two-directional
	Road dimension	<1m 1-1.5 m 1.5-2 m 2-2.5 m 2.5-3 m 3-3.5 m 3.5> m when exposure: exact dimension
	Road objects	Yes/No Bollard Yes/No Kerbs Yes/No Tram tracks Yes/No Parked cars
	Intensity	Very low Low Moderate High Very high

Table B.3: Intensity distribution and categorization with their corresponding map indication colors (in QGIS application)

Intensity (cyclists/week)	Relative Intensity (%)	Map indication (colour)
0-50	<2.5%	Very Low (Green)
51-200	2.5-10%	Low (Yellow)
201-500	10-25%	Moderate (Orange)
501-1000	25-50%	High (Red)
>1000	>50%	Very High (Purple)

Table B.4: Criteria for selection of number of controls on one route

Length of route	Number of routes
< 500 m	Other route
500-2000 m	1 control selection
2000-10000 m	2 control selection
> 10000 m	3 control selection

Table B.5: Factors for the confounder control process

Type	Variable	Categories
Human factors	Age	0-17 yr 18-54 yr 55+ yr
	Gender	Male Female
Behavioural factors	Alcohol	Yes No
	Distraction	Yes No
Environmental factors	Weather influence	Rain or other disturbance Dry
	Daylight	Light Dark

Table B.6: Level of association and interpretation of Phi and Cramer's V values (University of Toronto, 2017)

Level of association	Verbal description	Interpretation
0.00	No Relationship	Knowing the independent variable does not help in predicting the dependent variable.
.00 to .15	Very Weak	Not generally acceptable
.15 to .20	Weak	Minimally acceptable
.20 to .25	Moderate	Acceptable
.25 to .30	Moderately Strong	Desirable
.30 to .35	Strong	Very Desirable
.35 to .40	Very Strong	Extremely Desirable
.40 to .50	Worrisomely Strong	Either an extremely good relationship or the two variables are measuring the same concept
.50 to .99	Redundant	The two variables are probably measuring the same concept.
1.00	Perfect Relationship.	If we know the independent variable, we can perfectly predict the dependent variable.

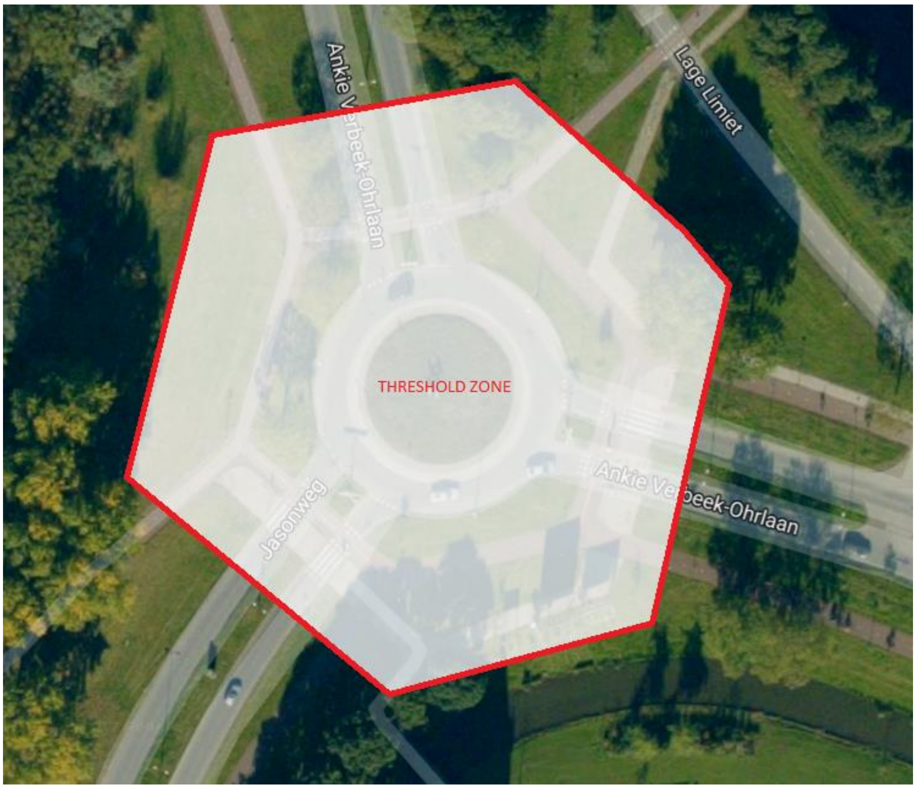

Figure B. 1: Threshold zone example at the location of a roundabout (10 meter) (Google earth, 2017)

