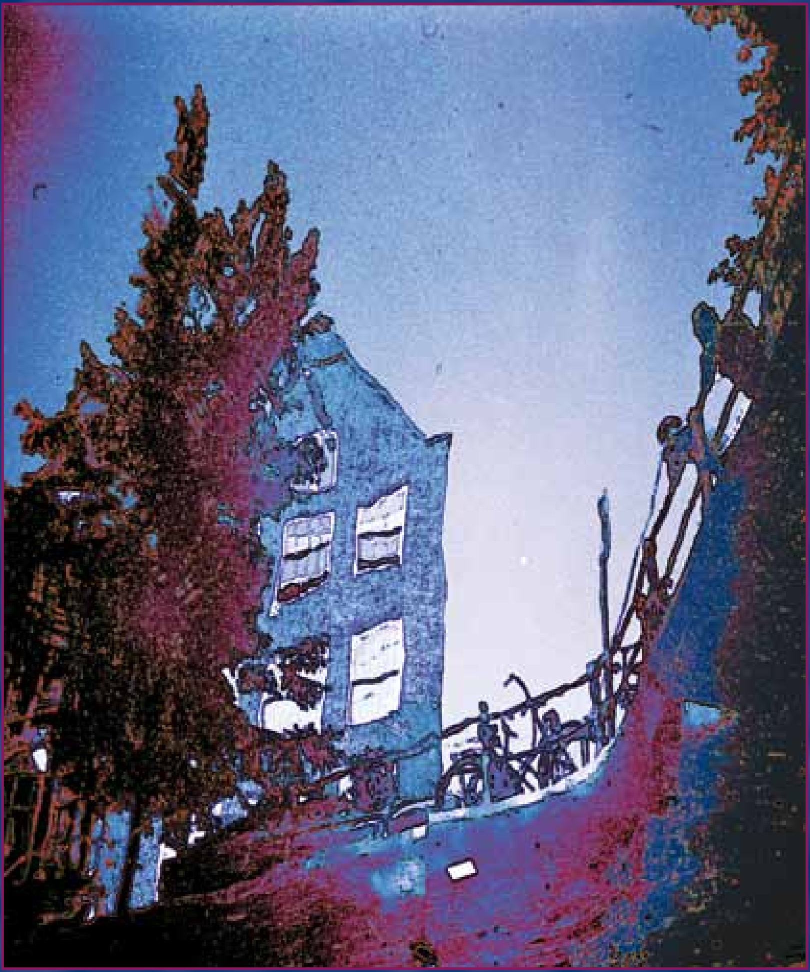
A safer road environment for cyclists



Paul Schepers

A safer road environment for cyclists

Paul Schepers

A safer road environment for cyclists

Proefschrift

ter verkrijging van de graad van doctor
aan de Technische Universiteit Delft,
op gezag van de Rector Magnificus prof.ir. K.C.A.M. Luyben,
voorzitter van het College voor Promoties,
in het openbaar te verdedigen op vrijdag 6 december om 15:00 uur

door

Johannes Petrus SCHEPERS

ingenieur in de geodesie en doctorandus in de psychologie
geboren te Roosendaal en Nispen

Dit proefschrift is goedgekeurd door de promotor:
Prof. ir. F.C.M. Wegman

Copromotor: Dr. M.P. Hagenzieker

Samenstelling Promotiecommissie:

Rector Magnificus,	voorzitter
Prof. ir. F.C.M. Wegman,	Technische Universiteit Delft, promotor
Dr. M.P. Hagenzieker,	Technische Universiteit Delft, copromotor
Prof. dr. G.P. van Wee,	Technische Universiteit Delft
Prof. dr. ir. M.F.A.M. van Maarseveen,	Universiteit Twente
Prof. dr. J.B.J. Smeets,	Vrije Universiteit
Prof. dr. R. Elvik,	Aalburg University
Dr. S. Daniels,	Universiteit Hasselt
Prof. dr. K.A. Brookhuis	Technische Universiteit Delft

Dit proefschrift is mede tot stand gekomen met steun van het Ministerie van Infrastructuur en Milieu, Rijkswaterstaat en de Stichting Wetenschappelijk Onderzoek Verkeersveiligheid SWOV.

SWOV-Dissertatiereeks
Stichting Wetenschappelijk Onderzoek Verkeersveiligheid SWOV
Postbus 1090
2260 BB Leidschendam
E: info@swov.nl
I: www.swov.nl

ISBN: 978-90-73946-12-5

Omslagillustratie: Berry den Brinker

Preface

Research on cycling safety is important from a societal point of view and past research left open a number of interesting research gaps. I was lucky enough to run a number of projects commissioned by the Ministry of Infrastructure and the Environment on this issue. I would like to thank Yvonne Need, the former head of my department, for allowing me the freedom to expand these projects with the help of interns and the interns for providing their input in the research: drs. T. van Houwelingen, drs. S. Maas, R. Michler Msc., drs. L. van de Sande and drs. J. Voorham. I published the results in scientific journals and express my gratitude to my co-authors for their useful comments and the inspiring discussions we had: Dr. B.P.L.M. den Brinker, Dr. M.P. Hagenzieker, Dr. E. Heinen, drs. K. Klein Wolt, ing. P.A. Kroeze, drs. R. Methorst, drs. W. Sweers, Prof. Dr. G.P. van Wee, Prof. ir. F.C.M. Wegman, ir. J.C. Wüst. The papers became the basis of this PhD thesis.

At the beginning of 2012 my co-author Berry den Brinker and I were taken by surprise as our paper "What do cyclists need to see to avoid single-bicycle crashes?" was awarded the 2011 Liberty Mutual Award and Liberty Mutual Medal. These prizes and the common thread of cycling safety through the studies inspired me to explore the possibilities of writing this PhD thesis. I would like to thank the management at Rijkswaterstaat, the Ministry of Infrastructure and the Environment, and SWOV for creating the opportunity to realize it. It was very helpful that I could spend time at SWOV to have discussions with experts and write this thesis. The discussions I had over the years with my direct colleagues at Rijkswaterstaat and the Ministry, such as Willem, Rob, Pieter, and Kate, were invaluable. Last but not least I thank Juliette for all her patience. Writing a PhD thesis takes a lot of spare-time and mental energy.

Finally, I hope that the results of my research will contribute to safe and pleasant cycling in the future!

Paul Schepers
Apeldoorn, 30 August 2013

Table of contents

1. Introduction

This thesis focuses on the question of how the road environment (road design and network characteristics) affects road safety for cyclists through effects on risk and exposure to risk. In this thesis, the term 'road design' is used to denote the location level (e.g. intersection design) while the term 'network characteristics' is used in relation to the network level (e.g. the presence of a road hierarchy and road classification). Road design plays a role in cyclists' crash and injury risk. Network characteristics affect mode and route choice (Heinen *et al.* 2010b) and thereby cyclists' exposure to risk. Policy interest in how road safety can be improved for cyclists has increased in recent years. To quote the European road safety policy document: "National and local governments are increasingly involved in promoting cycling and walking, which will require that more and more attention is paid to road safety issues. Most of the actions will have to be carried out at local level. Given the significant environmental, climate, congestion and public health benefits of cycling, it merits reflection whether more could not be done in this area." One of the seven objectives is to encourage the establishment of adequate infrastructures to increase the safety of cyclists and other vulnerable road users (European Commission 2010). This thesis goes into this question. This research has been carried out in the Netherlands where cyclist safety is a key road safety issue in the Strategic Road Safety Plan due to a rising proportion of cyclist deaths and seriously injured cyclists[1] in the total number of road traffic victims (Ministry of Infrastructure and the Environment 2008).

This chapter starts with a brief international overview of bicycle usage and cycling safety (Section 1.1). Scientific literature and a theoretical framework are described in Section 1.2. This framework is used to structure knowledge gaps and research questions in Section 1.3. Section 1.4 is about potential approaches to study cycling safety. Section 1.5 ends with an outline of the thesis. Because the goals of the thesis are described at the end of this chapter, we also present the main research questions here at the beginning to provide some guidance for readers.

---

[1] Injury severity of 2 or higher on the Maximum Abbreviated Injury Score (MAIS)

The thesis addresses the following research questions:

1. How does network-level separation of vehicular and cycle traffic in urban networks affect road safety?
2. How does a modal shift from short car trips to cycling affect road safety?
3. To investigate road design and crash risk, the following questions are addressed:
    a) How is the design of unsignalized priority intersections related to bicycle-motor vehicle crashes?
    b) What single-bicycle crash types can be distinguished and can these be related to infrastructure?
    c) What do cyclists need to see to avoid single-bicycle crashes?

1.1. Background

This section provides a brief international overview of bicycle usage and cycling safety with specific attention to the Netherlands where the studies of this thesis have been carried out.

1.1.1. Bicycle usage

There is a large variation in the amount of bicycle use among countries and cities. Low shares of cycling around 1% are found in Australia, Canada, and the United States, while high shares are found in European countries such as the Netherlands (26%), Denmark (18%), Germany, Sweden, and Belgium (10%) (Buehler and Pucher 2012). The proportion is higher for shorter trips, e.g. 35% of the trips up to 7.5 km are made by bicycle, which equals the proportion of those made by car (KiM 2011). There are large differences between cities as well. The share of cycling in the modal split is high in cities such as Münster in Germany (38%), and Copenhagen in Denmark (35%). Various European cities have shares around 20%, for example Bruges, Malmö, Florence, Prostejov, and Cambridge. The amount of cycling is low in the United States but a few cities such as Davis (16%), Boulder (10%), and Portland (6%) have an increased proportion of cycling in the modal split (Ministry of Infrastructure and the Environment 2009, Buehler and Pucher 2012). In the Netherlands, these shares range from 15% to almost 50% between municipalities (Rietveld and Daniel 2004). The bicycle also plays a role in longer journeys. More than 40% of Dutch train passengers cycle from home to the railway station and around 10% cycle from the railway station to their final destination (KiM 2011). The mean Dutch daily cycling distance per person is 2.5 kilometres, compared to 1.6 kilometres in Denmark, 0.5 kilometres in the European Union (EU), and 0.1 kilometres in the US (Pucher and Buehler 2008).

There are several explanations for these large variations in bicycle usages between countries and cities. Trip distances tend to be shorter in European cities than in American, Canadian, and Australian cities due to more mixed land use, less urban sprawl, and higher population densities (Heinen *et al.* 2010b, Buehler and Pucher 2012). Other explanations are climate, altitude differences, the presence of dedicated bicycle facilities, (perceived) safety, car ownership, the attitude to cycling within the culture, etc. (Rietveld and Daniel 2004, Heinen *et al.* 2010b). In developing countries, so called 'captives' walk and cycle because they lack alternatives (Servaas 2000).

The share of cycling seems related to cyclists' trip motives and the compilation of the population of cyclists. The bicycle is primarily seen as a daily transportation mode rather than a sport or leisure vehicle in countries with a high share of cycling in the modal split such as the Netherlands and Belgium (Ministry of Infrastructure and the Environment 2009, IMOB 2011). Cycling is mainly considered as a recreational tool in countries with low amounts of cycling such as the United States (Xing *et al.* 2010). In these countries with low amounts of cycling, men tend to cycle more than women (Heinen *et al.* 2010b). In contrast, women cycle slightly more frequently than men in, for instance, the Netherlands and Belgium (Ministry of Infrastructure and the Environment 2009, Heinen *et al.* 2010b, IMOB 2011). This may be related to the presence and quality of facilities and the high level of cycling safety in countries with high amounts of cycling. Women tend to attach greater value to bicycle facilities, smooth road surfaces, and road safety (Bergström and Magnusson 2003, Gerrard *et al.* 2008, Pucher and Buehler 2008, Heinen *et al.* 2010b).

1.1.2. Data sources for cycling safety and underreporting

Reliable, accurate data are needed to identify road safety problems, risk factors and priority areas but this is hampered by the problem of under-reporting of crashes in police statistics (Derriks and Mak 2007). It is not just under-reporting that is problematic for cyclist safety, but also the fact that it is selective. Cyclist crashes are more likely to be reported as the injury severity increases (Langley *et al.* 2003). The rate of reporting is much higher for bicycle crashes with motor vehicles involved than for bicycle crashes with no motor vehicles involved (Kroon 1990, Langley *et al.* 2003, Reurings and

Bos 2011). Cyclists seriously injured in bicycle-motor vehicle (BMV) crashes are more likely to be recorded by the police than seriously injured car occupant victims (SWOV 2011a). As bicycle crashes with no motor vehicles are strongly under-reported by the police, researchers often use (combinations of) medical registrations and surveys to study this crash type (e.g. Nyberg *et al.* 1996, Amoros *et al.* 2011). Some countries combine different data sources to estimate 'real' numbers of deaths and serious injuries, e.g. in the Netherlands the National Road Crash Register (BRON) for police-reported crashes with the national medical registration (LMR) and Statistics Netherlands' causes of death (Reurings and Bos 2011, SWOV 2011b).

1.1.3. Cycling safety

Cycling is safer in countries with higher amounts of cycling. Averaged over the years 2002 to 2005, the number of bicyclist fatalities per 100 million km cycled was 5.8 in the USA and 3.6 in the UK, compared to 1.7 in Germany, 1.5 in Denmark, and 1.1 in the Netherlands (Pucher and Buehler 2008). More explanations on the relationship between bicycle usage and road safety are provided in Section 1.2.2.2. Cycling safety will be described in this section for cyclist casualties in crashes without and with motor vehicles.

About 90% of all serious bicycle crashes with no motor vehicles are single-bicycle crashes, i.e. falls and obstacle collisions (Consumer Safety Institute 2011, Reurings and Bos 2011). Other types are bicycle-bicycle and bicycle-pedestrian crashes. Most serious and minor cyclist injuries are incurred in single-bicycle crashes (De Geus *et al.* 2012, Schepers *et al.* 2013a). Figure 1.1 depicts the share of hospitalized single-bicycle crash casualties in the total number of hospitalized bicycle crash casualties in 11 countries which ranges between 60 and 90% (figures based on medical registrations). Bicycle mode share is depicted on the abscis. The graph indicates that the share of hospitalized single-bicycle crash casualties does not differ much between countries with low and high amounts of cycling (Schepers *et al.* 2013a), for instance 62% in Iran and 82% in Canada (Karkhaneh *et al.* 2008, CIHI 2012) on the left side of the graph and 74% in the Netherlands and Denmark (Reurings and Bos 2011, Statistics Denmark 2013) on the right side of the graph.

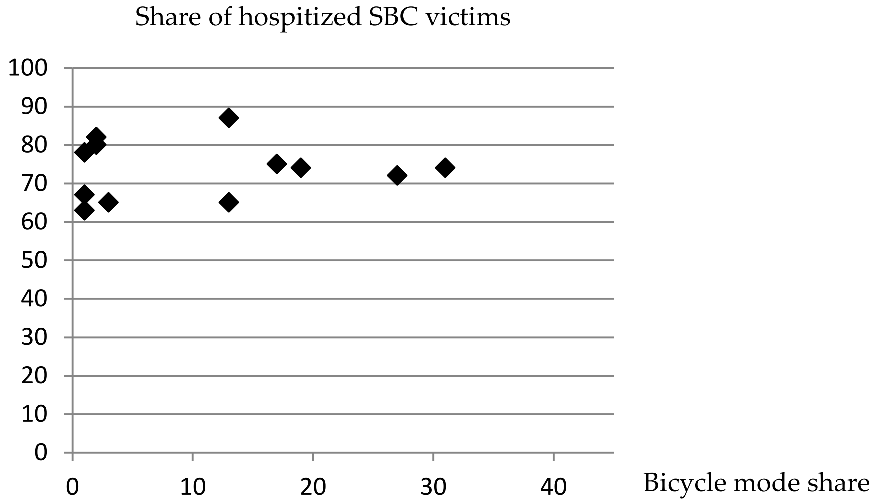


Figure 1.1. The proportion of hospitalized single-bicycle crash (SBC) casualties of the total number of cyclist casualties against the share of cycling in the modal split in 11 countries (figures gathered for a paper in the Routes/Roads magazine; Schepers *et al.* 2013a).

Most cyclist fatalities are due to crashes with motor vehicles (ETSC 2012). Table 1.1 shows the severity of bicycle crashes with and without motor vehicles in the Netherlands. Because police statistics are unreliable for this subdivision, Table 1.1 is based on Statistics Netherlands' Causes of Death registration and the National Medical Registration (Consumer Safety Institute 2011, Reurings and Bos 2011). The table indicates that bicycle crashes with no motor vehicles constitute the majority for even the most severe non-fatal crashes.

Bicycle crashes	Fatal	Critical (5)	Serious (4)	Severe (3)	Moderate (2)
With no motor vehicles	40	50	493	2208	6175
With motor vehicles	149	19	230	289	1328
Total	189	70	723	2497	7503
Column percentage					
With no motor vehicles	21	72	68	88	82
With motor vehicles	79	28	32	12	18
Total	100	100	100	100	100

Table 1.1. Injury severity of bicycle crashes between 2004 and 2009; MAIS between brackets for serious injuries (Consumer Safety Institute 2011, SWOV 2011a).

Collisions with cars account for the highest proportion of cyclist deaths in Europe (52% of deaths between 2008 and 2010). Collisions with goods vehicles and public transport make up 22% of cyclist deaths (ETSC 2012). The latter crash type is rare but severe. A substantial proportion of those occur with right-turning trucks (on a right-hand-drive lorry) (e.g. Niewöhner and Berg 2005, Schoon *et al.* 2008). Distributor roads and busy arterial roads have the highest share of BMV crashes (Liu *et al.* 1995, Danish Road Directorate 2000, Dijkstra 2003, Teschke *et al.* 2012).

The Netherlands, Sweden, Germany, and Denmark seem to have roughly similar trends in cyclist casualty numbers. An increasing number of cyclists were seriously injured in crashes with no motor vehicles while the number of cyclists seriously injured in bicycle-motor vehicle crashes slightly decreased (Larsson 2008, Berveling and Derriks 2012, Zwipp *et al.* 2012, Statistics Denmark 2013). These trends were further analysed in the Netherlands (Schepers and Vermeulen 2012). The number of seriously injured victims per km travelled by bicycle per age group increased slightly over the last decade, but the rise of the number of victims in crashes with no motor vehicles resulted mainly from an ageing population and more cycling per person among the elderly, i.e. more vulnerable cyclists (Van Norden and Bijleveld 2011, Berveling and Derriks 2012, Schepers and Vermeulen 2012).

1.2. Theoretical framework[2]

For designing a study and interpreting its findings, it is important to have a theoretical basis. A considerable number of road safety studies are not well underpinned by theory (Elvik 2004). This section describes a conceptual framework and positions theories within the framework. A number of criteria and issues played a role in decisions regarding the framework. Firstly, it is important to have a model that describes both exposure to risk resulting from travel behaviour and (crash and injury) risk, not only because governments have objectives for both bicycle use and cycling safety, but also because the road environment can affect both risk and exposure to risk. Secondly, it is helpful to study cycling safety using a general road safety framework instead of a model restricted to cycling. For instance, the degree to which cyclists are exposed to (high-speed) motorists is affected by the modal spit and the distribution of cyclists and other traffic over time and space. Thirdly, because accidents often result from combinations of mutually interacting variables, modelling approaches for crash research need to shift

---

[2] This Section was first published in Accident Analysis and Prevention: Schepers J.P., Hagenzieker, M.P., Methorst, R., Van Wee, G.P., Wegman, F.C.M., 2013. A conceptual framework for road safety and mobility applied to cycling safety. *Accident Analysis and Prevention*, In press.

from linear models (such as crash phase models) to non-linear models (Leveson 2004, Toft *et al.* 2012). Crash-phase models such as Heinrich's Domino Theory (Heinrich 1931) assume that accidents result from a series of events or circumstances and are thus preventable by eliminating one of the causes in the linear sequence. Fourthly, a conceptual framework or model is an abstraction or simplification of reality to help us better understand real-world systems, facilitate communication and integrate knowledge across disciplines (Heemskerk *et al.* 2003, Ford 2009). These goals are best served by a model with a level of complexity that users are able to comprehend.

Section 1.2.1 describes the conceptual road safety framework developed for this thesis and Section 1.2.2 its application to cycling (safety) and its link with land use and infrastructure characteristics. The results are discussed in Section 1.2.3.

1.2.1. The conceptual framework

Consistent with Asmussen and Kranenburg (1982), the conceptual framework contains factors determining exposure to risk (resulting from travel behaviour), crash risk, and injury risk (or injury severity). It combines Van Wee's (2009) passenger transport model for exposure to risk with the model of the three traffic safety pillars for risk (Othman *et al.* 2009), see Figure 1.2. These two models are chosen because of the comparable level of detail (a limited number of factors) and non-linear modelling approach with combinations of interacting variables.

1.2.1.1. Description of the framework

People are exposed to risk in traffic because they travel and because there are dangers present in traffic. As yet, we have not yet managed to achieve danger-free travel. The measures used in the road safety literature for exposure to risk are directly linked to travel behaviour, e.g. kilometres travelled and Annual Average Daily Traffic (AADT) (what the best measure is depends on the issue being studied, see Hakkert and Braimaister 2002). Therefore, travel behaviour and exposure to risk have been combined in the framework in one box. Similarly, crash and injury risk are put in one box although both are generally accepted as distinct dimensions of the road safety problem (Rumar 1999). This is done because the links to other elements in the model are similar, and it reduces the model's complexity. The model does not include the post-crash phase in which, for instance, the emergency medical system is relevant to the injury risk. Separate boxes for crash and injury risk would have to be inserted if elements relating to the post-crash phase were to be included in the model. The model is not a chronologically organized crash-phase model, but there is order in the sense that travel decisions taken *before* traffic participation (the focus of the upper part of the model) result in exposure to risk *during* traffic participation (the lower part of the model).

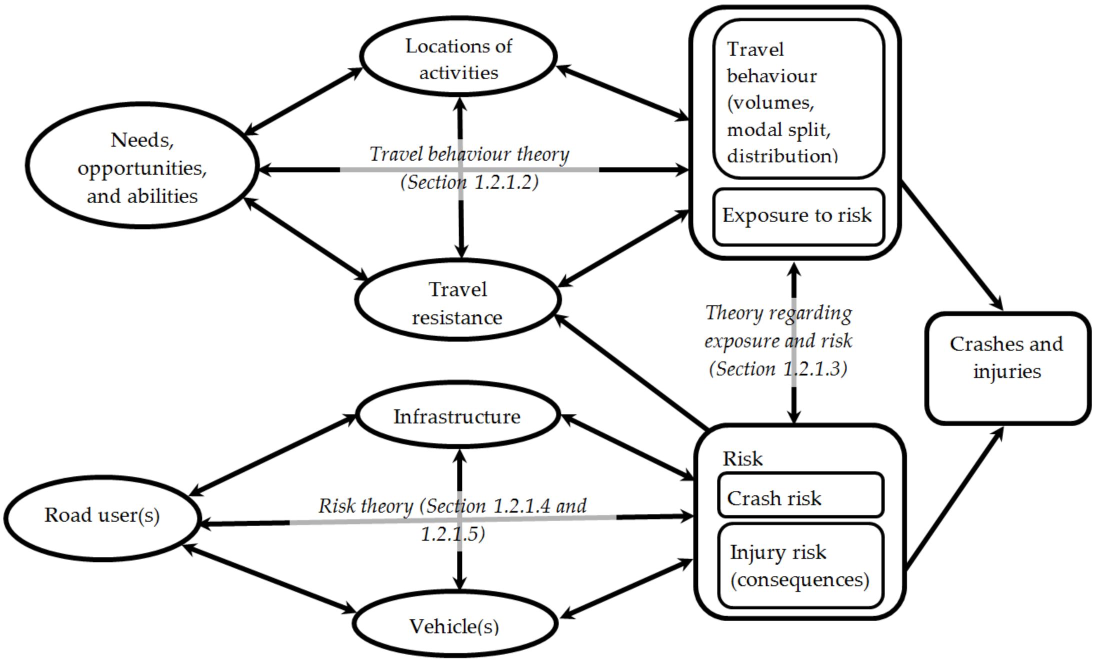


Figure 1.2. Conceptual framework for road safety, including exposure and risk; Sections describing the theories are referred to in parenthesis

Travel behaviour

Travel behaviour literature commonly distinguishes between traffic volumes, modal split and distribution of traffic over time and space (Van Wee 2009). Van Wee (2009) developed a model for passenger transport that contains elements determining travel behaviour: locations of activities, transport resistances (generalised transport costs), and needs, opportunities and abilities. People travel between *Locations of activities* to perform activities such as living, working, and shopping. Travel takes money and time and incurs non-monetary' costs such as discomfort, which together make up *Travel resistance*. Perceived risk, which is also a type of resistance, is modelled explicitly by an arrow from Risk to *Travel resistance*. Besides locations and travel resistance, travel behaviour is also affected by *Needs, opportunities, and abilities (NOA);* for instance the need for active travel, the possession of a driving license and car, or the physical fitness needed to walk and cycle. All three categories (locations, resistance, and NOA) are influential in all directions. *Travel behaviour* decisions sum up to traffic volumes, modal split, and the distribution of traffic over time and space (Van Wee and Maat 2003). Travel decisions taken by individuals before traffic participation have also been called 'strategic and lifestyle decisions' (Michon 1985, Hatakka *et al.* 1999), e.g. mode choice and moving to a new home. These decisions result in exposure to risk during traffic participation. Behaviour during traffic participation has been described as tactical and operational behaviour (Michon 1985).

The link between exposure and risk

The model comprises an arrow from Exposure to risk to Risk, because exposure affects risk. Most empirical studies show that risk decreases as exposure increases (Elvik 2009). An arrow from Risk to Exposure to risk is included to indicate that traffic participants are exposed to risks only to the extent that risks are present. The model also includes a feedback loop from Risk to Travel resistance. Risk may affect perceived risk which, in turn, can cause travellers to shift to other modes or even avoid trips (Heinen *et al.* 2010b, Van Wee *et al.* 2012).

Risk

Crash risk results from interaction between three elements, sometimes called the 'three traffic safety pillars': road user(s), vehicle(s), and infrastructure (e.g. Othman *et al.* 2009). Similarly, epidemiologists use the terms host, agent, and environment (Haddon 1980). Note that Haddon's definition of environment also includes the social environment. Single-vehicle crashes may involve only one vehicle and one road user, whereas 'conflicts' involve an interaction between several vehicles and road users (for a more detailed model that includes the interaction between road users, see Houtenbos 2008). Depending on the energy that is exchanged between road users, vehicles and infrastructure, crashes may result in injuries with varying levels of severity. Crashes may be fatal when forces transferred to victims exceed their biomechanical tolerance. This tolerance depends on age, health status, stature and other characteristics of road users involved in a crash (Corben *et al.* 2004). The framework provides for two-way arrows between *Risk* on the one hand and *Infrastructure*, *Vehicles* and *Road Users* on the other hand. The skills and capabilities of road users, and the quality of vehicles and infrastructure can be improved, e.g. for road users − education and requirements such as licence age limits and health requirements (Elvik *et al.* 2009, Winters *et al.* 2013). Reversing the direction of the arrows: high risks may lead to policies to reduce these risks, e.g. EuroNCAP for cars (EuroNCAP 2012) and

EuroRAP for roads (EuroRAP 2011) (for effectiveness studies, see e.g. Lie and Tingvall 2002, Vlakveld and Louwerse 2011).

Demarcation

In line with systems theory the framework depicts safety as an emergent property that arises when system components interact, but the components are also affected by the environment (Leveson 2004). Similarly, the framework has several inputs from the environment such as demographics, fuel prices, technological developments, etc. In the interests of reducing the framework's complexity these external influences are not conceptualized. Similarly, the framework does not depict a feedback loop from crashes and injuries to NOA to indicate the effect of injuries on abilities. Relationships that may exist between the model's exposure and risk elements (e.g. between *Infrastructure*, *Travel resistance* and between *Road users* and *NOA*) are excluded for the same reason and to emphasize the impact of differences in timing. Travel decisions taken before traffic participation result in exposure to risk during traffic participation. Using theories and concepts regarding exposure and risk, and the interaction between the two, the remainder of this section briefly describes how the elements in the framework interact.

The next section describes in terms of theories and concepts how the elements in the framework interact: travel behaviour theories, theories explaining the link between exposure and risk, crash risk theories, and injury risk theories.

1.2.1.2. Travel behaviour theories

The dominant theory for explaining travel behaviour is (random) utility maximization (McFadden 1974). This holds that people maximize their utility, e.g. a trip is made if the (expected) benefits of performing an activity at a location ('locations of activities') exceed the (expected) time, cost and effort of travel ('travel resistance'). Alternative models of bounded rationality have been developed which, without completely abandoning the idea that reason underlies decision-making processes, tend to be more psychologically plausible. For example, Prospect Theory accounts for decision heuristics such as loss aversion (Kahneman and Tversky 1979, Van de Kaa 2010). Regret theory holds that people wish to avoid the regret that a non-chosen alternative turns out to be more attractive than the chosen one (Chorus *et al.* 2008). The Theory of Planned Behaviour holds that attitudes towards behaviour, subjective norms and perceived behavioural control together shape an individual's behavioural intentions and behaviours (Ajzen 1985).

Deciding to make a trip may also depend on needs (e.g. driving as a status symbol), opportunities (e.g. having a railway station nearby to go by train), and abilities (e.g. being healthy enough to cycle) (see e.g. Vlek *et al.* 1997).

The theories mentioned so far help explain the links between determinants for travel behaviour (needs, resistance, locations). They also help explain the other links between the factors in the upper part of the framework. For instance people who greatly appreciate a large city's cultural and social activities (needs) will prefer living in a large city (location). People desiring safe and fast travel (travel needs / preferences) may seek a dwelling near a large railway station (location). A theory that helps to explain the link between locations of activities and NOA is that of time-space geography. It explains the movement of individuals in the spatial-temporal environment with the constraints placed on them by these two factors (Hägerstrand 1970). For instance, to be able to work with colleagues or eat family dinners together requires several people to be at the same place at the same time. Opportunities to go shopping depend on opening hours, etc. The relationship between locations of activities and resistances can be explained by the 'theory of constant travel time budgets', which holds that, at an aggregate level (e.g. the country or state level), average daily time spent on travel is fairly constant (Mokhtarian and Chen 2004). For example, this means that if a new motorway, railway, or cycle path is opened which reduces travel times (i.e. decreased resistance), some people may consider changing residential location or destinations such as the job location. Constant travel time budgets can be explained by utility theory. Besides seeking an optimal balance between time for activities and related travel, people compare the marginal disutility of extra travel time or additional trips with the marginal benefits of related activities (Van Wee *et al.* 2006).

1.2.1.3. Theories explaining the link between exposure and risk

The framework depicts a relationship between exposure and risk and shows an arrow from *Risk* to *Travel resistance*. Perceived risk, which is weakly correlated to actual risk, may influence travel behaviour (Vlakveld *et al.* 2008). The perception that a certain type of vehicle such as a bicycle is unsafe can be a deterrent to its use (Heinen *et al.* 2010b). An important concept to explain the influence of exposure on risk is the so called 'non-linearity of risk'. It holds that the number of crashes at a given road section or intersection increases proportionally less with the increase in the volume at that facility (at least above a certain amount of traffic that results in interactions between road users). There are possible explanations related to road user interaction and infrastructure, but most theoretical investigation into the relationship between flow and safety seems to lack detail (Ardekani *et al.* 2000). One explanation is that the second and subsequent vehicles of a platoon may have a much lower chance of being involved in a right-angle collision at a signalized intersection than the first vehicle (Ardekani *et al.* 2000). Other researchers have suggested that improved infrastructure may be one of the explanations for the non-linearity of risk, e.g. Jensen (1999) argues that cities are designed to meet different travel behaviour. Similarly, at the individual level it has been found that drivers travelling more kilometres have lower crash rates per kilometre. An explanation for this is that these drivers accumulate most of their kilometres on freeways or other divided multilane highways where crash rates are lower (Janke 1991).

1.2.1.4. Crash risk theories

The interaction between vehicles, road infrastructure and road users plays a role in crash risk, which can be explained using theories from physics and social sciences. The interaction between road users and roads is often called 'human factors', while the interaction between road users and vehicles is labelled as 'man-machine factors' (Birth *et al.* 2009). Four types of so called 'functional driver behaviour models' have the ability to describe how the road environment and vehicles can be adapted to fit road users' capabilities in order to reduce crash risk: perception models, cognitive models, workload models, and motivational models (Michon 1985, Ranney 1994, Weller and Schlag 2007). The first three describe what road users are *able* to handle; motivational models explain what drivers are *motivated* to do. Physical factors based on physics help to explain the interaction between vehicles and infrastructure, e.g. friction between tyres and the road surface to enable steering and braking (Elvik 2006) and superelevation to negotiate a curve (Aram 2010).

1.2.1.5. Injury risk theories

Theories from physics, such as Newtonian mechanics, and medicine (Sobhani *et al.* 2011) have been used to explain injury risk, i.e. the severity of injuries incurred in a crash. The energy damage model, often attributed to Gibson (1961), is based on the supposition that damage (injury) is a result of an incident energy whose intensity at the point of contact with the recipient exceeds the threshold of the recipient (Viner 1991, Toft *et al.* 2012). Crash energy may be released when there is a failure of hazard control mechanisms such as barriers. In road traffic it is the kinetic energy produced by the movement of people and vehicles that is a potential crash energy. Mass differences are crucial when motor vehicles and vulnerable road users collide. Energy may be exchanged between vehicles, road users, and infrastructure, meaning that it affects all three safety pillars. Crashes may be fatal when forces transferred to victims exceed their biomechanical tolerance, which depends on age, health status, stature, and other factors (Corben *et al.* 2004).

1.2.2. Application of the framework on cycling safety, land use, and infrastructure

This section applies the conceptual framework to the relationship between cycling safety, and land use and infrastructure characteristics. The framework elements most relevant to this issue are *Locations of activities* (land use), *Travel resistance* (network and road characteristics), and *Infrastructure* (road design). We have searched for scientific literature on cycling and cycling safety, preferably empirically validated or otherwise theoretically feasible, that is suitable for describing different parts of the model.

1.2.2.1. Travel Behaviour and Exposure

This section describes cycling travel behaviour and the distribution of traffic over time and space. It refers to both motorists and cyclists because modal split and distribution over time and space determine the degree to which cyclists are exposed to (high-speed) motorists.

Cycling travel behaviour (volumes and modal split)

This section describes studies that relate cycling to land use and infrastructure characteristics. More studies focused on mode choice than on cycling frequency (Heinen *et al.* 2010b). Because the decision to cycle and cycling frequency are strongly interrelated, it was decided not to make any further distinction between them in this section. Land use and infrastructure characteristics affect cycling distances. This is important because the disutility of cycling increases more than proportionally for longer distances, which might be explained by physiological factors and speed (Van Wee *et al.* 2006). Heinen *et al.* (2010b) conclude from their literature review on bicycle commuting that distance is a daunting factor for cyclists. Land use characteristics which contribute to shorter travel distances, such as a higher population density (e.g. a compact city) and mixed land-use, have been found to affect cycling positively (Heinen *et al.* 2010b).

Resistance is strongly linked to the physical and functional characteristics of infrastructure networks. The following effects on bicycle use for utilitarian purposes (all purposes apart from recreational/leisure purposes) have been found:

- Road structure density: According to Southworth (2005), a denser road structure is more suitable for non-motorized transportation because distances are generally smaller. However, neither Moudon *et al.* (2005) nor Zacharias (2005) found significant empirical evidence that can confirm the influence of the density of roadways and block size on cycling.
- Bicycle paths: While Heinen *et al.* (2010b) have found several studies which conclude that more bicycle paths result in a higher share of cycling (e.g. Barnes and Thompson 2006), they also found studies in which no significant effect was found (e.g. Moudon *et al.* 2005). Additional infrastructure might make little difference in countries where cycling facilities are more common (Heinen *et al.* 2010b).
- Number of stops: Rietveld and Daniel (2004) have found that the number of stops cyclists have to make on their routes is a deterrent to cycling.

Distribution of traffic over time and space

Little research has been done on the effect of infrastructure on the distribution of cycling traffic any 24 hour period. Perhaps the reluctance of older cyclists to cycle in darkness is influenced by the visual design of infrastructure and the presence of street lighting. It is obvious that land use (the distribution of activity locations over space) has an effect on the distribution of traffic (including cycling) over time and space. For instance, an entertainment centre may attract young visitors at night. Its location at the edge of town may result in longer average distances between it and the locations of the dwellings of young visitors, resulting in a lower share of cycling and longer cycling distances for those who do cycle. High exposure to dangerous situations such as driving at weekend nights has been found to be a cause of the high crash rate of young novice drivers (Vlakveld 2005). Similarly, research suggests that youngsters frequently cycle at night and frequently after having consumed alcohol (Reurings 2010).

A concept that helps to describe the distribution of traffic over space is 'street hierarchy'. This affects route choice by manipulating travel times, i.e. resistance (see for more information Hummel 2001). This concept became very influential after Buchanan (1963) published *Traffic in Towns*. In a hierarchical road structure, lower order roads (access roads in what Buchanan named 'environmental areas') serve access traffic, while higher order roads serve an efficient flow of through motor traffic (through roads such as motorways). In between are distributor or collector roads to distribute traffic from through roads to access roads and vice versa. A motorway network where cyclists are not allowed, with grade separated intersections, reduces cyclists' exposure to high-speed motorists. Access roads are designed for low speeds to keep through motor traffic away. A high share of short bicycle trips results in a high number of kilometres being travelled on access roads where exposure to (high-speed) motorists is limited. Research shows that the number of bicycle-motor vehicle crashes is indeed high along distributor roads and low on access roads (Liu *et al.* 1995, Berends and Stipdonk 2009, Teschke *et al.* 2012). However, hardly any study investigated whether there are fewer cyclist casualties in BMV crashes in municipalities where cyclists are more unbundled from vehicular traffic on the distributor road network (Van Boggelen *et al.* 2011). Depending on how the road network fits the needs of different transport modes, a road hierarchy may affect travel times for drivers and cyclists differently, thereby affecting modal choice. Cyclists may benefit from short cuts where roads are closed for motorists and from being allowed to use one-way streets in both directions, etc. Providing more direct routing for one mode in contrast to the other may increase mode share for the favoured mode (Frank and Hawkins 2008).

1.2.2.2. The relationship between exposure and risk

This section describes the relationship between exposure (resulting from travel behaviour) and risk: firstly the effect of exposure on risk and secondly the effect of (perceived) risk on exposure.

The effect of bicycle volumes on road safety

The number of crashes at a given road section or intersection increases proportionally less than the increase in the volume at that facility. The same applies to bicycle-motor vehicle crashes which increase proportionally less than the increase in the volume of both motor vehicles and cyclists. This means that the crash rate, the number of bicycle-motor vehicle crashes per passing cyclist, increases when motor traffic increases but decreases when the amount of cyclists increases (Brüde and Larsson 1993, Elvik 2009) but single-bicycle crashes have not yet been included in studies on this issue (Elvik 2009). Cycling safety research describes the non-linearity of risk as the 'safety in numbers' phenomenon (Jacobsen 2003). Jacobsen's (2003) explanation is that motorists modify their behaviour when they expect or experience people walking and bicycling. Theories regarding expectancy in traffic which can underpin this are described by researchers such as Houtenbos (2008) and Theeuwes and Godthelp (1995). Others have suggested that improved infrastructure may be one of the explanations for the non-linearity of risk (Brüde and Larsson 1993, Wegman *et al.* 2012). The non-linearity of risk implies that cyclists are safer where there are more cyclists. It is difficult to draw conclusions about how road safety in general will be affected because the non-linearity of risk also applies to other modes of transport.

Modal split and road safety

Cycling is associated with a considerably higher risk of injury accidents than travel by car (Wegman *et al.* 2012). One could therefore expect that a modal shift from car to bicycle would have negative effects on road safety in general. However, there are reasons why the effect is limited. The most important one is that after shifting from car driving to cycling, individuals are less hazardous to other vulnerable road users (including cyclists) because of the lower amounts of kinetic energy expended in the event of a crash. A number of studies have accounted for this factor (e.g. Stipdonk and Reurings 2012).

Using existing Crash Prediction Models (CPMs) in which a non-linear relationship between crashes and volumes is assumed, Elvik (2009) was the first to estimate the road safety effects of shifts from car to bicycle (and walking). His results suggest that if there are very large transfers of trips from motor vehicles to walking or cycling, the total number of accidents may be reduced. Stipdonk and Reurings (2012) followed a different approach to determine the effect of an exchange over a short period of time, i.e. without adapting infrastructure. Instead of (stochastic) CPMs, they applied a deterministic model, assuming a linear relationship between volumes and road crashes. The study results suggest that a modal shift from cars to bicycles leads to a small increase in the number of fatalities and a greater increase in the number of hospitalized casualties. The latter is due to the high numbers of cyclists injured in single-bicycle crashes. Stipdonk and Reurings (2012) find that effects vary across age groups. From a road safety perspective, the car-bicycle shift is, on balance, advantageous for young drivers and disadvantageous for elderly drivers.

The effect of risk on bicycle use

People, especially non-cyclists (Heinen and Handy 2012), generally perceive cycling to be less safe than walking, driving a car or using public transport.

This would imply that this form of travel resistance is higher for cycling (Elvik and Bjørnskau 2005). The risk of an accident is a deterrent to cycling (Parkin *et al.* 2007, Heinen *et al.* 2010b). Research indicates that cyclists prefer dedicated bicycle infrastructure because they perceive it to be safer (Heinen *et al.* 2010b). For instance, Gårder *et al.* (1998) found an increased volume of cyclists at road sections after cycle tracks had been installed. Vandenbulcke-Plasschaert (2011) suggests that actual and perceived risks of cycling may be one of the factors explaining the high amount of cycling in Flanders in the northern part of Belgium, as compared to Wallonia in the south. The same reasoning may be valid in explaining differences between countries. Rietveld and Daniel (2004) found that safety appears to matter as a component in generalised costs and that it explains part of the variation in the amount of bicycle use in Dutch municipalities. Pucher and Buehler (2008) suggest that safety may affect the compilation of the population of cyclists because women, the elderly and parents of young children appear to be especially sensitive to road safety. This may be another factor that explains differences in safety between different countries, i.e. cyclists in countries with higher amounts of cycling may be more cautious. Finally, the injuries incurred in crashes may affect bicycle use. Ormel *et al.* (2008) found more than one-third of all hospitalized single-bicycle crash victims cycled less after their accident because of a combination of physical problems and fear of taking another fall.