Appendix C Analysis results

Overall descriptive statics

Table C.1: Crashes against a road user or object

Type	Frequency	Percent (%)	Cumulative Percent (%)
A moving bicycle	412	13.1	13.1
A moving race bike	58	1.8	14.9
Standing still vehicle (e.g. car, bicycle, scooter)	68	2.2	17.1
A moving car	366	11.6	28.7
A moving motorcycle	14	0.4	29.2
A moving moped/scooter	64	2.0	31.2
A pedestrian	28	0.9	32.1
A bollard	75	2.4	34.5
A fence or a wall	24	0.8	35.3
A kerb	91	2.9	38.1
A tree or a bush	35	1.1	39.3
An animal	40	1.3	40.5
Otherwise, namely	85	2.7	43.2
Unknown	1786	56.8	100.0
Total	3146	100.0	

Collisions with kerbs

Table C.2: Reasons of kerb collisions

Reason	Frequency	Percent
Distracted	6	6.6
Only loss of control	67	73.6
Not reasonable	4	4.4
Other traffic influenced the riding line of cyclist	14	15.4
Total	91	100.0

Kerb collisions - Intersection and other road sections

Table C.3: Cases and controls for kerb collisions on intersections and other road sections (no intersection)

<table>
<tr><th colspan="3" rowspan="2"></th><th colspan="2">Road course</th><th rowspan="2">Total</th></tr>
<tr><th>Intersection</th><th>No intersection</th></tr>
<tr><td rowspan="4">Crash</td><td rowspan="2">Yes</td><td>Count</td><td>10</td><td>38</td><td>48</td></tr>
<tr><td>% within Crash</td><td>20.8%</td><td>79.2%</td><td>100.0%</td></tr>
<tr><td rowspan="2">No</td><td>Count</td><td>28</td><td>41</td><td>69</td></tr>
<tr><td>% within Crash</td><td>40.6%</td><td>59.4%</td><td>100.0%</td></tr>
<tr><td colspan="2" rowspan="2">Total</td><td>Count</td><td>38</td><td>79</td><td>117</td></tr>
<tr><td>% within Crash</td><td>32.5%</td><td>67.5%</td><td>100.0%</td></tr>
<tr><td colspan="6">Significant relation (χ²(1, n=117)=5.033; p=0.025; Phi=0.207)</td></tr>
</table>

Table C.4: Cases and controls for kerb collisions on intersections and other road sections (no intersection) on bicycle paths

			Road course		Total
			Intersection	No intersection	
Crash	Yes	Count	3	14	17
		% within Crash	17.6%	82.4%	100.0%
	No	Count	7	16	23
		% within Crash	30.4%	69.6%	100.0%
Total		Count	10	30	40
		% within Crash	25,0%	75.0%	100.0%
No significant relation					

Table C.5: Cases and controls for kerb collisions on intersections and other road sections (no intersection) on bicycle lanes

			Road course		Total
			Intersection	No intersection	
Crash	Yes	Count	4	7	11
		% within Crash	36.4%	63.6%	100.0%
	No	Count	7	9	16
		% within Crash	43.8%	56.3%	100.0%
Total		Count	13	16	27
		% within Crash	40.7%	59.3%	100.0%
No significant relation					

Table C.6: Cases and controls for kerb collisions on intersections and other road sections (no intersection) on streets

			Road course		Total
			Intersection	No intersection	
Crash	Yes	Count	3	17	20
		% within Crash	15.0%	85.0%	100.0%
	No	Count	14	16	30
		% within Crash	46.7%	53.3%	100.0%
Total		Count	17	33	50
		% within Crash	34.0%	66.0%	100.0%
Significant relation (χ^2(1, n=50)=5.362 ; p=0.021; Phi =0.327)					