1.2.2.3. Crash risk

This section describes how cycling risk is affected by infrastructure characteristics. The risk of collisions depends on the number of potential conflict points and how well road users are able to handle conflicts. For instance, a roundabout reduces the number of potential conflict points compared to an intersection which has favourable safety effects in general (Elvik 2004), although the effects found for cyclists are not consistent (Brüde and Larsson 2000, Dijkstra 2004, Daniels *et al.* 2009, Sakshaug *et al.* 2010) Measures such advance stop lines and bike boxes may make cyclists more visible to motorists (especially right-turning lorries) at signalized intersections in order to reduce crash risk (Hunter 2000, Niewöhner and Berg 2005). The risk of single-bicycle crashes is influenced by how well cyclists are supported when balancing and steering their bicycles, and avoiding obstacles (Van Boggelen *et al.* 2011). The abovementioned issues refer to the framework's link of *Infrastructure* to *Road users* (Section 3.3.1) and to *Vehicles* (Section 3.3.2). Human factors theories or ergonomics theories help explain how roads can be designed to fit road users' needs and capabilities (Birth *et* *al.* 2009). Theories from physics help to describe how infrastructure can be designed to help cyclists safely balance and steer their bicycles.

Human Factors

The application of ergonomics theories for optimal cycling safety depends on the context. While a complete overview of applications is outside the scope of this text, this paper gives some examples to show the value of human factor theories for cycling safety. Theories on perception help understand to what extent road users are able to perceive objects and where the road is going. For example, ambient-focal dichotomy is a powerful theory which describes vision and driving in terms of the visual system as being two parallel streams of processing, labelled the ambient and focal subsystems (Leibowitz and Owens 1977, Schieber *et al.* 2008). The proposition is that visual processing proceeds along two parallel streams, one dedicated to visual orientation for the question "Where am I?" (ambient vision) and the other to object recognition and identification for the question "What is it?" (focal vision) (Leibowitz and Post 1982, Previc 1998). Drivers use ambient vision to track and minimize instantaneous errors in lane position. They use focal vision to anticipate hazards and future alterations in the course of the road (Donges 1978). The ambient-focal dichotomy may be a useful theory to study the role of the visual design of bicycle facilities in single-bicycle crashes.

A powerful theory from cognitive psychology is 'expectancy' theory (Theeuwes and Hagenzieker 1993, Houtenbos 2008). Concepts such as Self-Explaining Roads (Theeuwes and Godthelp 1995), geometric consistency (Fitzpatrick *et al.* 1999), and the Sustainable Safety principle of predictability and recognizability (Wegman and Aarts 2006) all hold that roads should be designed in line with road users' expectations and such that they create the right expectations. An often-cited violation of expectations that results in errors occurs at priority intersections with two-way bicycle tracks. The risk of bicycle crashes is found to be elevated because drivers entering from the minor road have difficulties in detecting cyclists from the right (in case of right-hand driving) (Räsänen and Summala 1998). Summala *et al.* (1996) studied drivers' scanning behaviour at T-intersections. Drivers turning right from the minor road scanned the right leg of the T-intersection less frequently and later than those turning left because they do not expect traffic from the right.

Workload models indicate that humans have a limited information processing capacity and taking into account individuals' capabilities, workload can be either too high ('overload') or too low ('underload') (De Waard 1996). A concept linked to road design and related to the probability that some road users will be overloaded is 'complexity'. According to Elvik (2006), the 'law of complexity' holds that the more units of information a road user must attend to, the higher becomes the accident rate. This especially applies to situations subject to time pressure. For instance, older drivers and cyclists are more often involved in left-turning crashes and situations with associated time pressures where traffic from several directions has to be scanned (Goldenbeld 1992, Davidse 2007b). From the perspective of workload, the opposite of 'complexity' is 'monotony' (Birth *et al.* 2009) or 'highway hypnosis' − reduced alertness on long, straight roads (SWOV 2012).

Motivational models describe how road users adapt their behaviour to the environment if the driving task is self-paced (Ranney 1994). Homeostasis models assume that drivers are constantly aware of, monitor and seek to maintain a set level or range of a variable, such as risk (e.g. Wilde's risk homeostasis model; Wilde 1982) or task difficulty (e.g. Fuller's task-difficulty homeostasis model; Fuller 2005). A second group of theories claims that variables such as a perception or feeling of risk are only experienced at certain times during driving, i.e. when a certain threshold is exceeded (Lewis-Evans *et al.* 2011), for instance the Zero-Risk theory developed by Näätänen and Summala (1974). A problem with these motivational theories is that they do not describe to what extent road users may adapt their behaviour in response to certain measures. Bjørnskau (1994) proposed hypotheses designed to explain road user behavioural adaptation to road safety measures. For instance, highly visible changes to the road are more likely to lead to behavioural adaptation than measures that road users do not easily notice. Visible measures such as blue-painted bicycle crossings have been shown to result in behavioural adaptation. Fewer cyclists turned their heads to scan for traffic or used hand signals after the measure was implemented (Hunter *et al.* 2000). Note that Section 1.2.2.2 describes the risk perceived and its effect on decisions taken *before* traffic participation, whereas this section described the perception of risk and its effect on behaviour *during* traffic participation.

Physical factors

In the context of this paper, the term 'physical factors' is used to refer to the interaction between vehicles and road infrastructure. An example is the friction between tyres and the road surface needed for braking. Nyberg *et al.*

(1996) have shown that a slippery road surface contributes to single-bicycle crashes. They therefore advise investment in winter maintenance. The remainder of this section focuses on bicycle stability because it may play an important role in single-bicycle crashes.

A controlling rider can balance a forward-moving bicycle by turning the front wheel in the direction of an undesired lean, i.e. steering to the right when falling to the right, and vice versa. This moves the ground-contact points under the rider and results in a zig-zag movement. Most bicycles can balance themselves ('riderless') if moving above a given speed, because they are able to steer into the lean automatically. Godthelp and Wouters (1978) used an experiment to estimate that under normal circumstances and speeds, cyclists require a track width of about 1 metre to accommodate the resulting zig-zag movement and space for the bicycle. They recommend a minimum width of 2 metres for one-way bicycle tracks to enable cyclists to overtake safety.

Moore *et al.* (2011) found self-stability at speeds above approximately 15 km/h for a commonly used Dutch city bicycle and a male rider. Stabilizing a bicycle at low speed requires more active steering. Several factors, including geometry, mass distribution and gyroscopic effect all contribute in varying degrees to this self-stability. Long-standing hypotheses and claims that any single effect, such as gyroscopic or trail, is solely responsible for the stabilizing force have been discredited (Kooijman *et al.* 2011). The role of speed in stability suggests that the design of bicycle facilities should enable cyclists to maintain a minimum speed, e.g. sufficiently large curve radii and not too steep a slope (see e.g. CROW 2007).

The stability also depends on the freedom of the front fork to swivel. If it is locked, such as when the front wheel becomes stuck in the tram rails, the bicycle cannot be ridden. A difference in height between the road surface and shoulder surface makes it difficult for the cyclist to steer back after riding off the road, and can lead to falls (Schepers 2008). Finally, it is obvious that road surface irregularities such as potholes contribute to loss of control and thereby single-bicycle crashes (Nyberg *et al.* 1996). Dutch design guidelines advise that bicycle crossings intersect tram rails perpendicularly, the difference between the level of the road and shoulder surface be minimal, and the road surface be well maintained, etc. (CROW 2007, Van Boggelen *et al.* 2011).

1.2.2.4. Injury risk

This section explains injury risk for cyclists and how it is affected by infrastructure characteristics. The amount of kinetic energy produced is a function of the mass and velocity (speed): $\frac{1}{2}mv^2$ (m = mass; v = speed). The law of conservation of energy states that the total amount of energy in an isolated system is conserved over time. In road crashes, kinetic energy is partly conserved and partly converted to other types of energy such as deformation energy and heat. Part of the kinetic energy is transferred to the victims involved in the crash. Crashes may be fatal when these forces exceed the victims' biomechanical tolerance (Corben *et al.* 2004). Crumple zones, air bags, and crash barriers slow the stopping process and spread the crash energy of the crash out over time, reducing the peak spike of energy to the human body. Similarly, airbags on the windscreen (Rodarius *et al.* 2008) may protect cyclists in the event of a crash. This principle is called 'physical forgivingness' in the case of road side furniture (Wegman *et al.* 2012). The principle has to our best knowledge not yet been applied to the design of for instance obstacles with which cyclists may collide.

When different categories of vehicles or road users crash, their compatibility in terms of mass and speed influences the accident outcome. Compatibility refers to the differences between categories of road users in terms of the kinetic energy produced by their movements. The smaller these differences, the more compatible are road users. Elvik (2010) calculated for each transport mode, the ratio of the number of casualties among those involved in the crash divided by the number of casualties in the vehicle type under question. For instance, the ratio for transport mode x would be 0.5 if 500 road users were injured in other modes versus 1000 in mode x. The ratio ranged from 0.03 for pedestrians and 0.05 for cyclists to 0.27 for car occupants and 3.46 for truck occupants. The problem of incompatibility contributed to the development of the Sustainable Safety principle of 'homogeneity'. This states that where road users or vehicles with large mass differences use the same traffic space, the speeds should be so low that the most vulnerable road users and transport modes come out of a crash without any severe injuries (Wegman *et al.* 2012).

The idea that the most severe injuries can be prevented by keeping speeds under a threshold for certain combinations of road users led to the concept of 'safe speeds'. Tingvall and Haworth (1999) consider 30km/h a safe speed where vulnerable road users are mixed with motorized vehicles. Several studies have confirmed that there is a threshold around 30 km/h, above which the probability of injury and fatality for pedestrians and cyclists colliding with motor vehicles strongly increases (Kim *et al.* 2007, Rosén *et al.* 2011). However, this does not apply to lorries, where far lower speeds can easily end in a fatality if a cyclist goes under the wheels (Schoon 2006).

1.2.3. Discussion

This section presented a conceptual road safety framework incorporating factors determining exposure to risk (resulting from travel behaviour), risk (injury and crash risk), and the relationship between these two. It can help to identify potential policy effects resulting from both factors. For instance, not only the effect of a measure on risk at the level of a location but also the effect of the same measure on the exposure to risk resulting from a change in the distribution of traffic over time and space. The model is conceptual and does not allow for quantitative assessment of the effects on (injury) crash numbers.

1.3. Research gaps and questions

This section describes research gaps regarding the question of how the road environment affects road safety for cyclists. Recent literature is used in this introductory chapter, but the research gaps reflect the time the studies of this thesis were planned (between 2009 and 2011). The following three sections are to a large extent focused on the three parts of the framework: Section 1.3.1 on exposure to risk, Section 1.3.2 on the relationship between travel behaviour and risk, and Section 1.3.3 on risk. Section 1.3.4 describes the research questions to fill the gaps.

1.3.1. Network characteristics and cycling safety

Research shows that the number of bicycle-motor vehicle crashes is highest on distributor roads and lowest on access roads (Berends and Stipdonk 2009). However, hardly any studies have investigated whether there are fewer cyclist casualties in BMV crashes in municipalities where cyclists are more unbundled from vehicular traffic on the distributor road network (Van Boggelen *et al.* 2011). Most studies are focused on the bicycle facilities such as bicycle tracks that can be built on distributors (see e.g. Hamann and Peek-Asa 2013, Thomas and DeRobertis 2013) instead of the distribution of cyclists in a road network. Moreover, studies have not yet addressed the combined effect of a general road hierarchy with bicycle-specific measures such as bicycle bridges and tunnels to alleviate potential safety problems on distributor roads. Finally, depending on how it is implemented, the street hierarchy may affect resistance differently for different transport modes. This may have an effect on modal choice, an issue that has not yet received much attention in research.

1.3.2. The amount of bicycle use and road safety

Land use, network characteristics and other factors affect bicycle usage (Heinen *et al.* 2010b). To estimate the effect of a change in the amount of cycling, researchers have first focused on the risk for cyclists (e.g. Jacobsen 2003). It is not possible to draw conclusions about the effect on road safety in general by solely focusing on cycling safety. Elvik (2009) was the first to estimate the road safety effects of shifts from car to bicycle (and walking) using Crash Prediction Models (CPMs) in which a non-linear relationship between crashes and volumes is assumed. He selected CPMs from existing research in several countries using diverse study units (junctions, road sections, towns and countries). A study in which CPMs are developed using crash and mobility data from jurisdictions to estimate the road safety effects of a changed modal split of car and bicycle use (in the same jurisdictions) is lacking in scientific literature. Also, the currently available CPMs were developed for BMV crashes and not for single-bicycle crashes (Elvik 2009).

1.3.3. Road design and crash risk

A review study by Reynolds *et al.* (2009) and a more recent study by Lusk *et al.* (2011) show that purpose-built bicycle-specific facilities such as bicycle tracks reduce crashes and injuries among cyclists. Similar results were found in the Netherlands in a study that controlled for both car and bicycle volumes (Welleman and Dijkstra 1988). Intersection studies focused mainly on roundabouts. For instance, it was found that a separated cycle track decreases the risk for cyclists (Dijkstra 2004, Reynolds *et al.* 2009). Fewer studies are focused on signalized and unsignalized intersections (Reynolds *et al.* 2009).

Only a very few studies have focused specifically on the most common type of non-fatal bicycle crash, i.e. the single-bicycle crash. A good description of single-bicycle crash types seems to be lacking in the scientific literature, although high victim numbers are common (Kroon 1990, Veisten *et al.* 2007, Hagemeister and Tegen-Klebingat 2011). Nyberg *et al.* (1996) were one of the few who addressed straightforward direct causes related to road surface quality, i.e. an uneven or slippery road surface. Indirect risk factors such as the visibility of the roadway and obstacles for cyclists have not yet been studied.

1.3.4. Research questions

To fill the research gaps described in the previous sections, this study addresses the following research questions (chapter that addresses the question is included in parenthesis):

1. Network characteristics and cycling safety: How does network-level separation of vehicular and cycle traffic (unbundling) in urban networks affect road safety (Chapter 7)?
2. The amount of bicycle use and road safety: How does a modal shift from short car trips to cycling affect road safety (Chapter 3)? Because of the lack of research regarding single-bicycle crashes, this thesis will first address the relationship between the amount of bicycle use and single-bicycle crashes (Chapter 2).
3. To investigate road design and crash risk, the following questions are addressed:
    a) How is the design of unsignalized priority intersections related to bicycle-motor vehicle crashes (Chapter 4)?
    b) What single-bicycle crash types can be distinguished and can these be related to infrastructure (Chapter 5)?
    c) What do cyclists need to see to avoid single-bicycle crashes (Chapter 6)?

Reynolds *et al.* (2009) indicate both signalized and unsignalized intersections to be important research gaps. It was decided to focus on unsignalized priority intersections because crashes at this type of intersection are most frequent in Dutch cities (60% of the BMV intersection crashes on distributor roads in middle-sized Dutch cities as compared to 20% on signalized intersections, according to Schepers and Voorham (2010)). Questions 3b and 3c are focused on single-bicycle crashes. Because of the lack of research focused on this issue, question 3b is of an explorative nature. Question 3c is more specific and focused on the role of the visual design of infrastructure in single-bicycle crashes. Note that the emphasis of the thesis is on an urban context where most cycling takes place.

1.4. Potential approaches to study cycling safety

This section summarizes methods for crash research and some alternative research approaches to studying cycling safety. It ends with the research design of this thesis.

1.4.1. Research design

Vandenbulcke-Plasschaert (2011) distinguishes between exploratory and explanatory studies. Exploratory methods can be used as an initial step to achieve a better understanding of a chosen road safety problem, e.g. by describing crash types and doing in-depth research focused on a specific crash type (e.g. Räsänen and Summala 1998). They may also be an initial step before performing explanatory methods that are commonly used to estimate the relative importance of several factors in the occurrence and severity of crashes. There are three basic research designs that are suitable for (explanatory) crash studies (FHWA 2010):

1. Observational before/after studies;
2. Observational cross-sectional studies;
3. Experimental before/after studies.

The third type is rare in road safety research due to the reluctance to randomly assign locations for improvements. This weakens the internal validity, i.e. the confidence that the results of a study accurately depict whether one variable is or is not a cause of another. For instance, evaluating measures taken at locations with an unusually high crash frequency, introduces the regression to the mean bias in a before/after study. Researchers may compensate for this problem, for instance by incorporating non-treatment sites. A before/after design can have good internal validity when treatment and non-treatment sites are comparable and when crash data and volume data from both before and after a safety improvement are available (FHWA 2010). It can be difficult to meet these requirements in practice and/or to achieve a sufficient study size. For instance, the sample size of the before/after study by Vis *et al.* (1992) for traffic-calmed areas was sufficiently large to determine the effect on road safety in general but too small to isolate the effect on cycling safety. Cross-sectional or correlational studies are an alternative. The internal validity can be improved by multiple regression to statistically control for other variables such as traffic volumes. However, inferring causality should be done cautiously because of the risk of unexamined third variables (Heiman 1999).

1.4.2. Models for quantitative crash studies

According to Vandenbulcke-Plasschaert (2011), three types of explanatory models are generally identified in the literature and have been applied in research on cyclist safety:

1. Crash Frequency Models (also referred to as Crash Prediction Models)
2. Crash Category Models
3. Crash Severity Models

Crash Frequency Models are generally applied to compute the probability of observing a definite number of crashes as a function of a set of crash-related factors such as road characteristics. Poisson and Poisson-gamma (or Negative Binomial) models are the most common choices in the literature as crash frequency data are Poisson-distributed and consist of integers (Lord *et al.* 2005; Eenink *et al.* 2008). Crash Category and Crash Severity Models focus on estimating the probability that a crash falls into one definite crash category or severity level, still as a function of a set of crash-related factors. Binomial logistic specifications are widely used when the dependent variable is of binary form, e.g. the crash belongs to a category or not, or the crash was fatal versus none-fatale. Multinomial or ordered logit specifications are generally performed when multiple categories are available, e.g. no injury, slight injury, serious injury, and fatal (Vandenbulcke-Plasschaert 2011).

1.4.3. Challenges in crash research

A number of methodological problems in bicycle crash research can result in systematic errors. Most of the systematic variation of crash frequency is explained by traffic flows (Brüde and Larsson 1993). A shortcoming of many crash studies focused on bicycle facilities is that they do not control for the number of passing cyclists, although installing tracks may affect cyclists' route choice (Elvik *et al.* 2009, Winters and Teschke 2010). Reynolds *et al.* (2009) found a number of other difficulties. Researchers grouped several facilities with potentially different risks into a single category. For instance, cyclists on two-way bicycle tracks run a higher risk than cyclists on one-way bicycle tracks (Summala *et al.* 1996), so combining these results in systematic errors. Reynolds *et al.* (2009) also found studies that did not distinguish between crash types and/or did not discuss the problem of under-reporting of crash types. This is of particular importance for research on cycling safety since the reporting rate of single-bicycle crashes is much lower than the reporting rate of bicycle-motor vehicle crashes (Reurings and Bos 2011). For instance, on-road bicycle lanes with an adjacent parking lane or tram rails may increase the likelihood that a cyclist collides with a car door or skids on slippery tram rails. Such effects may go unnoticed in a study based on police statistics if these crash types are not distinguished. Note that the problems described above are related to the (quality of the) variables used. They cannot be overcome by the statistical approach used.

Other researchers have focused on problems in crash research related to the statistical approach (for an overview, see Lord and Mannering 2010). Potential problems are overdispersion (i.e. the variance exceeds the mean) and, although rare, underdispersion (i.e. the mean exceeds the variance). To correct for the overdispersion problem for the Poisson model, Wedderburn (1974) suggested that one could inflate the variance μ_i to $\tau\ \mu_i$ where τ is referred to as 'overdispersion parameter' (and $\tau \geq 1$). It was also suggested that the overdispersion parameter τ could be estimated by $\chi^2/(n - k)$, where χ^2 is the Pearson's chi-square statistic, n is the number of observations (i.e. the number of intersections), and k is the number of unknown regression parameters in the Poisson model. Miaou (1994) suggests that Negative Binomial (NB) regression is used if the overdispersion of crash data is found to be moderate or high (e.g. when the overdispersion parameter exceeds 1.3). NB regression is unable the handle underdispersed data (Lord and Mannering 2010). For all of the CPMs estimated in Chapters 2, 3, 4, and 7, the overdispersion parameters indicated minor to high overdispersion; high for the majority of the models (exceeded 1.3) and as low as 1.1 in the case of two models for fatalities in Chapter 3. For reasons of consistency, NB regression is utilized for estimation of all CPMs throughout this thesis.

A problem that recently received attention in research on bicycle crashes is 'spatial correlation' (e.g. Vandenbulcke-Plasschaert 2011, Siddiquia *et al.* 2012), i.e. the spatial units of analysis such as road sections or wards that are in close proximity may share unobserved effects. This violates the assumptions of the more 'traditional' Negative Binomial (NB) regression models and may worsen the precision of parameter estimates (Lord and Mannering 2010). Some researchers used a Bayesian NB model to account for spatial correlation and compared the results with the outcomes of analyses based on a non-Bayesian NB model. They found similar variables to be significant, but a small number of variables was only significant using the non-Bayesian NB model (e.g. Quddus 2008, Siddiquia *et al.* 2012). Not accounting for spatial correlation when it is present does not result in systematic errors but may lead to invalid hypothesis testing, i.e. wrongly concluding that a variable is significant at the chosen level of significance.

1.4.4. Other research approaches

Like other types of observational studies, crash studies have a high ecological validity because accidents occur in natural environments (Heiman 1999). Another advantage is that the dependent variable is directly related to policy objectives for reductions of casualty numbers. However, to minimize the above-discussed problems with internal validity, researchers complement crash research with experiments in laboratory settings and in the field. Different types of research are conducted in order to understand road user behaviour and crash impacts and subsequently the 'causal mechanisms' that may explain crashes and injuries. On one side of the spectrum, there is research in well-controlled laboratory settings on human behaviour and crash tests with instrumented dummies to study energy exchanged during a crash (Shinar 2007, Elvik 2009). On the other side of the spectrum, there is observational on-the-road research where almost nothing is under control of the researcher. This increases ecological validity 'at the expense of' internal validity. Between these extremes are laboratory studies in simulators that mimic the road environment and field experiments with instrumented vehicles (Shinar 2007).

Examples of the above-mentioned research approaches can also be found in the field of cycling safety research, e.g. an experiment in a laboratory setting, here being a treadmill, by Moore *et al.* (2011) to study bicycle dynamics, a crash test to study the effect of airbags on car windscreens (Van Schijndel-de Nooij 2012), a field experiment by De Waard *et al.* (2010) to study the effect of phoning, etc. An observational study by Summala *et al.* (1996) is interesting to show how observational research can complement crash research to help to explain causal mechanisms. Their crash study showed that cyclists on two-way bicycle tracks were more likely to be involved in crashes with motorists from side roads. In their observational study, they found that drivers from the minor road have difficulties in detecting cyclists from the right (in the case of right-hand driving). One specific type of observational research is 'conflict analysis', which is suitable for studying intersection safety. Conflicts are more frequent than crashes and the number of conflicts is related to the likelihood of crashes. In contrast to the pre-crash phase, the pre-conflict phase can be investigated by direct observation, also to study the effect of measures to improve cycling safety at intersections (Van der Horst 1990). In naturalistic driving studies, vehicle sensors and unobtrusively placed video cameras are used to study the phase directly prior to crashes and near-crashes (Dingus *et al.* 2006). Researchers are now starting to apply the same method to study cycling safety (Dozza *et al.* 2012).

1.4.5. Research design of this thesis

The studies of this thesis are all crash studies with a correlational design. This design is suitable for addressing a relatively broad range of road factors within a study (FHWA 2010). The first two questions are studied at the level of Dutch municipalities using CPMs, i.e. these jurisdictions serve as study units. Because crash numbers are sufficiently high at this level, separate models are developed for deaths and hospitalized casualties. Risk factors related to road design are investigated at the level of intersections using CPMs (question 3a) and at the level of crash scenes using accident-category models (question 3b and 3c). The crash numbers in these analyses are too small to differentiate between different levels of severity.

In all of the studies, bicycle crashes with and without motor vehicles are addressed separately to account for differences in the rate of reporting. Police statistics are used for BMV crashes while the analyses are complemented by other sources for crashes with no motor vehicles. Bayesian models are not utilized because spatial correlation is reduced in the studies in which hypotheses are tested (their study units rarely border on one another). Inferring causality from correlation studies should be done with care. To improve the underpinning of conclusions, theory and literature are researched and described in the introduction and discussion of the studies. Also, the crash study on the visibility of infrastructure is complemented by a psychophysical measurement of the visibility of critical information at crash scenes.

1.5. Outline of the thesis

The thesis has eight chapters, see Table 1.2. The first seven chapters contain papers published in peer-reviewed journals. As a result, there is some overlap between the chapters. Each of these papers addresses one specific research question. The three main research questions are included in the table. Research question 1 is addressed last in Chapter 7 because it uses the results of the preceding chapters. Chapter 8 summarizes the chapters and highlights the most important findings. It provides a discussion of the results and this research. The thesis ends with a reflection on the implications for policy and recommendations for further research. Figure 1.3 depicts the position of the questions and chapters in the conceptual framework.

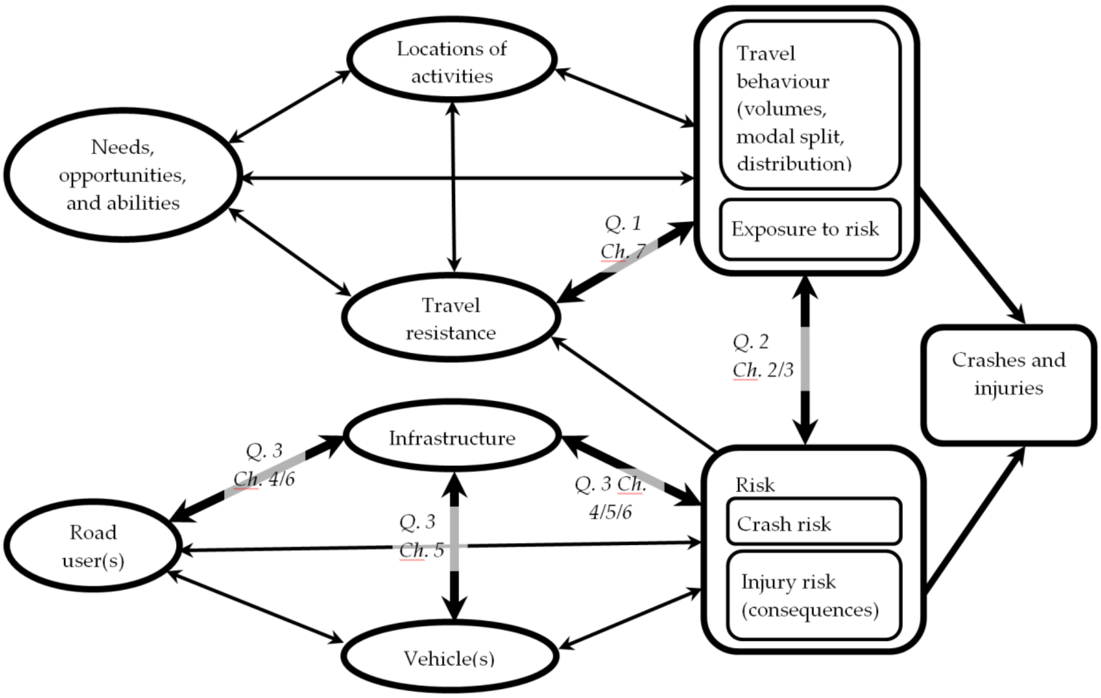


Figure 1.3. Chapters positioned within the conceptual framework (the arrows depicting relationships addressed in this thesis are in bold).

Ch.	Content / Research question	Journal and status
1	Introduction	Theoretical framework, Section 1.2: Schepers J.P., Hagenzieker, M.P., Methorst, R., Van Wee, G.P., Wegman, F.C.M., 2013. Accident Analysis and Prevention, In press.
	Research question 2	
2	To what extent does more cycling affect the risk of single-bicycle crashes?	Schepers, J.P., 2012, Injury Prevention, 18(4): 240-245.
3	How does a modal shift from short car trips to cycling affect road safety?	Schepers, J.P., Heinen, E., 2013. Accident Analysis and Prevention, 50(1): 1118-1127.
	Research question 3	
4	How is road design at unsignalized priority intersections related to bicycle–motor vehicle crashes?	Schepers, J.P., Kroeze, P.A., Sweers, W., Wüst, J.C.., 2011. Accident Analysis and Prevention, 43(3): 853-861.
5	Single-bicycle crash types and characteristics.	The explorative part of the paper focused on crash types: Schepers, J.P., Klein Wolt, K., 2012. Cycling Research International, 2: 119-135.
6	What do cyclists need to see to avoid single-bicycle crashes?	Schepers J.P., Den Brinker B.P.L., 2011. Ergonomics, 54(4): 315-327.
	Research question 1	
7	How does unbundling vehicular and cycle traffic in an urban network affect road safety?	Schepers, J.P., Methorst, R., Heinen, E., Wegman, F.C.M., 2013. Journal of Transport and Infrastructure Research, 13(3): 221-238.
8	Discussion, conclusions, and recommendations	

Table 1.2. Outline of the thesis.

2. To what extent does more cycling affect the risk of single-bicycle crashes?[3]

Abstract

Objective: This paper examines the relationship between the amount of bicycle use and the number of single-bicycle crashes (i.e., only one cyclist involved) in Dutch municipalities. Previous research has focused on crashes between bicycles and motor vehicles; however, most cyclists admitted to hospital are victims of single-bicycle crashes.

Methods: This correlational study used three data sets which included data relating to single-bicycle crashes and kilometres travelled by bicycle. Negative binomial regression was used to compare the amount of bicycling with the number of injuries incurred in single-bicycle crashes in Dutch municipalities.

Results: The likelihood of single-bicycle crashes varied inversely with the level of bicycle use. The exponent for the change in the number of single-bicycle crashes in response to changes in bicycle volumes was <1 in all analyses (i.e., the increase in the number of single-bicycle crashes in a given municipality is proportionally less than the increase in the number of bicycle kilometres travelled by its inhabitants). The value was reduced in analyses of single-bicycle crashes with more severe injuries.

Conclusions: Cyclists are less likely to be involved in a severe single-bicycle crash in municipalities with a high amount of cycling. Given the large numbers of patients admitted to hospital as a result of single-bicycle crashes, it is important to include the risks of these in road safety and health effect evaluations, and to take into account the non-linearity of the relationship between single-bicycle crashes and bicycle use if road safety measures are to affect the level of bicycle use.

2.1. Introduction

Several studies have shown that a motorist is less likely to collide with a cyclist (or pedestrian) where there is a higher incidence of cycling (or walking) (Jacobsen 2003, Robinson 2005, Elvik 2009). These studies indicate that the average cyclist is safer in communities where there is more cycling

---

[3] This chapter was first published in Injury Prevention: Schepers, J.P., 2012. To what extent does more cycling affect the risk of single-bicycle crashes? *Injury Prevention,* 18(4): 240-245.

because motorists adjust their behaviour in the expectation of encountering cyclists (Jacobsen 2003). To date, single-bicycle crashes (i.e., only one cyclist and no other vehicle involved such as a fall or collision with an obstacle; see e.g. Nyberg *et al.* (1996) for a more extensive description of these crashes) have not been included in studies on the relationship between bicycle crashes and bicycle use in spite of the fact that, in countries with a high proportion of cyclists, most cyclists admitted to hospitals are single-bicycle crash victims (Ormel *et al.* 2008). The lack of research on single-bicycle crashes may be due to heavy under-reporting in police statistics of this type of crash (Wegman *et al.* 2012) and the fact that most cyclists killed in traffic are victims of crashes between bicycles and motor vehicles (80% in the Netherlands) (Ormel *et al.* 2008). The most severe crashes tend to attract the greatest attention; however, large numbers of less severe crashes resulting in hospitalisation will generate a significant burden on health services. To achieve a more complete understanding of the safety effects of increasing levels of bicycle use, this correlational study focuses on the relationship between the amount of cycling and the likelihood of single-bicycle crashes. Knowledge of the relationship between bicycle volumes and single-bicycle crashes is important for evaluating the effects of measures that intentionally or unintentionally affect the amount of cycling. Using multiple data sets, analyses will be presented at the level of both individuals and municipalities within the Netherlands.

2.2. Hypothesis

There are at least two arguments to support the hypothesis that, at the level of municipalities, more cycling reduces the risk of single-bicycle crashes, meaning that the increase in the number of single-bicycle crashes in a given municipality is proportionally less than the increase in the number of bicycle kilometres travelled by its inhabitants. First, as the amount of cycling increases, authorities may improve infrastructure safety. According to Wegman *et al.* (2012) safe conditions for cyclists in countries with higher levels of cycling may be one of the explanations for their lower death rates. Such an explanation is possible for single-bicycle crashes as well. As the numbers of cyclists increase, politicians may be more likely to invest in the safety of bicycle facilities (e.g. adequate bicycle path and lane width, even road surfaces). Providing attractive bicycle lanes and paths may even encourage more people to commute by bicycle (Dill and Carr 2003).

Second, more experienced cyclists are likely to have fewer single-bicycle crashes because, with time, they have better control of their bicycles, they know what to expect and they have greater physical fitness. Cycling requires the rider to stabilise the bicycle, which is particularly difficult at lower speeds. The skills of controlling and manoeuvring a bicycle must be acquired and automatised through extensive experience (Wierda and Brookhuis 1991). Cyclists will have a better knowledge of where to expect hazards as a result of increased experience. For instance, it was found that collisions with bollards and road narrowings occurred more often to cyclists who were unfamiliar with the crash location (Schepers and Den Brinker 2011). As cycling improves health (De Hartog *et al.* 2010) (e.g., by strengthening muscles and the skeletal system, reducing obesity and improving stamina), it may also improve the ability of cyclists to avoid single-bicycle crashes and reduce the severity of their injuries. For instance, avoiding an obstacle on the road at the last moment may be easier for cyclists with an athletic build than for obese riders.

The hypothesis will be tested by comparing bicycle use (based on a survey) and numbers of single-bicycle crash victims (deaths and inpatients recorded by the police and trivial injuries reported in a survey) between municipalities, referred to as 'municipality level analyses'. Additionally, using a survey, it will be tested whether more experienced cyclists are less likely to be involved in single-bicycle crashes, referred to as 'individual level analysis'. The argument that increased experience decreases the likelihood of single-bicycle crashes is tested by the individual level analysis. Age and population density are included as control variables. Age may affect skill and frailty, while population density may affect the design of bicycle facilities.

2.3. Methodology

The relationship between the likelihood of single-bicycle crashes and the number of kilometres travelled by bicycle will be explored using negative binomial regression, which takes into account the problem of 'excess' zeros frequently observed in crash count data, i.e. many individuals or municipalities without crashes. The basic form of Crash Prediction Models is used (Eenink *et al.* 2008):

$$S = \alpha V^{\beta}\, \mathrm{e}^{\Sigma \mathrm{y_i x_i}}$$

The expected number of crashes S is a function of traffic volume V and a set of factors x_i, (where i = 1, 2, 3, ., n), i.e. the control variables. Exponent β indicates the change in the number of single-bicycle crashes in response to changes in bicycle volumes. When $\beta=1$ the growth in crashes with increasing exposure would be linear, $\beta<1$ indicates that the growth in crashes would be less than linear and $\beta=0$ indicates that the number of crashes is not related to exposure. α is a scaling parameter. The effects of various factors that influence the probability of crashes is modelled as an exponential function, that is a e (the base of natural logarithms) raised to a sum of product of coefficients y_i and values of the (control) variables x_i. Jacobsen (2003) applied the same model but without control variables.

Population density and age categories were used as control variables. Population density is important as it may influence both bicycle use (Dill and Carr 2003) and the likelihood of single-bicycle crashes, e.g. where population density is low, more space may be available to design bicycle facilities and, where it is high, more money may be available to invest in facilities. Municipalities are classified into three population density classes: high (>692 inhabitants/km^2), medium (263-692 inhabitants/km^2) and low (<263 inhabitants/km^2), each group representing 33% of all Dutch municipalities. Age influences both bicycle use (Zeegers 2010) and increased susceptibility to injury due to fragility (Li *et al.* 2003). A low number of single-bicycle crashes in a college town may be the result of low cyclist age rather than high bicycle volumes. Respondents are classified into three age groups (<24, 25-64 and 65+ years). These categories differ substantially in terms of the number of single-bicycle crash victims per kilometre travelled by bicycle (Ormel *et al.* 2008) (cyclists in the 65+ category are more likely to be hospitalised) and are sufficiently large to achieve reliable results. Crashes and exposure per respondent are used for individual level analyses. For analyses at the municipality level, the numbers of crashes and kilometres travelled by bicycle per municipality were split among these age groups, resulting in one record per municipality per age group in the data file for analyses at the municipality level. Instances of missing values for one of the variables are excluded from the analyses.

2.4. Data

2.4.1. Data collection method

Three existing data sets commissioned by the Dutch Ministry of Infrastructure and the Environment were used in this study to gather data on crashes and exposure. The data sets are summarised in Table 2.1. References to reports that describe the data collection methods and include the original questionnaire are included in the table. Statistics Netherlands data on population density of Dutch municipalities were also used (Statistics Netherlands 2011).

2.4.2. Description of the data sets and data collection methods

Periodic Regional Road Safety Survey (PRRSS)

The Periodic Regional Road Safety Survey (PRRSS) is conducted every 2 years (up to 2005 by Traffic Test and since 2007 by TNS NIPO) for general monitoring of road safety and traffic behaviour. It includes questions on the number of bicycle crashes and bicycle kilometres travelled each year. The answer category 'not applicable' and unanswered questions were treated as missing values. Most single-bicycle crash victims sustained injuries that did not need to be treated at an Accident and Emergency department and were categorised as 'trivial injuries'. Respondents are selected in two stages. Using the 2005 survey as an example (Barten *et al.* 2006):

- Stage 1 (December 2005): a sample of addresses was drawn from across the Netherlands. Potential respondents aged 15 years or more were asked to return a reply card, indicating whether they were prepared to participate in the survey.
- Stage 2 (February 2006): a sample of persons, stratified according to age and gender, was drawn from the Stage 1 respondents. They received the questionnaire.

Data obtained from the 2001, 2003, 2005, 2007 and 2009 surveys were combined. The average response rate was 61%.

National Travel Survey (NTS)

The National Travel Survey (NTS) describes the travel behaviour of the Dutch population. Every month a sample of households is drawn from the Borough Basic Administration (a government database of relevant personal information regarding residents of the Netherlands such as date of birth and address) to ensure all types of travellers and households and all days are proportionately represented. Each member of the household is requested to record all journeys made on a particular day. Respondents are telephoned if they have not responded or to clarify missing answers, otherwise the respondent is excluded from the final data set (Rijkswaterstaat 2010). Data between 2004 and 2009 were used to determine the numbers of kilometres travelled by bicycle in all 431 Dutch municipalities. A total of 140,852 households (317,258 persons) completed questionnaires, giving a response rate of 70.5%.

Police-recorded crashes

The study covered all police-recorded single-bicycle crash victims across all 431 Dutch municipalities over a 6-year period (2004-2009), a total of 990 inpatients and 78 deaths. Besides details such as the crash location, the police records indicated whether the crash resulted in death or hospitalisation.

Data set for crashes	Reference	Description
PRRSS	(Barten *et al.* 2006)	Single-bicycle crashes per respondent and victims per municipality (i.e. of the municipality's citizens), trivial injuries
Police-recorded crashes	-	In-patients (admitted into hospital for at least one night) / deaths per municipality
Data set for exposure		
PRRSS	(Barten *et al.* 2006)	Kilometres travelled by bicycle per respondent per year
NTS	(Rijkswaterstaat 2010)	Kilometres travelled by bicycle per municipality: by its citizens (as an exposure measure for municipality level analysis on trivial injuries) and by people within the borders of the municipality (as an exposure measure for municipality level analysis on in-patients and deaths)

Table 2.1. Data sets for crashes and exposure used in this study (for more information: www.swov.nl/uk/research/kennisbank/inhoud/90_gegevensbronnen/gegevens.htm**).**

PRRSS and NTS were compared with Dutch population gender and age statistics (Statistics Netherlands 2011). In the analyses, data from these surveys have been weighted to represent age and gender in the overall population. The weighting factor in the NTS data set enables the outputs to reflect the Dutch population more closely, i.e. besides a ratio to correct for response biases (e.g. the response rate of young adults is lower than that of older people), it includes a ratio of population size divided by sample size.

Use of the data sets for municipality level analyses

Single-bicycle crash victims in PRRSS (trivial injuries) and police-recorded victims (inpatients and deaths) were used for municipality level analyses. In PRRSS, respondents are asked to identify their municipality of residence. The sample of addresses for PRRSS is drawn so that citizens in all Dutch municipalities have about an equal chance of being invited to complete the questionnaire and report their involvement in single-bicycle crashes. The total number of victims from all 431 Dutch municipalities was subsequently distributed among the three age groups. The same process was carried out for crash victims whose details were recorded by the police.

The NTS was used to select exposure data for municipality level analyses for both sources of crash data because it is specifically designed to achieve reliable mobility statistics. As respondents taking part in the PRRSS reported their place of residence and not the location of the crash, the number of bicycle kilometres travelled by citizens of a given municipality were summed to serve as an exposure measure (for the analysis of trivial injuries in Table 2.2). The study period of PRRSS (2001-2009) differs from the study period of NTS (2004-2009). It is assumed that the difference will not affect the outcomes as the average number of kilometres travelled between 2004 and 2009 was only about 2% higher than that between 2001 and 2009 (Statistics Netherlands 2011).

The police-recorded crash data note crash locations. As an exposure measure for police-recorded crashes, the part of external trips (i.e. leaving and arriving in different municipalities) that fell within the borders of a given municipality was added to the length of internal trips (i.e. leaving and arriving within the same municipality–about 90% of all bicycle trips) for the analyses of inpatients and deaths in Table 2.2. Some trips go through more than two municipalities. The part of those trips that fell between different municipalities could not be assigned to municipalities (see Section 3.2.1 for a more detailed description of how the exposure measure was determined). The difference between the exposure measure for analysis of trivial injuries (bicycle kilometres of the citizens of a municipality) and the measure for police-recorded inpatients and deaths (bicycle kilometres covered within the borders of a municipality) is small as more than 90% of all bicycle trips start in a cyclist's municipality of residence.

Use of the data sets for individual level analyses

PRRSS contains the responses of individuals to questions on the number of single-bicycle crashes and the number of kilometres travelled by bicycle per year. These data were used for an analysis of single-bicycle crashes with trivial injuries at the level of individual cyclists (see Table 2.3).

2.5. Results

Tables 2.2 and 2.3 present descriptive statistics, while Tables 2.4 and 2.5 show the results of the regression analyses. Table 2.2 is based on crash and exposure data for municipality level analyses; Table 2.3 on crash and exposure data for individual level analysis. Exposure data for municipality level analyses were based on NTS; exposure data for the individual level analysis on PRRSS. The number of kilometres travelled by bicycle in Table 2.2 reflects how many kilometres are travelled by cities' inhabitants per year. Table 2.3 indicates how many kilometres are travelled per year by respondents who indicated that they use a bicycle.

The exponent for the growth in crashes in Table 2.4 (i.e. parameter β in equation 1) is less than 1 in all three analyses, indicating that the increase in the number of trivial injuries, in-patients and deaths caused by single-bicycle crashes in municipalities is proportionally less than the increase in the numbers of kilometres travelled by bicycle by a municipality's citizens. This result is in accordance with the hypothesis stated in the introduction, i.e. more cycling reduces the risk of single-bicycle crashes. The result of the analysis on in-patients (the analysis with the highest number of crashes) is shown graphically for the three age groups in Figure 2.1. Regression lines as described in Table 2.4, with an exponent for the growth in crashes of 0.76 (leaving population aside), are added to the scatter plots.

The confidence intervals of the exponents for the growth in crashes in the analyses were compared. The coefficients are lower in analyses on more severe injuries, i.e. lowest in the analyses on deaths and highest in the analysis on trivial injuries.

Age group	Dependent variable		Independent variable, million km per year per municipality		
			travelled by citizens (NTS)		
	Trivial injuries (PRRSS)		Number of respondents	Mean	SD
15-24	101		34,008	6.1	8.5
25-64	340		177,108	17.5	34.9
65	97		54,764	3.1	3.4
Missing values	4		0		
Total	542		265,880	8.9	21.7
	In-patients (police recorded)	Deaths (police recorded)	travelled within municipalities (NTS)		
			Number of respondents	Mean	SD
0-24	242	6	85,386	12.5	17.5
25-64	527	35	177,108	16.7	32.5
65	221	37	54,764	2.9	3.2
Total	990	78	317,258	10.7	22.0

Table 2.2. Descriptive statistics used for municipality level analyses (data source between brackets; The data set consists of 1293 records for three age groups and 431 municipalities).

Age group	Number of respondents	Missing values	Dependent variable (trivial injuries)			Independent variable (km travelled by bicycle per year)	
			Total	Mean	SD	Mean	SD
15-24	3,697	54	99	0.027	0.18	1,540	2,786
25-64	37,338	1,475	346	0.010	0.11	1,131	1,918
65	10,745	990	97	0.010	0.11	1,311	2,634
Total	51,779	2,518	542	0.011	0.12	1,197	2,154

Table 2.3. Descriptive statistics of PRRSS data used for the individual level analysis (Respondents who replied that they never use a bicycle and respondents who did not answer the question on exposure or crash involvement are treated as missing values).

Injury severity	Trivial injuries	In-patients	Deaths
Exponent for growth in crashes	0.80 (0.69 to 0.91)	0.76 (0.66 to 0.85)	0.52 (0.38 to 0.66)
Relative risk per age category			
15-24	1 (reference)		
0-24		1 (reference)	1 (reference)
25-64	1.29 (1.00 to 1.67)	1.79 (1.49 to 2.16)	3.43 (2.30 to 5.10)
65	1.44 (1.09 to 1.91)	2.74 (2.15 to 3.50)	8.42 (5.40 to 13.11)
Relative risk per population density class			
low (< 263 per km^2)	1 (reference)	1 (reference)	1 (reference)
medium (263-692 per km^2)	1.05 (0.80-1.34)	0.97 (0.79-1.19)	0.86 (0.62-1.26)
high (>692 km^2)	1.24 (0.94 to 1.64)	0.86 (0.70-1.07)	1.43 (0.91-2.25)

Table 2.4. Estimation results for municipality level regression analyses on single-bicycle crashes (95% Wald CI).

	Estimation result for trivial injuries
Exponent for growth in crashes	0.63 (0.61 to 0.65)
Relative risk per age category	
15-24	1 (reference)
25-64	0.59 (0.56 to 0.63)
65	0.67 (0.63 to 0.72)

Table 2.5. Estimation results for individual level regression analyses on trivial injuries (95% Wald CI**)**.

In addition to the municipality level analyses, one individual level analysis on trivial injuries was conducted, see Table 2.5. Again, the exponent for the growth in crashes is significantly less than 1, indicating that more experienced cyclists are less likely to sustain injuries due to single-bicycle crashes. Improved safety of individual cyclists due to increased experience is likely to be one of the explanations for the results that were found at the level of municipalities.

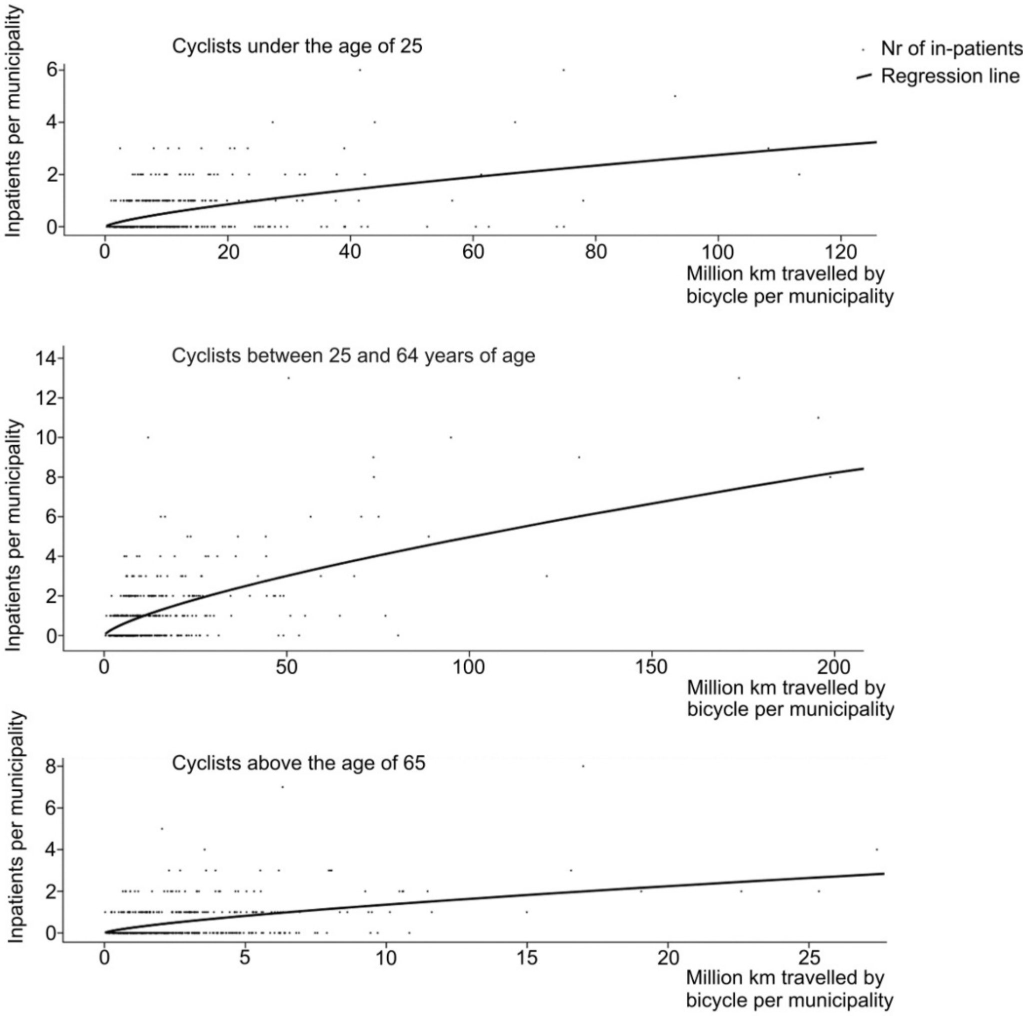


Figure 2.1. Number of inpatients as a result of single-bicycle crashes per municipality versus the number of kilometres travelled per municipality per year between 2004 and 2009 by cyclists for three age groups.

Of the control variables (i.e. age and population density), only age was significantly correlated to the number of single-bicycle crashes. Older cyclists are more likely to sustain severe injuries in single-bicycle crashes. The relative risk of older cyclists tends to grow as the severity of such crashes increases, e.g. the relative risk of older cyclists is highest in the analysis on deaths. The results of the municipality and individual level analyses on trivial injuries in Tables 2.4 and 2.5 are less consistent. It can be concluded that older cyclists are more likely to sustain severe injuries if they are involved in single-bicycle crashes, but it cannot be concluded whether they are more likely to be involved in single-bicycle crashes.

2.6. Discussion

While it is already known that crashes between bicycles and motor vehicles are less likely to occur where there is a greater incidence of cycling (Jacobsen 2003, Robinson 2005) this study shows that more cycling also reduces the risk of single-bicycle crashes. At the municipality level, the increase in the number of single-bicycle crashes in a given municipality is proportionally less than the increase in the number of bicycle kilometres travelled by its inhabitants. This result adds to the ongoing body of literature exploring the relationship between bicycle use and cycling safety.

One explanation for this finding is that cyclists in municipalities with a higher amount of cycling are more experienced and have fewer single-bicycle crashes. This is due to the fact that, over time, they have better control, know what to expect and have greater physical fitness. This explanation is supported by the finding that the likelihood of sustaining injuries due to single-bicycle crashes was lower among more experienced cyclists. A second explanation is that authorities may improve infrastructure safety as the amount of cycling increases, as has been suggested by Wegman *et al.* (2012) and that attractive bicycle facilities may encourage more people to commute by bicycle (Dill and Carr 2003). The link between the number of kilometres travelled by bicycle in municipalities and the quality of their bicycle facilities is outside the scope of this study and needs to be tested in future research.

Crash severity

The results show that the exponent for the growth in crashes is lowest for crashes with severe injuries. This outcome may be due to different factors working at varying levels of crash severity. The advantages of being more experienced may be greater for more severe crashes as skills and fitness influence both the likelihood of being involved in a single-bicycle crash and the likelihood of sustaining injuries. However, more research is needed as some of these differences may result from the different research methods used to construct the underlying data sets. Also, the regression analysis on deaths is based on a relatively small casualty number resulting in more uncertainty regarding the regression parameters in the CPM for deaths.

Age

Age was included as a control variable, but it is also an important factor for reliably estimating the results of increasing amounts of cycling if the increase differs between age groups. Older cyclists sustain more severe injuries in single-bicycle crashes than younger cyclists. The results of the likelihood of being involved in a crash were less consistent. Susceptibility to injury due to fragility of older cyclists (in this study defined as >65 years of age) seems to be the most important explanation for the increased likelihood of sustaining severe injuries in single-bicycle crashes, a finding that is comparable to susceptibility to injury of older drivers (Li *et al.* 2003).

Recommendations for practitioners

Given the high numbers of single-bicycle crashes, it is important to include the risk of these crashes in road safety and health effect evaluations and to take into account the non-linearity of the relationship between single-bicycle crashes and bicycle use if road safety measures are to affect the level of bicycle use. Not doing so may result in biased conclusions. A more complete estimation of road safety effects can be achieved using the models developed by Elvik (2009), which can be applied to single-bicycle crashes, bicycle-motor vehicle crashes and others. A more accurate estimate of health effects can be achieved by taking into account health benefits from increased physical exercise, risks associated with higher exposure to air pollution, and decreased air pollution emissions when car trips are replaced by bicycle trips (De Hartog *et al.* 2010). As single-bicycle crashes often result in minor or even severe injuries but are only rarely fatal, the disability-adjusted life years and quality-adjusted life years measures (which include both mortality and morbidity) are more suitable for evaluating the disease burden from single-bicycle crashes than the life years gained measure which includes mortality only (McKenna *et al.* 2005, Robberstad 2005).

3. How does a modal shift from short car trips to cycling affect road safety?[4]

Abstract

Governments aim to promote a shift from car to bicycle, but concerns about road safety seem to represent an important argument against this encouragement. This study examines the road safety impact of a modal shift from short car trips to cycling in Dutch municipalities. The road safety effect is estimated using Crash Prediction Models (CPMs) that account for the non-linearity of risk. CPMs are developed utilizing Negative Binomial regression. This study is the first to develop CPMs using crash and mobility data from municipalities, and utilizing these models to estimate the effects of changing modal splits of current car and bicycle use to modal splits that actually exist in these municipalities. The results suggest that, under conditions such as in Dutch municipalities, transferring short trips made by cars to bicycles does not change the number of fatalities, but increases the number of serious road injuries. The neutral effect on fatalities, despite the high fatality risk for cyclists, can be explained by there being fewer cars on the road to pose a risk to others, the shorter length of bicycle trips compared to the car trips they replace, and the "safety in numbers" phenomenon. The rise in the number of serious road injuries is due wholly to the high number of cycling crashes with no other vehicle involved. The effect of a modal shift is dependent on the age of the population in which the shift is concentrated, and can be influenced by measures affecting cyclists' injury risk.

3.1. Introduction

Policy interest in promoting a shift from car to bicycle trips has increased substantially in recent times. Car use is associated with transportation and spatial problems, such as congestion and parking difficulties, while cycling is an environmentally sustainable mode of transport with associated public health benefits (De Hartog *et al.* 2010, Heinen *et al.* 2010a). For short trips up to about 7.5 km (70% of all trips in the Netherlands), many consider cycling a

---

[4] This chapter was first published in Accident Analysis and Prevention: Schepers, J.P., Heinen, E., 2013. How does a modal shift from short car trips to cycling affect road safety? *Accident Analysis and Prevention*, 50(1): 1118-1127.

good alternative to car driving, as shown by the fact that 35% of such trips are made by bicycle. The car has the same share, walking has a share of 27%, and public transport is hardly used for short trips (KiM 2011). However, concerns about road safety would seem to represent an important argument against encouraging cycling (Elvik 2009), given that cycling is associated with a considerably higher risk of accident-related injury than driving. For determining to what extent this argument is valid, this study uses crash and mobility data from Dutch municipalities to estimate the road safety effects of a modal shift from car to bicycle.

3.1.1. Factors influencing the road safety effect of a modal shift

The literature describes at least five factors about why a modal shift from car to bicycle has a smaller effect on road safety than might expected, given the higher risk of cyclists sustaining injuries compared to car occupants:

1. After shifting from car driving to cycling, individuals are less hazardous to other vulnerable road users (including cyclists) because of the lower amounts of kinetic energy expended in the event of a crash (Wegman *et al.* 2012).
2. Simple risk figures overestimate improvements to road safety due to replacing short car trips by bicycle trips, because the relatively safe part of long car trips, that driven on motorways, is included in the risk figures of car occupants. Across Europe, whereas 25% of the kilometres driven are on motorways, motorway accidents account for only 8% of traffic deaths (De Hartog *et al.* 2010).
3. Bicycle trips are often shorter than the car trips they replace (Van Boggelen *et al.* 2005). Drivers need to travel from low-speed access roads (i.e. local roads in residential areas) to higher speed distributor roads (i.e. arterial roads) to find the fastest route. Cyclists, on the other hand, use a more fine-grained network of roads, cycle tracks and short cuts to find their shortest route - usually the fastest. In terms of kilometres per trip, cyclists are thus less exposed to hazards in traffic than drivers.
4. The average cyclist is safer in communities where there is more bicycling because motorists adjust their behaviour in the expectation of encountering cyclists, i.e. the “safety in numbers” phenomenon (Jacobsen 2003).
5. Authorities may improve infrastructure safety as the amount of cycling increases (Wegman *et al.* 2012) and vice versa (Dill and Carr 2003).

Given these factors, it is conceivable that a shift from car to bicycle trips would be associated with constant or even reduced crash numbers.

3.1.2. Estimating the road safety effect of a modal shift

Earlier studies have estimated the road safety effect of a hypothetical modal shift by multiplying the volumes of cyclists and cars before and after the change by risk figures (e.g. Stipdonk and Reurings 2012). This method assumes a linear relationship between volumes and crashes, whereas empirical studies show that the relationship is highly nonlinear (Elvik 2009). Consequently, it cannot account for the 'safety in numbers' effect. Elvik (2009) was the first to estimate the road safety effects of shifts from car to bicycle (and walking) using Crash Prediction Models (CPMs) in which a nonlinear relationship between crashes and volumes is assumed. In this study, we will develop and utilize CPMs to model the effect of exchanging bicycle trips for car trips, taking the five factors noted above into account.

3.1.3. Crash Prediction Models (CPMs)

Elvik (2009) used the following CPM for bicycle-motor vehicle crashes:

$$BMC = \alpha Vm^{\beta 1} Vb^{\beta 2}$$

in which BMC is the predicted annual number of bicycle crashes Vm and Vb represent the volume of motor vehicles and cyclists. The coefficient α is a scaling parameter, which ensures that the predicted number of accidents is in the same range as the recorded number of accidents. Coefficients $\beta 1$ and $\beta 2$ describe the shape of the relationship between traffic volume and the number of accidents. The growth in crashes varies according to the value of β:

- $\beta = 1$: the growth would be linear;
- $\beta < 1$: the growth in crashes would be less than linear;
- $\beta = 0$: indicates that the number of crashes is not related to exposure.

As shown in a number of studies, either coefficient often takes on a value between 0.3 and 0.9. Elvik (2009) used similar models for other crash types that would be affected by a modal shift, using parameter estimates from existing research. The volumes of cyclists and motor vehicles before and after a hypothetical modal shift were entered into the CPMs to estimate the road safety effects.

3.1.4. Aim of the study

According to Elvik (2009), the available CPMs refer only to motorised traffic in general, without distinguishing between the different types. In addition, most CPMs have been developed for intersection crashes, whereas modal shifts occur across a wider area. This study aligns with and continues Elvik's research, and also adds to it in three ways:

1. It considers all the transport modes involved in car and bicycle crashes.
2. CPMs are developed for municipalities as a whole so that the area where the exchange takes place coincides with the area where crashes occur.
3. Single-bicycle crashes are included. These crashes are poorly reported in official road accident statistics, although they result in high numbers of seriously injured victims (Wegman *et al.* 2012). The first Crash Prediction Models for single-bicycle crashes have been developed only recently (Schepers 2012, see Chapter 3).

The remainder of the paper is organized as follows. The development of CPMs is described in Section 3.2. Section 3.3 addresses the issue of distance, which is needed to estimate how many bicycle kilometres correspond to car kilometres in case short car trips are replaced by bicycle trips. Finally, Section 3.4 applies the models to an exchange of short car trips by bicycle trips

3.2. CPMs for victims in car and bicycle crashes

To determine the effect of a modal shift in Dutch municipalities from short car trips to cycling CPMs were developed for the recorded numbers of deaths and in-patients – people who are hospitalized for at least 24 hours – in car and bicycle crashes. Data on police-recorded crash victims in the 387 municipalities with more than 10,000 inhabitants were fitted on exponential models, using negative binomial regression modelling. This serves as statistical approximation to the crash process (Lord *et al.* 2005). Rural municipalities having less than 10,000 inhabitants (10% of all Dutch municipalities and home to 2% of the population) are excluded because of the low numbers of victims and the low numbers of respondents in the survey on which municipality mobility data rely. Assuming that the amount of use of transport modes other than cars and bicycles remains at the same level, the models will be based on the numbers of kilometres by car (Kc) and by bicycle (Kb) within the municipalities. Car kilometres driven on motorways are excluded because these are unlikely to be part of short car trips that could be replaced by cycling. This results in the following victim types (model form between brackets):

1. cyclist victims in:
    - bicycle-car crashes ($\alpha Kc^{\beta 1}Kb^{\beta 2}$)
    - other bicycle-motor vehicle crashes ($\alpha Kb^{\beta 1}$)
    - with no motor vehicle involved ($\alpha Kb^{\beta 1}$)
2. car occupants in road crashes: car-motor vehicle crashes and single-car crashes (αKc^{β})
3. other victims in car crashes: pedestrians, mopeds, motor cycles, vans, and so on (αKc^{β})

There are two additional control factors: population density and the influence of age. Population density is important as it may affect both bicycle use (Dill and Carr 2003) and the likelihood of bicycle crashes. This influence could work in two directions: where population density is low, there may be more space available for bicycle facilities; where it is high, there may be more money available to invest in facilities. Therefore, municipalities are classified into three population density classes:

- high, above 742 inhabitants per km^2;
- medium, 272-742 inhabitants per km^2;
- low, under 272 inhabitants per km^2.

Each group represents 33% of all Dutch municipalities having more than 10,000 inhabitants.

Age influences both bicycle use (Zeegers 2010) and increased susceptibility to injury due to fragility (Li *et al.* 2003). For example, a low number of bicycle crashes in a college town may be the result of low cyclist age rather than high bicycle volumes. The numbers of victims and the kilometres travelled by bicycle and by car per municipality were split amongst four age groups (up to 17, 18-24, 25-64, and 65+), resulting in the data file containing one record per municipality per age group. In the regression on bicycle victims in bicycle-car crashes, the number of bicycle kilometres per municipality per age group and the number of car kilometres per municipality are used.

Using relative risk R_j for the four age groups and relative risk R_k for the three population density classes, the final models for the total number of victims per crash type used in this section have the following form:

1. cyclist victims in:
    - bicycle-car crashes: $\sum_{jk} \alpha Kc_k^{\beta 1}Kb_{jk}^{\beta 2} R_j R_k$
    - other bicycle-motor vehicle crashes: $\sum_{jk} \alpha Kb_{jk}^{\beta} R_j R_k$

2. car occupants in road crashes: $\sum_{jk} \alpha K c_{jk}^{\beta}$
3. other victims in car crashes: $\sum_{jk} \alpha K c_{k}^{\beta}$

The control variables x_i ($i = 1, 2, 3, \ldots, n$) are modelled as an exponential function, that is, as e (the base of natural logarithms) raised to a sum of product of coefficients, y_i, and values of the variables, x_i ($e^{\Sigma y_i x_i}$). The exponential of the coefficients is the relative risk.

3.2.1. Data

Police-recorded crash data and mobility data from the Dutch National Travel Survey (NTS) are used, supplemented with route information data and Statistics Netherlands data on population density of Dutch municipalities (Statistics Netherlands 2011). These datasets are now subsequently discussed.

Police-recorded crashes
Police-recorded crash data cover all recorded car and bicycle crash victims (only single-bicycle crash victims were excluded) over a six year period (2004-2009) across all 387 Dutch municipalities having more than 10,000 inhabitants. In total 2,704 deaths and 40,749 in-patients are included. Police records include details on the crash location, victim characteristics, and whether the crash resulted in death or hospitalization.

National Travel Survey (NTS)
NTS describes the travel behaviour of the Dutch population. A sample of households is drawn every month from the Borough Basic Administration to ensure all types of travellers and households and all days are proportionately represented. Each member of the household is requested to record all journeys made on a particular day. Respondents are telephoned if they have not already responded, or to clarify missing answers; otherwise the respondent is excluded from the final data set (Rijkswaterstaat 2010). In total 140,852 households (317,258 persons) completed questionnaires between 2004 and 2009, corresponding to a response rate of 70.5%. The included weighting factor enables the outputs to closely reflect the Dutch population.

Route analyses for determining the amount of cycling and car use
To take into account the second of the five factors influencing the road safety effect of a modal shift (overestimation of the difference in road safety between short car and bicycle trips), the amount of bicycle and car use per municipality, excluding kilometres driven on motorways, was determined. NTS notes the municipality of departure and arrival, and trip variables such

as the trip length. Given the limited number of entrances to motorways and their often peripheral location in municipalities, it is reasonable to assume that motorways are rarely used for internal trips (i.e. leaving and arriving in the same municipality). Trip length is an adequate measure for the amount of kilometres for internal trips.

Nevertheless, NTS does not include route information such as which part of external trips is travelled on motorways or within the borders of a given municipality. By conducting route analyses, that part of external trips that fell within the borders of a given municipality (excluding the part travelled on motorways) was determined using Google Earth route planner service for car trips (Google 2011) and the Dutch Cyclists' Union route planner for bicycle trips (Fietsersbond 2011). The latter includes solitary bicycle tracks that do not run parallel to a road; Google Earth contains a layer for municipality borders. For car trips the fastest route was planned. Although drivers often plan routes that are somewhat slower, this is a good approximation (Koning and Bovy 1980). For bicycle trips, the shortest route was planned, this being a good approximation of their route choice behaviour (Gommers and Bovy 1987).

This labour-intensive task was carried out on the 2008 NTS dataset. By exception, it was allowed (normally it is not for privacy reasons) to use a dataset containing the most detailed available ZIP codes, i.e. a six-position zip code (comprising, on average, 20 addresses) for the point of departure and return of around of one quarter of the trips, and a combination of six-position and four-position ZIP codes (consisting of on average 2500 addresses) for the remainder. A maximum of 100 external car and bicycle trips leaving a given municipality were analysed to achieve a manageable amount of work. Denoting N as the number of external trips, every N/100th trip was analysed when more than 100 external trips were reported in NTS, as was the case in one third of the municipalities. The average number of external trips in the other two thirds of the municipalities was 60, and only two municipalities had less than 25 external trips in the NTS data set. The result was the average length of the 2008 external car and bicycle trips per municipality, excluding kilometres driven on motorways.

The total amount of car and bicycle use per municipality was calculated by multiplying the average length of the 2008 external trips by the number of external trips in the NTS dataset between 2004 and 2009, and adding to that the total length of the internal trips between 2004 and 2009. Some trips went through more than two municipalities; the part of those trips that fell between different municipalities could not be assigned to a municipality.

3.2.2. Results

Table 3.1 presents descriptive statistics of crash victims per crash type (2004 - 2009), according to age group; Table 3.2 quantifies annual bicycle and car use per municipality (2004 - 2009) Note that the annual amount of bicycle and car use for all municipalities together is obtained by multiplying the average use by the number of municipalities and age groups in the dataset.

Table 3.3 shows the results of the negative binomial regression analyses on recorded victims in car and bicycle crashes in municipalities, 2004-2009. In most cases, the exponent for the growth in crashes in response to the amount of car and bicycle use is significantly lower than 1, indicating that the increase in the number deaths and in-patients in municipalities is proportionally less than the increase in the numbers of kilometres travelled by bicycle and car. This also applies to cyclist fatalities and in-patients, indicating that as the number of cyclists increases, the risk faced by each cyclist is reduced.

Cyclists older than 65 years of age run an higher risk of being killed or hospitalized than younger cyclists. The fact that the risk of being killed is even more elevated than the risk of being hospitalized is probably due to the fragility of older people. Car occupants run the highest risk of being hospitalized or killed when they are between 18 and 24 years of age, when people are often inexperienced car drivers and susceptible to age-related factors such as peer pressure (SWOV 2010a). The effect of population density differs between victims in different crash types. In highly populated municipalities, fewer cyclists are killed in bicycle-car crashes whereas more people are hospitalized in both bicycle-car and other bicycle-motor vehicle crashes. The risk of car occupants being killed or hospitalized reduces as the population density increases.

The results show that the risks differ significantly between age categories and population density classes. This may impact the effect of a modal shift from short car trips to the bicycle if the exchange is unequally spread amongst these groups. This will be taken into account in the calculations in Section 3.4 after determining the difference in trip length of the same short trip by car and bicycle.

Age group	Cyclist victims in car crashes					
	Deaths			In-patients		
	μ	σ^2	Tot	μ	σ^2	Tot
65+	0.55 (0-6)	0.75	212	4.45 (0-43)	30.59	1724
25-64	0.30 (0-9)	0.59	115	8.38 (0-161)	221.18	3242
18-24	0.05 (0-2)	0.05	18	1.73 (0-44)	16.68	670
0-17	0.17 (0-4)	0.23	67	4.59 (0-35)	30.02	1775
Total	0.27 (0-9)	0.44	412	4.79 (0-161)	80.07	7411
	Car occupant victims in car crashes					
	Deaths			In-patients		
65+	0.73 (0-6)	1.14	282	6.35 (0-48)	39.46	2459
25-64	1.72 (0-14)	3.93	665	29.95 (0-305)	1240.87	11591
18-24	0.97 (0-6)	1.80	377	12.71 (0-113)	164.88	4918
0-17	0.14 (0-3)	0.20	54	3.09 (0-36)	15.86	1196
Total	0.89 (0-14)	2.08	1378	13.03 (0-305)	472.07	20164
	Cyclist victims in other motor vehicle crashes					
	Deaths			In-patients		
65+	0.44 (0-5)	0.62	169	1.74 (0-20)	6.02	674
25-64	0.30 (0-8)	0.60	117	3.57 (0-101)	55.21	1382
18-24	0.08 (0-4)	0.14	30	0.72 (0-16)	2.62	280
0-17	0.17 (0-3)	0.20	66	1.93 (0-17)	6.31	747
Total	0.25 (0-8)	0.41	382	1.99 (0-101)	18.55	3083
	Car crash victims in other transport modes than a car (cyclists excluded)					
	Deaths			In-patients		
All age groups together	0.34 (0-8)	0.52	532	6.52 (0-242)	169.06	10091

Table 3.1. Recorded crash victims per crash type from 2004 up to 2009 in municipalities per age group (minimum and maximum per municipality between brackets; the data set consists of 1548 records for 4 age groups and 387 municipalities).

Age group	Bicycle use		Car use	
	μ	σ	μ	σ
65+	3.18	3.28	11.67	13.51
25-64	17.96	33.90	89.82	125.98
18-24	3.62	6.80	8.72	11.62
0-17	10.07	11.35	15.84	19.63
Total	8.71	19.21	31.51	72.64
Population density class				
high (>742 inh./km^2)	15.18	30.95	50.48	114.03
medium (272-742 inh./km^2)	6.26	8.10	23.32	38.49
low (< 272 inh./km^2)	4.70	4.66	20.76	28.73
Total	8.71	19.21	31.51	72.64

Table 3.2. Amount of bicycle and car use (10^6 km/year/municipality) travelled from 2004 up to 2009 (The data set consists of 1548 records for 4 age groups and 387 municipalities).

Victim's transport mode	Cyclists				Car occupants		Car crash victims in other transport modes than a car, cyclists excluded	
Crash type	Car crashes		Motor vehicle crashes (except car crashes)		All crash types			
Parameter:	Deaths	In-patients	Deaths	In-patients	Deaths	In-patients	Deaths	In-patients
Exponent for growth in crashes in response to:								
Amount of bicycle use per age group per municipality	0.26 (0.07–0.45)	0.44 (0.34–0.54)	0.90 (0.79–1.00)	0.81 (0.75–0.88)				
Amount of car use per age group per municipality					0.73 (0.64–0.82)	0.79 (0.74–0.83)		
Amount of car use per municipality	0.62 (0.41–0.83)	0.55 (0.44–0.67)					0.83 (0.72–0.93)	0.92 (0.86–0.99)
Relative risk per age category:								
65+	4.15 (3.02–5.70)	1.59 (1.34–1.88)	7.12 (5.46–9.27)	2.24 (1.90–2.65)	6.28 (4.76–8.27)	2.65 (2.37–2.96)		
25-64	1.38 (1.06–1.80)	1.23 (1.08–1.39)	1.00 (0.78–1.29)	1.07 (0.93–1.24)	3.48 (2.59–4.68)	2.43 (2.14–2.77)		
18-24	0.37 (0.23–0.58)	0.50 (0.41–0.60)	1.10 (0.78–1.56)	0.87 (0.72–1.06)	11.02 (8.34–14.55)	6.90 (6.16–7.73)		
0-17(reference)	1	1	1	1	1	1		
Relative risk per population density class:								
high (>742 inh./km^2)	0.70 (0.55–0.88)	1.36 (1.21–1.53)	1.01 (0.79–1.28)	1.32 (1.14–1.53)	0.38 (0.32–0.45)	0.64 (0.58–0.71)	0.90 (0.73–1.12)	1.34 (1.18–1.52)
medium (272-742 inh./km^2)	0.89 (0.72–1.11)	1.19 (1.07–1.34)	1.16 (0.92–1.47)	1.05 (0.91–1.21)	0.65 (0.55–0.76)	0.81 (0.74–0.88)	0.94 (0.76–1.16)	1.10 (0.98–1.24)
low (< 272 inh./km^2) (reference)	1	1	1	1	1	1	1	1

Table 3.3. Estimation results for regression on recorded victims in car and bicycle crashes in municipalities from 2004 up to 2009 (95% Wald CI).

3.3. Length of short car trips compared to short bicycle trips

To determine the road safety effect of a modal shift from car trips to cycling, it is necessary to know by how many bicycle kilometres the car kilometres are replaced. It is suggested that bicycle trips are shorter than the car trips they replace (Van Boggelen *et al.* 2005). To test this hypothesis, we analysed car and bicycle trips in the NTS 2008 shorter than 7.5 km.

3.3.1. Method and data

Three bicycle trips and three car trips shorter than 7.5 km were drawn at random from the NTS dataset for half of the municipalities (every two municipalities in the dataset). Only trips with a six-position zip code for the address of departure and return were selected. To determine the difference in distance covered by car versus bicycle for these trips, an approach of drivers' and cyclists' route choice was needed.

For both cyclists and drivers, travel time is the most important factor in route choice. For cyclists, travel time explains route choice slightly better than distance, but the difference is small, due to there being little difference in speeds attained by cyclists on different route options. Around 50% of all cyclists chose a route that deviated less than 5% from the shortest route, with 55% of the actual route overlapping with the shortest route (Gommers and Bovy 1987, Aultman-Hall *et al.* 1997). On routes of, on average, 10 minutes, drivers chose routes that were, on average, 13% slower and longer than the fastest and shortest route (Koning and Bovy 1980). It is possible that this percentage has decreased due to the use of navigation systems by car drivers, but their use during short routine car trips that are the focus of this study is probably limited. As described in Section 3.2.1, the route planners of the Dutch Cyclists' Union (Fietsersbond 2011) and Google Maps (Google, 2011) were used.

3.3.2. Results

Route analyses were conducted for 1,152 trips in 192 municipalities. The length of both car and bicycle trips were compared against each of the three population density classes. Several models were fitted, using curve estimation in SPSS, to predict the length of the fastest route by bicycle with the length of the fastest route by car as the independent variable. A simple linear model without a constant had one of the best model fits (applied to low, medium, and high population density, R^2 was as high as 0.98, 0.97, and

0.95). We selected the linear model form for its good fit and its simplicity as it has only one model parameter. For municipalities with a low, medium, and high population density, the linear regression line has a slope of 0.87 (t=111.0, p<0.001), 0.81 (t=114.7, p<0.001), and 0.77 (t=82.8, p<0.001). These findings are in accordance with the hypothesis formulated by Van Boggelen *et al.* (2005) that bicycle trips are shorter than short car trips. Also, the results indicate that fewer bicycle kilometres are needed to replace a car trip in high population density municipalities than in those with a low population density.

3.4. Estimation of the road safety effect of a model shift using the CPM method

To estimate the road safety effect of a modal shift from car trips to cycling in Dutch municipalities, the CPMs as developed in Section 3.2 are applied, supplemented with two CPMs recently developed for single-bicycle crashes by Schepers (2012, see Chapter 3). The CPMs are estimated for in-patients. Since 2009, the definition of in-patient has been replaced by that for serious road injury, the current definition being ‘victims admitted into hospital for at least one night, with an injury severity of at least 2 according to the Maximum Abbreviated Injury Score (MAIS)’. The Dutch government has set targets for deaths and serious road injuries. MAIS is an international measure used in medicine to describe injury severity, ranging from 1 (minor) to 6 (fatal). The analyses undertaken in Sections 3.2 had to utilize recorded numbers of in-patients and deaths because that was the only measure available at the municipality level. Since the new MAIS-based measure offers, at a national level, a realistic assessment of the number of serious road injuries rather than recorded numbers of in-patients, the road safety effects in this paper are expressed in changes in the number of fatalities and serious road injuries, according to MAIS.

3.4.1. Mobility data and amount of car and bicycle use in scenarios for a modal shift

Table 3.4 shows the total annual amount of bicycle and car use (excluding kilometres travelled on motorways) split amongst the four age groups and three population density classes used as input for the CPMs to determine the effect of a modal shift. Under Situation 2004-2009, the two columns on the left show the amount of bicycle and car use 2004-2009. The right-hand column shows the amount of car use for trips up to 7.5 km (derived from

NTS), again broken down in the same age groups and population density classes.

The columns under the heading *Scenario: 10% of the amount of car use on short trips replaced by cycling* show the amount of bicycle use increases with 10% of the amount of car use replaced for trips up to 7.5 km multiplied by 0.87, 0.81, and 0.77 for municipalities with a low, medium, and high population density. Scenarios for other percentages of car kilometres replaced by cycling are calculated in the same way.

		Situation 2004-2009			Scenario: 10% of the amount of car use on short trips replaced by cycling	
Population density	Age	Bicycle use (10^9 km/year)	Car use (10^9 km/year)	Car use for trips up to 7.5 km (10^9 km/year)	Bicycle use (10^9 km/year)	Car use for trips up to 7.5 km (10^9 km/year)
1. high (>742 inh./km^2)	1. 65+	0.61	2.28	0.91	0.68	2.19
	2. 25-64	4.24	18.89	5.65	4.67	18.33
	3. 18-24	0.93	1.73	0.48	0.97	1.69
	4. 0-17	2.05	3.14	1.30	2.15	3.01
	Total	7.83	26.05	8.34	8.47	25.21
2. medium (272-742 inh./km^2)	1. 65+	0.34	1.12	0.39	0.37	1.08
	2. 25-64	1.55	8.35	2.34	1.74	8.11
	3. 18-24	0.29	0.87	0.23	0.30	0.85
	4. 0-17	1.03	1.60	0.63	1.08	1.54
	Total	3.21	11.94	3.58	3.50	11.58
3. low (< 272 inh./km^2)	1. 65+	0.28	1.11	0.28	0.30	1.08
	2. 25-64	1.16	7.52	1.59	1.30	7.36
	3. 18-24	0.18	0.77	0.15	0.19	0.76
	4. 0-17	0.82	1.39	0.40	0.85	1.35
	Total	2.44	10.79	2.42	2.65	10.55
Total		13.48	48.78	14.33	14.62	47.35

Table 3.4. Amount of bicycle and car use per year travelled from 2004 up to 2009 and in a scenario in which 10% of the amount of car use on short trips replaced by cycling.

3.4.2. Data on deaths and serious road injuries

To avoid problems of under-reporting in police statistics, our estimations are based on 'real' numbers of fatalities and serious injuries per crash type. Real numbers of fatalities are determined using a combination of data from the National Road Crash Register and Statistics Netherlands' causes of death in the Netherlands. Real number of serious road injuries are acquired by combining data from the National Road Crash Register and the national Medical Registration's hospital data (real numbers are publicly available at the Cognos website of the Dutch Institute for Road Safety Research; SWOV, 2011). Besides real numbers of deaths and serious road injuries, some other characteristics, such as the victim's age and mode of transport, are known, but numbers per crash type are not available and have to be estimated. The mode of transport is sufficient information for car occupant victims; three groups of cyclist victims need to be distinguished: bicycle-car crashes, other bicycle-motor vehicle crashes, and crashes with no motor vehicle involved.

Cyclist crashes with no motor vehicle involved are hardly recorded by the police, even if victims are severely injured. Therefore the National Road Crash Register is of minimal use in distinguishing between cyclists injured in crashes with and without motor vehicles. Causes of Death registration and the National Medical Registration are the only sources suitable to assign the real number of deaths and serious road injuries between cyclist victims who were injured in crashes with and without motor vehicles. These two sources indicate that each year between 2004 and 2009, 40 cyclists were killed (Consumer Safety Institute 2011) and 7,400 seriously injured (Reurings and Bos 2011) in crashes with no motor vehicle involved. Other cyclist victims were involved in crashes with motor vehicles, i.e. 149 cyclist deaths and 1,555 seriously injured cyclists. Neither source contains other crash information.

Bicycle crashes with motor vehicles are well recorded by the police. Therefore, the number of cyclist victims in other crash types can be estimated by multiplying their share in the National Road Crash Register with the number of victims in motor vehicle crashes according to the other two sources. The numbers of victims in car crashes who are not cyclists or car occupants are determined in the same way. The victim numbers used in this study are shown in the left column of Table 3.5.

3.4.3. CPM parameters and application

The model parameters from the analyses in Section 3.2 are used to estimate the road safety effect of a modal shift. Table 3.5 outlines the CPMs' parameter values per crash victim type, supplemented with CPMs for bicycle victims in crashes with no motor vehicles involved, according to Schepers (2012). Because of the high level of under-reporting of single-bicycle crashes in police statistics, he used self-reported crash data from surveys additional to police-recorded crash data. These CPMs are used to estimate the effect on the number of cyclist victims in crashes with no motor vehicle involved. Besides a model of other victims in car crashes (not car occupants or cyclists), it is theoretically possible to develop a model for other victims (not car occupants or cyclists) in bicycle crashes. This has not been done because the number of in-patients and deaths in these crashes is too low to develop a model and, for the same reason, the impact of excluding these crashes is small. The scaling parameters are calibrated to ensure that the predicted victim numbers correspond to the real numbers in the column headed Victims per year (2004 - 2009) in Table 3.5.

3.4.4. Model shift scenario´s

The CPMs are valid for estimating the effect of a modal shift from short car trips to cycling as far as modal splits of cycling and car driving have actually been realized in the municipalities whose data have been used to develop CPMs. In the municipalities with the highest bicycle use such as Groningen and Zwolle, the share of cycling in the modal split is about 50% above the Dutch average, with car driving in the modal split about inversely proportional to cycling (Ministry of Infrastructure and the Environment 2009). Therefore, the road safety effect of a modal shift is estimated for scenarios in which the amount of car use on trips up to 7.5 km is halved and replaced by cycling.