Table C.7: Odds ratios for kerb collisions on intersections

	OR	Lower	Upper	Significance Level
Overall (street, bicycle path and lanes)	0.3853	0.1653	0.8982	0.0272
Streets	0.2017	0.0487	0.8357	0.0273

Kerb collisions – Road and bicycle infrastructure width

Table C.8: Binary logistic regression results for collisions with kerbs related to the road and bicycle infrastructure width

Street width		B	S.E.	Wald	df	Sig.	Exp(B)	Low	High
(n=36)	Road Dimension	-,088	.273	.104	1	.747	.915	.536	1.564
	Constant	.711	1.548	.211	1	.646	2.036		
Bicycle path width		B	S.E.	Wald	df	Sig.	Exp(B)	Low	High
(n=27)	Road Dimension	-.504	.504	1.003	1	.317	.604	.225	1.621
	Constant	1.880	1.568	1.437	1	.231	6.554		
Bicycle lane width		B	S.E.	Wald	df	Sig.	Exp(B)	Low	High
(n=19)	Road Dimension	-.983	1.194	.679	1	.410	.374	.036	3.881
	Constant	1.886	1.970	.917	1	.338	6.595		

Table C.9: Overview of mean widths for collisions with kerbs related to the road and bicycle infrastructure width

	Case mean width (m)	Control mean width (m)
Street	5.46	5.59
Bicycle path	2.83	3.15
Bicycle lane	1.52	1.68

Crashes due to riding off the road

Figure C.1: Example of case in which the location of the edge of the bicycle path is not straightforward

Table C.10: Reasons of riding off the road crashes

Reason	Frequency	Percent
Only cycling off the road	78	56.1
Give way to other traffic	17	12.2
No sight on road	8	5.8
Not able to go back on road	23	16.5
Not reasonable	13	9.4
Total	139	100.0

Riding off the road - Intersection and other road sections

Table C.11: Cases and controls for riding off road crashes related to the road course

			Road Course			Total
			Intersection	Straight	Curve	
Crash	Yes	Count	7	50	12	69
		% within Crash	10.1%	72.5%	17.4%	100.0%
	No	Count	10	39	4	53
		% within Crash	18.9%	73.6%	7.5%	100.0%
Total		Count	17	89	16	122
		% within Crash	13.9%	73.0%	13.1%	100.0%
No significant relation						

Table C.12: Cases and controls for riding off road crashes related to the road course on bicycle paths

			Road Course			Total
			Intersection	Straight	Curve	
Crash	Yes	Count	4	31	8	43
		% within Crash	9.3%	72.1%	18.6%	100.0%
	No	Count	6	25	3	34
		% within Crash	17.6%	73.5%	8.8%	100.0%
Total		Count	10	56	11	77
		% within Crash	13.0%	72.7%	14.3%	100.0%
No significant relation						

Table C.13: Cases and controls for riding off road crashes related to the road course on streets

			Road Course			Total
			Intersection	Straight	Curve	
Crash	Yes	Count	3	17	4	24
		% within Crash	12.5%	70.8%	16.7%	100.0%
	No	Count	4	14	1	19
		% within Crash	21.1%	73.7%	5.3%	100.0%
Total		Count	7	31	5	43
		% within Crash	16.3%	72.1%	11.6%	100.0%
No significant relation						

Table C.14: Odds ratios for riding off road crashes

		OR	Upper	Lower	Significance Level
Overall	Intersections	0.4855	0.1714	1.3753	0.1738
	Straight	0.9447	0.4213	2.1181	0.8901
	Curves	2.5789	0.7812	8.5137	0.1200

Riding off the road – Road and bicycle infrastructure width

Table C.15: Average width in riding off the road crashes per road type

	Case mean width (m)	Control mean width (m)
Street	4.13	5.31
Bicycle path	2.28	2.58

Table C.16: Binary logistic regression results for riding off the road crashes related to the street and bicycle path width

Street width		B	S.E.	Wald	df	Sig.	Exp(B)	Low	High
(N=39)	Road Dimension	-.589	.274	4.611	1	.032	0.555	.324	.950
	Constant	3.217	1.340	5.761	1	.016	24.958		
Bicycle path width		**B**	**S.E.**	**Wald**	**df**	**Sig.**	**Exp(B)**	**Low**	**High**
(N=75)	Road Dimension	-.852	.412	4.280	1	.039	0.426	.190	.956
	Constant	2.360	1.032	5.232	1	.022	10.587		

Kerbs and riding off the road comparison

Table C.17: Results for kerb collisions and riding off the road crashes in urban and rural areas

			Area		Total
			Urban	Rural	
Type	Kerb	Count	74	15	89
		% within Type	83.1%	16.9%	100.0%
	Riding off road	Count	41	96	137
		% within Type	29.9%	70.1%	100.0%
Total		Count	115	111	226
		% within Type	50.9%	49.1%	100.0%
Significant relation (χ^2(1, n=226)=61,141; p<0,001; Phi=0,520)					

Table C.18: Cases and controls for kerb collisions and riding off the road crashes on intersections

			Crash type		Total
			Kerb collision	Riding off the road crash	
Crash	Yes	Count	10	7	17
		% within Crash	58.8%	41.2%	100.0%
	No	Count	28	10	38
		% within Crash	73.7%	26.3%	100.0%
Total		Count	38	17	55
		% within Crash	69.1%	30.9%	100.0%
No significant relation					

Table C.19: Cases and controls for kerb collisions and riding off the road crashes on straight and curved road sections

			Crash type		Total
			Kerb collision	Riding off the road crash	
Crash	Yes	Count	38	42	100
		% within Crash	38.0%	62.0%	100.0%
	No	Count	41	43	84
		% within Crash	48.8%	51.2%	100.0%
Total		Count	79	105	184
		% within Crash	42.9%	57.1%	100.0%
No significant relation					

Table C.20: Binary logistic regression results for the relation of the width in riding off the road crashes and kerb collisions on streets and bicycle paths

Street width		B	S.E.	Wald	df	Sig.	Exp(B)	Low	High
(N=44)	Road Dimension	-.883	.328	7.233	1	0.007	0.414	.217	.787
	Constant	4.359	1.592	7.498	1	0.006	78.181		
Bicycle path width		**B**	**S.E.**	**Wald**	**df**	**Sig.**	**Exp(B)**	**Low**	**High**
(N=59)	Road Dimension	-1.191	.472	6.364	1	0.012	0.304	.121	.767
	Constant	4.009	1.278	9.844	1	0.002	55.075		

Collisions with bollards

Figure C.2: An example of a 'bollard' or obstacle on a location that is not straightforward

Table C.21: Bollard crash characterization in bollard collisions

Bollard crash characterization	Frequency	Percent
Crash with regular bollard	51	66.2
Crash not on the road	6	7.8
Bollard was not the primary cause of the crash	4	5.2
Crash with other object (light, traffic sign)	10	13.0
Unknown circumstances	6	6.8
Total	77	100.0

Table C.22: Average width next to bollard in bollards collisions

	Case mean width (m)	Control mean width (m)
Bicycle path	1.43	1.69

Table C.23: Road type distribution of bollard collision cases

	Frequency	Percent
Bicycle path – street connection	5	14.7
Bicycle path	28	82.4
Bicycle lane	1	2.9
Total	34	100.0

Table C.24: Binary logistic regression results for bollard collisions related to bicycle path widths next to the bollard

Bicycle path width		B	S.E.	Wald	df	Sig.	Exp(B)	Low	High
(N=53)	Road Dimension	1.712	.816	4.397	1	.036	5.540	1.118	27.446
	Constant	-3.231	1.308	6.103	1	.013	.040		

Handlebar collisions

Table C.25: Reasons of crashes against other cyclists

Type	Frequency	Percent (%)	Cumulative Percent (%)
Front wheel of cyclist against another back wheel	112	23.8	23.8
Handlebar collision	88	18.7	42.6
A crash in which the cyclist crashed into the flank of another cyclist	37	7.9	50.4
A crash in which another cyclist crashed into the flank of the cyclist	69	14.7	65.1
A crash in which the cyclist crashed into its predecessor	12	2.6	67.7
A crash in which cyclist had a frontal crash	37	7.9	75.5
Otherwise, namely	115	24.5	100.0
Total	470	100.0	

Table C.26: Survey results for cycling together or alone during handlebar collisions