	Victims per year (2004-2009)				Relative risks R_jR_k*												Victims per year after a modal shift; % of replaced car kilometres on trips up 7.5 km		
		α	$\beta 1$	$\beta 2$	R_1R_1	R_2R_1	R_3R_1	R_4R_1	R_1R_2	R_2R_2	R_3R_2	R_4R_2	R_1R_3	R_2R_3	R_3R_3	R_4R_3	10%	30%	50%
Cyclist fatalities in:																			
bicycle car crashes	77	0.88	0.62	0.26	2.89	0.96	0.26	0.70	3.70	1.23	0.33	0.89	4.15	1.38	0.37	1.00	77	78	77
other BMV crashes	72	3.25	0.90		7.15	1.01	1.11	1.01	8.26	1.16	1.28	1.16	7.12	1.00	1.10	1.00	78	89	100
crashes with no motor vehicle involved**	40	1.18	0.52		7.24	2.95	0.86	0.86	8.17	3.33	0.97	0.97	8.42	3.43	1.00	1.00	42	45	49
Car occupants in road crashes	252	3.26	0.73		2.38	1.32	4.17	0.38	4.07	2.26	7.14	0.65	6.28	3.48	11.02	1.00	247	237	227
Other victims in car crashes (cyclists excluded)	101	3.64	0.83		0.90				0.94				1.00				99	94	89
Total	542																543	543	542
Change in deaths per scenario																	0.7	1.1	0.2
Cyclists seriously injured in:																			
bicycle car crashes	1,092	14.55	0.55	0.44	2.16	1.67	0.68	1.36	1.89	1.46	0.59	1.19	1.59	1.23	0.50	1.00	1,114	1,148	1,170
other BMV crashes	463	27.12	0.81		2.96	1.41	1.15	1.32	2.36	1.12	0.92	1.05	2.24	1.07	0.87	1.00	495	558	620
crashes with no motor vehicle involved	7,400	325.04	0.76		3.92	2.56	1.43	1.43	2.36	1.54	0.86	0.86	2.74	1.79	1.00	1.00	7,906	8,887	9,832
Car occupants in road crashes	2,574	37.82	0.79		1.70	1.56	4.43	0.64	2.14	1.96	5.57	0.81	2.65	2.43	6.90	1.00	2,518	2,405	2,291
Other victims in car crashes (cyclists excluded)	2,820	59.62	0.92		1.34				1.10				1.00				2,742	2,586	2,430
Total	14,349																14,776	15,585	16,343
Change in serious road injuries per scenario																	427	1,236	1,994

* Relative of j age groups (1. 65+, 2. 25-64, 3. 18-24, 4. 0-17) and k population density classes (1. high, 2. medium, 3. low)

** in Schepers (2012) cyclist victims between 0 and 24 years of age as a whole were the reference category

Table 3.5. Real numbers of deaths and serious road injuries per year (2004–2009), CPM parameters, and estimated road safety effects of a shift to cycling of 10%, 30% and 50% of the amount of car use for short trips up to 7.5 km.

As a second step in the scenario analyses, we studied hypothetical scenarios in which the modal shift would be limited to the four age groups or the three population density classes separately. This is done because the road safety effects differ between age groups and municipalities differ in population density. The results show the contribution of groups to the total effect.

As a third step in the analyses we studied the effect on road safety of two scenarios in which municipalities are hypothesized to have a below or above average cyclist injury risk and assuming all else remains the same (for instance car occupant injury risk). This is done because it is conceivable that measures increasing cyclist safety (both before and after an exchange) also affect the road safety impact of an exchange. As a result, the effect of the modal shift on road safety could improve or worsen compared to the current (baseline) situation on which the CPMs are based. This is researched by multiplying the total number of cyclist victims both before and after the exchange by a factor of 0.8 and 1.2, i.e. adjusting the scaling parameter by 20%. These calculations are thus not based on additional calculated CPMs. Further, in contrast to the other scenarios that apply to age groups or density classes (of which the outcomes sum up to the total effect), the scenarios for cyclists' injury risk apply to all victims together.

3.4.5. Results: effect estimates for modal shift scenario shift scenarios

The estimated changes in the number of deaths and serious injuries for modal shifts of 10%, 30% and 50% of the amount of car use for trips up to 7.5 km by cycling are shown in the right three columns headed *Victims per year after a modal shift of short car trips: % of replaced car kilometres on trips up 7.5 km* in Table 3.5. The effect on the number of deaths is very small. The rise in the number of cyclists killed in traffic is compensated by a drop in the number of deaths amongst car occupants and other victims in car crashes. The estimates for shifts of 10%, 30% and 50% indicate that the number of serious road injuries increases after an exchange of short car trips for cycling. The main explanation of this result is the high number and corresponding increase of seriously injured cyclist victims in crashes with no motor vehicle involved. Not including these crash victims in the results would reduce the number of seriously injured victims.

Effect on the number of deaths
The results for deaths are shown graphically in the upper part of Figure 3.1. The graphs show the contribution of four age groups (left) and three population density classes (middle) to the total effect, and the effect in

scenarios where cyclists would run a 20% lower/higher risk of being injured in an accident (right). From the graphs it can be derived what the effect would have been had the modal shift been limited to a given age group, municipalities in a certain population density class, or municipalities where the point of departure for safety of cyclists compared to drivers is better or worse.

The effect of a modal shift on the number of deaths is strongly negative if only older car occupants exchange car trips for cycling. This can be explained by the relative risks for deaths in Table 3.3. The relative risk of older cyclists compared to other age groups is more elevated than the relative risk of older car occupants. The result is very positive for the 18-64 age group, and neutral for those aged under 18. Per exchanged car kilometre the gain in safety is greatest for the 18-24 age group, taking into account that many more kilometres are exchanged in the 25-64 age group (see Table 3.4). The results can be explained by the relative risks noted in Section 3.2 that are high for young car drivers and not for young cyclists, while the opposite applies to older drivers.

The analyses for population density classes suggest that population density affects the outcome of a modal shift from car trips to cycling only to a small extent. Drivers run a significantly lower risk in high density municipalities as compared to low density municipalities; however this does not apply to the same extent to cyclists. On the other hand, less bicycle kilometres are needed to replace car trips in densely populated municipalities. Therefore, the effect on road safety is only slightly affected by the population density of the municipalities where the exchange takes place.

Finally, a 20% decrease/increase in the chance of cyclists being injured in crashes has a large impact on the effect of a modal shift. A modal shift results in an increase of the total number of deaths if the risk of bicycle injuries increases by 20%, while the total number of fatalities is estimated to decrease if the risk decreases by 20%. This shows that the effect of a modal shift is likely to be affected by investments in cyclist safety. For instance, bicycle tunnels under busy arteries reduces the exposure to motorized traffic and increases the likelihood that an exchange of car trips for bicycle trips results in a positive road safety effect.

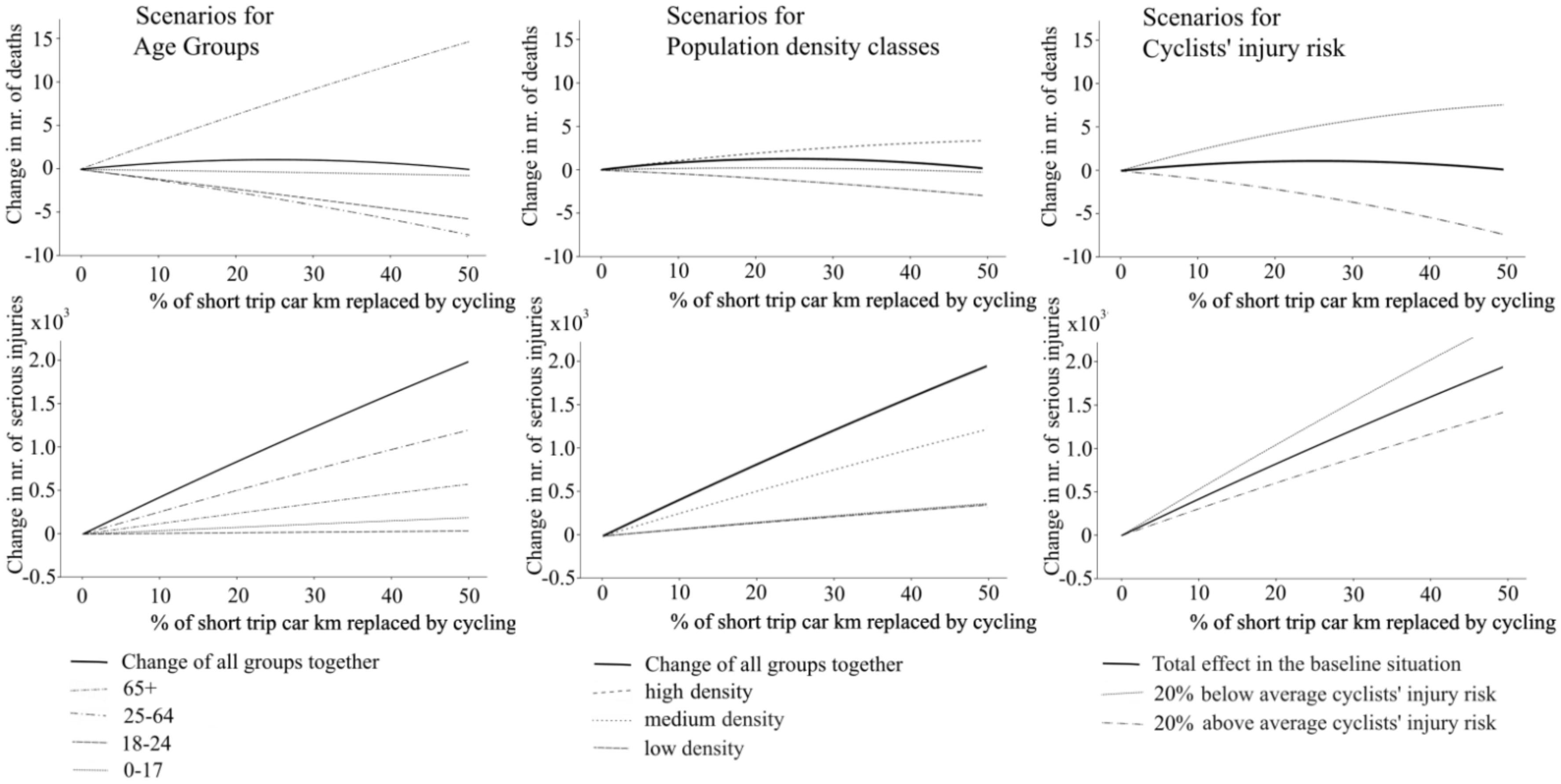


Figure 3.1. Effects on the number of deaths (top) and serious injuries (bottom) of an exchange from short car trips to cycling: the contribution of four age groups (left), three density classes (middle), and the effect in scenarios with a 20% lower or higher cyclist injury risk (right).

Effect on the amount of serious injuries
Our model assessment indicates that the number of serious road injuries will increase in almost all scenarios after a modal shift to cycling. Only where people up to 24 years of age alone exchanged short car trips for cycling is an almost neutral effect likely on the number of serious road injuries. As mentioned before, the increase in injuries results from the rise in the number of cyclist victims in crashes with no motor vehicle involved. Figure 3.1 shows that the greatest rise in the number of serious road injuries is to be expected in densely populated municipalities. However, the difference mainly results from more kilometres being exchanged in these municipalities as compared to other municipalities. Finally, even if the risk of bicycle injuries decreases by 20% the number of serious road injuries would increase.

3.5. Discussion

This paper aimed at determining to what extent a shift from short car trips to bicycle trips affects road safety. Cycling is considered a relatively healthy and sustainable mode of transport. However, concerns on road safety represent an important argument against stimulating cycling as cycling is associated with a considerably higher risk of injury accidents and deaths than driving. For determining to what extent this argument is valid, this study focused on the road safety effects in Dutch municipalities using CPMs. Elvik (2009) was the first researcher who applied CPMs to estimate the effect of a modal shift from car trips to cycling.

The current study is the first one in which CPMs are developed using crash and mobility data from municipalities (excluding car kilometres on motorways) and in which the effect of transfers leading to modal spits of car and bicycle use that actually exist in these municipalities is determined. Moreover, this study has included single-bicycle crashes, an important share of all bicycle crashes in the Netherlands and other countries with high amounts of cycling (Veisten *et al.* 2007, Schepers 2012). With regard to the number of deaths, the outcome of this study matches the results of the study by Elvik (2009), i.e. transferring a substantial part of trips made by motor vehicles to cycling (even more than the 50% shown at the right side of Figure 3.1) leads to fewer victims. As for the number of serious road injuries, the outcome of this study is clearly more negative than the outcome of Elvik's study (2009), due to the current study also including cyclist victims in crashes with no motor vehicle involved, predominantly single-bicycle crashes.

This study is the first with age in the CPMs. The effect on the number of deaths of a transfer of car trips up to 7.5 km is neutral, but there are substantial differences between age groups. The number of fatalities above the age of 65 is expected to increase, while that for the 18-64 age group is expected to decrease. Per exchanged car kilometre, the gain is greatest for the 18-24 age group of young drivers. This result is relevant as far as a modal shift would be spread unequally amongst age groups.

3.6. Recommendations

Road authorities have the opportunity to improve infrastructure safety. To test whether the impact of a modal shift can be influenced by such policies, the effect of a 20% reduction in cyclists' injury risk is estimated. In other words, what would happen if the exchange only took place in municipalities that have reduced cyclist risks by 20% (assuming a constant risk for other transport modes)? The results show that in this scenario, the number of deaths would reduce, due to a modal shift. The number of serious road injuries is still expected to increase, but would be 25% less than would have been the case without the 20% reduction in cyclist injury risk. These results show that research should not be limited to estimating the quantitative effect of more cycling, but should also address the question posed by Wegman *et al.* (2012): "How to make more cycling good for road safety?"

Governments try to encourage cycling, as it offers benefits to both community and the individual, but concerns about road safety would seem to represent an argument against this action (Elvik, 2009). This paper showed that a shift from car to bicycle use has little effect on the risk of death. However if more people start cycling, the number of serious injuries is expected to increase, mainly due to single-bicycle crashes. This finding implies that encouraging cycling does not lead to an increase in deaths, but it does increase the amount of serious road injuries. Given cycling's other advantages such as health benefits (De Hartog *et al.* 2010), and the fact that additional measures could be taken to reduce the risk of single-bicycle crashes, it may still be worthwhile to encourage a modal shift.

3.7. Conclusions[5]

Based on this study, the following conclusions can be drawn on the effects of a shift from short car trips to cycling under conditions such as in Dutch municipalities:

- A modal shift has little effect on the number of road deaths.
- However, the number of serious injuries would be expected to increase, mainly due to an increase in single-bicycle crashes.
- Population density affects the outcome of a modal shift only to a small extent.
- There are substantial differences between age groups in the effects of a modal shift. The number of fatalities above the age of 65 is expected to increase, while the number in the 18-64 age group is expected to decrease. Per exchanged car kilometre, the road safety gain is greatest for 18-24 age group of young drivers.

---

[5] Note that for development of the CPMs in Chapter 2, all 431 Dutch municipalities were included. In this Chapter, 44 municipalities having less than 10,000 inhabitants were excluded. Reanalyses on the dataset used for the Chapter 2 study indicated only small changes in outcomes had these municipalities been excluded there as well. The exponent for the change in the number of hospitalized single-bicycle crash victims in response to changes in bicycle use remains unchanged. The exponent for fatalities increases from 0.52 to 0.56. Reanalyses on the dataset used for Chapter 3 indicated a slightly greater increase in deaths due to a modal shift (e.g. 1 instead of 0.2 fatalities due to a replacement of 50% of car kilometres on trips up 7.5 km). This does not affect the conclusions of Chapter 3.

4. How is the design of unsignalized priority intersections related to bicycle–motor vehicle crashes?[6]

Abstract
In this study, the safety of cyclists at unsignalized priority intersections within built-up areas is investigated. The study focuses on the link between the design of priority intersections and bicycle–motor vehicle (BMV) crashes. Across 540 intersections that are involved in the study, the police recorded 339 failure-to-yield crashes with cyclists in four years. These BMV crashes are classified into two types based on the movements of the involved motorists and cyclists: type I: through bicycle related collisions where the cyclist has right of way (i.e. bicycle on the priority road); type II: through motor vehicle related collisions where the motorist has right of way (i.e. motorist on the priority road). The probability of each crash type was related to its relative flows and to independent variables using negative binomial regression. The results show that more type I crashes occur at intersections with two-way bicycle tracks, well-marked, and reddish coloured bicycle crossings. Type I crashes are negatively related to the presence of raised bicycle crossings (e.g. on a speed hump) and other speed reducing measures. The accident probability is also decreased at intersections where the cycle track approaches are deflected between 2 and 5m away from the main carriageway. No significant relationships are found between type II crashes and design factors such as the presence of a raised median.

4.1. Introduction

Collisions between bicycles and motor vehicles have caused severe life and property losses in many countries (Wang and Nihan 2004). The Netherlands is one of the safest countries for cyclists, as crash risks for cyclists are lower in countries with higher bicycle use. In 2007, thirty-four percent of all trips up to 7.5km were made by bicycle (Ministry of Infrastructure and the Environment 2009). In spite of this, the numbers of traffic deaths and in-patients among cyclists are substantial in the Netherlands (over twenty

---

[6] This chapter was first published in Accident Analysis and Prevention: Schepers, J.P., Kroeze, P.A., Sweers, W., Wüst, J.C.., 2011. How are road factors at unsignalized priority intersections related to bicycle-motor vehicle crashes? *Accident Analysis and Prevention*, 43(3): 853-861.

percent of all recorded traffic deaths and in-patients). The majority of bicycle–motor vehicle (BMV) crashes occur within built-up areas at unsignalized priority intersections, such as where a distributor road intersects with a local road. Over ninety-five percent of these are failure-to-yield crashes.

This study was issued by the Dutch Ministry of Infrastructure and the Environment in order to develop measures for road authorities. The study is therefore focused on the link between priority intersection design characteristics and BMV crashes. As small crash numbers limit the number of variables that can be included in regression analyses, only those road features were selected for which our literature research (see Sections 4.1.1 and 4.1.2) revealed that they were potentially relevant for failure-to-yield crashes with cyclists. Furthermore, only design characteristics were included, e.g. speed humps, while non-design characteristics, like speed, were excluded.

BMV crashes are classified into two types depending on who had priority (i.e. the cyclist in the case of type I crashes; the motorist in the case of type II crashes). Separate analyses are conducted for both crash types as different traffic flows and road features influence each group. For instance, the number of type I crashes is directly related to the amount of motorized traffic on the side road (i.e. the volume of motorists entering or leaving the main road) and only indirectly to the volume of motorists on the main road. Furthermore, most road features affect specific traffic flows. For instance, painting a bicycle track along the main road may have an influence on cyclists on the main road and on motorists crossing the track when entering or leaving the main road. Therefore, this road feature may be related to type I crashes while a relationship with type II crashes is less likely.

4.1.1. Type I crashes and road design

In type I crashes, the cyclist rides on the priority road and is hit by a vehicle that is leaving or entering the side road. Cyclists on the distributor road have priority over vehicular traffic. An in-depth study of bicycle–car collisions in four Finnish cities showed that cyclists most often noticed the driver before the accident and believed the driver would give way as required by law. However, only a small portion of the drivers noticed the cyclist before impact (Räsänen and Summala 1998). Several priority intersection design characteristics that can be linked to type I crashes have been studied in the last decades. How these factors affect the behaviour of cyclists and motorists and thereby cycling safety is described in terms of visual scanning strategies (based on expectations), risk compensation, and the complexity of the driving task.

A lot of studies focused on safety effects of bicycle facilities along distributor roads. In their meta-analysis Elvik (2009) found a significant increase of bicycle accident numbers due to bicycle tracks at junctions. It is suggested that the crash numbers increase at junctions with bicycle tracks because of a lack of attention due to the physical separation of cyclist and motor traffic. According to Herslund and Jørgensen (2003), drivers who search the road area for possible counterparts may focus their attention on the location where cars usually are. Welleman and Dijkstra (1988) studied the risks (numbers of crashes per passing cyclist) at crossroad branches of priority intersections with different bicycle facilities for cyclists on the main road. In this study, cycle lanes were found to be most risky for cyclists. Cycle paths and mixed traffic on the carriageway did not significantly differ from each other. The risk of bicycle crashes is found to be elevated at priority intersections with two-way cycle tracks along the distributor road, as drivers entering from the side road have difficulties in detecting cyclists from the right (Schnüll *et al.* 1992, Wachtel and Lewiston 1994, Räsänen and Summala 1998). Summala *et al.* (1996) studied drivers' scanning behaviour at T-intersections. Drivers turning right from the minor road scanned the right leg of the T-intersection less frequently and later than those turning left. Drivers develop a scanning strategy, which concentrates on more frequent and major dangers but ignores and may even mask visual information on less frequent dangers.

A sight obstacle makes that situation even more hazardous, because drivers cannot even detect cyclists with peripheral vision (Räsänen *et al.* 1999). On the contrary, Henson and Whelan (1992) suggested that good visibility at T-junctions was associated with a greater probability of bicycle crashes when a cyclist was riding among cars. They assume that a form of 'risk compensation' operates. When visibility is poor drivers behave cautiously at the junction, counteracting the obvious danger. A wider entry width of the minor road was associated with a decreased safety of cyclists riding on the main road. The extra space may invite vehicles to queue two abreast on the minor road. A left-turning vehicle could screen a cyclist from a vehicle waiting to turn right (Henson and Whelan 1992).

The results of studies on the effect of markings are inconsistent. The city of Portland studied the effects of blue pavement markings in combination with a “Yield to Cyclist” sign for crossings where the cyclist travels straight and the motorist crosses the bicycle lane in order to exit a roadway, or merge onto a street from a ramp. Significantly higher numbers of motorists yielded to cyclists and slowed before entering the blue pavement areas. However, the blue pavement also resulted in fewer cyclists turning their heads to scan for traffic or using hand signals (Hunter *et al.* 2000). Jensen (2008) studied the safety effects of blue cycle crossings at signalized intersections. The safety effect depends on the number of blue cycle crossings at the junction. One blue cycle crossing reduces the number of junction crashes by ten percent, whereas marking of two and four blue cycle crossings increases the number of crashes by twenty-three and sixty percent, respectively. Schnüll *et al.* (1992) did not find bicycle crashes to be affected by the type of marking at priority intersections without traffic lights. Like Gårder *et al.* (1998), they did show that cyclists riding on the priority road are less at risk if they use raised bicycle crossings as compared to crossings delineated by white painted rectangles. Raising a bicycle crossing leads to somewhat increased bicycle speeds, but significantly reduced motor vehicle speeds (Gårder *et al.* 1998). Similarly, Van der Horst (1990) found a speed hump to induce a lower average speed close to a cycle track amongst drivers entering from the minor road. A study of cyclist safety at minor priority junctions showed, moreover, that the establishment of speed reducing exit constructions leads to a fall in the number of bicycle crashes of up to fifty percent (Herrstedt 1979).

To conclude, two intersection design characteristics seem to reduce the complexity of the driving task when giving way to cyclists on the main road, thereby improving cycling safety. The addition of a left-turn lane or left-turn section on the main road was found to decrease type I crashes, but this is only studied at priority intersections outside built-up areas (CROW 2002). It enables drivers leaving the main road to slow down and stop without hindering through traffic. Schnüll *et al.* (1992) studied the safety effect of the distance between the cycle track and the side of the major road. A clearance between 2 and 4m at priority intersections was found to be most favourable. Brüde and Larsson (1992) found a distance between 2 and 5m from the major road to be safest for both signalized and unsignalized intersections in an accident study. According to Elvik (2009), the aim of a bent-out crossing is to give drivers turning into the side road extra time to notice crossing cyclists, and to allow vehicles waiting to exit the side road to do so without blocking the crossing point.

4.1.2. Type II crashes and road design

In type II crashes the cyclist crosses the priority road and is hit by a through vehicle on the main carriageway. These crashes take place at both priority intersections and single separate bicycle crossings (i.e. where a solitary (or standalone) cycle track crosses the priority road). Less is known about these crashes as compared to type I crashes. An in-depth study of bicycle–car collisions in four Finnish cities showed that cyclists rarely did anything to avert these crashes, while drivers often did something. As compared to type I crashes the cyclist victims were more often unfamiliar with the accident location and under eighteen years of age. For cyclists, crossing a major road is more demanding than crossing a minor road (Räsänen and Summala 1998). The complexity of the traffic situation seems to play a role in these crashes.

Only a limited number of studies are focused on the link between intersection design characteristics and type II crashes. Therefore, we also looked at one thorough study on pedestrian crossing safety. Zegeer *et al.* (2001) studied the safety effects of two design factors related to the complexity of the traffic situation for pedestrians. Road features found to be related to the frequency of pedestrian crashes (taking the average daily pedestrian and motor vehicle volumes into account) were the number of lanes of the main carriageway and the presence of a raised median or crossing island. The Dutch Design Manual for Bicycle Traffic (CROW 2007) provides recommendations to avoid type II crashes, but no studies were found that confirmed the underlying assumptions. Middle islands that enable cyclists to cross in two phases are recommended for busy streets. The presence of middle islands often coincides with a left-turn section or lane (in between raised medians) on the main road for left-turning drivers and cyclists crossing the main road. In Dutch research on priority intersections outside urban areas, it was found that the addition of a left-turn lane reduced the number of type II crashes (CROW 2002). Also, three-armed priority intersections are preferred over four-armed intersections. The type of junction may also effect the risk of type I crashes. A specific type of intersection where only type II crashes occur is a single separate bicycle crossing. Zegeer *et al.* (2001) did not find a significant difference in pedestrian crash rate between priority intersections and mid blocks.

4.1.3. Bicycle Crash Prediction Models

The average daily numbers of motor vehicles and cyclists are important predictors of bicycle crashes. According to Brüde and Larsson (1993) it may be hard to decide whether additional factors that describe the design in greater detail influence the number of crashes, as traffic flows explain the systematic variation in accident frequency to such a large extent. Brüde and Larsson (1993) developed bicycle and pedestrian Crash Prediction Models for intersections of the following kind:

$$E(\mu) = \alpha N_M^{\beta 1} N_C^{\beta 2}$$

where $E(\mu)$ is the predicted annual number of bicycle crashes, N_M is the average daily number of incoming motor vehicles, N_C the average daily number of passing bicyclists, and α, $\beta 1$ and $\beta 2$ are estimated parameters. Coefficients $\beta 1$ and $\beta 2$ describe the shape of the relationship between traffic volume and the number of crashes. As shown by a lot of studies either coefficient often takes on a value between about 0.3 and 0.9 (Elvik 2009). This means that the percentage increase of the number of crashes is less than the percentage increase of traffic volume. The more cyclists there are the lower is the risk faced by each cyclist (i.e. bicycle crashes per passing cyclist). This effect is sometimes called "safety in numbers" (Jacobsen 2003).

The above described model can be extended to the basic form of nearly all modern crash prediction models (Eenink *et al.* 2008):

$$E(\mu) = \alpha N_M^{\beta 1} N_C^{\beta 2} e^{\Sigma y_i x_i}$$

The expected number of crashes, $E(\mu)$, is a function of traffic volumes and a set of risk factors, x_i ($i=1, 2, 3, \ldots, n$), i.e. the design factors under investigation. The effects of various risk factors that influence the probability of crashes, given exposure, is modelled as an exponential function, that is as e (the base of natural logarithms) raised to a sum of product of coefficients, y_i, and values of the variables, x_i, denoting the presence of road features.

4.2. Methods

The present study uses a correlational design to study whether BMV crashes are related to intersection design characteristics. A problem in accident studies is the preponderance of "excess" zeros frequently observed in crash count data, i.e. many intersections without crashes in a given period of time. Lord *et al.* (2005) have shown that this arises from low exposure and/or inappropriate selection of time/space scales. The selection of intersections was based on the volumes of cyclist and motor vehicle traffic to limit this problem. Non-signalized intersections where the major road had a speed limit of 50 km/h were selected if they were high on either or both of these volumes. Seven municipalities were contacted before the study to determine main cycle routes and busy distributors (ADT around 8000 and higher). Half of the priority intersections were selected because they were part of a main cycle route and half because they were part of a busy distributor road. We considered a study period of four years (2005–2008) to be of adequate length to gather enough recorded crashes without running a high risk of changes in the infrastructure after 2005. Municipalities were contacted to ask which intersections were reconstructed in the study period so that these could be excluded.

Estimates of daily cyclist and motor vehicle volumes at each intersection were determined by volume counts in the second half of 2009, which were expanded to estimate daily volumes based on hourly adjustment factors derived from the Dutch National Travel Survey (Rijkswaterstaat 2010). Like in Henson and Whelan's (1992) study, counts were conducted for twenty minutes in the off-peak period and outside school vacation periods. Like in Wang and Nihan's (2004) study we distinguished different movements to relate each accident type to its relative flows. This means through cyclist traffic on the main road and motorized vehicles entering or leaving the major road for type I crashes, and through motorized traffic on the main carriageway and cyclists crossing the major road for type II crashes.

In this study, NB regression was used to examine the relationship between the number of crashes per intersection and the independent variables. The regression coefficients were estimated based on maximum likelihood estimation using Generalized Linear Models in SPSS. The significance of coefficients was checked using the method analogical to the t-test used in conventional regression analyses referred to as the Wald test (Agresti 1996). The following intersection design characteristics were selected to study type I crashes:

- type of bicycle facility: cycle lane, one-way bicycle path, two-way bicycle path, or no bicycle facility (i.e. cyclists mixed with other traffic);
- distance between the bicycle track and the side of the main carriageway: 0-2m, 2-5m, over 5m;
- visibility from the minor road: unrestricted view over 100m or more at 2m before the main road or it's adjacent cycle path, or restricted (i.e. worse visibility);

- marking and use of colours:
    - colour: reddish coloured crossing, or else;
    - quality of (other) markings (white painted rectangles to delineate cycle tracks; or white stripes or continuous lines to delineate cycle lanes): well-visible; hardly visible, or no marking;
- presence of a speed reducing measure for motorists that enter or leave the priority road (e.g. a raised bicycle crossing);
- number of lanes of the side road (i.e. entry width);
- presence of a left-turn lane or left-turn section on the main road;
- type of intersection: three-armed, or four-armed.

The following intersection design characteristics were selected to study type II crashes:

- number of lanes of the main road;
- presence of middle islands:
    - no raised middle islands;
    - raised middle islands that enclose a left-turn section, i.e. cyclist are enabled to cross the main road in two phases and share the space with left-turning motorists;
    - raised middle islands with a separate space for cyclists;
- presence of speed-reducing measures for through motor vehicles on the main road, e.g. speed humps;
- type of intersection: four-armed, three-armed, or single separate bicycle crossings (i.e. where a solitary cycle track crossed the priority road).

Examples are included in Figure 4.1 and 4.2 to clarify the above-mentioned design characteristics.

The first two variables for type II crashes are combined into six categories as their effects may interact. BMV crash data in the Dutch National Road Crash Register are aggregated at the intersection level and without further classification into our two accident types. Consequently, we had to conduct additional data collection work to satisfy our specific study requirements. With the index numbers of the crashes at the priority intersections in our selection, we called up the original police records that include a brief description of the accident, and, in many cases, a collision site figure. This enabled us to assign crashes to one of the two accident types.

Figure 4.1. Example of a well-marked, raised bicycle crossing for through cyclists on a one-way cycle track with a distance of over five metres from the priority road; a raised middle island with a separate space for cyclists crossing the two-lane priority road.

Figure 4.2. Example of a bicycle lane for through cyclists, an exit construction at minor roads and raised middle islands that enclose a left-turn section for both cars and cyclists crossing the two-lane priority road.

4.3. Results

In total, 540 priority intersections were included in this study, of which 490 were susceptible to type I crashes (type I crashes, by definition, cannot happen at single separate bicycle crossings) and 524 to type II crashes (i.e. type II crashes cannot happen at three-armed junctions with one two-way cycle path that crosses the side road, and at intersections where crossing the main road is forbidden). Descriptives are presented in Table 4.1. Type I crashes, where the cyclist has right of way, happen more often than type II crashes, where the driver has priority. However cyclists run a relatively higher risk of type II crashes per passing cyclist.

Crash Type	Number of inter-sections	Crash numbers 2005-2008	Crash variance	Average daily number of motorized vehicles[1]	Average daily number of cyclists[2]	Risk (per million passing cyclists)
I	490	183	0.66	2.200	1.500	0.17
II	524	156	0.65	7.000	850	0.24

	Number of intersections with # number of accidents									
	0	1	2	3	4	5	6	7	8	9
I	371	78	27	10	2		1	1		
II	417	82	16	5	1		1		1	1

[1] motorized vehicles entering or leaving the main road for type I crashes; through motorized traffic on the main carriageway for type II crashes

[2] through cyclist traffic on the main road for type I crashes; cyclists crossing the main carriageway for type II crashes

Table 4.1. Numbers of intersections, crashes, traffic volumes, and risks.

4.3.1. Results for type I crashes

Eight independent variables are selected for the type I accident risk model, using the total number of type I crashes per intersection between 2005 and 2008 as the dependent variable. The estimated regression coefficients and their significance levels shown by Wald statistics and corresponding P-values are presented in Table 4.2. For traffic volumes, positive coefficients indicate positive relationships with accident numbers. For intersection design characteristics, a factor level with a greater coefficient indicates a greater probability of crashes. The sign of a coefficient for a factor level is dependent upon that factor level's effect relative to the reference category. The exponential of the regression coefficient for categorical variables is included in the table as it is interpretable as relative risk (i.e. relative to the reference category). Ratios greater than one indicate that the presence of the characteristic in question increases the probability of an accident.

Besides traffic volumes, four design factors are significantly related to type I crashes (at the five percent level). The use of a red colour and high quality markings to delineate bicycle crossings are positively related to type I crashes while speed-reducing measures for vehicles entering or leaving the side road are negatively related to type I crashes. The type of bicycle facility and its clearance from the main road is also related to type I crashes. Significantly fewer crashes occur at intersections where the cycle path approaches are deflected 2 to 5m away from the main carriageway. The accident probability is almost the same for cycle lanes and cycle paths with a distance between the track and the side of the main road under 2m. More type I crashes occur at intersections with two-way cycle tracks. No significant link was found between visibility from the minor road, type of intersection and type I crashes. The number of intersections where the main road has no bicycle facility was too low to distinguish 'no bicycle facility' as a separate category in Table 4.2. This category was combined with cycle lanes because both lack a physical separation between cyclists and motorists. The category of cycle lanes is treated separately in Table 4.3, where shared roadways are excluded.

The use of colour and high quality markings seem to have an adverse effect on safety. An additional analysis was conducted to differentiate between cycle tracks and cycle lanes as the type of marking and layout are different (see for instance Figures 4.1 and 4.2). The results are shown in Table 4.3. The directions of the effects are similar to those shown in Table 4.2. The use of red colour and high quality markings are related to an increase of type I crashes. However, the effect size is greater for cycle tracks than for cycle lanes and greater for the use of well visible markings than for the use of colour. Only the relationship between the use of well visible markings on bicycle tracks and type I crashes is significant.

Parameter	Number of inter-sections	Regression parameter (95% Wald CI)	Exponential of the regression parameters (95% CI)	Wald χ^2	*P*-value
Constant		-9.43 (-12.21 to -6.65)		44.22	<0.001
Volume of motorized vehicles entering or leaving the major road		0.73 (0.50 to 0.96)		38.30	<0.001
Volume of through cyclists		0.48 (0.24 to 0.73)		13.56	<0.001
Two-way versus one-way cycle track					
one-way cycle path or other provision	423	0 (reference)	1 (reference)		
two-way cycle path	67	0.56 (0.01 to 1.11)	1.75 (1.01 to 3.03)	4.00	0.046
Distance between the bicycle facility and the side of the main carriageway					
cycle lane or no cycle facility	232	0 (reference)	1 (reference)		
cycle track 0-2m	43	0.03 (-0.69 to 0.74)	1.03 (0.50 to 2.10)	0.01	0.944
cycle track 2-5m	127	-0.61 (-1.20 to -0.01)	0.55 (0.30 to 0.99)	4.01	0.045
cycle track over 5m	88	-0.07 (-0.71 to 0.57)	0.93 (0.49 to 1.76)	0.05	0.823
Use of a red colour and quality of markings for bicycle crossings					
none	137	0 (reference)	1 (reference)		
red colour	190	0.38 (-0.16 to 0.93)	1.47 (0.85 to 2.52)	1.93	0.165
high quality markings	80	0.55 (-0.13 to 1.24)	1.74 (0.88 to 3.45)	2.52	0.112
red colour and high quality marking	83	0.93 (0.33 to 1.53)	2.53 (1.39 to 4.60)	9.16	<0.01
Raised bicycle crossing or other speed reducing measure for vehicles entering or leaving the side road					
not present	277	0 (reference)	1 (reference)		
present	213	-0.70 (-1.15 to -0.26)	0.49 (0.32 to 0.77)	9.49	<0.01
Visibility from the minor road					
good	341	0 (reference)	1 (reference)		
restricted	115	0.32 (-0.15 to 0.78)	1.37 (0.86 to 2.19)	1.75	0.186
bad	34	-0.62 (-1.78 to 0.54)	0.54 (0.17 to 1.72)	1.09	0.297
Number of lanes of the side road					
one	22	0 (reference)	1 (reference)		
two	456	-0.89 (-1.84 to 0.06)	0.41 (0.16 to 1.07)	3.35	0.067
three	12	-0.76 (-2.21 to 0.68)	0.47 (0.11 to 1.98)	1.07	0.300
Left-turn lane or left-turn section on the main road					
not present	341	0 (reference)	1 (reference)		
present	149	0.11 (-0.33 to 0.56)	1.12 (0.72 to 1.74)	0.26	0.612
Type of intersection					
three-armed	314	0 (reference)	1 (reference)		
four-armed	176	-0.16 (-0.58 to 0.26)	0.85 (0.56 to 1.30)	0.56	0.455

Table 4.2. Estimation results for the type I accident risk model (Log likelihood is -337.55).

Parameter	Number of inter-sections	Regression parameter (95% Wald CI)	Exponential of the regression parameters (95% CI)	Wald χ^2	*P*-value
Constant		-9.63 (-12.63 to -6.62)		39.40	<0.001
Volume of motorized vehicles entering or leaving the major road		0.70 (0.47 to 0.94)		33.89	<0.001
Volume of through cyclists		0.44 (0.17 to 0.71)		10.40	<0.01
Type of bicycle facility					
cycle lane	193	0 (reference)	1 (reference)		
cycle path	258	-0.43 (-1.27 to 0.41)	0.65 (0.28 to 1.51)	1.01	0.315
Use of red pavement					
none	179	0 (reference)	1 (reference)		
reddish coloured cycle lane	131	0.28 (-0.41 to 0.97)	1.32 (0.66 to 2.64)	0.63	0.428
reddish coloured cycle path	141	0.27 (-0.32 to 0.85)	1.30 (0.73 to 2.34)	0.79	0.375
Use of markings for cycle tracks and cycle lanes					
no or low quality markings	292	0 (reference)	1 (reference)		
well visible markings on cycle lanes	31	0.46 (-0.29 to 1.21)	1.58 (0.75 to 3.37)	1.43	0.232
well visible markings on cycle tracks	128	0.76 (0.16 to 1.35)	2.13 (1.17 to 3.86)	6.19	0.013

Table 4.3. Estimation results for the type I accident risk model in relation to markings on cycle tracks and cycle lanes (Log likelihood is -329.33).

4.3.2. Results for type II crashes

Five independent variables are included in the type II accident risk model, using the number of type II crashes per intersection between 2005 and 2008 as the dependent variable. The results are shown in Table 4.4. Traffic volumes are significant predictors of type II crashes. No significant relationships were found between type II crashes and intersection design characteristics. Given the small number of intersections with middle islands, we put together the two categories of middle islands. The analysis was repeated with four instead of six categories (main roads with two, respectively, more than two lanes were still treated separately). Again, none of the results except the relationships between volumes and type II crashes, were found to be statistically significant. The signs of the parameters for middle islands did not change, i.e. intersections of two-lane main roads with middle islands were found to have a (non-significant) higher probability of type II crashes as compared to intersections without middle islands (Wald χ^2 (1, 523) = 2.53; *P* = 0.11). Like in Table 4.4, the relationship was reversed for intersections of main roads with more than two lanes (Wald χ^2 (1, 523) = 1.03; $P = 0.31$).

Parameter	Number of intersections	Regression parameter (95% Wald CI)	Exponential of the regression parameters (95% CI)	Wald χ^2	*P*-value
Constant		-9.48 (-12.52 to -6.43)		37.16	<0.001
Volume of through motorized vehicles		0.50 (0.20 to 0.79)		10.85	<0.001
Volume of cyclists crossing the major road		0.56 (0.36 to 0.76)		29.15	<0.001
Speed reducing measure for through motorized vehicles on the priority road					
not present	438	0 (reference)	1 (reference)		
speed hump or other measure	86	0.24 (-0.28 to 0.77)	1.28 (0.76 to 2.16)	0.83	0.361
Raised median and number of lanes of the priority road					
two lanes; no raised median	238	0 (reference)	1 (reference)		
two lanes; middle islands that enclose a left-turn section for both cars and cyclists	110	0.39 (-0.12 to 0.91)	1.48 (0.89 to 2.47)	2.24	0.134
two lanes; raised middle islands with a separate space for cyclists	83	0.36 (-0.28 to 0.99)	1.43 (0.76 to 2.70)	1.23	0.267
more than two lanes; no raised median	45	0.51 (-0.22 to 1.24)	1.67 (0.80 to 3.45)	1.89	0.169
more than two lanes; middle islands that enclose a left-turn section for both cars and cyclists	17	-0.04 (-1.16 to 1.09)	0.96 (0.31 to 2.96)	0.00	0.948
more than two lanes; raised middle islands with a separate space for cyclists	31	0.09 (-0.70 to 0.89)	1.10 (0.50 to 2.43)	0.05	0.815
Type of intersection					
single separate bicycle crossing	47	0 (reference)	1 (reference)		
four-armed intersection	175	0.25 (-0.52 to 1.02)	1.28 (0.59 to 2.78)	0.40	0.528
three-armed intersection	302	-0.19 (-0.95 to 0.58)	0.83 (0.39 to 1.78)	0.23	0.635

Table 4.4. Estimation results for the type II accident risk model (Log likelihood is -326.36).