	Frequency	Percent	Cumulative Percent
I was cycling alone	13	14.8	14.8
I was cycling with one other cyclist	50	56.8	71.6
I was cycling in a group (more than one other)	23	26.1	97.7
Unknown	2	2.3	100.0
Total	88	100.0	

Table C.27: Binary logistic regression results for handlebar collisions related to street and bicycle path width

Street width		B	S.E.	Wald	df	Sig.	Exp(B)	Low	High
(N=25)	Road Dimension	.708	.352	4.060	1	.044	2.031	1.020	4.044
	Constant	-4.39	1.970	4.984	1	.026	.012		
Bicycle path width		B	S.E.	Wald	df	Sig.	Exp(B)	Low	High
(N=48)	Road Dimension	.366	.359	1.038	1	.308	1.441	.714	2.911
	Constant	-1.080	1.020	1.123	1	.289	.339		
One-directional bicycle path width		B	S.E.	Wald	df	Sig.	Exp(B)	Low	High
(N=23)	Road Dimension	.825	.806	1.050	1	.306	2.283	.471	11.071
	Constant	-1.95	1.865	1.098	1	.295	.142		
Two-directional bicycle path width		B	S.E.	Wald	df	Sig.	Exp(B)	Low	High
(N=25)	Road Dimension	.382	.505	571	1	.450	1.465	.544	3.944
	Constant	-1.285	1.643	.611	1	.434	.277		

Table C.28: Average widths in handlebar collisions per road type

	Case mean width (m)	Control mean width (m)
Street	4.69	6.29
Bicycle path	2.61	2.86
One-directional bicycle path	2.15	2.39
Two-directional bicycle path	3.03	3.28

Crashes on intersections

Table C.29: Cases against objects and road users in relation to the road course

	Straight road	A curve	An intersection	A roundabout	Other, namely	Unknown	Total
A moving bicycle	255	72	48	7	21	9	412
A moving racebike	38	11	4	0	4	1	58
Standing still vehicle (e.g. car, bicycle, scooter)	53	3	2	0	9	1	68
A moving car	119	30	124	55	33	5	366
A moving motorcycle	7	3	3	0	1	0	14
A moving moped/scooter	29	11	14	0	7	3	64
A pedestrian	19	6	0	0	2	1	28
A bollard	33	13	8	1	17	3	75
A fence or a wall	8	12	0	0	4	0	24
A kerb	48	24	4	3	12	0	91
A tree or a bush	17	12	0	0	6	0	35
An animal	33	4	0	0	1	2	40
Otherwise, namely	57	11	5	1	8	3	85
Unknown	835	389	133	30	292	107	1786
Total	1551	601	245	97	417	135	3146

Table C.30: Cases and controls for crashes on intersections or other road courses

			Analysis		Total
			Intersection	No intersection	
Crash	YES	Count	42	63	105
		% within Crash	40.0%	60.0%	100.0%
	NO	Count	25	93	118
		% within Crash	21.2%	78.8%	100.0%
Total		Count	67	156	223
		% within Crash	30.0%	70.0%	100.0%
Significant relation (χ^2(1, n=223)=9.357 ; p=0.002; Phi =0.205)					

Table C.31: Cases and controls for bicycle-bicycle crashes on intersections or other road courses

			Analysis		Total
			Intersection	No intersection	
Crash	YES	Count	12	28	40
		% within Crash	30.0%	70.0%	100.0%
	NO	Count	8	32	40
		% within Crash	20.0%	80.0%	100.0%
Total		Count	20	60	80
		% within Crash	25.0%	75.0%	100.0%
No significant relation					

Table C.32: Cases and controls for motor vehicle-bicycle crashes on intersections or other road courses

			Analysis		Total
			Intersection	No intersection	
Crash	YES	Count	22	12	34
		% within Crash	64.7%	35.3%	100.0%
	NO	Count	7	31	38
		% within Crash	18.4%	81.6%	100.0%
Total		Count	29	43	72
		% within Crash	40.3%	59.7%	100.0%
Significant relation (χ^2(1, n=72)=15.981; p<0.001; Phi =0.471)					

Table C.33: Cases and controls for single-bicycle crashes on intersections or other road courses

			Analysis		Total
			Intersection	No intersection	
Crash	YES	Count	8	23	31
		% within Crash	25.8%	74.2%	100.0%
	NO	Count	10	30	40
		% within Crash	25.0%	75.0%	100.0%
Total		Count	18	53	71
		% within Crash	25.4%	74.6%	100.0%
No significant relation					