4.4. Discussion

Several findings of this study are useful for the development of countermeasures to prevent type I crashes with through bicyclists on priority roads crossing a minor road at a non-signalized intersection within a built-up urban area. The most effective measure to improve the safety of cyclists is the use of speed-reducing measures for drivers leaving or entering the main road (e.g. a raised bicycle path and/or exit construction). It is suitable in most cases as it does not require additional space in contrast to the construction of a bicycle path or an increase of the clearance between a bicycle track and the side of the priority road. A one-way bicycle path with a clearance between 2 and 5m is safer than a cycle lane. Marking bicycle crossings with red coloured pavement or white rectangles seems to have an adverse effect of the safety of cyclists, particularly in the case of cycle tracks. Cyclists seem more at risk at intersections with two-way bicycle paths as compared to intersections with other facilities. In choosing between one-way and two-way cycle tracks practitioners have to take possible effects on the itinerary level into account. The advantage of one-way cycle tracks along a distributor road may be diminished if a large share of all cyclists has to make a detour by crossing the priority road two times or even chooses to ride against traffic at the left side of the main road. None of the investigated design factors showed a statistically significant correlation with type II crashes with cyclists crossing the main road. This may be partly due to small sample sizes and type II crash numbers but most effect sizes were also smaller for the type II Crash Prediction Model as compared to the type I Crash Prediction Model.

4.4.1. Bicycle crashes and traffic volumes

The coefficients of the Crash Prediction Models (β1 and β2) were in the same range as reported by other researchers (i.e. between 0.3 and 0.9; Elvik 2009) and there were interesting differences between the models for type I and type II crashes. In the Crash Prediction Model for type I crashes, the coefficient for the volume of motorized vehicles is higher than the coefficient for the volume of bicycles. A growth of x percent in motorized traffic entering or leaving the side road leads to a greater rise of type I crashes than an increase of x percent in through cyclist traffic. For type II crashes it is the other way around, although the difference is small and non-significant in this case. The relationship (i.e. the size of the coefficients) may be dependent on which party has to give priority to whom. Cyclists have priority over motorists in type I crashes; in the case of type II crashes it is the other way around. The party who has to give priority (often called the 'secondary direction' in the literature on Crash Prediction Models) seems to adapt his or her behaviour the most to the number of counterparts, i.e. the parameter for the secondary direction is higher than for the primary direction. On the contrary the parameter for the primary direction is often found to be the highest in other studies, although the results are inconsistent for unsignalized intersections (e.g. Reurings *et al.* 2005).

4.4.2. Design factors and type I crashes

The findings on type I crashes are discussed in terms of visual scanning strategies (based on expectations), risk compensation, and the complexity of the driving task. We found that priority intersections with one-way cycle paths have the same or even less bicycle crashes than intersections with other or no bicycle facilities, while other researchers concluded that cycle tracks increase the number of cycle crashes at junctions (Elvik and Vaa, 2009). The difference may result from several causes. It is assumed that cycle tracks are less safe than cycle lanes because drivers' scanning strategies are primarily focused on where motorists are and thus less on physically separated bicycle tracks (Herslund and Jørgensen, 2003). Our study is conducted in the Netherlands, one of the countries with the highest level of cycling where most adults have grown up riding a bicycle. Drivers in countries with high levels of cycling may adapt their scanning routines because they learn where to expect cyclists. This may partly explain the "safety in numbers" effect, i.e. the risk faced by each cyclist declines as the number of cyclists increases (Jacobsen 2003). Another explanation is methodological in that we have controlled for the volumes of motorists and cyclists. Most of the studies that Elvik and Vaa (2009) used in their meta-analysis have not controlled for the number of cyclists, i.e. the results refer to changes in the total numbers of crashes after cycle tracks were installed. Like us, Welleman and Dijkstra (1988) did control for the cyclist volumes and found that unsignalized priority intersections with bicycle paths improved the safety of bicyclists as compared to intersections with bicycle lanes. Welleman and Dijkstra's (1988) study was also conducted in the Netherlands. Their results may be due to the high level of cycling in the Netherlands as well.

Two-way bicycle crossings decrease cyclist safety at unsignalized priority intersections. This is due to the visual scanning strategy of right-turning drivers from the minor road who scan the right leg of the T-intersection less frequently and later than those turning left (Summala *et al.* 1996). The visual scanning problem of right-turning drivers was recently confirmed by a study on visual scanning behaviour in Groningen, a Dutch city with an above average level of cycling (Van Haeften 2010).

Like other researchers (e.g. Gårder *et al.* 1998; Herrstedt, 1979; Schnüll *et al.* 1992) we found that raised bicycle crossings and other speed-reducing measures are effective in reducing the number of bicycle crashes at priority intersections, while red coloured pavement and other markings seemed to deteriorate the safety of cyclists. In general, these road features seem to increase cyclists' speed and reduce their visual scanning, while drivers decrease their speed and improve their visual scanning (Gårder *et al.* 1998, Hunter *et al.* 2000). A possible explanation for our results is that both marked crossings and raised bicycle crossings have an effect on cyclists' behaviour, while raised bicycle crossings have the largest effect on drivers' behaviour. This hypothesis could be tested in future research by comparing cyclists' and drivers' viewing behaviour and speed between crossings that are, or are not, raised, and that have pavement markings of varying quality.

We confirmed the finding by Schnüll *et al.* (1992) and Brüde and Larsson (1992) that a distance between the cycle track and the side of the distributor road between 2 and 5m is safest for cyclists. This distance may decrease the complexity of the driving task in that it offers drivers turning into the side road extra time to notice cyclists (Elvik and Vaa, 2009). A larger clearance may also prevent severe crashes with right-turning trucks. Niewöhner and Berg (2005) recommended to redirect bicycle paths away from the middle of the junction to keep cyclists out of the blind spot on the passenger side of trucks. Their findings seem to point in the same direction as ours.

4.4.3. Design factors and type II crashes

No significant relationships were found between type II crashes and the investigated intersection design characteristics. The amount of research and understanding of these crashes is limited compared to type I crashes. On the one hand the complexity of the traffic situation seems to play a role as was suggested by Räsäsen and Summala (1998). At intersections where the main road has three or more lanes, less type II crashes occur if there are raised middle islands. The difference is not significant, but the sign of the effect has a plausible direction in accordance with our expectation. Enabling cyclists to cross in two phases might lower the demands and increase safety for roads with more than two lanes. On the other hand our findings suggest that 'risk compensation' or underestimation of the crossing task by cyclists plays a role as well. Raised middle islands seem to have an adverse effect on safety at intersections of two-lane roads, although this difference is not significant either. Another indication that risk compensation of cyclists might play a role is the relationship between type II crashes and the intensity of motorized traffic. The number of crashes rises less than proportionally to the numbers of motorized vehicles on the main road. Cyclists seem to be able to compensate to a certain extent for the increased demands of elevated traffic volumes on arterial roads.

4.4.4. Recommendations for practitioners

Two things should be taken into account by practitioners when applying the outcomes of this study. In the first place, the outcomes concern the intersection level, while decisions between one-way and two-way cycle tracks should be based on the effect on the itinerary level as well. The same applies to the choice between cycle tracks and cycle lanes, as the latter bicycle facility is more prone to crashes on road links (Welleman and Dijkstra, 1988). In the second place, this study is focused on bicycle crashes. Practitioners have to take all crashes into account. Of particular importance is the question of whether mopeds (with a maximum speed limit of 45 km/h in the Netherlands) are allowed to use cycle tracks as Welleman and Dijkstra (1988) found that bicycle paths have the highest moped crash rate. We expect that raised bicycle crossings have a positive safety effect for all road users due to the decreased speed of motorists. For instance, Gårder *et al.* (1998) found a decreased number of pedestrian crashes. We have not found other relevant studies on the overall safety effects of unsignalized priority intersection design characteristics.

4.4.5. Recommendations for further research

We focused on the links between bicycle crashes and intersection design. Intersection design characteristics may also influence crash severity, especially speed reducing measures. About eighteen percent of both type I and type II accident victims were hospitalized or killed in the crash. Crashes seemed to be less severe at intersections with speed-reducing measures. The number of deaths and in-patients were too small to include severity in the analyses. Further research could focus on the link between road features and crash severity. Also, a finer crash typology can be used in further research. However, distinguishing more crash types results in even fewer crashes per intersection. Possibly, different research approaches, like Zegeer *et al.'s* (2001) design where the rare crash sites were selected beforehand and augmented by near control sites, will be necessary for carrying out valid analyses on infrequent crash types. Given the ageing of the population, it would for instance be interesting to study how intersection design characteristics affect the risk of left-turning crashes in which older cyclists are often involved (Goldenbeld 1992).

5. Single-bicycle crash types and characteristics[7]

Abstract
Most research on cyclist safety is focused on bicycle-motor vehicle crashes. Only a few studies address single-bicycle crashes (i.e. a fall or obstacle collision), in spite of the fact that most cyclists admitted to hospitals are single-bicycle crash victims. This explorative study developed a categorization of single-bicycle crash types based on the scarce literature that is available and theory on bicycle dynamics. This categorization was tested using a questionnaire study that was conducted in the Netherlands among bicycle crash victims treated at an Emergency Care Department. The questionnaire contained open questions about the crash and closed questions on possible direct causes, crash characteristics, and circumstances. The results indicate that about half of all single-bicycle crashes are related to infrastructure: the cyclist collided with an obstacle (1ai), rode off the road (1aii), the bicycle skidded due to a slippery road surface (1bi), or the rider was unable to stabilize the bicycle or stay on the bike because of an uneven road surface (1bii). The first two categories happen due to the cyclist inadvertently taking a dangerous riding line, while the last two happen under more direct influence of the road surface conditions. Other types related to the cyclist are loss of control at low speed (2a), due to forces on the front wheel (2b), or poor or risky riding behaviour (2c). Bicycle defects (3) contribute to a small group of crashes. Finally, some cyclists fall because of an external force such as a gust of wind (4).

5.1. Introduction

High numbers of single-bicycle crashes (e.g. a fall or obstacle collision) are common in countries where many people use a bike as a means of transport (Kroon 1990, Veisten *et al.* 2007, Ormel *et al.* 2008, Heesch *et al.* 2011, De Geus *et al.* 2012). For instance, most cyclists admitted to hospitals in the Netherlands are single-bicycle crash victims, e.g. three-quarters of all cyclist traffic incident victims and one-third of all traffic incident victims (Ormel *et al.* 2008). Despite these high crash numbers, a good description of single-bicycle crash types is missing in scientific literature. This explorative study

---

[7] This chapter represents the explorative part about crash types which was first published in Cycling Research International: Schepers, J.P., Klein Wolt, K., 2012. Single-bicycle crash types and characteristics. *Cycling Research International*, 2, 119-135.

aims to develop a crash typology and describe the crash types. Literature on single-bicycle crashes (Section 5.1.1) and bicycle dynamics (Section 5.1.2) are studied to develop a draft categorization of single-bicycle crash types based on direct causes.

5.1.1. Description of single-bicycle crashes in existing literature

A literature search was conducted to find existing studies that describe single-bicycle crashes. The results can serve as a starting point for a draft categorization of single-bicycle crash types. Google Scholar (Google 2012) and SafetyLit (San Diego State University 2012) were used for the literature search. The search terms were firstly “single-bicycle crash” and secondly “fall obstacle bicycle-crash”. Of the results, only 18 papers and reports referred to single-bicycle crashes (including falls off the bicycle) in the title or summary. Of those 18 papers, 2 contained crash descriptions. This may result from the fact that single-bicycle crashes are very rarely reported in official road crash statistics (Elvik and Mysen 1999, Wegman *et al.* 2012). Since we only found 2 studies and none conducted in the Netherlands, we have asked specialists in Dutch research institutions involved in road safety research whether they knew of studies including single-bicycle crashes. This resulted in 2 additional research reports. Crash types found in the 4 studies are described in the remainder of this section.

Firstly, Nyberg *et al.* (1996) performed a survey study among bicyclists treated as inpatients and outpatients at the University Hospital of Northern Sweden. Only crashes of 314 victims who deemed the road or bicycle track surface to be the major contributing factor to the crash were studied. The road surface factors that had contributed to the injuries included snow, ice, wet leaves and gravel on the roadway, cracks, holes, uneven paving and a steep lateral slant. Victims also collided with kerbs and stationary objects.

Secondly, in Canada, Frendo (2010) classified the crashes of 300 injured cyclists who visited an emergency department and completed a questionnaire. Half involved no other road users and included crash types such as: collision with a man-made obstacle such as a kerb or fence, collision with a parked vehicle, fall due to the road surface such as potholes or objects on the road surface such as tree branches, collision avoidance, bicycle malfunction, wheel lodge (e.g. a grocery bag carried on the handle bars lodged in the wheel), cycling behaviour such as braking too hard or cornering too fast.

Two Dutch studies that focused on single-bicycle crashes were identified. The first, a study by Kortstra and Schoone-Harmsen (1987) was based on victims' statements at Emergency Care Departments. The second, a study by Schoon and Blokpoel (2000) used a survey of bicycle crash victims who were treated at an Emergency Care Department in 1995. The survey was not specifically focused on single-bicycle crashes, however the answers to open-ended questions were coded to identify if the victim was involved in a single-bicycle crash. The description of single-bicycle crashes identified in these two Dutch studies is similar to outcomes reported by Frendo (2010) and Nyberg *et al.* (1996). However, the Dutch studies also report crashes with older cyclists at low speed, especially loss of balance while mounting or dismounting the bike, and crashes with younger cyclists while performing stunts with their bike. This seems relevant given that in the Netherlands people of all ages use a bicycle, especially for utilitarian trips where speeds can be low (Ministry of Infrastructure and the Environment 2009).

5.1.2. The stability of the bicycle and the cyclist

As research on single-bicycle crashes is scarce, theory on bicycle dynamics was explored to find potential direct causes as un underpinning for a crash typology. A controlling rider can balance a forward-moving bicycle by turning the front wheel in the direction of an undesired lean. This moves the ground-contact points under the rider (Jones 1970). Most bicycles can balance themselves (riderless) if moving above a given speed which depends on factors such as geometry and mass distribution (Kooijman *et al.* 2011). Mathematical models including such factors are available to describe the bicycle's lateral stability (e.g. Meijaard *et al.* 2007). Moore *et al.* (2011) found self-stability at speeds above approximately 16 km/h for a commonly used Dutch city bicycle and a male rider. To conclude, the studies show that sufficient speed supports the bicycle's stability.

Independent of whether the rider actively steers or not, the ridability of a bicycle depends crucially on the freedom of the front fork to swivel. If it is locked, even dead ahead, the bicycle cannot be ridden (Jones 1970; Kooijman *et al.* 2011). This implies that the front wheel has to be prevented from locking up, for instance due to hard braking or a branch into the spokes of the front wheel. Otherwise the rider may lose control or be launched over the handlebars (Beck 2009).

Another problem that can be difficult to correct once it occurs is skidding. Skidding depends on the coefficient of friction between the tyres and the road surface and is also subject to the condition of the tyres and the state of the road surface. As regards to the road surface condition, mud, water, wet leaves, and oil can reduce the friction. To prevent skidding while braking and cornering, the tyres should offer sufficient traction (i.e. the frictional force that keeps a tire from skidding). Smooth tyres of race bicycles get as good traction as those with tread, assuming appropriate inflation power. The tyres of racing bikes are narrower resulting in a smaller contact patch and more weight per square inch. This doesn't affect traction on smooth road surfaces. However, a wider tire will deform easier around road surface irregularities which makes riding more comfortable and provides more grip. For riding on soft surfaces, such as sand or mud, a wide front tire is essential (Brown 2009, Fietsersbond 2012).

Finally, in many cases cars will not roll over in case of a collision and they offer a level of protection to occupants if a crash occurs. On the contrary, falling is almost unavoidable for cyclists if they hit an obstacle and except for a helmet (if worn) the rider is unprotected. The cyclist may be injured by the fall or by hitting an object, e.g. a bollard. As a result, cyclists may sustain severe injuries in seemingly innocent crashes.

5.1.3. Crash types based on direct causes

Wagenaar and Reason (1990) identified two distinct classes of causes in road traffic accident scenarios, i.e. direct causes and latent factors. Direct causes occur immediately prior to the accident, while latent factors refer to those causes that might have been present in the system for a long time. We base our crash categorization on direct causes. The direct causes consist of causes related primarily to the infrastructure, the cyclist, or the bicycle, depending on where the force that resulted in the accident came from. Infrastructure can be a direct cause through the road surface condition or the collision energy released when crashing into an object. Note that direct causes may be explainable by several latent factors. For instance, while the force may have come from hitting an obstacle (i.e. infrastructure) the latent factors may be a combination of the design decision to put the obstacle on the road way, alcohol use by the rider, and malfunction of the bicycle light making it more difficult to detect and avoid the obstacle. Note further that Wagenaar and Reason (1990) suggest that to be effective, countermeasures should focus on the identification of latent factors rather than direct causes. The next chapter contains research focused on a specific latent factor, i.e. visibility of infrastructure.

Based on the literature review and theory on bicycle dynamics, we suggest the following crash categorization:

1. Infrastructure-related crashes:
    a. preceded by the cyclist inadvertently taking a dangerous riding line:
        i. colliding with an obstacle on the roadway (deliberately) designed and build by road authorities, such as a road narrowing or bollard on the bicycle track to prevent cars from entering, and parked vehicles.
        ii. riding off the road and colliding with a kerb or off-road obstacle
    b. linked to road surface quality:
        i. skidding due to a slippery road surface
        ii. loss of control due to an uneven road-surface (e.g. a pothole or damage from tree roots) or a loose object on the road surface (e.g. a branch)
2. Cyclist-related crashes; loss of control:
    a. At low speed when it requires more effort to stabilize the bicycle, e.g. (dis)mounting
    b. Due to (moving) baggage, that may hit the front wheel
    c. Riding behaviour:
        i. abrupt steering manoeuvres, e.g. avoidance
        ii. braking mistakes
        iii. stunting, e.g. doing a wheelie
3. Bicycle malfunction, e.g. chain break, broken part of the frame, etc.
4. Other, or no recall of the crash by the victim

There will be some overlap between these crash types. For instance, a cyclist goes off course because baggage carried on the handle bars hits the front wheel after which the rider hits a kerb and falls. This will be categorized both into crash type 1a and 2, because forces causing the fall are both related to the cyclist (baggage hitting the front wheel) and the infrastructure (front wheel hitting the kerb).

The reason for classifying collisions with parked vehicles in group 1a related to infrastructure is that the location of parking places relative to (bicycle) traffic is in the Netherlands described in guidelines. For example, the Dutch Design Manual for bicycle traffic advises against cycle lanes with parking bays because of opening car doors (CROW 2007).

Loss of control due to an uneven road-surface or a loose object on the road surface are both classified in one group because a bump or loose object on the road may result in the same instability. However, the measures to prevent these problems are different.

5.2. Procedures and method of study

Many road crash studies are based on police-reported crashes. However, single-bicycle crashes are very rarely reported in official road crash statistics (Wegman *et al.* 2012; Elvik and Mysen 1999). Therefore, VeiligheidNL ("Consumer Safety Institute") performed a retrospective study. Questionnaires were sent to cyclists who had had an accident with their bicycle and were treated at an Emergency Care Department. These participants were retrieved from LIS (LetselInformatieSysteem; Dutch Injury Surveillance System). LIS records statistics of people being treated at the Emergency Care Departments of a selection of hospitals in the Netherlands, following an accident, violence or self-inflicted injury. The selection of hospitals is a sample of hospitals in the Netherlands with a continuously staffed Emergency Care Department. Thirteen hospitals spread over the Netherlands, representative of the Dutch population in terms of level of urbanization, participated in this study.

The outcomes of the previous studies on single-bicycle crashes that were mentioned in Section 5.1 were used to develop a questionnaire consisting of closed and open-ended questions. The open-ended questions and an example of a closed question are included in Table 5.1. Other questions were about direct causes, latent factors (e.g. alcohol use prior to the crash), circumstances, and characteristics of the victims. Parents were asked to fill in the questionnaire together with their child if the victim was younger than 12 years of age. On average, it took respondents about 20 minutes to answer all of the 40 questions. The survey was sent to the victim 2 months after treatment at the Emergency Care Department. Between February and June 2008, 2,975 questionnaires were sent, 1,156 (39 per cent) were returned. A total of 1,142 could be used for analyses. Of these participants 16 per cent were hospitalized after treatment at the Emergency Care Department. Crashes that occurred on unpaved roads through woods or of which the road type is unknown are excluded because they may not meet the official Dutch definition of a road traffic accident that includes the criterion that the crash should have occurred on a public road (n=65). A total of 669 single-bicycle crashes in which the cyclist (not the passenger) was injured were analysed in this study.

Answers on both open and closed questions were used to categorize crashes according to the crash typology (see Section 5.1.3). This was done by two researchers independently. The results were compared and discussed to arrive at a final categorization.

Examples of questions

Nr 1. Description of the crash. We would like to know what happened precisely when you had the crash.

1a. At what kind of road were you riding? What was the purpose of your trip? Was there an extraordinary situation?

1b. What happened next, what went wrong?

1c. Where you injured? What injury did you sustain? Which area(s) of your body was wounded?

Nr 4. What happened exactly (you can mark more than one category)?

I fell:

- ☐ While mounting the bike
- ☐ While dismounting the bike
- ☐ While braking
- ☐ While descending a slope
- ☐ While climbing a slope
- ☐ While overtaking
- ☐ While turning left
- ☐ While turning right
- ☐ While I was just cycling (no specific manoeuvre or activity)
- ☐ Other, …

I collided with an object or obstacle:

- ☐ Lighting post
- ☐ Traffic sign
- ☐ Bollard
- ☐ Fence or wall
- ☐ Kerb
- ☐ Tree
- ☐ Animal
- ☐ Other, …

---

[1] See Ormel *et al.* 2008 for the complete questionnaire

Table 5.1. Two examples of questions in the survey.

5.3. Results

Classification in Crash Types

Two researchers have independently classified the 669 crashes according to the crash typology (see Section 5.1.3). The results show that fifteen percent of the cases were categorized differently. This low percentage shows that the crash typology is suitable to categorize single-bicycle crashes. The differences were subsequently discussed and a final categorization was chosen. We classified 88 per cent of the crashes in at least one of the categories described in Section 5.1.3, 17 per cent in two and 1 per cent in three categories. The researchers agreed that 12 per cent did not fit in one of the categories. These were assigned to a fourth group. The groups are described in the following with numbers and percentages of the single-bicycle crashes in the sample between brackets.

Group 1. Infrastructure-related crashes:

1a. preceded by the cyclist inadvertently taking a dangerous riding line

  i. collisions with obstacles on the road, including parked cars (n=77; 12%)

    About half of the objects that cyclists collided with were bollards that were put on the road to prevent cars from entering a cycle track or stretch of the road, or road narrowings to slow down motorized vehicles. Most bollards stood in the middle of the road and a few on the verge of the road. About one third of the victims hit a car door or parked vehicle. A few cyclists hit a fence that was put on the road to clear it for a cycle race or road works.

  ii. riding off the road (n=142; 21%)

    Two thirds of the victims hit a kerb, in most cases with the front wheel. In a few cases the cyclist kept too little distance from the kerb and hit the kerbstone with one of the pedals. One third of the victims swerved into the shoulder. They were unable to steer back to the road because of the height difference between the road and shoulder surface. Other victims fell because of an uneven or sandy shoulder surface or they collided with obstacles on the shoulder like trees, light posts, and fences.

1b. linked to road surface quality

  i. skidding due to a slippery road surface (n=118; 18%)

    All the crashes in this group have in common that one of the wheels, mostly the front wheel, skidded because of a slippery road surface. Skidding crashes without a clear link to the road surface were not included in this group. There were several subcategories:

- The road surface was slippery in more than one third of the cases due to dirt, e.g. sand, gravel, mud, wet leaves, oil or grease on the road surface.
- Elements in the road surface with lower friction caused a little over a quarter of the skidding accidents: iron plates and concrete plates with metal edges for temporary road surfaces, moss-covered or synthetic tiles, certain marking materials, wooden (bridge) surfaces without an asphalt layer on top of it, tram rails, cattle grids, drain covers, etcetera. The road surface was wet in most of these cases.
- One fifth of the victims skidded on ice or snow.
- Almost one fifth of the crashes resulted from longitudinal grooves or raised edges in the road surface. A wheel can easily skid when crossing raised edges or tram rails at too small an angle. The front wheel skidded and got stuck in the tram rails in a few cases.

ii. loss of control due to an uneven road-surface or loose object on the road (n=46; 7%)

About two thirds of the victims rode over bumps or potholes. They lost control over their bike and fell or swerved over the road to crash with a kerb or an object. Other victims rode over an object on the road and lost control. A few of them flew over de handlebars after a piece of wood or branch got tangled into the front spokes.

Group 2. Cyclist-related crashes:

2a. loss of control at low speed (n=105; 16%)

The majority of single-bicycle accidents at low speed happened while mounting or dismounting the bike. A lot of victims caught their coat, bag, or shoelace on a part of the bicycle and were unable to stabilize the bike or themselves. Some victims lost balance as their food slipped off the pedal or as they tried to make a sharp turn or look behind for traffic before dismounting. Others fell after they dismounted, because they carried a heavy load on their bicycle, used only one hand to hold the handle bars, or twisted their ankle.

2b. loss of control due to forces on the front wheel or handlebars (n=54; 8%)

Many victims put baggage on the handlebars. They lost control as it hit the front wheel, was pushed against the handlebars while moving the pedals, or became entangled in the front wheel spokes. Some of the bikes flipped over in the latter case. In some cases a foot slipped off a pedal and became tangled in the front wheel spokes. Some got off balance as a passenger or baggage on the luggage carrier moved.

2c. loss of control due to riding behaviour:

i. abrupt steering manoeuvres (n=87; 13%)

Most of the victims in this category did not manage to balance or stay on the bike while they got out of the way for traffic or displayed a shock reaction after being scared by traffic. Victims made steering faults like steering too much, braking too much while steering, or holding the handle bars with only one hand while steering. Some occurred with children with limited cycle skills (according to their parents who filled in the questionnaire).

ii. braking mistakes (n=41; 6%)

This accident group is a combination of brake defects and wrong braking. In most cases one of the wheels skidded or the cyclist flew over the handlebars. It is not always clear whether the rider was braking too hard or braking hard without using the rider's arms to brace against the deceleration. In some cases the brakes did not work well or even broke down (these could have been categorized as defect as well).

ii. stunting (n=11; 2%)

A small group of adolescents stunted with their bike and got out of balance, for instance while doing a wheelie.

Group 3. Bicycle malfunction (36; 5%):

Several defects resulted in single-bicycle crashes: the chain broke or came off, the tire inflation was too low resulting in skidding while cornering, the fender or the front fork broke off, a wheel, saddle, or handlebars were loose or broke off.

Group 4. Other or unknown (n=80; 12%)

Some victims were unable to describe the details of their accident as they were unconscious because of the event or they were unable to provide enough information for us to categorize the crashes. Other victims had accidents that did not fit into one of the other categories. A substantial number of crashes could have been classified in an additional category of crashes due to external forces unrelated to the cyclist and the infrastructure. This finding could be useful for future research. Several cyclists fell because an animal ran against their bike, they lost control due to a gust of wind and a few were victims of an act of aggression, e.g. they were pulled off their bike.

Not Analysed (i.e. not part of the total number of 669 analysed crashes). Crashes that occurred on unpaved roads through woods or of which the road type is unknown (n=65).

Crashes belonging to one or more infrastructure related crash types account for more than half of all the single-bicycle accidents in the sample (n=350; 52 per cent).

5.4. The relationship with bicycle use

One of the research questions of this thesis is about the relationship between the amount of bicycle use and the risk of bicycle crashes. We have conducted Chi-square analyses to compare the crash types on the amount of bicycle use (unanswered questions are treated as missing values). Cyclists who cycle less than one day per week are less often involved in collisions with obstacles on the road ($\chi^2(2, N=654) = 6.2$; $p = 0.046$). They are more often involved in crashes at low speed ($\chi^2(2, N=653) = 6.8$; $p = 0.033$) and crashes in which they lose control while braking ($\chi^2(2, N=654) = 5.9$; $p = 0.051$). The latter is almost significant.

5.5. Discussion

Literature on single-bicycle crashes is scarce which can be explained by the fact that despite the high numbers of serious injuries incurred (Schepers 2012), single-bicycle crashes are very rarely reported in official road crash statistics (Wegman *et al.* 2012; Elvik and Mysen 1999). We have therefore based a draft crash typology not only on crash literature but also on bicycle dynamics. This categorization was tested using a questionnaire study that was conducted among bicycle crash victims treated at an Emergency Care Department. The typology appeared to be suitable to categorize single-bicycle crashes shown by the fact that the classifications conducted by two researchers independently were consistent (only fifteen per cent of the cases were categorized differently). Such crash types can be used in future explanatory research.

5.5.1. Infrastructure-related crash types

One group of infrastructure-related crash types is preceded by a dangerous riding line (i.e. riding off the road and obstacle collisions) and the other group is related to the road surface condition (i.e. skidding and loss of control due to an uneven road surface), i.e. the quality of the pavement (e.g. friction) and maintenance. The first group may be related to the visual design of the infrastructure (see also the next chapter) and factors such as the forgivingness of obstacles and the shoulder.

5.5.2. Cyclist-related crash types

The most frequent cyclist-related crash type is losing control at low speed when steering is needed for stability. This mostly occurs while mounting or dismounting the bike. More research could be done on this issue, for instance from the perspective of Human Movement Sciences and Gerontology, the latter because the elderly are overinvolved in this crash type (Ormel *et al.* 2008).

5.5.3. The effect of bicycle use on crash likelihood

One of the research questions of this thesis is about the relationship between the amount of bicycle use and the risk of bicycle crashes. As described in Chapter 2, cyclists are less likely to be involved in severe single-bicycle crashes in municipalities with a high amount of cycling (Schepers 2012). One explanation was that cyclists gain better control and greater physical fitness the more they cycle. This hypothesis is supported by the outcomes of the Chi-square analyses described in Section 5.4. Cyclists who cycle the least (i.e. less than one day per week) are most likely to be involved in two crash types that seem to be linked to cycling skills and strength, i.e. falling while (dis)mounting and loss of control due to braking mistakes.

5.6. Conclusion

This study shows that single-bicycle crashes can be categorized according to direct causes. Depending on where the force that resulted in the crash came from, crashes can be classified as related to infrastructure, the cyclist (e.g. poor riding behaviour), the bicycle (e.g. a defect), or an external force (e.g. a strong gust of wind). Infrastructure-related crashes make up the largest group. They occur due to the cyclist inadvertently taking a dangerous riding line, or under more direct influence of the road surface conditions. Research on single-bicycle crashes is still in its infancy and more research is needed to develop and evaluate countermeasures which also requires more insight into latent factors.

6. What do cyclists need to see to avoid single-bicycle crashes?[8]

Abstract

The number of single-bicycle crash victims is substantial in countries with high levels of cycling. To study the role of visual characteristics of the infrastructure, such as pavement markings, in single-bicycle crashes, a study in two steps was conducted. In Study 1, a questionnaire study was conducted among bicycle crash victims (n = 734). Logistic regression was used to study the relationship between the crashes and age, light condition, alcohol use, gaze direction and familiarity with the crash scene. In Study 2, the image degrading and edge detection method (IDED-method) was used to investigate the visual characteristics of 21 of the crash scenes. The results of the studies indicate that crashes, in which the cyclist collided with a bollard or road narrowing or rode off the road, were related to the visual characteristics of bicycle facilities. Edge markings, especially in curves of bicycle tracks, and improved conspicuity of bollards are recommended

6.1. Introduction

Many studies have been conducted on how drivers' visual capabilities and limitations can be supported by road design. Marked centre and edge lines provide a visual reference to guide motorists in the driving task (McGee and Hanscom 2006). The Norwegian Handbook on Road Safety (Elvik *et al.* 2009) provides a comprehensive summary of crash studies. These studies date back several decades, showing the long research history into safety and visibility of infrastructure for drivers of motorised vehicles. As a consequence, most countries have strict guidelines for markings on roads for drivers. In contrast, no edge-of-track markings are recommended for guidance of cyclists in manuals for bicycle facilities (Director of Environmental Services 1998, Danish Road Directorate 2000, CROW 2007). This suggests an untested general assumption that cyclists can do without enhanced visual contrast for environmental elements within the riding distance due to a lower speed than drivers. The majority of the research on cyclist safety is performed from the perspective of car drivers. Previous research mainly focused on the visibility

---

[8] This chapter was first published in Ergonomics: Schepers, J.P., Den Brinker, B.P.L.M., 2012. What do cyclists need to see to avoid single-bicycle crashes? *Ergonomics*, 54(4):315-327.

of cyclists and pedestrians to avoid collisions with motorised vehicles (i.e. cyclists should be visible for motorists), for instance, Kwan and Mapstone (2004) on visibility aids, Jensen (2008) and Nygårdhs *et al.* (2010) on the visibility of bicycle crossings at intersections.

This paper questions the assumption that cyclists can do without a minimal level of guidance and conspicuity of (design-related) obstacles on their way. The absence of a minimal level of contrast may lead to single-bicycle crashes (only one cyclist involved), where riders lose their lane position or collide with obstacles as was suggested by Den Brinker *et al.* (2007). This issue is of importance as the number of single-bicycle crash victims in the Netherlands is substantial and continues to rise. Each year, Accident and Emergency Departments treat 46,000 injuries sustained in single-bicycle crashes. Of these, approximately 6000 victims are admitted to the hospital, one-third of all traffic victims. A high number of single-bicycle crashes and substantial medical costs are common in countries with a high proportion of cyclists (Elvik and Mysen 1999, Veisten *et al.* 2007, Ormel *et al.* 2008). Single-bicycle crashes are very rarely reported in official road crash statistics (Elvik and Mysen 1999). The dearth of data might explain why few studies have been conducted in this area, and even fewer that focus on single-bicycle crashes in relation to road characteristics (Kortstra and Schoone-Harmsen 1987, Nyberg *et al.* 1996, Schoon and Blokpoel 2000).

The study by Kortstra and Schoone-Harmsen (1987) was based on victims' statements at Emergency Care Departments, of which one-third was detailed enough to be included in the analysis. Schoon and Blokpoel (2000) used a survey of bicycle crash victims who were treated at an Emergency Care Department in 1995. The answers to open-ended questions were coded if the victim was involved in a single-bicycle crash. The study by Nyberg *et al.* (1996) is the most relevant one for the present study, as it is the only one that specifically focused on the relationship between single-bicycle crashes and road characteristics. They performed a questionnaire study among bicyclists treated as inpatients and outpatients at the University Hospital of Northern Sweden. Only crashes of victims who deemed the road or bicycle track surface to be the major contributing factor to the crash were studied. The road surface factors that had contributed to the injuries included snow, ice, wet leaves and gravel on the roadway, cracks, holes, uneven paving and a steep lateral slant. Victims also collided with kerbs and stationary objects. Inspections of the scene were not conducted; therefore, it was not possible to measure the visual characteristics of the infrastructure.

Owing to the fact that this study focuses on the role of the characteristics of the visual design in single-bicycle crashes, i.e. guidance and conspicuity of obstacles, the present study was conducted in two steps. In the first step, a survey was performed among single-bicycle crash victims to investigate whether crash characteristics could be related to vision (see Study 1 in Section 6.3). In the second step, crash scenes were inspected and an objective psychophysical method was used to measure its visual characteristics (see Study 2 in Section 6.4).

6.2. Cyclists' needs for markings and other visual properties

Cyclists' needs for markings and other visual properties of the infrastructure, i.e. 'visual accessibility', should be based on the tasks they perform and the effort required to carry out these tasks. Theory on focal vs. ambient vision that is fruitfully studied in the context of the driving task (Section 6.2.1) is used in order to develop a framework of reference with this heuristic for the cycling task (Section 6.2.2).

6.2.1. Focal vs. ambient vision

Focal and ambient visual resources vary along a number of dimensions (Leibowitz and Post 1982, Previc 1998). The primary functions of the focal visual system are visual search, object recognition and related tasks requiring high visual acuity. According to Previc (1998), this system relies on saccades as the primary motor system. Although focal vision can extend beyond the fovea, its strengths are greatest in the fovea. In contrast, the ambient visual system is involved in orienting in earth-fixed space, spatial orientation and postural control in locomotion. This system typically encompasses the front 180° of the visual field, is lower field dominant (because of the importance of optic flow information in ground-based locomotion) and involves peripheral vision.

Schieber *et al.* (2008) have adapted Donges' (1978) two-level model of driver steering that is in accordance with the ambient-focal dichotomy:

1) The guidance-level that involves focal/far vision to garner information from the 'far' road ahead. The driver uses this information to anticipate and prepare for hazards and future alterations in the course of the road.
2) The stabilisation-level that involves ambient/ near vision regarding current (i.e. instantaneous) deviations between the vehicle's actual path and its desired path. Peripheral vision is used to track and minimise instantaneous errors in lane position.

Schieber *et al.* (2008) refer to an experiment that indicates where ambient/near visual processes give way to focal/far visual processes. In an experiment in a driving simulator it was tested how far down the roadway, defined from the position of the driver, edge lines needed to be visible to support optimal lane tracking. Lateral lane position variability reached minimum levels within just 2 s of roadway preview time (COST 331, 1999). The stabilisation-level seems insufficient for lane-keeping on a road with tight curves. Drivers with a simulated low visual acuity have some deficiencies in terms of preparatory vehicular positioning in anticipation of sharp curves, resulting in more lane excursions (Brooks *et al.* 2005).

Schieber *et al.* (2008) as well as Horrey *et al.* (2006) have summarised results of research on the driving task, which can be interpreted in terms of the focal-ambient dichotomy. Vehicular guidance (i.e. ambient vision) is found to be remarkably robust in the face of great reductions in available high-spatial-frequency information, achieved experimentally via blur and low luminance. Conversely, driving processes thought to be mediated by focal vision, i.e. sign and hazard recognition at a distance, are increasingly worsened due to low visual acuity (e.g. Higgins *et al.* 1998, Owens and Tyrrell 1999, Brooks *et al.* 2005). Leibowitz and Post (1982) formulated the 'selective degradation hypothesis' to describe the fact that visual recognition abilities are selectively degraded in low illumination while visual guidance is preserved. The results of experiments using the forced-peripheral driving technique are in line with the ambient-focal heuristic. Drivers are able to perform a lane-keeping task relying exclusively on peripheral vision (Summala *et al.* 1996), while they do not perform well in detecting a closing headway or looming vehicle in peripheral vision (Summala *et al.* 1998, Terry *et al.* 2008).

Drivers of all ages experience serious visual impairment in low illumination conditions, particularly a degradation of visual recognition abilities, i.e. the 'selective degradation hypothesis' (Owens and Andre 1996). Older drivers also suffer from a deterioration of steering performance in low light conditions (Owens and Tyrrell 1999, Wood and Owens 2005). This problem may be related to a gradual decline of peripheral vision, contrast sensitivity, dark adaptation and glare sensitivity across the adult lifespan (Johnson and Keltner 1983, Owens and Andre 1996). Younger drivers are overconfident at night because visual guidance is preserved. Consequently, they generally stay unaware of their reduced recognition abilities. The fact that older drivers do experience decreased steering performance may explain their reluctance to drive at night (Owens and Tyrrell 1999).

6.2.2. Comparison between cycling and driving

Cycling is compared with driving and the ambient-focal dichotomy is used to hypothesise about visual requirements for cycling facilities. The first question is about the requirements for ambient vision. Cyclists are in the open while drivers are in their car; thus, cyclists' lower visual field is less restricted, which offers them more optic flow, i.e. more support for ambient vision. This eases the cycling task, but, in contrast to driving, cycling requires stabilising the bike. Although cyclists have a low speed compared to drivers, they cannot completely rely on focal vision to carry out their task. For instance, while steering through a gap between two obstacles, it is difficult to control the path of the bike by fixating on the obstacles. Moreover, a decrease of cycling speed causes an increase of the effort required to stabilise the bicycle. Under unfavourable circumstances (e.g. gusty headwinds) cycling may require a track width of up to 80 cm (CROW 2007).

Because of their lower speed, cyclists need a smaller 'visibility distance' than drivers to support ambient vision. Even in this smaller distance, peripheral information needs to be available. Pedestrians, who even have a lower speed, are already known to suffer from a restricted peripheral vision, so cyclists are supposed to suffer from that too. A loss in the peripheral visual field (i.e. an extreme degradation of ambient vision) is associated with unwanted contacts and disorientation (Turano *et al.* 2002). Likewise, Lemmink *et al.* (2005) found that turning time during a shuttle run test (i.e. running back and forth between two parallel lines) increases significantly when sprinting with a restricted peripheral field of view, indicating the use of peripheral vision for the control of directional changes.

The second question for the comparison between driving and cycling is about the requirements for focal vision. Drivers generally drive faster than cyclists and are likely to confine their gaze to a narrower view. The faster a vehicle moves, the further the driver needs to look ahead for hazards and changes in the course of the road. In straight-road driving, gaze is increasingly constrained by increasing speed (Rogers *et al.* 2005). In contrast, as cyclists travel at a lower speed, they would not have to look as far ahead, i.e. cyclists need a smaller visibility distance. However, problems may arise when important information is poorly visible in the visual periphery within this distance. First, focal vision may deteriorate if the minimal requirements of short-range visibility for ambient vision are not met. More fixations on the roads' edges would be needed to determine the course of the road if the edges are poorly visible. This would worsen focal vision as it relies on saccades. Second, even if the requirements for ambient vision are met, cyclists need to focus their attention on other traffic in complex traffic situations or may look at the surroundings. Visibility in the visual periphery is needed to guarantee that a bollard (post used to keep motor vehicles off a cycle track), road narrowing or curve timely captures the attention of approaching cyclists.

Peripheral visual information is generally believed to help select the object to which the eyes are sent next (Loschky *et al.* 2005). Detection is dependent on the size and salience of objects. Saliency typically arises from contrasts between items and their neighbourhood (Den Brinker and Beek 1996, Schubö 2009). Background 'clutter' (i.e. high information density) decreases the visibility of critical information (Hole *et al.* 1996). In the case of cyclists, it should be borne in mind that there is often salient information for drivers in their surroundings. The standards for markings and street lighting for roads are at a higher level than for bicycle facilities. A change in the course of an unmarked bicycle track along a well-marked, well-lighted and wide road may go undetected, even if a cyclist would fixate on the right part of the bicycle path. Habak *et al.* (2002) found that strong signals from the periphery facilitate the percept when central signals are weaker, but not the reverse. The comparison herein between driving and cycling suggests that critical information needs to be visible in the visual periphery for safe cycling.

6.2.3. Research approach

As single-bicycle crashes are rarely recorded by the police, a questionnaire study was conducted (i.e. Study 1) among single-bicycle crash victims treated at Accident and Emergency Departments to be able to study the crash characteristics. Part of the questions in the inquiry are likely to be related to the impact of the visual characteristics of the infrastructure: light conditions; age; influence of alcohol; familiarity with the crash scene (i.e. with obstacles and sudden changes in the course of the road); gaze direction. Study 2 is added to strengthen the basis for conclusions by investigating the visibility (in the visual periphery) of critical information at crash scenes. A visual analysis was conducted based on pictures that were taken under the same light and viewing conditions as prior to the crash.

6.3. Study 1: Questionnaire sent to bicycle crash victims

6.3.1. Procedure and method

VeiligheidNL (Consumer Safety Institute) performed a retrospective study. Questionnaires were sent to cyclists who had had a crash with their bicycle and were treated at an Emergency Care Department. These victims were retrieved from Letsel Informatie Systeem (Dutch Injury Surveillance System), which records statistics of people being treated at the Emergency Care Departments of 13 hospitals in the Netherlands, following an accident, violence or self-inflicted injury. The selection of hospitals is a representative sample of hospitals in the Netherlands with a continuously staffed Emergency Care Department.

The outcomes of the previous studies on single-bicycle crashes that were mentioned in Section 6.1 were used to develop a questionnaire consisting of closed and open-ended questions. The open-ended questions and an example of a closed question are included in Table 5.1. Other questions were about the location, the date and time when the crash occurred, the purpose of the trip, the speed at the time of the crash, the light and weather conditions at the time of the crash, use of alcohol, drugs and medicine prior to the crash, potentially distracting activities at the time of the crash (e.g. mobile phone use or conversing with a fellow cyclist), gaze direction prior to the crash, the type of and quality of the bike, injuries, average bicycle use before the crash and changes in behaviour afterwards. It took about 20 min to answer all the questions. The survey was sent 2 months after the victim was treated at the Emergency Care Department. Between February and June 2008, 2975 questionnaires were sent; 1156 (39%) were returned. Such response was comparable to similar surveys, such as other surveys by the Dutch Consumer and Safety Institute. A total of 1142 could be used for analyses. Of these victims, 16% were hospitalized after treatment at the Emergency Care Department. Unanswered questions were treated as missing values in the analysis.

As the assumption that cyclists can do without a minimal level of guidance and conspicuity of (designrelated) obstacles on their way is questioned in Section 6.1, single-bicycle crashes were categorised into a group that may be related to the visual design of the crash location (group V) and a group that contains all other crashes (group NV). Crashes were classified to group V if the critical information that the cyclist needed to see to be able to avoid the crash was intentionally designed, i.e. the edge of the road, the obstacle or the tram rails. Crashes unrelated to vision were classified to group NV, for instance, losing balance due to baggage that becomes entangled in the spokes of a wheel, or due to cracks and holes in the road surface (i.e. road features that were not part of the initial design). This resulted in the following two categories:

(1) Group V (n = 180): cyclist collided with a kerb, bollard or road narrowing, fell onto the shoulder (or crashed into an off-road object), or fell because a wheel was deflected on contact with tram rails parallel to the direction of bicycle traffic.
(2) Group NV (n = 554): skidding, loss of control due to bumps and holes in the road surface, a bicycle defect, loss of control while mounting or dismounting the bicycle, etc.

Note that as these categories are chosen specifically for the purposes of the study described in this chapter, there is no one-to-one relationship with the categories defined in the previous chapter.

Binary logistic regression was used to assess the association of crashes in group V with the following variables: gender; age (under or above 60 years of age); light condition at the time of the crash; alcohol use; gaze direction at the time of the crash (behind, to something next to the road, or else). Gender was included as a control variable. In this paper, the age group of above 60 years of age is referred to as ‘older cyclists’. The victims in group NV were used as controls. Odds ratios with 95% CI and p values were calculated.

An additional analysis was added to provide insight in the avoidance of adverse light conditions by older cyclists. To determine the number of kilometres travelled by bicyclists the Dutch National Travel Survey was used. This is a survey on the travel behaviour of the Dutch population (Rijkswaterstaat 2010). Data were used from the period of 2003–2007, February–June, i.e. the months in which the crashes happened. Times of departure were combined with the Dutch sunrise and sunset timetable (KNMI 2009), to separate between kilometres travelled in daylight and in twilight and darkness. The proportion of kilometres travelled by bicycle in darkness and twilight was determined per age group.

6.3.2. Results

There were 734 single-bicycle crashes, of which 180 were classified as visual-design related (group V) and 554 that were classified in the other group (group NV). The results of the binary logistic regression indicate that the crashes in group V are related to age, alcohol use and the gaze direction before the crash (see Table 6.1). The crashes also tended to happen more often in dark and twilight and to cyclists who were unfamiliar with the crash location, but these differences are not significant.

In Figure 6.1, the percentage of kilometres travelled by cyclists in darkness and twilight is presented by age. Almost 10% of all bicycle kilometres are travelled in darkness and twilight. As indicated in Figure 6.1, older cyclists avoid riding their bicycle in darkness. This finding may explain why light condition is not significantly related to crashes in group V. The cyclists with the worst visual capabilities may avoid adverse light conditions.

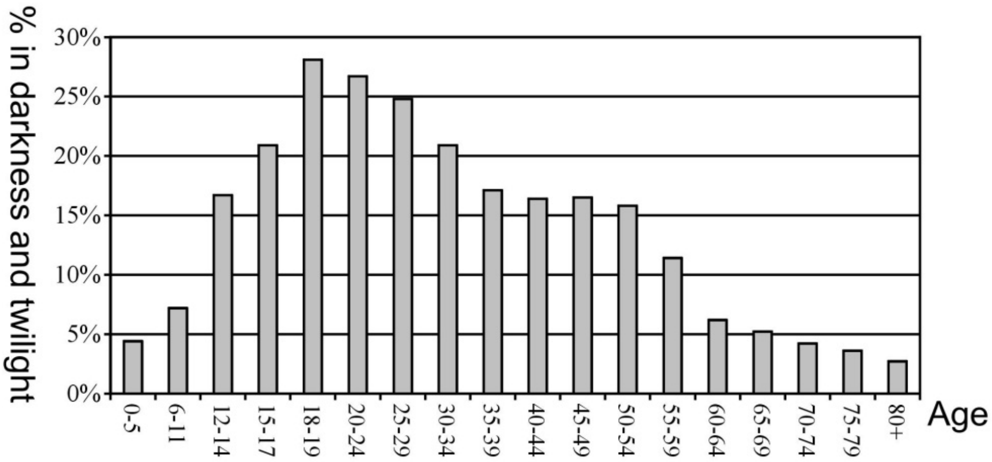


Figure 6.1. Share of the distance travelled by bicycle in darkness and twilight per age group.

	Accidents[1]			
	group V (n = 180)	group NV (n = 554)	OR (95% CI)[2]	*P*
Gender:				
male	94 (52)	295 (53)	0.96 (0.67-1.38)	0.843
female	86 (48)	258 (47)	1.00 (reference)	-
Age (years):				
≥ 60	70 (39)	166 (30)	1.71 (1.17-2.50)	<0.01
< 60	110 (61)	387 (70)	1.00 (reference)	-
Light condition:				
dark and twilight	46 (26)	84 (15)	1.60 (0.92-2.77)	0.095
daylight	133 (74)	467 (85)	1.00 (reference)	-
Alcohol use[3]:				
yes	31 (17)	43 (8)	2.20 (1.14-4.25)	0.019
no	148 (83)	510 (92)	1.00 (reference)	-
Gaze direction before the accident:				
at something next to the road	18 (10)	15 (3)	4.21 (1.99-8.93)	<0.001
behind	14 (8)	14 (3)	3.87 (1.76-8.54)	<0.001
other direction	147 (82)	524 (95)	1.00 (reference)	-
Familiarity with the accident location:				
not familiar	32 (18)	76 (14)	1.45 (0.90-2.33)	0.128
familiar	144 (82)	470 (86)	1.00 (reference)	

[1] Number and column percentages (in parentheses); discrepancies in totals are due to missing values

[2] Odds ratios (OR) (Group V vs Group NV) and 95% confidence intervals (CI) from binary logistic regression analysis

[3] Two or more alcohol containing beverages, six hours before the accident

Table 6.1. Association of single-bicycle crashes with visually related variables.

Group V is divided into the following two categories to conduct additional analyses on gaze direction and familiarity with the crash scene:

(1) Cyclist collides with a bollard or road narrowing or rides off the road in a curve (n = 83).

(2) Cyclist hits a kerb, rides into a shoulder or falls because a wheel is deflected on contact with tram rails on a straight road section or crossing (n = 97).

Collisions in the first group happen more often to distracted cyclists (see Table 6.2) and cyclists who were unfamiliar with the crash location (see Table 6.3). As Table 6.4 indicates, crashes in the second group happen more often among cyclists who looked behind prior to their crash.

Single-bicycle accident type Cyclist[1]:	Cyclist looked next to the road yes	 no	 total	row % (yes)
(1) hits a kerb or rides into a shoulder, or falls because a wheel is deflected on contact with tram rails (straight section or crossing)	4	92	96	4%
(2) collides with bollard or rides off the road in a bend	14	69	83	17%
(3) other	15	539	554	3%
Total	33	700	733	5%

[1] The second category is higher than the first and third ($\chi^2(2, N=733) = 33.7$; $p < 0.001$); the total is under 734 due to missing values

Table 6.2. Crash types of cyclists distracted by objects or the scenery next to the road.

Single-bicycle accident type Cyclist[1]:	Victim familiar with the accident location yes	 no	 total	row % (yes)
(1) hits a kerb or rides into a shoulder, or falls because a wheel is deflected on contact with tram rails (straight section or crossing)	84	11	95	12%
(2) collides with bollard or rides off the road in a bend	60	21	81	26%
(3) other	470	77	547	14%
Total	614	109	723	15%

[1] The second category is higher than the first and third ($\chi^2(2, N=723) = 8.8$; $p = 0.012$); the total is under 734 due to missing values

Table 6.3. Familiarity of single-bicycle crash victims with the accident location.

Single-bicycle crash type Cyclist[1]:	Cyclist looked behind yes	 no	 total	row % (yes)
(1) hits a kerb or rides into a shoulder, or falls because a wheel is deflected on contact with tram rails (straight section or crossing)	11	85	96	11%
(2) collides with bollard or rides off the road in a bend	3	80	83	4%
(3) other	14	540	554	3%
Total	28	705	733	4%

[1] The first category is higher than the second and third ($\chi^2(2, N=733) = 17.8$; $p < 0.001$); the total is under 734 due to missing values

Table 6.4. Crash types of cyclists who looked behind prior to the accident.

The questionnaire also included a question about physical problems. In total, 10 victims responded that they had problems with their vision (1.4% of all victims of single-bicycle crashes). According to Melief and Gorter (1998), 1-2% of the Dutch population is visually impaired. There are no data on their use of bicycles. According to Den Brinker *et al.* (2007), some people who are blind, according to the definition (visual acuity of 3/60 or less in the better eye or restriction of visual field to 10°), are still using their bicycle. In fact, for people who do not have a driving licence due to a visual acuity below 30/60, it can be the only efficient means of independent transport. The number of victims is too small to draw firm conclusions, but the results are in line with expectations. As indicated in Table 6.5, visually impaired cyclists are more frequently involved in the crashes of group V.

	Crashes			
Visually impaired[1]	group V	group NV	total	row % (group V)
yes	6	4	10	60%
no	173	549	722	24%
Total	179	553	732	24%

[1] Visually impaired are more often involved in crashes in Group V ($\chi^2(1, N=732) = 6.9; p < 0.01$); the total is under 734 due to missing values

Table 6.5. Single-bicycle crashes among visually impaired victims.

6.4. Study 2: Image degrading and edge detection analyses of single-bicycle crash locations

6.4.1. Procedure and method

A psychophysical analysis was performed to determine the visibility of large shapes (e.g. the distinction between the verge and the road surface) in the visual periphery: the image degrading and edge detection-method (IDED-method). The IDED-method was developed to determine the visibility of contrasts in the periphery of normally sighted people and the overall visibility of contrasts for people with low vision (Den Brinker and Daffertshofer 2005). The basic principles of the method are that the contrast-transfer properties of the eye's optical system are known to be nearly as good in the periphery as in the fovea (Wang *et al.* 1997) in contrast to the visual acuity that very rapidly falls off with eccentricity (Larson and Loschky 2009). Therefore, the visibility of an object at a certain eccentricity is determined by the visual acuity associated with the eccentricity and a minimum (constant) contrast. Visual acuity is determined by image degrading (i.e. the first step of the IDED-method); contrast level by edge detection (i.e. the second step of the IDED-method). The IDED-method was applied on all crash scenes of which photographs could be taken under the same light and weather conditions as during the crash.

About half of the respondents who filled in the questionnaire reported their telephone number or email address. Victims of crashes in group V were interviewed. It was possible to exactly locate 37 crash scenes. Of these 37, 16 were excluded because the interview revealed that it was unlikely that the characteristics of the visual design played a role in the crash. For instance, one of the victims hit a bollard that was occluded by a fellow cyclist just in front of her. All the 21 remaining crash scenes were inspected and analysed with the IDED-method.

Photographs were taken under the same conditions as during the crash: light, twilight or dark and wet or road-surface. The distance ahead of the crash location was 12.5 m, based on the following reasoning. According to Schieber *et al.* (2008), drivers need about 2 s of preview time to support ambient/near vision. Rumar and Marsh (1998) have summarised literature on preview times and concluded that 5 s is a realistic preview time for long-range visual guidance, with 3 s as an absolute minimum. Cyclists have an average speed of around 15 km/h, or 4.2 m/s (CROW 2007). These data suggest a visibility distance of 12.5 m for focal/far and ambient/near vision, within which the roads' edges and (gaps between) obstacles need to be visible in the visual periphery.

In the first step of the analysis, the images are degraded to simulate the effect of a given lowered acuity that is typical for a certain level of eccentricity. Technically, a Gaussian low pass filter degrades the image (Roelofs 1997). The second step uses edge detection, according to Sobel, that is calibrated to display all the contrasts that exceed a critical contrast level as measured according to Michelson. The contour lines in the resulting image show details that are visible given the predefined visual acuity and contrast level. Although 0.3 is often advised as a minimum contrast level for the design of the build environment (Wijk 2008), a lower level of 0.15 was used, as ambient vision is known to be especially sensitive to low-contrast/lowspatial-frequency information in normally sighted adult observers (Schieber *et al.* 2008). An iterative process is used to calculate at which level of visual acuity and associated eccentricity the critical information is visible. Information that the cyclist needed to see to be able to avoid the crash is labelled as 'critical', i.e. the edge of the road surface, the obstacle or the tram rails.

Figure 6.2a,b presents an example of the result of an IDED-analysis of a location where a bicycle path is delineated with a clear edge-of-track marking. Figure 6.2b shows that the edge line remains visible when the picture is blurred to a level of acuity of 0.1, the highest level of blurring that was tested. The relationship between the level of blur and the level of visual acuity was applied, as determined by Roelofs (1997), who used Landolt ring targets. A visual acuity of 0.1 corresponds to an eccentricity of 20˚. For the relationship with eccentricity, research by Larson and Loschky (2009), who examined the limits of visual resolution in natural scene viewing, was used.

Figure 6.2a. Bicycle path delineated with a clear edge-of track marking.

Figure 6.2b. Result of the IDED-analysis of the photograph in figure 6.2(a) that is blurred to a level of acuity of 0.1 (only contrast differences above 0.15 are shown).

6.4.2. Results

The 21 crash scenes were divided into three categories:
(1) cyclist hits a kerb or rides into a shoulder (n = 10);
(2) cyclist collides with a bollard or road narrowing (n = 7);
(3) cyclist falls as a wheel was deflected on contact with tram rails (n = 4).
The results of the IDED-analyses for these three categories are shown in Table 6.6. maximum acuity to which the pictures could be blurred without losing the critical information is shown in the right column. The critical information remains visible at an average level of acuity of 0.27 for the first, 0.18 for the second, and 0.12 for the third category, corresponding to eccentricities of 8, 12, and 15 degrees. The estimation for the last category is likely to be an underestimation, as two of the pictures were not blurred further than the maximum level we tested.

	Light condition		Road situation			
Type of crash scene	Dark or twilight	Day-light	Curve or intersection	Straight section	Examples in Figures	Average level of acuity (minimum - maximum)[1]
Cyclist hits a kerb or rides into a shoulder	6	4	8	2	6.3(a), 6.3(b), 6.4(a), 6.4(b)	0.27 (1 - 0.13)
Cyclist collides with a bollard or road narrowing	3	4	3	4	6.5(a), 6.5(b)	0.18 (0.27 - 0.13)
Wheel was deflected on contact with tram rails	3	1	2	2	6.6(a), 6.6(b)	0.12 (0.35 - 0.10)
Total	13	8	13	8		

[1] Acuity corresponding to the level of blur to which the critical information remained visible

Table 6.6. Information on the crash scenes and results of the IDED-analyses.

Figures 6.3a,b and 6.4a,b present the IDED-analyses of two situations in the first category. Figure 6.3a shows the situation where, even without blur, no luminance differences could be found between the verge and the road surface. This implies that the road edge was difficult to see, even when looked at under a high level of acuity (the dashed line shows the left side of the bicycle track). Figure 6.4a shows a curve where the contrast between the cycle path and the sidewalk was minimal. The spaces between the tiles offered sufficient contrast to be visible, but only at a relatively high level of acuity. An arrow that suggested a straight continuation of the path remained visible when the picture was blurred to a level of acuity of 0.1.

Figure 6.3a. Single-bicycle crash scene where the victim rode into the verge.

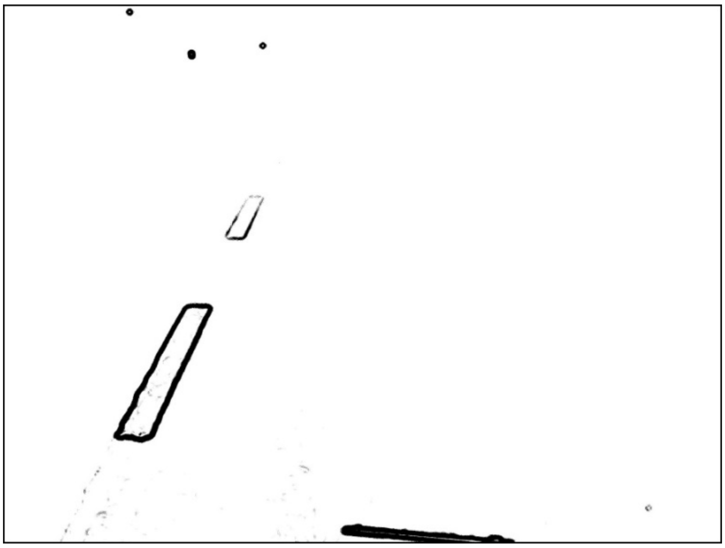


Figure 6.3b. Result of the IDED-analysis of the photograph in figure 6.3(a) that is not blurred (the luminance difference of the road's edge is too low to be detected by the IDED-method, even without blurring).

Figure 6.4a. Single-bicycle crash scene where the victim hit a 3 cm high kerb.

Figure 6.4b. Result of the IDED-analysis of the photograph in figure 6.4(a) that is blurred to a level of acuity of 0.5 (only contrast differences above 0.15 are shown).

Figure 6.5a,b shows the results of an IDED analysis of a crash scene where the victim hit a bollard in the middle of the cycle track. The bollard remains visible when blurred to a level of visual acuity of 0.2. However, an additional difficulty is that the bollard is masked in that it is coloured red–white and placed in the middle of a reddish-coloured bicycle path with a dashed white centreline. Figure 6.6a,b shows the results of an IDED analysis of a crash scene where the victim fell because a wheel was deflected on contact with rails parallel to the direction of the bicycle traffic. The tram rails remain visible at the highest level of blurring due to the light that is reflected by the tram rails.

Figure 6.5a. Single-bicycle crash scene where the victim hit a bollard.

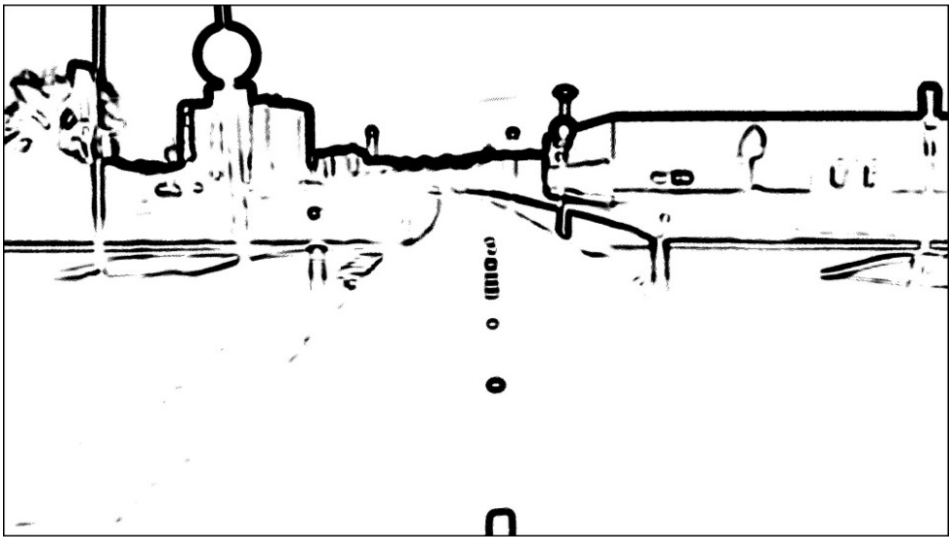


Figure 6.5b. Result of the IDED-analysis of the photograph in figure 6.5(a) that is blurred to a level of 0.2 (only contrast differences above 0.15 are shown).

Figure 6.6a. Single-bicycle crash scene where the victim fell because the front wheel was deflected on contact with tram rails.

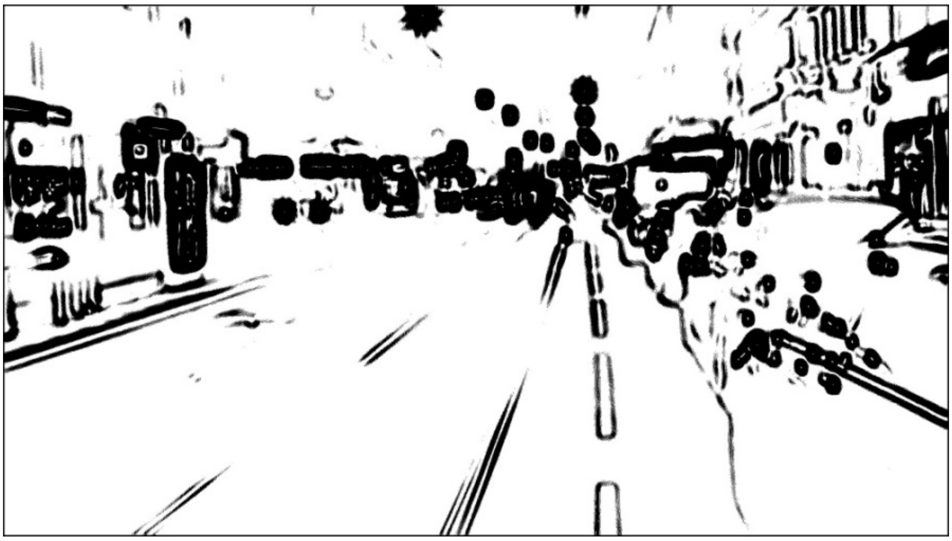


Figure 6.6b. Result of the IDED-analysis of the photograph in figure 6.6(a) that is blurred to a level of 0.1 (only contrast differences above 0.15 are shown).

Given the results of the IDED analyses and the descriptions of the crashes by the victims, it seems that some crashes were predominantly caused by deficiencies of focal vision, while others were primarily caused by problems with ambient vision. For instance, the victim did not notice the presence of a curve in the bicycle track at the crash scene that is presented in Figure 6.4a. As he did not notice the presence of the curve, it is likely that the crash was predominantly related to problems with focal vision. Conversely, the victim who rode off the road at the scene presented in Figure 6.3a was riding along a straight bicycle lane, as was clearly indicated by the dashed line along the left side (the line remained visible if the picture was blurred in an extra analysis to a low level of acuity of 0.1). She stated that she noticed too late that she rode off the road and then skidded. It is likely that problems with ambient vision, i.e. monitoring the bike's path, contributed to her crash.

6.4.3. Additional measurement: the detection conspicuity of obstacles

An additional psychophysical method, 'the detection conspicuity measure' (Toet *et al.* 1998), was conducted to determine the conspicuity of the obstacles in the second category in Section 6.4.2. As this method is designed for small targets in terms of viewing angle, it is not appropriate for judging the other two categories in Section 6.4.2. In this approach, detection conspicuity is operationally defined by the maximal lateral distance between target and eye fixation at which the target can be distinguished. Toet *et al.* (1998) found a correlation of 0.84 (n = 62) between detection conspicuity as determined by their method and search time.

The detection conspicuity of seven obstacles (six bollards and one road narrowing) was determined by the above described conspicuity measure. The angular distance between the fixation location at which the obstacle was first noticed and the obstacle was, on average, 13° with a minimum of 6 and a maximum of 22°. The average level of eccentricity found with the conspicuity measures matched the average level of eccentricity of 12° that was found using the IDED-method. Moreover, a Pearson correlation of 0.77 (n = 7; p = 0.043) was found between the results of the conspicuity measures and the IDED-analyses.

6.5. Discussion

While past research (e.g. Nyberg *et al.* 1996) demonstrated the relevance of road surface factors such as ice on the roadway and uneven paving for single-bicycle crashes, the present study has focused on the indirect factor of visibility of bicycle facilities and obstacles. It was hypothesised that the following categories of single-bicycle crashes are visual-design related: cyclist collides with a kerb, bollard or road narrowing; falls onto the shoulder (or crashed into an off-road object); or falls because a wheel is deflected on contact with tram rails parallel to the direction of the bicycle traffic. Study 1 revealed that several visually related factors were indeed correlated with these crashes, which supports the hypothesis. Compared to other victims,

victims of these crashes more often used alcohol prior to the crash and were more often over 60 years of age (i.e. with lower visual capabilities).

The crashes tended to happen more often under adverse light conditions although that difference was not significant. The fact that older cyclists avoid cycling under adverse light conditions may explain this finding. In other studies, it was found that older drivers limit their exposure to driving situations that they believe to be more difficult (e.g. rain, night, heavy traffic, rush hour) (Ball *et al.* 1998). This has been linked to the fact that older drivers, in contrast to younger drivers, experience decreased steering performance under low luminance conditions (Owens and Tyrrell 1999). Older cyclists' reluctance to cycle at night may be related to the same problem in addition to other factors such as feelings of insecurity. This might indicate that they suffer from a similar impairment of ambient vision that is needed for precise steering.

To further establish the relationship with the characteristics of the visual design, 21 crash locations were investigated in Study 2. The IDED analyses revealed that the critical information was difficult to see in the visual periphery at crash scenes where the victim rode off the road or collided with a bollard or road narrowing. The present results indicate that visibility of critical information in the visual periphery is indeed important for safe cycling. The IDED analyses revealed fewer problems with regard to the visibility of tram rails. It is likely that these crashes are primarily caused by other factors.

For Study 2, 37 scenes of crashes in group V were exactly located. Of these 37, 16 were excluded because the additional interview revealed that it was unlikely that the characteristics of the visual design played a role in the crash (e.g. a bollard was occluded by a fellow cyclist). Suppose the researchers had the same detailed crash information in Study 1 as was available for the small sample of crashes in Study 2. In that case, they could have classified more precisely between crashes that are related or unrelated to the visual design, resulting in reduced noise in the dependent variable that was used and probably in stronger results than were already found in Study 1. For instance, of the crashes in group V, about one-quarter happened in darkness or twilight, while more than half of the crashes that were selected for the IDED analyses happened in adverse light conditions.

6.5.1. Ambient and focal vision

Detailed information of the 21 crashes in Study 2 indicated that problems with both ambient and focal vision played a role in the investigated crashes. Study 1 revealed differences between crashes within group V that may be related to the distinction between ambient and focal vision. This first group, crashes in which a cyclist hit a kerb or rode into a shoulder on a straight section, happened more often to cyclists looking behind, but not more often to cyclists looking at something at the side of the road (compared with victims of other single-bicycle crashes). As there was no specific danger to be identified, focal vision seems less relevant. Ambient vision is likely to be more important as looking behind limits peripheral vision and requires balance. The second group, crashes in which a cyclist hit an obstacle or rode off the road in a curve, happened more often to cyclists looking at something at the side of the road, but not more often to cyclists looking behind (i.e. the other way around). Recognising the danger, i.e. focal vision, seems more important in these crashes. Viewing at larger eccentricities hinders focal vision.

Although answers on gazing patterns may be biased, as victims might be motivated to describe their crashes in ways that place blame externally, such a bias cannot completely explain the difference in gaze direction that was found between the two crash groups within group V. Moreover, crashes in the second group happened more often to cyclists, who were unfamiliar with the crash location, i.e. had fewer expectations to guide visual search, because one does not know where to expect hazards (Martens and Fox 2007). This result suggests that the focal operations that are typically well represented in consciousness play a more important role in crashes involving a curve or obstacle than ambient functions, which often operate in the absence of awareness (Leibowitz and Post 1982).

6.5.2. Recommendations for practitioners

The authors recommend starting where single-bicycle crashes are concentrated and no side effects for motorists are to be expected, i.e. obstacles and curves in cycle tracks. This can be realised by applying edge lines on curves in bicycle paths, especially paths with high levels of cycling, no street lighting or a risk of glare from oncoming vehicles. Two-way cycle tracks can be treated with warning centrelines in curves (longstretched lines instead of short lines) as is advised in the Dutch Design manual for bicycle traffic (CROW 2007). It is recommend to increase the conspicuity of bollards by colours that contrast well with their surroundings and by the use of an introductory profiled marking that also alerts cyclists riding behind another cyclist. It should also be assessed whether a bollard is necessary to keep drivers off a cycle track, based on its attractiveness for motorists and the possible harm caused by illegal use.

This study shows that characteristics of the visual design play a role in crashes where cyclists collide with a kerb, bollard or road narrowing, or ride onto the verge, but it does not indicate what the minimal requirements for visibility are. It is too early to advise edge-lines on all bicycle facilities. For instance, before deciding to install edge lines on cycle lanes, road authorities should take possible side effects into account, such as an increase of drivers' speed (Steyvers and De Waard 2000).

Apart from measures to limit the risk of cyclists riding off the road, measures can be taken to limit the consequences when cyclists fail to keep the bike in the centre of the lane. Bicycle facilities can be designed sufficiently wide and with a small difference in height between the surface of the road and the verge to enable cyclists to return to the road safely.

6.5.3. Recommendations for future research

The IDED-method was used to determine the visibility of obstacles and large shapes in the visual periphery for normally sighted people. For obstacles (i.e. small targets in terms of viewing angle), the results of the IDED analyses were compared with the results of the detection conspicuity measure in Section 6.4.3. The results of both measures matched fairly well, which was an important validation step of the IDED-method. Nonetheless, further research is desirable. First, the validation with the detection conspicuity measure was done with normally sighted observers and should be extended to other groups, as cycling facilities should be designed to meet the needs of the large majority of cyclists, including older and low vision cyclists (i.e. 'Design for All'). Second, the IDED-method was validated only with relatively small obstacles, i.e. six bollards and one road narrowing. However, cyclists discern the course of the road by large shapes with rather low contrasts, such as the separation between the road surface and the verge. Research on the usability of information for cyclists should focus on the ability to resolve the location and orientation of large shapes in relation to their contrast and eccentricity. The detection conspicuity measure is not suitable as a validation procedure for large shapes that cover a larger area of the visual field.

7. Road safety and bicycle usage impacts of unbundling vehicular and cycle traffic in Dutch urban networks[9]

Abstract

Bicycle-motor vehicle crashes are concentrated along distributor roads where cyclists are exposed to greater volumes of high-speed motorists than they would experience on access roads. This study examined the road safety impact of network-level separation of vehicular and cycle traffic in Dutch urban networks, a strategy for which the term 'unbundling' is used. Unbundling vehicular traffic and cycle traffic in an urban network is operationalized as the degree to which cyclists use access roads and grade-separated intersections to cross distributors. The effect on the share of cycling in the modal split is also assessed as unbundling may affect the competitiveness of cycling compared to driving in terms of trip length. The analyses were conducted on Dutch municipalities with more than 50,000 inhabitants. Negative binomial regression was used to analyse the effect on the number of police-reported cyclist deaths and in-patients in bicycle-motor vehicle crashes. A mediation model was tested, with Structural Equation Modelling hypothesizing that unbundling corresponds positively with the cycling modal share via the length of car trips divided by those by bicycle. The results of this study suggest that unbundling improves cycling safety, and increases the share of cycling in the modal split. We recommend unbundling vehicular and bicycle traffic in urban networks, e.g. establishing large traffic-calmed areas with short cuts and standalone paths for cyclists (and pedestrians) and, where feasible, grade-separated intersections such as bicycle tunnels.

7.1. Introduction

Research shows that the likelihood of bicycle-motor vehicle (BMV) crashes is higher on distributor roads than on access roads (Liu *et al.* 1995, Berends and Stipdonk 2009, Schepers *et al.* 2011, Teschke *et al.* 2012). Many cycling safety studies focused on separation between cyclists and motorists along

---

[9] This chapter was first published in EJTIR: Schepers, J.P., Heinen, E., Methorst, R., Wegman, F.C.M., 2013. Road safety and bicycle usage impacts of unbundling vehicular and cycle traffic in Dutch urban networks. *European Journal of Transport and Infrastructure Research*, 13(3): 221-238.

distributor roads by bicycle tracks (Reynolds *et al.* 2009, Wegman *et al.* 2012, Thomas and DeRobertis 2013). These studies, however, have not yet addressed network-level separation (Schepers *et al.* 2013b). This form of separation can be achieved by cyclists using access roads in traffic-calmed areas and crossing distributor roads at grade-separated intersections (bicycle tunnels and bridges). Network-level separation reduces cyclists' exposure to high-speed motorists and can therefore be hypothesized to correspond positively with cycling safety. In this paper we are using the term 'unbundling', first used in this context by two native English speakers (Johnson and Murphy 2013), to encompass the range of measures which might be used in network-level separation.

This study examines the road safety impact of unbundling vehicular and cycle traffic in Dutch urban networks. The effect on cycling's share of the modal split is also assessed as, in terms of trip length, unbundling may affect the competitiveness of cycling compared to driving. We hypothesize that increased unbundling corresponds positively with road safety and bicycle usage. Sections 7.1.1 and 7.1.2 describe literature to underpin these hypotheses. The operationalization and measurement of unbundling is further described and exemplified in Section 7.2 on data and methods. The results of a Principal Components Analysis will be presented in Section 7.3. Sections 7.4 and 7.5 describe the results of the analyses on road safety and cycling mode share respectively. The outcomes are further discussed in Section 7.6.

7.1.1. Research on unbundling and road safety

This section explains the hypothesis that a higher degree of unbundling is associated with improved road safety. Dutch road safety policy is founded on the Sustainable Safety vision which was introduced at the beginning of the nineties (Koornstra *et al.* 1992, Wegman *et al.* 2008). Two of its key principles are Homogeneity and Functionality. Homogeneity implies that differences in speed, direction, and mass should not be too large, e.g. a safe speed to mix cyclist with motorized traffic is no higher than 30 km/h (Tingvall and Haworth 1999). Functionality refers to classification of roads in a hierarchical road network. Agreement on implementation of the vision was reached in 1998, resulting in the construction of large traffic-calmed areas and the development of a hierarchical road classification by which Dutch roads are classified as *access* roads, *distributor* roads, or *through* roads. By 2008, the speed limit on 85% of the roads in built-up areas classified as *access* *roads* had been reduced to 30 km/h (Weijermars and Wegman 2011). Table 7.1 lists the speed limits and the location of cyclists for the three classes of road.

Road classes	Speed limits in urban areas	Location of cyclists
Access roads	30 km/h	Mixed with other traffic
Distributor roads	50 or 70 km/h	Separated from motorised traffic by bicycle tracks or bicycle lanes
Through roads	100 or 120 km/h	Cycling not allowed

Table 7.1. Road classification and speed limits in the Netherlands.

Functionality concentrates motorized (through) traffic, resulting in relatively high volumes of vehicular traffic on distributor and through roads, and low volumes on access roads, which have to be (re)designed for low speeds. Application of the homogeneity principle means that cyclists on distributor roads are separated from vehicle traffic on road sections by bicycle tracks and speed reduction at intersections. Research confirms that speed reduction reduces the likelihood of BMV crashes at intersections on distributor roads (Gårder *et al.* 1998, Schepers *et al.* 2011), but the combination of bicycle tracks and speed reduction at intersections does not seem to be sufficient to achieve the low levels of BMV crashes on access roads. Even though these measures are widely applied in the Netherlands, over 80% of all police-reported fatal and severe BMV crashes in built-up areas between 2004 and 2009 occurred on 50 or 70 km/roads, i.e. on distributor roads (SWOV 2011a). This can be explained by the volumes of high-speed vehicular traffic that cyclists are exposed to on distributors, especially at intersections. Section 1.1.1 and 1.1.2 further discuss literature on road safety on distributors and in traffic-calmed areas.

Distributor roads

Most research on cycling safety on distributors focused on the effect of the type of bicycle facility (Wegman *et al.* 2012). Welleman and Dijkstra (1988) found there were 59% fewer BMV crashes on distributor road sections with bicycle tracks (including unsignalized minor intersections) as compared to those with bicycle lanes. On the other hand, they found there were 50% more BMV crashes at distributor road intersections where bicycle tracks were present. At the time the study was conducted, most of these intersections were signalized. It has been found that replacing an intersection with a roundabout reduces the number of crashes with bicycles (and mopeds) by 60% (Van Minnen 1990) but the reverse, an increase, has also been found (Daniels *et al.* 2008).

Schepers and Voorham (2010) inspected BMV crash locations on intersections of 50 and 70 km/h distributor roads in three middle-sized Dutch cities. The results showed that around 60% of the crashes occurred at unsignalized priority intersections. Around two-thirds of cyclist casualties in BMV crashes at these intersections had been riding along the distributor (i.e. the cyclist had right of way); around one-third had been crossing the road (i.e. the motorist had priority) (Schepers *et al.* 2011). The risk per passing cyclist doubled when cyclists crossed a distributor as compared to when they crossed a minor road. It was found that a well-designed one-way bicycle track incorporating a deflection between 2 and 5m away from the main carriageway and speed-reducing measures could reduce the number of crashes for through cyclists. Unfortunately, no significant effects were found for road factors related to BMV crashes with cyclists crossing the distributor road (Schepers *et al.* 2011). Speed-reducing measures such as a speed hump did not reduce the crash risk (Schepers *et al.* 2011) but may reduce the injury risk (Kim *et al.* 2007, Wegman *et al.* 2012).

Traffic-calmed areas

A meta-analysis shows that area-wide urban traffic-calming schemes in residential areas reduce the total number of injury accidents by, on average, 25%. (Elvik 2001). However, low-cost designs, also applied in the Netherlands during recent years, were expected to result in only a 15% reduction (Schoon 2000). Cyclist crashes are not distinguished in these studies. An inspection of bicycle crash sites at 30 km/h access roads by Berends and Stipdonk (2009) suggested that the absence of a credible speed limit increased the risk of bicycle crashes in traffic-calmed areas. A number of BMV crashes can be prevented by speed management in residential areas where only low-cost traffic-calming measures are implemented (Weijermars and Wegman 2011).

Provided space is available, and the above described measures have not yet been implemented, there is scope for improving cycling safety on both distributor and access roads. However, it would appear from current knowledge that the extent of the effects of existing safety measures for distributor roads is insufficient to achieve the low likelihood of BMV crashes on access roads.

7.1.2. Research on unbundling and bicycle use

This section explains the hypothesis that a higher degree of unbundling is associated with a higher share of cycling in the modal split. A number of studies have already addressed how the built environment affects bicycle use, e.g. high densities and mixed land use are related to increased amounts of cycling (Heinen *et al.* 2010b). More relevant to this study is research at the network level. Research on the relationship between bicycle networks and bicycle use generally finds that factors contributing to shorter travel distances affect cycling positively (Heinen *et al.* 2010b). As an indication of the relevance of distance, the share of cycling in the 2010 modal split in the Netherlands was around 41% for trips between 1 and 2.5 km, reducing to 33% between 2.5 and 5 km and 23% between 5 and 7.5 km (Statistics Netherlands 2011). However, existing studies have not investigated the effect of how bicycle and pedestrian networks align with networks for through motor traffic, i.e. distributor roads (Frank and Hawkins 2008). Frank and Hawkins (2008) focused on pedestrians in the modal split and tested for the availability of each distinct mode's networks. Providing more direct routes for walking in contrast to those for driving was found to result in an increased share of walking in the modal split. They did not study cycling. Rietveld and Daniel (2004) compared the travel times of 12-16 trips made by both bicycle and car around the city centres of 103 Dutch municipalities. They found that, in terms of travel time, increased competitiveness of the bicycle in comparison with the car increases bicycle use. It is not clear, however, to what extent network characteristics contributed to this finding; factors such as congestion also play a role in travel time.

In the Netherlands, measures to unbundle cyclist and vehicular traffic are most often combined with creation of shorter routes for cyclists, i.e. short cuts available only to non-motorized traffic and the authorization of contraflow cycling on one-way streets. Unbundling may contribute to the bicycle's competitiveness in terms of trip length and thereby increase the share of cycling in the modal split. It is not expected that unbundling is necessarily directly correlated to the amount of bicycle use. High levels of unbundling are to be expected in towns and areas built since the 1970s which often have below-average densities and less mixed land-use, factors that are found to reduce bicycle use (Heinen *et al.* 2010b). Accordingly, the share of cycling in the modal split may even be somewhat below average in these areas, but would have been even lower had unbundling not contributed to the bicycle's competitiveness.

7.1.3. Study scope

This study investigates to what extent municipalities with a higher degree of unbundling have fewer cyclists hospitalized or killed following BMV crashes. The study included all 66 Dutch municipalities with more than 50,000 inhabitants, representing over 8 million people. Single-bicycle crashes are excluded as unbundling measures are not expected to have a substantial effect on such accidents. The effect on the number of casualties in car crashes is included to achieve a broader understanding of the road safety effects. The study also addresses effects on the share of cycling in the modal split. Other effects of unbundling, such as lower exposure to car exhaust fumes or reduced feelings of personal security, are not addressed in this study.