Table C.34: Odds ratios for crashes on intersections

	OR	Lower	Upper	Significance Level
All crashes	2.4800	1.3755	4.4713	0.0025
Motor vehicle – bicycle crashes	8.1190	2.7558	23.9199	0.0001
Single-bicycle crashes	1.0435	0.3555	3.0628	0.9383
Bicycle-bicycle crashes	1.7143	0.6130	4.7941	0.3043

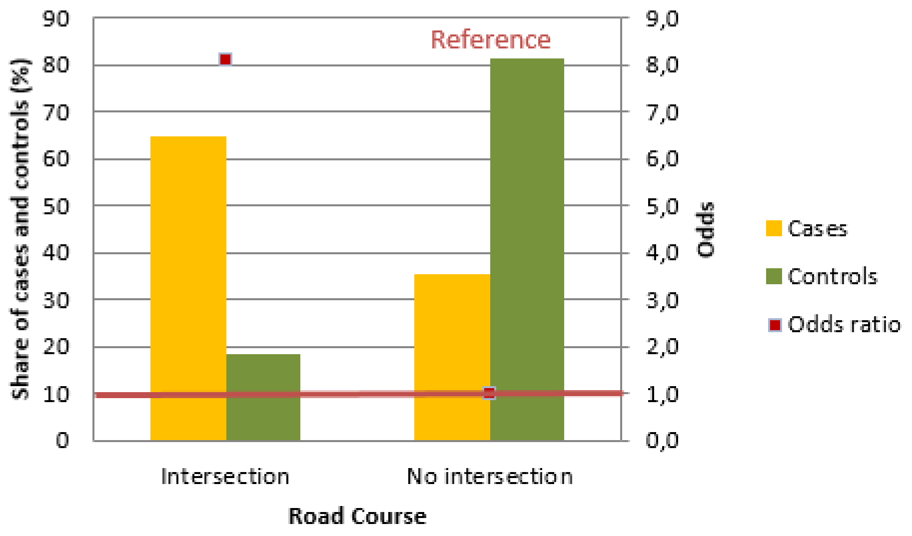

Figure C.3: Results for the likelihood of having a motor vehicle-bicycle crash on intersections and straight/curved road sections

Crashes on bicycle paths and lanes

Table C.35: Cases and controls for crashes on bicycle paths and lanes

			Analysis		Total
			Bicycle path	Bicycle lane	
Crash	YES	Count	21	8	29
		% within Crash	72.4%	27.6%	100.0%
	NO	Count	34	11	45
		% within Crash	75.6%	24.4%	100.0%
Total		Count	55	19	74
		% within Crash	74.3%	25.7%	100.0%
No significant relation					

Crashes on one- and two-directional bicycle paths

Table C.36: Odds ratios for having a crash on two-directional bicycle paths compared one-directional bicycle paths

	OR	Lower	Upper	Significance Level
Crashes without motor vehicles	1.9048	1.0653	3.4057	0.0298
Bicycle-bicycle crashes	3.9684	1.2163	12.9480	0.0223
Single-bicycle crashes	1.0626	0.4603	2.4529	0.8868
Motor-vehicle bicycle crashes	2.2500	0.5357	9.4502	0.2681

Table C.37: Cases and controls for bicycle crashes without motor vehicles on one- and two-directional bicycle paths

			Analysis		Total
			Two-directional bicycle path	One-directional bicycle path	
Crash	YES	Count	80	28	108
		% within Crash	74.1%	25.9%	100.0%
	NO	Count	63	42	105
		% within Crash	60.0%	40.0%	100.0%
Total		Count	143	70	213
		% within Crash	67.1%	32.9%	100.0%
Significant relation (χ^2(1, n=213)=4.780; p=0.029; Phi =0.150)					

Table C.38: Cases and controls for bicycle-bicycle crashes on one- and two-directional bicycle paths

			Analysis		Total
			Two-directional bicycle path	One-directional bicycle path	
Crash	YES	Count	29	5	34
		% within Crash	85.3%	14.7%	100.0%
	NO	Count	19	13	32
		% within Crash	59.4%	40.6%	100.0%
Total		Count	48	18	66
		% within Crash	72.7%	27.3%	100.0%
Significant relation (χ^2(1, n=66)=5.583; p=0.018; Phi =0.291)					