7.2. Data and methods

This section describes the data and methods used in this study. The present study uses a correlational design to examine how the estimated degree of unbundling of vehicular and cycle traffic is related to:

- the likelihood of cyclists being injured or killed in BMV crashes
- the likelihood of being injured or killed in car crashes, excluding cyclists (to give a more general picture of the effect on road safety)
- the share of cycling in the modal split.

Unbundling is a characteristic of a municipality's urban road network that we relate to its level of road safety and modal share of cycling. The study is therefore conducted at the municipality level. Municipalities with more than 50,000 inhabitants have been selected because most of the kilometres by bicycle are travelled in urban networks.

A sample of 66 study municipalities is expected to have sufficient statistical power to reject a null-hypothesis. Power is a function of sample size and sample variance: the statistical power grows as the former increases and the latter decreases (Cohen 1996). A low sample variance is expected in this study due to there being over 50,000 inhabitants per study unit and a study period of 6 years (between 2004 and 2009).

Section 7.2.1 describes the data and measurements used to determine the degree of unbundling. We complement databases for road traffic injuries and mobility data with route analyses to estimate the degree of unbundling and the competitiveness of cycling compared to driving (expressed as the length of trips by car divided by those by bicycle). Section 7.2.2 addresses the variables used for the analyses, and Section 7.2.3 describes the methods used to analyse road safety and bicycle use.

7.2.1. Data and measures

Police-reported crash data and mobility data from the Dutch National Travel Survey (NTS) are supplemented with the results of route analyses of trips reported in the 2008 NTS to estimate the degree of unbundling and the length of trips by bicycle and car, and the length of trips made by car compared to those made by bicycle. These data were combined with Statistics Netherlands (2011) data on population density and age of the population in Dutch municipalities, and the Netherlands slope map for altitude differences (Rijkswaterstaat 2011a).

Police-reported crashes

Police-reported crash data were used to determine the level of road safety, and comprised reported cyclist victims in BMV crashes and car crash victims over a six-year period (2004-2009) across the 66 middle-sized municipalities. In the case of BMV crashes, a total of 339 deaths and 5,611 casualties admitted to a hospital were included in the analyses; car crash casualties amounted to 617 deaths and 13,389 hospitalized casualties. Crash victims on motorways are excluded. The outcomes, therefore, are relevant only for roads where cyclists are allowed.

Under-reporting is a significant problem in bicycle crash studies (Wegman *et al.* 2012). Reurings and Bos (2011) showed that less than 10% of seriously injured victims of crashes with no motor vehicles involved (of which around 80% are single-bicycle crashes) are recorded by the police. On the other hand, cyclists seriously injured in BMV crashes (central to this study) are more likely to be recorded by the police than seriously injured car crash victims (SWOV, 2011). Under-reporting of bicycle crashes is not expected to be problematic is this study because we do not expect that under-reporting is related to the independent variables.

National Travel Survey

The National Travel Survey (NTS) is used to determine the share of cycling in the modal split for trips up to 7.5 km. The NTS describes the travel behaviour of the Dutch population, and is based on a sample of households drawn every month from the Municipal Basic Administration to ensure all types of travellers and households and all days are proportionately represented. Each member of the household is requested to record all journeys made on a particular day and report this online. Respondents are telephoned if they do not respond or to clarify missing answers, otherwise they are excluded from the final dataset (Rijkswaterstaat 2010). Between 2004 and 2009, a total of 140,852 households (317,258 persons) completed questionnaires, corresponding to a response rate of 70.5%.

Operationalization of unbundling in the Dutch context

Within the context of the Dutch road classification system, unbundling is operationalized by two factors:

- The proportion of the trip length where cyclists ride on access roads, including standalone paths. The higher the proportion, the higher the degree of unbundling.
- The number of dedicated grade-separated intersections (bicycle tunnels or bridges) per kilometre travelled by bicycle. A higher number implies a higher degree of unbundling.

Figure 7.1 depicts an urban road network, with two routes to the same destination to illustrate the degree of unbundling.

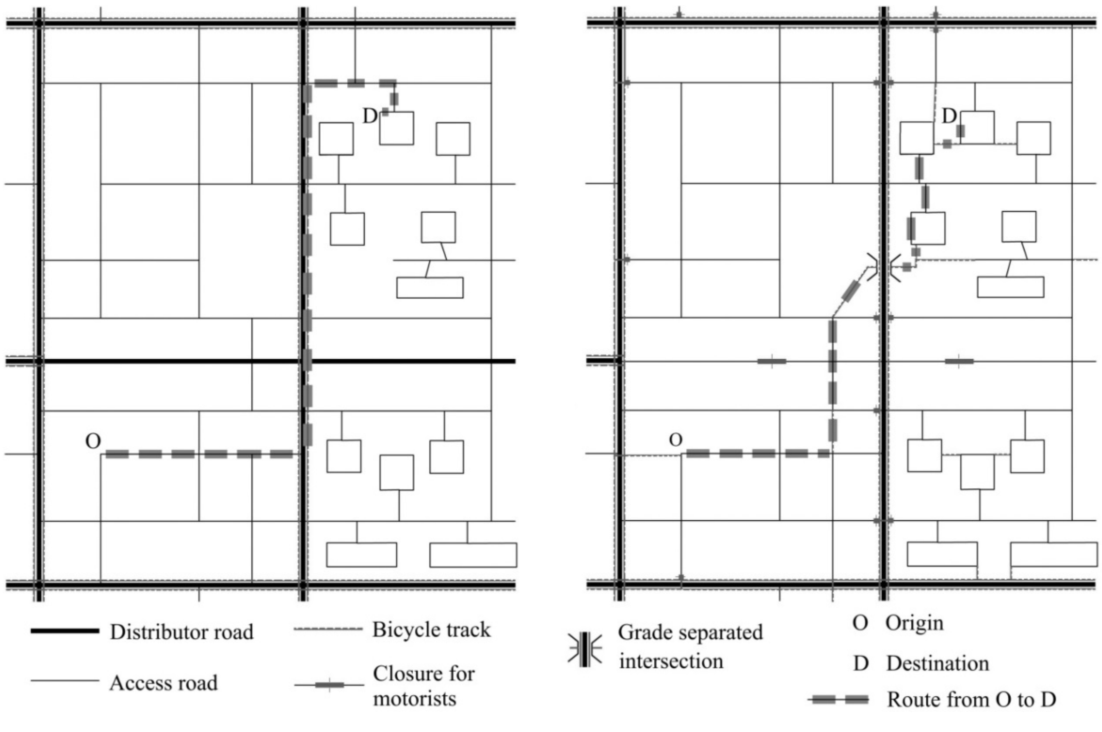


Figure 7.1. Examples of unbundling for two cycle routes; the degree of separation is low for the route in the left-hand figure and high for the route in the right-hand figure.

About 50% of the route in the left-hand figure is along a distributor road. There are no grade-separated intersections. The right-hand figure shows an adapted network with larger traffic-calmed areas, several bicycle-pedestrian short cuts and a bicycle tunnel accessible by a standalone bicycle track. The degree of unbundling is highest in the right-hand figure: 100% on access roads with 1 bicycle tunnel.

Route analyses

In this study, route analyses were carried out on the 2008 NTS dataset to measure the degree of unbundling. The shortest route is used as a proxy for cyclist routes, while the fastest route according to route planners is used as a proxy for car routes (see Schepers and Heinen (2013) for a more extensive explanation). Special permission was given to use a dataset containing the most detailed available ZIP codes, i.e. a six-position zip code (comprising, on average, 20 addresses) for the point of departure and return of around of one quarter of the trips, and a combination of six-position and four-position ZIP codes (consisting of on average 2,500 addresses) for the remainder. For privacy reasons, access to this dataset is not normally granted. Every first bicycle trip up to 7.5 km made each month, with a six-position zip code for the address of departure and return, was selected. This resulted in 12 trips per municipality (a total of 792 trips).

Cyclists' route choice behaviour was approximated by planning the shortest routes according to the Dutch Cyclists' Union route planner (Fietsersbond 2011). Data about which roads are distributor roads was needed to estimate the degree of unbundling. Roads with a 50 km/h speed limit on the Dutch Speeds Map (Rijkswaterstaat 2011b) were defined as distributor roads; roads with a 30 km/h speed limit and standalone bicycle tracks as access roads. The Dutch Cyclists' Union route planner was used to determine the share of the trip length through traffic-calmed areas and the number of grade-separated intersections, i.e. the degree of unbundling. The route planner was also used to determine the share of the trip length along distributor roads on bicycle tracks, and on standalone bicycle tracks for the other part of the trip through 30 km/h areas. Route analyses were used to determine the length of trips by bicycle and car. Car routes were approximated by planning the fastest route according to Google Maps (Google 2011) so that the length of the same trips travelled by bicycle and by car could be compared. Route analyses of 1,152 trips in 192 municipalities conducted in the Schepers and Heinen (2013) study were used to increase the sample size for the analysis of the relationship between the proportion of cycling in the modal split and the difference in length between car and bicycle trips. The trips analysed in that study and this current study partly overlap. The total number of trips used for this study amounts to 1,528.

7.2.2. Methods

This section describes the variables and methods used in the analyses on road safety and bicycle use.

Variables

The number of deaths and hospitalized casualties among cyclists in BMV crashes and casualties in car crashes per municipality is the dependent variable in road safety analysis. The share of cycling is the dependent variable in the analyses on the modal share of cycling. As described in the last section, the following independent variables were measured by route analyses:

- Share of the trip length through 30 km/h areas (%)
- Grade-separated intersections (no./km)
- Share of the trip length along distributor roads on bicycle tracks (%)
- Share of the trip length through 30 km/h areas on standalone paths (%)
- Trip length ratio (for the competitiveness of cycling): length of trips by car divided by those by bicycle

The first two variables define unbundling.

The presence of bicycle tracks is included as a control variable in the analyses on safety and bicycle use. A number of other variables need to be controlled in these analyses. Provision needs to be made for the control of kilometres travelled by bicycle and by car, the age of the population and population density. Important control variables for analyses on bicycle use are (Rietveld and Daniel 2004, Heinen *et al.* 2010b):

- the proportion of youngsters in the population, defined as inhabitants up to and including 17 years of age
- the presence of a university
- the presence of significant differences in altitude, defined as those greater than 50m within urban areas
- population density, defined in the same way as in the earlier study by Schepers and Heinen (2013): three groups, each containing one-third of all municipalities (low: < 272/km^2, medium 272-742/km^2, high: >742/km^2)
- city size in terms of number of inhabitants, operationalized using three categories of municipalities determined by testing which category

boundaries led to the greatest differences in bicycle use, resulting in small: <50,000; medium 50,000-175,000; high: >175,000.

To avoid overfitting, these control variables need to be addressed without adding additional parameters to the regression analyses.

Data reduction

Regression analyses are conducted to estimate the effect of unbundling on safety and cycling mode share. The number of independent variables explicitly included (further described in the next section) has to align with the sample size in order to avoid overfitting. A rule of thumb for regression analysis holds that the number of observations should be at least 20 times greater than the number of variables under study (Schneider *et al.* 2010). This means that a maximum of three independent variables can be included in analysis (with a sample size of 66 municipalities), and that data reduction is needed to model the above-mentioned variables. We therefore carry out Principal Components Analysis (PCA) on the variables measured in the route analyses. Besides reducing the number of variables, this step helps to avoid multicollinearity. PCA attempts to represent all of the variance of the observed variables and results in a reduced number of uncorrelated factors for regression analysis (Floyd and Widaman 1995, Garson 2012).

Negative Binomial regression for road safety analyses

Using Generalized Linear Models in SPSS, Negative Binomial (NB) regression was carried out to test the effect of unbundling on numbers of police-reported crash victims. The basic form of nearly all modern crash prediction models used for NB regression is (Eenink *et al.* 2008):

$$E(\mu) = \alpha V_M^{\beta 1} V_C^{\beta 2} e^{\Sigma y_i x_i}$$

The expected number of bicycle crash victims, $E(\mu)$, is a function of traffic volumes of motor vehicles (V_M) and cyclists (V_C) and a set of risk factors, x_i (i = 1, 2, 3, …, n), . The coefficient α is a scaling parameter, which ensures that the predicted number of crashes is in the same range as the police-reported number of crashes. Coefficients $\beta 1$ and $\beta 2$ describe the shape of the relationship between traffic volume and victim numbers. The effects of various risk factors that influence the probability of crashes, given exposure, is modelled as an exponential function, that is as e (the base of natural logarithms) raised to a sum of product of coefficients, y_i, and values of the variables, x_i, denoting the presence of risk factors.

NB regression serves as statistical approximation to the crash process (Lord *et al.* 2005). Although the Poisson model has served as a starting point for crash-frequency analysis for several decades, researchers have often found that crash data exhibit over-dispersion (i.e. the variance exceeds the mean), which makes the application of the simple Poisson regression problematic. NB regression, which is now the most frequently used model in crash-frequency modelling, overcomes this problem (Lord and Mannering 2010) and accordingly has been used in this study.

Because of the number of observations involved, applying the above-described form of model, including all control variables, results in too large a number of independent variables. In linear regression analysis and Structural Equations Modelling, researchers statistically partial out the effects of control variables from the model variables and then test the model in order to avoid too complex a model. This method is not an option in the case of NB regression, where the values of the dependent variable are count data. Therefore, the authors first predicted the number of cyclist and car crash deaths and in-patients by using the Crash Prediction Models (CPMs) developed in an earlier study (Schepers and Heinen 2013). These comprised the following variables:

- kilometres travelled by bicycle and by car (excluding kilometres travelled on motorways)
- age of cyclists and car crash victims
- population density of the municipalities.

CPMs were developed for the same study period (2004-2009) and for a larger set of 387 municipalities (see Schepers and Heinen 2013). The number of victims predicted by the CPMs, E_{CPM}, is included as an offset. The model that will be tested in this study has the following form:

$$E(\mu) = \alpha E_{CPM} e^{\Sigma y_i x_i}$$

The expected number of victims, $E(\mu)$, is a function of an offset, E_{CPM}, multiplied by e raised to a sum of product of coefficients, y_i, and values of the factors under investigation, x_i.

Structural Equation Modelling for analyses on bicycle use

The indirect effect between unbundling and the cycling modal share via the length of trips by car divided by those by bicycle is tested using Structural Equation Modelling (SEM) in SPSS Amos. As with the road safety analyses, the availability of bicycle tracks will be included explicitly in the model as a control variable. SEM uses covariance analysis whereby model parameters are determined such that variances and covariances of the variables implied by the model system are as close as possible to the observed variances and covariances (Golob 2003). The size of the indirect effect between the degree of unbundling and the share of cycling is the product of path coefficients. We conducted Sobel's (1982, 1988) test to examine whether the indirect effect is significant.

Other control variables important to the amount of cycling were partialled out of the covariance matrix prior to analysis. The technique for partialling out the effects of one or more (control) variables from other variables in order to find the relationship between them is called partial correlation. For example, Ley (1972) describes a researcher interested in the relationship between variables A and B, with the effects of C partialled out from both. He would have to correlate the residual scores of A and B, after the parts of A and B predictable from C have been subtracted. This results in a partial correlation between A and B (controlled for variable C). In our study, the controls were partialled out instead of being explicitly modelled because the latter would have resulted in a high number of independent variables.

Note that the path between trip length ratio and the share of cycling is determined using additional data from the cases in the study by Schepers and Heinen (2013). This increases the sample size for this relationship in the path model to 192. Data on the degree of unbundling and availability of bicycle tracks was available for 66 of these 192 municipalities. The other path coefficients are therefore determined using the 66 cases (for which route analyses are conducted in this study) and treating the other cases as missing values.

7.3. Data reduction

This section describes the Principal Components Analysis (PCA) to reduce the number of variables measures in the route analyses. Trip length ratio (length of trips by car divided by those by bicycle) is not included in the PCA. This variable needs to be included explicitly in the SEM analysis to test the indirect effect of unbundling on bicycle mode share.

Table 7.2 shows the means, standard deviations, and correlations for the 4 route analysis variables. The results of the route analyses suggest that cyclists travel around two-fifths of bicycle kilometres in built-up areas on distributor roads and three-fifths through traffic-calmed areas. Per kilometre, cyclists on average pass 0.1 grade-separated intersections such as bicycle tunnels and bridges. The correlations show that both variables defined to operationalize the degree of unbundling (share of the trip length through 30 km/h areas and the number of grade-separated intersections per km) are highly correlated (a correlation coefficient of 0.58). Including both variables in the regression analyses results in biased parameter estimates due to multicollinearity. The results of NB regression analyses (using the four variables in the upper part of Table 7.2) indicated large changes in the estimated regression coefficients when either of the two highly correlated variables was added or deleted. This problem is avoided by using PCA.

Based on the Kaiser-Guttman criterion (eigenvalue > 1), two factors could be retained in the PCA that together explain 76% of the variance of the observed variables. These have been included in Table 7.2 as the Degree of unbundling and the Availability of bicycle tracks (along both distributor roads and standalone paths through residential areas). Positive factor figures indicate higher degrees of separation and ample availability of bicycle tracks. The varimax-rotated solution is shown in Figure 7.2. The share of the trip length along distributor roads and the number of grade-separated intersections per km both have factor loadings greater than 0.80 on the unbundling factor and low factor loadings on the bicycle tracks factor. The share of the trip length on bicycle tracks along distributor roads and the share of the trip length on standalone paths in 30 km/h areas have factor loadings greater 0.65 on the bicycle tracks factor and lower loadings on the unbundling factor. The share of the trip length on standalone paths through 30 km/h areas has, besides a loading of 0.66 on the bicycle tracks factor, also a loading of 0.54 on the unbundling factor. This may result from the fact that standalone paths are often used in conjunction with bicycle tunnels and bridges to give cyclists access to grade-separated intersections. The unbundling factor score thus consists of the share of the trip length where cyclists ride along distributor roads, the number of grade-separated intersections per km and, to a lesser extent, the availability of standalone paths.

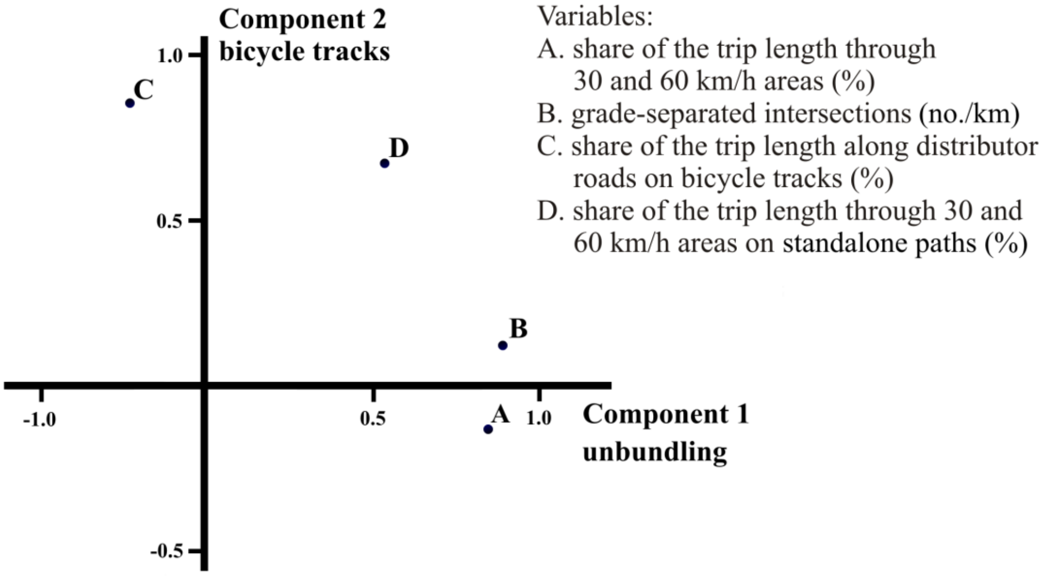


Figure 7.2. Factor loadings of the four independent variables on the unbundling and bicycle tracks factor.

			Correlations					
Variables	Mean	SD	1.	2.	3.	4.	5.	6.
Independent variables:								
1. Share of the trip length through 30 km/h areas (%)	59.2	11.9	1	0.58**	-0.14	0.23	0.84**	-0.14
2. Grade-separated intersections (no./km)	0.1	0.1		1	-0.07	0.43**	0.88**	0.09
3. Share of the trip length along distributor roads on bicycle tracks (%)	59.5	19.8			1	0.25*	-0.20	0.88**
4. Share of the trip length through 30 km/h areas on standalone paths (%)	15.3	10.1				1	0.54**	0.66**
Factor scores:								
5. Degree of unbundling	0	1					1	0.00
6. Availability of bicycle tracks	0	1						1

* p < 0.05 (two-tailed)
** p < 0.01 (two-tailed)

Table 7.2. Descriptive Statistics for the Route Analysis Variables (N=66).

The route analyses variables that will be explicitly included in the road safety analyses are:

- Degree of unbundling of vehicular and cycle traffic based on 66 municipalities
- Availability of bicycle tracks based on 66 municipalities

These route analyses variables will be included in the analysis on bicycle usage as well, next to the trip length ratio based on 192 municipalities (see Section 7.2.2).

7.4. Results of road safety analyses

This section describes the results of the road safety analyses conducted to test the hypothesis that unbundling corresponds positively with cycling safety. Table 7.3 shows descriptive statistics. Per municipality, around 5 cyclists were killed and 85 were hospitalized in police-reported BMV crashes between 2004 and 2009. The numbers of reported casualties in car crashes (excluding cyclists) amounted to 9 deaths and 203 hospitalizations.

			Correlations					
Variables	Mean	SD	1.	2.	3.	4.	5.	6.
Crash victims 2004– 2009:								
1. Cyclist deaths in BMV crashes	5.1	2.8	1	0.81**	0.68**	0.78**	-0.28*	-0.02
2. Cyclist hospitalizations in BMV crashes	85.0	39.6		1	0.68**	0.90**	-0.27*	-0.04
3. Deaths in car crashes (excluding cyclists)	9.3	5.3			1	0.83**	-0.27*	-0.14
4. Hospitalized casualties in car crashes (excluding cyclists)	202.9	171.0				1	-0.30*	0.00
Factor scores:								
5. Degree of unbundling	0	1					1	0.00
6. Availability of bicycle tracks	0	1						1

Table 7.3. Descriptive Statistics for the Variables Used in the Crash Analyses (*p <.05. **p <.01; two-tailed).

The results of NB regression analyses on police-reported crash victims between 2004 and 2009 are shown in Table 7.4. The results show that the likelihood of cyclists being hospitalized or killed due to BMV crashes is lower in municipalities with a higher degree of unbundling. The availability of bicycle tracks is not found to be related to the crash likelihood. The regression coefficients can be interpreted as follows. The coefficient for unbundling in the regression analysis of cyclist deaths is -0.27, meaning that an increase in an unbundling score of 1 (or 1 Standard Deviation as the factors are standardized variables) in a given municipality leads to a reduction of 24% (1 minus exp(-0.27) in the likelihood of being killed in BMV crashes). Likewise, the likelihood of cyclists being hospitalized in BMV crashes decreases by 15%. The likelihood of car crash victims being hospitalized is also significantly lower in municipalities where the degree of unbundling is higher (a difference of 12%). The likelihood of being killed in car crashes is also associated with unbundling, but this is only significant at the 10% level.

	Cyclist victims in BMV crashes		Victims in car crashes (excl. cyclists)	
Variables	Fatalities	Hospitalized	Fatalities	Hospitalized
Casualty numbers	339	5,611	617	13,389
Regression parameters for:				
Degree of unbundling	-0.27 (-0.47 to -0.07)*	-0.16 (-0.25 to -0.06)**	-0.10 (-0.22 to 0.01)	-0.13 (-0.20 to -0.06)**
Availability of bicycle tracks	0.01 (-0.17 to 0.19)	-0.03 (-0.12 to 0.06)	-0.11 (-0.23 to 0.02)	-0.01 (-0.09 to 0.07)
Log likelihood	-169.7	-349.7	-206.0	-404.2

Table 7.4. Estimation results for regression on police-reported crash casualties (95% Wald CI; (*p <.05. **p <.01; two-tailed).

7.5. Results of analyses on bicycle use

This section describes the results of the analyses conducted on bicycle mode share to test the hypothesis that unbundling corresponds positively with bicycle usage. Table 7.5 shows descriptive statistics of the variables used in the analyses. The average share of cycling in the modal split for trips up to 7.5 km is 34%. It ranges between 12 and 49% in the 66 municipalities for which route analyses were conducted. Trips are, on average, 20% longer by car than by bicycle (ranging between 6 and 51%). The degree of unbundling and availability of bicycle tracks are factor scores with an average of zero and standard deviation of 1. Two new towns (Lelystad and Almere) have the highest degrees of unbundling.

SEM was used to test the mediation model shown in Figure 7.3. The model comprises the indirect effect of unbundling on cycling mode share via the trip ratio, and the bicycle tracks factor. The effects of variables 5 − 11 have been partialled out of the model variables 1 − 4. The results show that the specified model provided an acceptable fit to the data, indicated by a Chi-square statistic that was not significant ($\chi^2(1, N=192) = 0.002, p=0.96$). The CFI value was 1.00. A rule of thumb for CFI is that a good model should exhibit values greater than 0.90 (Golob 2003).

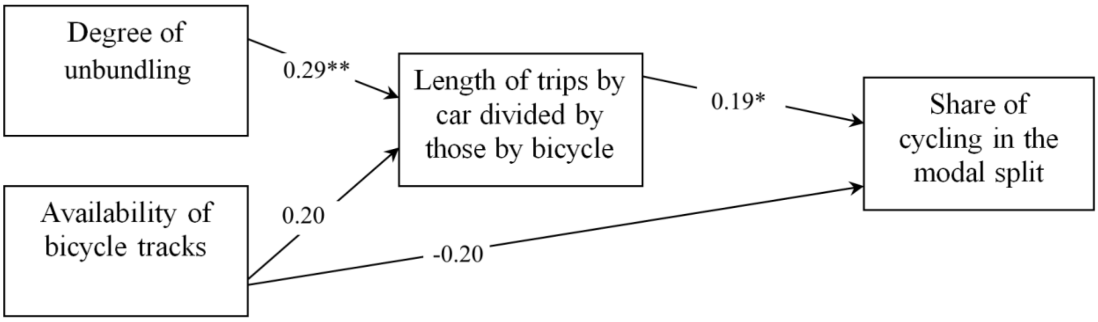


Figure 7.3. Structural model with standardized parameter estimates (*p <.05. **p <.01).

Variables	Mean	SD	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.
1. Share of cycling in the modal split for trips up to 7.5 km	34.0	7.1	1	0.12	0.07	-0.17	0.35**	-0.10	-0.01	0.01	-0.06	0.03	-0.37**
2. Length of trips by car compared to by bicycle	1.2	0.1	0.15*	1	0.26*	0.15	-0.13	-0.12	0.29**	0.18*	0.17*	0.12	-0.03
3. Degree of unbundling	0.0	1.0	0.04	0.24*	1	0.00	0.18	0.19	-0.15	0.01	-0.01	-0.11	-0.13
4. Availability of bicycle tracks	0.0	1.0	-0.16	0.16	-0.02	1	0.03	-0.03	0.01	0.00	0.00	-0.20	-0.18
5. Share of youngsters in the population (% up to 17 years of age)	22.6	2.4					1	0.01	-0.19**	-0.19**	-0.16**	-0.33**	-0.29**
6. Medium population density (272-742/km^2)	33.1	47.1						1	-0.50**	-0.16**	-0.10*	-0.13*	0.08
7.High population density (>742/km^2)	33.3	47.2							1	0.41**	0.21**	0.25**	0.04
8. Medium size (50.000-175.000 inhabitants)	15.0	35.7								1	-0.06	0.13**	0.10*
9. Large size (> 175.000 inhabitants)	2.1	14.2									1	0.60**	-0.02
10. Presence of a university	3.1	17.4										1	0.15**
11. Presence of large altitude differences (>50m within built-up areas)	2.8	16.6											1

Table 7.5. Descriptive Statistics for the Variables Used in the Bicycle Usage (correlations above the diagonal are for raw scores; correlations below the diagonal are partial correlations that have variables 5-11 partialled out; *p <.05. **p <.01).

The path coefficients are shown in Figure 7.3. A higher degree of unbundling is related to a higher ratio for the length of trips by car divided by those by bicycle ($\beta = 0.29$, $p < 0.01$), this being related to a higher share of cycling in the modal split ($\beta = 0.19$, $p = 0.01$). None of the coefficients of the paths from bicycle tracks to other variables is significant. The indirect effect of the degree of unbundling via the trip length ratio on the share of cycling can be estimated to 0.06 (0.29 multiplied by 0.19). The two-tailed Sobel test showed that the indirect effect was almost significant (t = 1.86, p = 0.063). While this small indirect effect is in line with the hypotheses, the result is only significant at the 10% level. The statistical significance is further discussed in Section 7.6.

7.6. Conclusions and discussion

This study, using data at the municipality level, examined the effects on road safety and bicycle use of unbundling vehicular and cycle traffic in urban networks. A higher degree of unbundling is associated with cycling through traffic-calmed areas and grade-separated crossing of distributor roads, i.e. by bicycle bridges and tunnels. Cyclists can be guided to these structures by use of standalone paths through residential areas. The results of this study suggest that:

- municipalities with a higher degree of unbundling have fewer cyclist casualties (hospitalized or killed) in BMV crashes;
- measures taken for unbundling tend to improve the competiveness of cycling (car trips become longer relative to the same trips made by bicycle), thereby slightly increasing the share of cycling in the modal split.

The positive effect on cycling safety can be explained by the fact that cyclists are exposed to lower numbers of motorists in municipalities where there is a greater degree of separation between them. The likelihood of car crash victims (cyclists excluded) being hospitalized is also significantly lower in municipalities where the degree of unbundling is higher (the effect is smaller than for cyclist casualties). Other road users' safety also benefits from measures such as large traffic-calmed areas associated with unbundling. The small positive effect on bicycle use can be explained by the improved competitiveness of cycling compared to driving. The trip length by bicycle becomes relatively shorter than the same trip made by car due to measures such as short cuts where roads are closed to motor vehicles, authorization of contraflow cycling on one-way streets (SWOV 2010b). The finding that reducing lengths of trips by bicycle compared to those by car is related to the share of cycling in the modal split aligns with earlier research by Rietveld and Daniel (2004), who found that competitiveness in terms of travel time plays an important role in bicycle use.

Because of its positive effects on road safety and bicycle usage, we recommend the unbundling of motor and cycle traffic in urban networks (see also Furth (2012) and Van Boggelen *et al.* (2011) for recommendations concerning the implementation). Another argument in support of unbundling is the outcome of a recent study by Jarjour *et al.* (2013), indicating that unbundling decreases cyclists' exposure to vehicle-related air pollutants. According to De Hartog *et al.* (2010), the health effects of inhaled air pollution can be as serious as those of traffic accidents.

The statistical significance of the results regarding cycling modal share

It was hypothesized that unbundling corresponds positively with the cycling modal share via the length of car trips divided by those by bicycle. It can therefore be argued that the null-hypothesis has to be tested using a one-tailed probability because the hypothesis clearly states the direction of the effect (Heiman 1999). The one-tailed probability of the indirect is significant (p = 0.031), which supports the hypothesis. Section 7.5 presented only the two-tailed Sobel test which was almost significant (p =0.063).

Effect of more cycling on road safety

The road safety effect of unbundling was determined using Crash Prediction Models (CPMs) to control the kilometres travelled by bicycle and car in each municipality, i.e. the results reflect *ceteris paribus* effects. However, policies to separate cyclists from the distributor road network tend to increase the share of cycling in the modal split. Results from two recent Dutch studies estimating the effect of an increased share of cycling in the modal split suggest that transferring short trips made by cars to bicycles does not change the number of fatalities (Schepers and Heinen 2013), or leads to only a small increase (Stipdonk and Reurings 2012). Both studies suggest a greater increase in the number of hospitalized casualties as a result of more single-bicycle crashes (see also Schepers 2012). The road safety effects of unbundling are found to be strong and robust, whereas its effects on the share of cycling in the modal split are small. It is therefore expected that the direct effects of unbundling on road safety, as identified in this study, will be more numerous than the additional indirect effects of more cycling.

Study limitations and recommendations for future research

A strength of this study compared to earlier studies conducted at a spatially aggregated level is that an empirically-based measure of traffic volumes per municipality could be derived from the NTS. This is important because volumes explain the largest part of the systematic variation in crash frequency (Brüde and Larsson 1993). Researchers often have to rely on proxies for bicycle use per spatial unit, based on population per square mile, numbers of employed, number of school children, etc. (e.g. Vandenbulcke-Plasschaert 2011, Siddiquia *et al.* 2012). However, a limitation of the NTS is that kilometres travelled in municipalities cannot be split between kilometres travelled inside and outside city limits. The CPMs developed in the Schepers and Heinen (2012) study − also used for this study − are developed to estimate the casualty numbers inside and outside city limits. This is disadvantageous because the current study focuses on an issue within city limits. The effect on the outcome is expected to be minimal because we selected municipalities with over 50,000 inhabitants where the largest part of the population lives within city limits. Of the police-reported cyclist fatalities between 2004 and 2009 in the municipalities in our sample, almost 85% occurred within city limits. The figure for police-reported hospitalized cyclists was over 90% (SWOV, 2011), meaning that only between 10 and 15% of casualties are most likely unaffected by unbundling. This means that, because BMV crashes outside city limits are not likely to be affected by unbundling, the effect of unbundling may be even greater than found in our study. Future research could consider estimating volumes within city limits (e.g. by using multimodal traffic models) to analyse the effect of unbundling (CROW 2007).

Another reason for not drawing firm conclusions on size of the effect is that it depends on the composition of measures adopted by road authorities. For instance, traffic-calmed areas may differ in size and the extent to which motor vehicle speed is successfully reduced. This indicates that the effect of such measures may differ in quality, which makes it even more difficult to study how such measures contribute to the effects of unbundling. While winding residential streets may successfully lower speed, they may also decrease the recognizability of routes for cyclists. This may reduce the likelihood of them choosing routes through such areas, but it could be countered by a recognizable network of more direct standalone bicycle tracks, etc. This suggests that the success of an unbundling strategy depends on how well the measures are aligned. Isolating and quantifying the effects of individual measures may be difficult and may deny the importance of the combined effect of a range of measures to overall effectiveness. However, it could be valuable to focus on the most important elements and their relative importance, e.g. routes through traffic-calmed areas *vs* grade-separated intersections to cross distributors.

8. Discussion, conclusions and recommendations

This thesis is focused on the question of how the road environment (network characteristics and road design) affects road safety for cyclists through effects on risk and exposure to risk. Policy interest in how infrastructure safety can be improved for cyclists has increased in recent years. Encouraging the establishment of safer infrastructure for cyclists is one of the seven objectives of the European road safety policy document (European Commission 2010) . This research has been carried out in the Netherlands where cycling safety is a key issue in the Strategic Road Safety Plan (Ministry of Infrastructure and the Environment 2008), due to a rising proportion of cyclists killed and seriously injured in the total number of road traffic casualties.

The research questions formulated in this thesis address three main topics. The first subject is about how the road environment affects travel behaviour and exposure. For instance, the distribution of cycle and vehicular traffic over space determines the extent to which cyclists are exposed to motorists. The second is about the road environment's effect on crash risk. The third topic is the relationship between exposure and risk. A decrease or increase in crash numbers is not proportional to changes in either bicycle usage or crash risk. For instance, the risk of bicycle crashes may decrease when there are more cyclists on the road because motorists may modify their behaviour (see e.g. Brüde and Larsson 1993, Jacobsen 2003), i.e. exposure would affect risk. Risk-adverse people who perceive cycling to be dangerous may take up cycling when the risk of bicycle crashes decreases (Heinen *et al.* 2010b, Van Wee *et al.* 2012), i.e. risk would affect exposure. One of the innovative aspects of this thesis is that it contains studies related to all three topics, aiming to increase the knowledge of how the environment contributes to or helps prevent bicycle crashes. Most research is restricted to one of the three issues. Figure 8.1 depicts the research questions within the conceptual framework described in the introduction.

Section 8.1 summarizes the findings of the studies conducted to answer the research questions. Section 8.2 reflects on the outcomes. Both Sections are organized according to the topics of travel behaviour and exposure, risk, and the relationship between these two. Sections 8.3 and 8.4 describe research and policy recommendations.

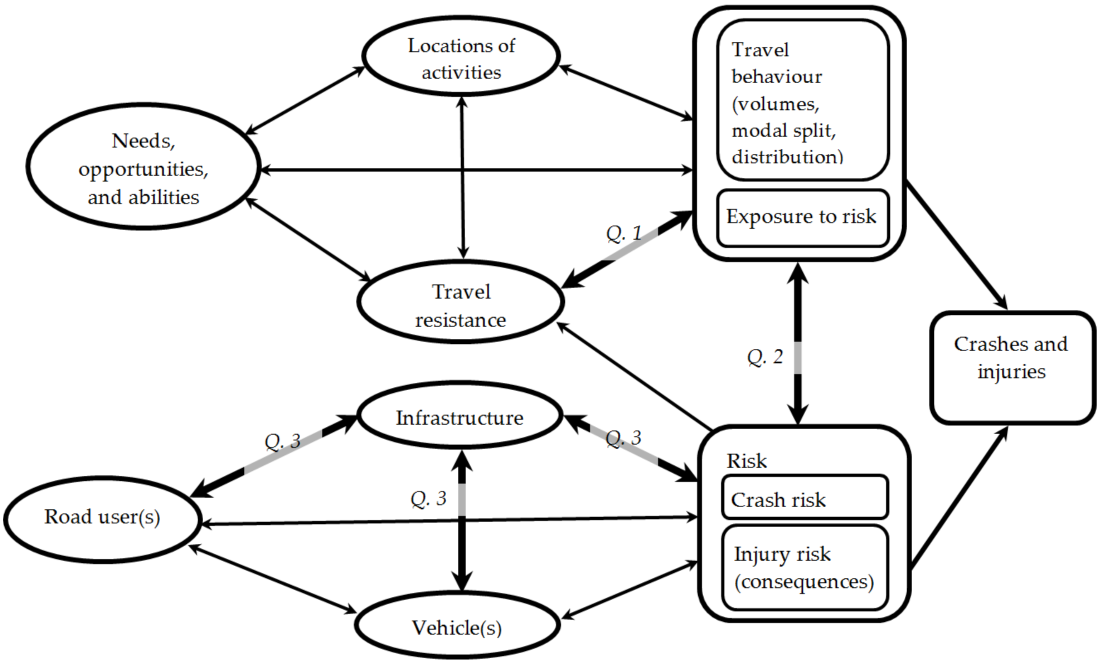


Figure 8.1. Research questions positioned within the conceptual framework (the arrows depicting relationships addressed in this thesis are in bold).

8.1. Overview of the results

This section provides an overview of the results by answering the research questions. Each subsection addresses one of the three central topics and starts with the research gaps to explain how the study has contributed to current knowledge. The details of the methods and data are described in the chapters and are not repeated in this section.

8.1.1. Travel behaviour and exposure

This section focuses on how characteristics of the road environment affect travel behaviour and thereby exposure and road safety. Researchers have studied the effect of characteristics such as road structure density and stopping frequency that may affect bicycle usage because trips become shorter and/or faster by bicycle (see Rietveld and Daniel 2004, Heinen *et al.* 2010b). Another aspect of travel behaviour is the distribution of vehicular traffic and cyclists over space. This affects where and how often cyclists encounter motorists. Research shows that the likelihood of bicycle-motor vehicle (BMV) crashes is highest on distributor roads and lowest on access roads (Liu *et al.* 1995, Schepers 2006, Berends and Stipdonk 2009, Teschke *et al.* 2012), which can be explained by the volumes and speed of vehicular traffic that cyclists are exposed to on distributors. However, fewer studies investigated whether there are fewer cyclist casualties in BMV crashes in municipalities where cyclists are more unbundled from vehicular traffic on the distributor road network (Van Boggelen *et al.* 2005, Van Boggelen *et al.* 2011). Most studies focused on the effects of bicycle facilities such as bicycle tracks that can be built on distributors (e.g. Reynolds *et al.* 2009), i.e. measures taken at the location level instead of the distribution of cyclists in a road network. Therefore, research question 1 was formulated as follows (see Chapter 7): *How does unbundling vehicular and cycle traffic in an urban network affect road safety?* Unbundling is operationalized by separating cyclists from vehicular traffic on distributor roads by use of access roads, standalone bicycle tracks and grade-separated intersections to cross distributors.

The results of the study described in Chapter 7 suggest that unbundling improves cycling safety. Municipalities with a higher degree of unbundling have fewer fatally and severely injured cyclists per kilometre cycled. The effect on the share of cycling in the modal split was also investigated as the measures implemented for unbundling may affect the competitiveness of cycling compared to driving. Cyclists may benefit from short cuts where roads are closed for motorists and from being allowed to use one-way streets in both directions, etc. The results of the study suggest that measures taken for unbundling decreased the distance of trips by bicycle compared to those by car, which corresponds positively with the share of cycling in the modal split.

8.1.2. The relationship between exposure, risk and road safety

Characteristics of the road environment may encourage or discourage cycling. To estimate the road safety effect of a change in the amount of cycling, researchers have first focused on the risk for cyclists. Several studies have shown that a motorist is less likely to collide with a cyclist where there is a higher incidence of cycling (e.g. Jacobsen 2003, Robinson 2005). However, it is not possible to draw conclusions about the effect on road safety in general by solely focusing on cycling safety. To the author’s best knowledge, Elvik (2009) was the first to estimate the road safety effects of shifts from car to bicycle using Crash Prediction Models (CPMs) in which a non-linear relationship between crashes and volumes is assumed. Empirical studies show that the relationship between crashes and traffic volumes is highly non-linear. Elvik selected CPMs from existing research in several countries using different study units (junctions, road sections, towns, and countries). A study in which CPMs are developed using crash and mobility data from jurisdictions to estimate the road safety effects of a changed modal split of car and bicycle use in the same jurisdictions is lacking in scientific literature. Also, the currently available CPMs were developed for BMV crashes and not for single-bicycle crashes (Elvik 2009).