Table C.39: Cases and controls for single-bicycle crashes on one- and two-directional bicycle paths

			Analysis		Total
			Two-directional bicycle path	One-directional bicycle path	
Crash	YES	Count	35	17	52
		% within Crash	67.3%	32.7%	100.0%
	NO	Count	31	16	47
		% within Crash	66.0%	34.0%	100.0%
Total		Count	66	33	99
		% within Crash	66.7%	33.3%	100.0%
No significant relation					

Table C.40: Cases and controls for motor vehicle-bicycle crashes on one- and two-directional bicycle paths

			Analysis		Total
			Two-directional bicycle path	One-directional bicycle path	
Crash	YES	Count	9	5	14
		% within Crash	64.3%	35.7%	100.0%
	NO	Count	8	10	18
		% within Crash	44.4%	55.6%	100.0%
Total		Count	17	15	32
		% within Crash	53.1%	46.9%	100.0%
No significant relation					

Crash injury severity

Table C.41: Frequencies of different kinds of treatment

Treatment	Frequency	Percent	Cumulative Percent
No further treatment	714	18.7	18.7
Hospitalized	826	21.6	40.4
Specialist	1081	28.3	68.7
Family doctor	309	8.1	76.8
Physiologist	631	16.5	93.3
Other	255	6.7	100.0
Total	3816	100.0	

Table C.42: Injury severity categories frequencies

Injury severity	Frequency	Percent	Cumulative Percent
Unkown treatment	427	13.6	13.6
Low severity	1008	33.0	46.6
High severity	1681	53.4	100.0
Total	3146	100.0	

Injury severity due to collisions with bollards

Table C.43: Odds ratio for a high injury severity due to collisions with bollards

	OR	Lower	Upper	Significance Level
Bollard crashes	1.8694	1.0531	3.3182	0.0326

Table C.44: The injury severity in collisions with bollards

			Severity		Total
			Moderate Injuries	Severe Injuries	
Crash	No obstacle	Count	575	942	1517
		% within Crash	37.9%	62.1%	100.0%
	Bollard crash	Count	16	49	65
		% within Crash	24.6%	75.4%	100.0%
Total		Count	591	991	1582
		% within Crash	37.3%	62.7%	100.0%
Significant relation (χ^2(1, n=1582)=4.703; p=0.030; Phi =0.055)					

Injury severity due to collisions with doors of parked cars

Table C.45: Odds ratio for a high injury severity due to collisions with doors of parked cars

	OR	Lower	Upper	Significance Level
Car door crashes	0.5549	0.3348	0.9197	0.0223

Table C.46: The injury severity in collisions with car doors

			Severity		Total
			Moderate Injuries	Severe Injuries	
Crash	No obstacle	Count	575	942	1517
		% within Crash	37.9%	62.1%	100.0%
	Car door crash	Count	12	16	28
		% within Crash	42.8%	57.2%	100.0%
Total		Count	587	958	1545
		% within Severity	38.0%	62.0%	100.0%
No significant relation					

Injury severity due to bicycle-bicycle crashes

Table C.47: Categories of bicycle-bicycle crashes

	Frequency	Percent	Cumulative Percent
Same direction	214	59.6	59.6
Opposing direction	37	10.3	69.9
Crossing direction	108	30.1	100.0
Total	359	100.0	

Table C.48: The injury severity in bicycle-bicycle crashes

			Severity		Total
			Moderate Injuries	Severe Injuries	
Direction	Same	Count	95	99	194
		% within Direction	49.0%	51.0%	100.0%
	Opposing	Count	8	22	30
		% within Direction	26.7%	73.3%	100.0%
Total		Count	103	121	224
		% within Direction	46.0%	54.0%	100.0%
Significant relation (χ^2(1, n=224)=5.203; p=0.023; Phi =0.152)					

Table C.49: Odds ratio for a high severity due to opposing direction bicycle crash

	OR	Lower	Upper	Significance Level
Opposing direction bicycle-bicycle crashes	2.6389	1.1203	6.2160	0.0264