Research question 2 was formulated to address the above-described gaps (Chapters 2 and 3): *How does a modal shift from short car trips to cycling affect road safety?* To answer this question, Crash Prediction Models (CPMs) were developed for Dutch municipalities. Models were developed for bicycle crashes with motor vehicles and single-bicycle crashes. As single-bicycle crashes are under-reported by the police, the study also included another source (self-reported crashes from a questionnaire study). It was found that cyclists are less likely to be involved in a severe single-bicycle crash in municipalities with a high amount of cycling. This may have several explanations including improved infrastructure in municipalities with higher amounts of cycling. Another explanation holds that cyclists gain better control and greater physical fitness the more they cycle. This hypothesis was supported by the outcomes of the study presented in Chapter 5. Cyclists who cycle the least (i.e. less than one day per week) are most likely to be involved in two crash types that seem to be linked to cycling skills and strength, i.e. falling while (dis)mounting and loss of control due to braking mistakes.

The volumes of cyclists and motor vehicles before and after a hypothetical modal shift were entered into the CPMs to estimate the road safety effects. The results suggest that, ceteris paribus, under conditions such as in Dutch municipalities, transferring short trips made by cars to bicycles does not change the number of fatalities, but increases the number of serious road injuries. The rise in the number of serious road injuries is due to high numbers of severe single-bicycle crashes. The effect of a modal shift is dependent on the age of the population in which the shift is concentrated (i.e. more favourable for young and less favourable for older drivers). Furthermore, the results suggest that it may be possible to influence the effect of a modal shift by measures specifically affecting cyclists' injury risk.

8.1.3. Crash risk

This section focuses on how characteristics of the road environment affect crash risk, firstly the risk of bicycle-motor vehicle crashes (BMV) and secondly the risk of single-bicycle crashes.

Bicycle-motor vehicle crashes

A review study by Reynolds *et al.* (2009) and a more recent study by Lusk *et al.* (2011) suggest that purpose-built bicycle-specific facilities such as bicycle tracks reduce crashes and injuries among cyclists. Similar results were found in the Netherlands in a study that controlled for both car and bicycle volumes (Welleman and Dijkstra 1988). Intersection studies focused mainly on roundabouts. For instance, it was found that a separated cycle track decreases the risk for cyclists (Dijkstra 2004, Reynolds *et al.* 2009). Fewer studies focused on signalized and unsignalized intersections, and studies that do lack an integral approach to isolate the effect of specific design factors (Reynolds *et al.* 2009, Hamann and Peek-Asa 2013). As most intersection crashes with cyclists on distributor roads occur at unsignalized intersections (Schepers and Voorham 2010), question 3a was formulated (Chapter 4): *How is the design of unsignalized priority intersections related to bicycle-motor vehicle crashes?*

Failure-to-yield crashes with cyclists were studied to answer this question. These BMV crashes are classified into two types based on the movements of the involved motorists and cyclists:

- type I: through bicycle related collisions where the cyclist has right of way (i.e. bicycle on the priority road);
- type II: through motor vehicle related collisions where the motorist has right of way (i.e. motorist on the priority road).

The results show that more type I crashes occur at intersections with two-way bicycle tracks, well-marked, and reddish coloured bicycle crossings. Type I crashes are negatively related to the presence of raised bicycle crossings (e.g. on a speed hump) and other speed reducing measures. The accident probability is also decreased at intersections where the cycle track approaches are deflected between 2 and 5m away from the main carriageway. No significant relationships are found between type II crashes and design factors such as the presence of a raised median.

Single-bicycle crashes

Only a very few studies have focused specifically on the most common type of non-fatal bicycle crash, i.e. the single-bicycle crash. A good description of single-bicycle crash types seems to be lacking in the scientific literature, although high numbers of victims are common (Kroon 1990, Langley *et al.* 2003, Veisten *et al.* 2007, Hagemeister and Tegen-Klebingat 2011). Several studies indicate a role of direct causes related to road surface quality, i.e. an uneven or slippery road surface (e.g. Nyberg *et al.* 1996, De Geus *et al.* 2012).

Indirect risk factors such as the visibility of the roadway and obstacles for cyclists have not yet been studied. Therefore studies were conducted to address two research questions.

Question 3b is about single-bicycle crash types (Chapter 5): *What single-bicycle crash types can be distinguished and can these be related to infrastructure?* A categorization of single-bicycle crash types was developed using literature, theory, and a survey among bicycle crash victims treated at Emergency Care Departments. In this section, only crash types related to infrastructure are described. The results indicate that about half of all single-bicycle crashes are related to infrastructure: the cyclist collided with an obstacle (1), rode off the road (2), the bicycle skidded due to a slippery road surface (3), or the rider was unable to stabilize the bicycle or stay on the bike because of an uneven road surface (4). The last two confirm the role of direct causes such as poor road surface quality, which were also described by, for instance, Nyberg *et al.* (1996). The first two suggest that indirect causes such as the visibility of the road surface may also play a role. Question 3c focuses on this issue (Chapter 6): *What do cyclists need to see to avoid single-bicycle crashes?*

To study the role of visual characteristics of the infrastructure, such as pavement markings, in single-bicycle crashes, a study in two steps was conducted. In Study 1, a questionnaire study was conducted among bicycle crash victims to study the relationship between the crashes and age, light condition, alcohol use, gaze direction, and familiarity with the crash scene. In Study 2, the image degrading and edge detection method (IDED-method) was used to investigate the visual characteristics of a small sample of the crash scenes. The results of the studies indicate that crashes in which the cyclist collided with a bollard or road narrowing or rode off the road were related to the visibility of bicycle facilities.

8.2. Reflection on the results

The main outcomes of the studies were described in Section 8.1 for each research question. This section reflects on the outcomes. The contributions of the studies to the scientific literature and remaining research gaps are discussed per research topic in Sections 8.2.1 up to 8.2.3, and jointly in Section 8.2.4. Other sections focus on the internal and external validity of the studies of the thesis (Sections 8.2.5 and 8.2.6) and finally technological trends and their potential effects (Section 8.2.7).

8.2.1. Travel behaviour and exposure

The results of the study described in Chapter 7 showed that the likelihood of BMV crashes is lower in municipalities in which cyclist and motor traffic is more unbundled. This result can be explained by the distribution of traffic that lowers cyclists' exposure to (high-speed) motorists, especially at intersections. The 'working ingredients' are thus a reduction of exposure to motorists and the reduced speeds of these motor vehicles which decreases risk. The results also show a small positive effect on the share of cycling in the modal split. These results are important for road safety policy and bicycle plans which often have targets regarding both safety and bicycle usage (European Commission 2010, ETSC 2012). Unbundling may also increase the health benefits of cycling. In a recent study it was found that, when compared to busier roads, cyclists using a network of (low-traffic) residential streets are less exposed to vehicle-related air pollution (Jarjour *et al.* 2013).

The study focused on unbundling was not suitable for studying how individual measures contribute to its implementation and road safety benefits. A composition of measures may contribute to unbundling, e.g. large traffic-calmed areas, bicycle tunnels and bridges accessible by solitary bicycle tracks, street closures for cars, etc. The sample size of 66 municipalities was too small to isolate the effect of the individual measures. Even if the sample size would have been greater, examining the effect of individual measures had been difficult. Traffic-calmed areas may differ in size and the extent to which motor vehicle speed is successfully reduced, i.e. the effect of measures such as traffic calming may differ in quality, which makes it even more difficult to study how such measures contribute to the effects of unbundling. Moreover, a cauliflower design for a residential area's road network with winding roads may successfully reduce speed, but it may decrease the recognizability of routes for cyclists. This may reduce the likelihood that they chose routes of which a large part is through these areas, which could be countered by a recognizable network of more direct standalone bicycle tracks, and so on. This suggests that the success of an unbundling strategy depends on how well the measures are aligned, i.e. isolating the effects of individual measures in research may be difficult and may deny the importance of the whole composition of measures to the overall success.

As described above, it may be difficult to conduct research to determine the contribution of individual measures to cycling safety and bicycle usage. However, other research methods may also contribute to the knowledge of how a successful policy for unbundling may be developed. More research could be focused on cyclists' route choice along distributors versus through traffic-calmed areas. The goal of unbundling is to have cyclists choosing routes through residential areas. Examples of measures that may increase the attractiveness of routes through residential areas are standalone bicycle tracks and bicycle streets. Moreover, priority on these routes may reduce cyclists' stopping frequency which could reduce travel time. Rietveld and Daniel (2004) found a lower stopping frequency to correspond well with bicycle usage. To the best of the author's knowledge, the effect of measures affecting stopping frequency on route choice have not yet been studied. Research on cyclist route choice could be an interesting line of research to develop knowledge for unbundling strategies.

8.2.2. Effect of exposure on road safety

The studies described in Chapters 2 and 3 suggest that, under circumstances such as in Dutch municipalities, exchanging short car trips for bicycles hardly affects the number of fatalities but increases the number of serious road injuries. The latter is because of increasing numbers of single-bicycle crash victims. The models for bicycle crashes are also applicable to estimate the road safety effects of an increase in bicycle trips (extra trips instead of substituted trips) to the extent that the additional trips are on average comparable to current bicycle trips. The studies improved the knowledge of the link between exposure and road safety, but a number of research gaps remain.

The models are based on the current distribution of bicycle usage inside and outside city limits. The models do not explicitly distinguish between bicycle and car kilometres inside and outside city limits, because the source on which the studies are based (the Dutch National Travel Survey) does not differentiate between these two. Estimations of the road safety effects of additional trips of which a large part is travelled outside city limits are thus less reliable. For this purpose, CPMs have to be developed for kilometres travelled by bicycle and by car both inside and outside city limits. Future research could consider estimating volumes within city limits combining NTS data with (multimodal) traffic models (CROW 2007).

Another interesting research question would be what the safety effects are of a shift from longer journeys by car to journeys by train with bicycles for travelling to and from the railway station. In the Netherlands, the number of kilometres travelled by train increased by 15% as compared to an increase of

3% by car between 2000 and 2010. The proportion of bicycle trips as part of a train journey increased from 2.5% to 4% of all bicycle trips (KiM 2011). This may be partly due to investments in bike parking at railway stations and the successful bike-sharing programme called 'OV-fiets' ('public transport bicycle'), which enables people to cycle from the station to their destination (Pucher and Buehler 2012). To estimate the road safety effects of a shift from car trips to journeys by train and bicycle, CPMs have to be developed for train trips. Given the high level of safety of public transport, such a shift may have a positive impact on road safety.

Estimations of the road safety effect of a modal shift are an important input for studies on the health effects of a modal shift such as the study by De Hartog *et al.* (2010). This study underestimated the health burden of bicycle crashes in that it is based only on mortality and not morbidity. Single-bicycle crashes often result in minor or even severe injuries but are rarely fatal. However, given the large health benefits of physical exercise, it is likely that the health benefits outweigh the health risks even if these non-fatal crashes would are included. Nevertheless, more research on this issue is needed to draw firm conclusions. The health burden due to minor and serious injuries can be estimated in DALYs (Disability Ajusted Life Years) to include it in health effect studies (see e.g. Dhondt *et al.* 2013). It has also been found in the study reported in Chapter 3 (and similarly by Stipdonk and Reurings 2012) that per exchanged car kilometre, the road safety effect is worst for the elderly. On the other hand, in a supplement to their paper[10], De Hartog *et al.* (2010) indicate that the largest estimated gain in life years due to increased physical activity was also for the elderly. This suggests that the net health effects are probably not strongly affected by the distribution of a modal shift over age groups. This hypothesis could be tested in future research with health effects estimated in DALYs.

The studies of this thesis developed CPMs to account for the non-linearity of risk. However, there are still several possible explanations for this non-linearity and the studies' internal validity is not strong enough for inferring causality. Jacobsen's (2003) explanation is that motorists modify their behaviour when they expect to see or experience people walking and bicycling ('safety in numbers'), while other researchers claim that infrastructure is improved in response to increased amounts of cycling

---

[10] Website Fietsberaad:
http://www.fietsberaad.nl/library/repository/bestanden/do_the_health_benefits_of_cycling_outweigh_the_risks.pdf

(Brüde and Larsson 1993, Wegman *et al.* 2012), or vice versa (Dill and Carr 2003, Pucher *et al.* 2010). A better understanding of factors explaining the non-linearity of risk is important for policy makers, e.g. policy could focus on infrastructure if the non-linearity results from improved infrastructure (Bhatia and Wier 2011, Wegman *et al.* 2012). A similar lack of internal validity seems to apply to research on the effect of perceived risk on bicycle use. Not only is reduced perceived risk associated with increased bicycle usage, it also tends to alter the compilation of the cyclist population. Some 'risk-adverse' groups, such as women and the elderly, may be the first to take up cycling as the risk decreases (Pucher and Buehler 2008, Heinen *et al.* 2010b). These particular groups of cyclists may have a different risk profile which could change cyclists' average crash rates when they take up cycling. Exploration of the causal mechanisms that might explain the relationship between risk and exposure is a challenge for future research, and could help substantiate the links in between the upper and lower part of the conceptual framework. We will further reflect on this relationship in Section 8.2.4 using the conceptual framework.

8.2.3. Risk

The thesis broadens research on bicycle facilities from the mere presence of a facility, which is what most research has looked at (Reynolds *et al.* 2009), to how its specific design helps prevent BMV and single-bicycle crashes. For instance, the study described in Chapter 4 indicates that at an unsignalized intersection, a raised bicycle crossing deflected between two and five metres from the main carriageway has a lower likelihood of BMV crashes than a crossing adjacent to the carriageway without a speed reducing measure. In both cases there is a bicycle track but the risk at the intersection differs substantially. Likewise the results of the studies described in Chapters 5 and 6 suggest that the likelihood of single-bicycle crashes may be below average on a bicycle track with a good road surface quality, no elements such as drain covers that may become slippery when wet, no obstacles such as bollards on the roadway, and edge lines to delineate its course.

Reynolds *et al.* (2009) indicated in their literature review that some investigators did not define the bicycle facilities they studied or grouped facilities that may have different risks. The fact that many researchers did not address design characteristics other than the type of facility may have resulted in confounded outcomes. The studies described in Chapters 4, 5, and 6 indicate that design characteristics matter for safety. Another problem in studies focused on the impact of transportation infrastructure is the lack of control for the number of cyclists at risk (Elvik *et al.* 2009, Reynolds *et al.* 2009). Also, many studies rely on police-reported crashes. Bicycle crashes with motor vehicles are more likely to be reported than single-bicycle crashes (Reynolds *et al.* 2009, Wegman *et al.* 2012). This means that the results of a study based on police-reported crashes, in which single-bicycle and bicycle-motor vehicle crashes are not distinguished, are biased in favour of the latter crash type. Also, because cyclist fatalities mostly result from bicycle-motor vehicle crashes while serious injuries mostly result from single-bicycle crashes, it may not be a good idea to combine fatalities and serious injuries in one KSI measure (Killed and Seriously Injured). Rules of thumb for future research on bicycle crashes and infrastructure are to include all the design features that are considered relevant for the crash type under study, to control for traffic volumes (of cyclists and of motorists in the case of BMV crashes), and to distinguish between crash types and levels of severity.

The study described in Chapter 4 focused on unsignalized intersections and cycling safety. Several previous studies related to infrastructure focused on roundabouts (e.g. Dijkstra 2004, Daniels *et al.* 2008, Daniels *et al.* 2009, Sakshaug *et al.* 2010). A number of research gaps relating to intersection crashes remain because, as yet, not all relevant intersection types have been studied. Future research could focus on signalized intersections where around one out of five BMV intersection crashes on distributor roads in middle-sized Dutch cities occur (Schepers and Voorham 2010). The review study by Reynolds *et al.* (2009) indicated that only a few studies have focused on this intersection type. It is likely that both traffic lights arrangement (e.g. for red light running) and design features play a role in crashes at this intersection type, which makes such research even more challenging than research at unsignalized intersections. A first step could be to focus on specific types of signalized intersections, e.g. intersections with bicycle tracks and separate signals for cyclists or intersections without such facilities.

There are also research gaps related to single-bicycle crashes. The results of the studies described in Chapters 5 and 6 suggest that road features, e.g. the visual design of the infrastructure and the coefficient of friction between the tyres and the road surface, play a role in single-bicycle crashes. However, there is, to the best of the author's knowledge, no *evaluation* research on measures to prevent single-bicycle crashes such as edge lines, improved winter maintenance, and forgiving shoulders. Such research is important to determine the effect including side effects like potential behavioural adaptation. Before-after or cross-sectional studies could provide knowledge regarding the effect of measures, but suitable data sources for such research are lacking. The reporting rate in police statistics is very low, while medical registrations lack essential details such as the crash location. The large size of the problem justifies more research on single-bicycle crashes including research on the effects of preventive measures. A prerequisite for the next step in research on single-bicycle crashes is a registration in which these crashes are recorded with more details regarding crash type and location and during a period sufficiently long to acquire data for correlational and/or before-after studies. An option would be to conduct a pilot project targeted at single-bicycle crashes in municipalities by expanding the registration at the emergency care departments of the hospitals in these municipalities. By including a crash location, effect studies for single-bicycle crashes become feasible. For instance, this would enable investigating to what extent the number of single-bicycle crashes during winter would be reduced on a selection of routes after winter maintenance is improved. Innovative research methods such as *in-depth research* on cycling crashes and *naturalistic cycling* (observing cyclists in a natural environment) may also increase our understanding of single-bicycle crashes (Davidse 2007a, Dozza *et al.* 2012). However, these methods seem to be unsuitable for evaluating the effect size of infrastructure measures.

The sample size of the studies focused on *crash* risk was insufficient to address *injury* severity as well. For policy makers it may be of interest to know to what extent measures reduce crash risk on the one hand and injury consequences on the other, because targets are often formulated in terms of numbers of severe injuries and fatalities. Future research can focus on how road design is related to injury severity, e.g. by comparing fatal crashes with severe crashes using Crash-severity models (see e.g. Kim *et al.* 2007). For instance, the study described in Chapter 4 suggests that deflecting a bicycle track along a distributor road between 2 and 5 metres from the main carriageway reduces the risk of BMV crashes about as much as a speed reducing measure. However, a speed reducing measure will also reduce injury severity. Research using Crash Severity Models may help to test how road features contribute to a reduction of crash severity. This may show that of the two above-mentioned design features, which affect crash risk to the same degree, speed reducing measures may most strongly decrease injury consequences.

Research focused on crash severity (using Crash Severity Models) seems complementary to research focused on crash risk (using Crash Prediction

Models). Even though Negative Binomial regression modelling is possible when some study units (intersections, road sections, or other geographical units) have zero crashes, the total number of crashes needs to be sufficiently large to acquire reliable results (Lord and Mannering 2010). At the level of larger geographical areas (e.g. municipalities in Chapters 2, 3, and 7), it is possible to achieve sufficiently large numbers of severe crashes. This enables separate models for crashes with varying levels of severity to be developed (e.g. a specific model for fatal crashes). However, at the level of road sections or intersections, this is difficult because many have no severe crashes over a period of several years. For instance, the study on intersection crashes described in Chapter 4 included 540 intersections which allowed analyses of the total number of crashes only (most of which with minor injuries or material damage only). Studies using Crash Severity Models can efficiently achieve reliable results with a sufficiently large sample of crashes with severe versus minor injuries. Recording the infrastructure features can be restricted to the locations of these crashes, i.e. no locations without crashes need to be included. In contrast, in a study using a Crash Prediction Model, a large number of locations without crashes would have to be taken into the study. This problem is surmountable when studying crash risk (regardless of crash severity) because most road sections and intersections have one or more crashes. An efficient way of conducting research regarding infrastructure at the level of road sections and intersections would be to combine research on *crash* risk (using Crash Prediction Models) with research on *injury* severity (using Crash Severity Models). Note finally that surrogate measures such as Safety Performance Indicators like speed (Hakkert *et al.* 2007) and traffic conflicts (Van der Horst 1990) are also available in case of low crash numbers. The use of these and of Injury Severity Models were outside the scope of this thesis.

8.2.4. The three issues discussed jointly using the conceptual model

The three central issues of this thesis (exposure, crash risk, and the relationship between these two) were depicted in the conceptual framework described in the introduction (see also Figure 8.1). To discuss how the three topics are connected, this section elaborates the discussion on the relationship between exposure and risk which was already started in Section 8.2.2. The conceptual framework and results from studies on all three topics (from Chapters 2, 3, 4, and 7) are used in this discussion.

To study the relationship between exposure and risk, Crash Prediction Models (CPMs) were developed at the level of municipalities (see Chapters 2 and 3). These CPMs help to describe the relationship between exposure and risk mathematically. The conceptual framework is used to discuss, conceptually, which factors may play a role in the relationship, both directly and indirectly. It therefore helps to identify which factors may affect the outcomes of estimated CPM parameters. Take, for example, two cities – A and B – where different factors caused an increase in bicycle usage (see Figure 8.2). In response to high road safety *risks* run by cyclists, city A decides to invest in safer *infrastructure* for cyclists. This results in a *risk* decrease and accordingly a lower perceived risk, i.e. in a reduction of this type of *travel resistance*. As a result, more people take up cycling, i.e. the *exposure* increases. In this chain, a risk decrease goes hand in hand with an increase in bicycle usage. Because of congestion problems, city B raises parking fees for motor vehicles. The revenues are used to build and finance free, guarded bicycle storages near the city centre and railway station. The *travel resistance* increases for motor vehicles and decreases for bicycles. In this chain, an increase in bicycle usage is not accompanied by measures to decrease cyclists' crash risk. The 'safety in numbers' phenomenon (motorists modify their behaviour in the expectation of cyclists) may apply to both cities to the same degree, i.e. more cyclists on the road may lead to a decreased crash risk among cyclists. In the conceptual framework this relates to the arrow between risk and exposure. In this example, both cities may experience an equal increase in the amount of bicycle usage but the decrease in cyclists' crash risk is greatest in city A.

The examples of city A and B show that in a study on the direct relationship between exposure and risk, there may be 'confounding' factors that affect both exposure and risk. The statistical relationship between exposure and risk found in a study may not only reflect the actual relationship between these variables, but also how the confounder affects both variables. A statistical way of isolating the (direct) relationship between exposure and risk would be to include infrastructure variables in the CPM. This has, for instance, been done in the CPMs fitted on intersection crashes in a small number of cities in Chapter 4 with numbers of passing cyclists as exposure measure (see also Elvik 2009). Cyclists in these cities probably use various intersections in the study sample. Assuming that there are no large differences in bicycle usage between cities which coincide with different infrastructure policies, the possibility is diminished that systematic differences in the risk profiles of the cyclists crossing the intersection play a role. The results of studies at the intersection level suggest that the non-linearity of risk found in these CPMs is partly due to factors such as behavioural adaptation by drivers (in the expectation of more cyclists), as suggested by Jacobsen (2003) and Brüde and Larsson (1993).

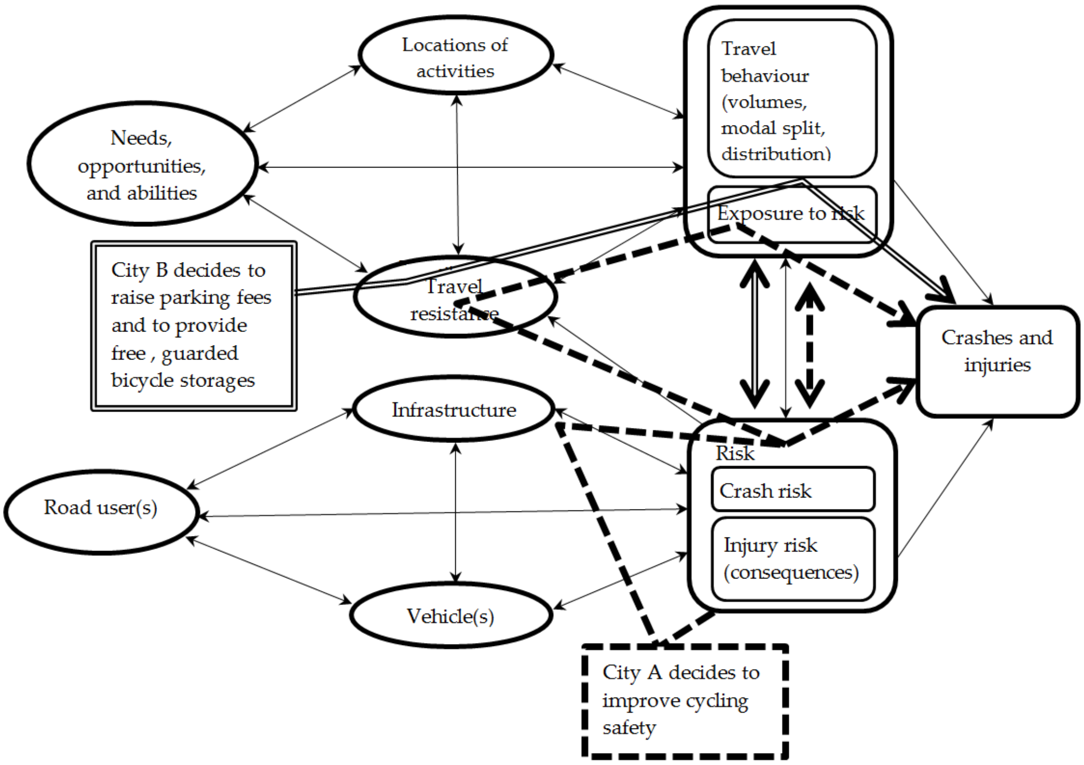


Figure 8.2. Examples of chains of effects leading to changes in both risk and exposure in two cities.

However, there were no data available to include infrastructure factors in CPMs developed at the municipality level (see Chapters 2 and 3). It can therefore not be ruled out that improved infrastructure also plays a role in the non-linearity in these models. The same applies to differences in the compilation of the cyclist population, e.g. risk-adverse cyclists may take up cycling as infrastructure is improved, which changes the average cycling risk. It could be that these factors play only a minor role in the Netherlands where municipalities with very low levels of cycling are hard to find and where application of guidelines may guarantee a minimum level of infrastructure quality. On the other hand, the results of Chapter 7 suggest that unbundling improves cycling safety and may also increase bicycle usage to some extent. The sample of cities in Chapter 7 was too small to fit an integral model including both exposure and infrastructure factors. If data on infrastructure factors are available on a larger scale, these could be included as control variables in a model that focuses on the relationship between exposure and risk. Such data could thus help to acquire more knowledge of the actual relationship between exposure and risk in future research.

Finally, it is important to stress that this thesis focussed on the interaction between the road environment and cycling safety. The conceptual framework used in this study clearly shows that factors unrelated to the road environment play a role as well. Take for example cycling under the influence of alcohol, of which the decision to do so is related to the upper part of the model and the risk to the lower part of the model. Future research in these areas is important for road safety policy.

8.2.5. Internal validity: causality

The crash studies described in this thesis have a correlational (or cross-sectional) design. Strictly speaking, no causal relationship can be demonstrated as a correlational design does not allow to establish whether the supposed cause actually precedes the effect. Only true experiments with a strong theoretical underpinning and random assignment of participants to treatment conditions offer strong evidence for causal inferences. However, there is a consensus that the outcomes of well-conduced correlational research can at least tentatively support evidence-based practice and a number of criteria that increase the likelihood of the outcomes being causal have been suggested (Thompson *et al.* 2005, Elvik *et al.* 2009). Such criteria are briefly discussed in this section taking the studies about design of unsignalized intersections (described in Chapter 4) and unbundling (described in Chapter 7) as examples.

A special form of a correlational study is a before-after study with a control or comparison group. Even though this study design lacks random assignment to treatment conditions, its outcomes may yield stronger support for the claim that the cause actually preceded the effect than cross-sectional studies (Heiman 1999). In can be difficult to put this design in practice because it is difficult to achieve a sufficiently large sample size and to address problems like the regression to the mean bias. Another difficulty is isolation of effects of factors when multiple measures are implemented simultaneously. For example, *studying the effect of unbundling* is almost impossible with a before-after design because it entails a combination of several measures and implementation takes much time. The suitability of a before-after design also depends on the specificity of the subject. Some of the claims on *design of unsignalized intersections* could be strengthened with before-after studies if road authorities would enable such research at a sufficiently large scale. For instance, they could install speed reducing measures at a number of intersections to allow for evaluation.

The remainder of this section is about cross-sectional studies for which a number of criteria related to internal validity have been described (Heiman 1999, Elvik 2011). A first criterion is a theoretical basis resulting in hypotheses and an explanation of the 'causal mechanism'. Merely looking at which correlations are statistically significant at the five percent level is dangerous because five percent of all correlations can be expected to be significant even if there is no true effect. It is of importance to understand the 'causal mechanisms' or 'working ingredients'. For instance, visual scanning strategies (based on expectations) and risk compensation were used to discuss the design characteristics of unsignalized intersections in Chapter 4. One outcome was an increased likelihood of BMV-crashes at well-marked crossings which was unexpected given the crossing's increased conspicuity. We could only speculated that the measure may not have had a great impact on drivers' visual scanning strategy while cyclists may have become less cautious. It was therefore recommended that this hypothesis (relating to causal mechanisms) should be tested in future research by comparing cyclists' and drivers' viewing behaviour between crossings having pavement markings of varying quality. For another finding, elevated risks for cyclists on two-way bicycle tracks, insight in the causal mechanism has already increased. In observational studies focused on drivers' viewing behaviour it was found that drivers coming from the minor road insufficiently scan for cyclists from the right, the 'non-expected' direction in the case of right-hand driving (Van Haeften 2010). This explains the elevated risk of collisions with cyclists from this direction.

Another issue is the specificity of effects (Elvik 2011). For instance, crashes in Chapter 4 were split in crashes with cyclists riding on the distributor road (who have priority) and cyclists crossing the distributor road (who should yield to traffic on the distributor road) to allow for more specific analyses. Unbundling is a municipality level characteristic which is less specific. As a result, the support for the outcomes of Chapter 7 on unbundling being causal is less strong than for the outcomes of Chapter 4.

Finally, control for confounding variables is probably most important to rule out reasonable alternative explanations for correlations (Elvik 2011). This was done in the studies of this theses by including possible confounders as predictor variables in the regression analyses. It has been tested whether the variables under study were still statistically significant and whether the size of the effect was large enough to be relevant from a road safety perspective after controlling for these variables.

8.2.6. External validity: transferability to other settings

The studies of this thesis have all been conducted in the Netherlands where the proportion of cycling in the modal split is higher than anywhere else in the world. Cycling has a share of 35% in trips up to 7.5 km, varying from 15 to 50% between municipalities (Rietveld and Daniel 2004). This suggests that the results may apply to other countries with a high level of cycling and to some extent to countries with a medium amount of cycling comparable to the Dutch cities with the lowest level of cycling. Further use should be done with caution. Compared with countries where fewer people cycle, the Dutch are younger when they start cycling and they use bicycles more for utilitarian purposes such as commuting and shopping than for sport (Ministry of Infrastructure and the Environment 2009). Moreover, the Netherlands has a long tradition of guidelines and implementation of measures with attention to cycling safety (e.g. CROW 1993).

On the other hand, some outcomes are probably generalizable to some extent because they are linked to broadly applicable theories and principles, e.g. how humans process information, how energy is transferred to victims in the case of a crash, the homogeneity principle in Sustainable Safety (see Section 8.3), etc. Outcomes related to these theories may be transferable between countries in contrast to factors related to a country's culture such as driving style. For instance, the mechanism explaining improved cycling safety as a result of unbundling vehicular and cycle traffic in an urban network is decreased exposure of cyclists to high-speed motorists (see Chapter 7). These results may apply to other countries to the extent that they have implemented a road hierarchy with traffic-calmed areas in which cyclists are exposed to less high-speed vehicular traffic. Similarly, skidding due to a slippery road surface, as described in Chapter 5, is transferable to other countries due to the physical effect of surface friction. The prevalence of such crashes is dependent on country-specific factors such as climate, e.g. Sweden may have more crashes due to snow and ice on the road than the Netherlands (Nyberg *et al.* 1996). The effect of the visibility of infrastructure on single-bicycle crashes (see Chapter 6) is related to general visual capabilities and limitations which would suggest that the outcomes may be generalized to other countries. The prevalence of such crashes is affected by the age of the cyclist population (which, of course, differs between countries) because visual capabilities decrease in old age. The results concerning the design of unsignalized priority intersections (see Chapter 4) and BMV crashes may also be transferable to other countries. For instance, the effect of speed reducing measures and one-way versus two-way bicycle tracks is related to speed, workload and expectations. These mechanisms can be expected to apply to other countries as well. While comparing results of studies conducted in different countries, one should be aware of how design elements such as bicycle tracks are defined (Reynolds *et al.* 2009).

It is more difficult to judge the transferability of the results of our study regarding the effect of a modal shift from short car trips to cycling (Chapter 3), because our theoretical understanding of the relationship between exposure and risk is still limited (Bhatia and Wier 2011). Nevertheless, the results found by Elvik (2009) regarding changes in casualty numbers of crashes with motor vehicles due to a modal shift from cars to bicycles are roughly comparable to the results found in the study on this issue reported in Chapter 3. The effects of changing numbers of single-bicycle crashes due to a modal shift have not yet been estimated in studies from other countries.

8.2.7. Technological trends

The studies contained in this thesis are all based on data between 2004 and 2009, i.e. under the circumstances, and with the cyclist characteristics, and type of bicycle usage during this particular period. Only at the end of this period did ownership of electrically assisted bicycles in the Netherlands significantly increase, resulting in around 10% of all bicycle kilometres in 2012 being travelled on electrical bicycles (Van Oijen *et al.* 2013). Motor output is progressively reduced and finally cut off as the bicycle reaches a speed of 25 km/h. Cruising speed is on average 19 km/h (Van Oijen *et al.* 2013). Cyclists on regular bicycles have a 3 km/h lower average speed (Schepers 2010). Due to usage and risk differences, a modal shift from cars to electric bicycles may have a different impact on road safety than a shift to regular bicycles. For instance, it has been suggested that bicycle tracks are safer for cyclists than for moped riders because the latter travel at a markedly higher speed. Drivers do not expect high speeds on bicycle tracks at intersections (Welleman and Dijkstra 1988, Hagenzieker 1995, Van Loon 2001). However, the speed difference of around 3 km/h between regular and electrically assisted bicycles may be too small to have a substantial impact on risk. Another difference is the greater mass of electric bicycles (due to the weight of the battery) which may interfere with (dis)mounting. A recent study showed that the share of single-bicycle crashes while (dis)mounting was slightly higher among users of electrically assisted bicycles than among users of regular bicycles, but the difference was statistically not significant. Firm conclusions could not be drawn because other user characteristics such as health status might have played a role as well (Kruijer *et al.* 2013). More research is needed to increase our knowledge about the consequences of increased use of electric bicycles and possible interaction with infrastructure safety.

The outcomes regarding BMV crashes might change in the distant future as new vehicle technologies will be implemented. Passive systems such as airbags on the windscreen of a car can reduce the impact of the first contact if a crash occurs (Rodarius *et al.* 2008). Active systems such as Pre-Crash Protection of Vulnerable Road Users reduce the impact speed through the detection of vulnerable road users and fully automatic emergency braking (Wilmink *et al.* 2008). ISA (Intelligent Speed Adaptation) can help to reduce the speed at intersections which may reduce the crash risk and injury consequences of BMV crashes. A mandatory, automatic system (fully preventing the driver from exceeding the limit) could significantly reduce the increased likelihood of BMV crashes at intersections of distributor roads. This would decrease the need for unbundling vehicular and cycle traffic for safety reasons. New intelligent transport systems are promising but there are a number of challenges to achieve acceptability and to implement these systems, e.g. how to convince drivers to pay for safety features geared towards vulnerable road users and how to address detection problems and false alarms (Wilmink *et al.* 2008, Vlassenroot *et al.* 2011). Penetration in the vehicle fleet will also take a long time. To conclude, vehicle safety systems have the potential to prevent some of the BMV crashes that can already be prevented by infrastructure measures, but it is uncertain by when they will mature and to what degree they will be able to be marketed.

8.3. Putting research into practice

Several government agencies aim to reduce the number of cyclist casualties (Ministry of Infrastructure and the Environment 2008, European Commission 2010). While much knowledge is developed at an (inter)national level because of scale advantages, most of the actions will have to be carried out at local level (European Commission 2010). It is therefore important that the knowledge developed in this thesis is integrated in guidance and disseminated among road authorities. Many of the outcomes, most of which were available in Dutch before they were published in journals, have already been incorporated in two guidelines commissioned by the Ministry of Infrastructure and the Environment:

- Van Boggelen, O., Schepers, J.P., Kroeze, P.A., Van Der Voet, M., 2011. Fietsberaadpublicatie 19: Samen werken aan een veilige fietsomgeving (Collaborating to improve cycling safety). Fietsberaad, Utrecht.
- Den Brinker, B., 2012. Senioren-proof wegontwerp voor fietsers (Road design for older cyclists). Blijf Veilig Mobiel, Woerden.

Besides specific recommendations formulated in guidelines, a number of more general recommendations can be made. Authorities seeking to improve cycling safety are advised to adopt a Safe System approach. According to the OECD (2012) policy should focus on improving the inherent safety of the traffic system, not simply securing cyclists in an inherently unsafe system. An example is the Dutch Sustainable Safety Approach of which the principles are summarized in Table 8.1.

During the development of Sustainable Safety, road safety researchers and policy makers could not be aware of the problem of single-bicycle crashes because these were heavily underreported by the police (Weijermars *et al.* 2013). However, most of the recommendations based on the studies of this thesis align well with the Sustainable Safety principles. For instance, removing obstacles (following from Chapters 5 and 6) is consistent with the *Forgivingness* principle. Speed management and grade separation (following from Chapter 7) align well with the *Homogeneity* principle. On the other hand, the five principles do not address the stability problem of two-wheeled vehicles such as bicycles. For instance, almost one-fifth of all single-bicycle crashes are skidding accidents due to a slippery road surface. Solutions like avoiding the use of low-friction materials, a clearance between cyclists and tram rails, and winter maintenance do not follow from any of the five principles. A general principle such as ‘Design to support the balancing and steering task of two-wheelers’ could be considered in future research.

Sustainable Safety principle	Description
Functionality of roads	Monofunctionality of roads as either through roads, distributor roads, or access roads in a hierarchically structured road network
Homogeneity of mass and/or speed and direction	Equality of speed, direction, and mass at moderate and high speeds
Predictability of road course and road user behaviour by a recognizable road design	Road environment and road user behaviour that support road user expectations through consistency and continuity of road design
Forgivingness of the environment and of road users	Injury limitation through a forgiving road environment and anticipation of road user behaviour
State awareness by the road user	Ability to assess one's capacity to handle the driving task

Table 8.1. Description of the five Sustainable Safety principles.

The three original Sustainable Safety principles (Functionality, Homogeneity and, Recognizability) were translated into twelve so-called 'functional requirements' (Janssen 1997). The first three align well with network-level separation of vehicular and cyclist traffic (unbundling) to improve cycling safety and increase bicycle usage:

1. residential areas must be adjoining and as large as possible;
2. a minimal part of the journey should be travelled on relatively unsafe roads;
3. journeys must be as short as possible

The first requirement automatically increases the share of cyclists' trip length on access roads because cycling trips are relatively short. Thereby the second requirement is also met because access roads are safer for cyclists (lower exposure to high-speed motorists). The third requirement may not be directly related to road safety for cyclists. However, the study on unbundling (Chapter 7) suggests that measures such as short cuts for cyclists and authorization of contraflow cycling on one-way streets correspond positively with the share of cycling in the modal split because they improve the length of trips by bicycle compared to those by car. They may also increase the acceptance of Sustainable Safety measures in general. Weijermars *et al.* (2013) refer to a publication by Slop and Van Minnen (1994) who suggested traffic-calmed areas enclosing frequent destinations such as primary schools and supermarkets with a road structure adapted to cyclists and pedestrians. They indicated that this reduces potential conflicts of vulnerable road users crossing distributor roads. It is recommended that these ideas are considered in future research. Such research may also include the question posed by

Weijermars *et al.* (2013) of whether it is feasible to distinguish between bicycle facilities with a flow function and an exchange function.

A Safe System approach aligns safety management decisions with broader transport and planning decisions that meet wider economic, human and environmental goals (OECD 2008). For cycling policy, it is key to take into account the effects on both cycling safety and bicycle usage because the latter determines the degree to which other goals are met. This thesis shows that transferring short trips made by cars to bicycles does not change the number of fatalities, but increases the number of serious road injuries (Chapter 3). As described in Section 8.2.2, the health burden of more serious injuries due to single-bicycle crashes has not yet been sufficiently included in studies on the health effects of cycling (e.g. De Hartog *et al.* 2010). However, it is likely that the net benefits of a modal shift from car trips to cycling remain positive. This would support the importance of pursuing the double goal of improved bicycle safety and increased bicycle usage. From an 'equity perspective', increased inclusiveness can be added as a third objective. For instance, improving the visibility of obstacles and the road's course may decrease the likelihood of single-bicycle crashes and enable older cyclists to keep cycling. In a survey among low vision cyclists, respondents indicated to avoid adverse light conditions, unfamiliar routes, roads where, for instance, obstacles are poorly visible, and busy traffic. The majority stated that they would increase their amount of cycling if the visual design was improved (Fabriek *et al.* 2010).

References

Agresti, A., 1996. Categorical Data Analysis. John Wiley, New York.

Ajzen, I., 1985. From Intentions to Actions: A Theory of Planned Behavior. In: Kuhl, J., Beckmann, J. eds. Action Control: From Cognition to Behavior. Springer-Verlag, New York.

Amoros, E., Chiron, M., Thélot, B., Laumon, B., 2011. The injury epidemiology of cyclists based on a road trauma registry. BMC Public Health 11, 653.

Aram, A., 2010. Effective Safety Factors on Horizontal Curves of Two-lane Highways. Journal of Applied Sciences 10, 2814-2822.

Ardekani, S., Hauer, E., Jamei, B., 2000. Traffic Impact Models. In: Gartner, N., Messer, C.J., Rathi, A.K. eds. Traffic Flow Theory: A State of the Art Report. Federal Highway Administration, Washinton.

Asmussen, E., Kranenburg, A., 1982. An Analysis of the Traffic Phenomenon. Institute for Road Safety Research, Leidschendam.

Aultman-Hall, L., Hall, F.L., Baetz, B.B., 1997. Analysis of Bicycle Commuter Routes Using Geographic Information Systems: Implications for Bicycle Planning. Transportation Research Record 1578, 102-110.

Ball, K., Owsley, C., Stalvey, B., Roenker, D.L., Sloane, M.E., Graves, M., 1998. Driving avoidance and functional impairment in older drivers. Accident Analysis and Prevention 30 (3), 313-22.

Barnes, G.R., Thompson, K.B., 2006. A longitudinal analysis of the effect of bicycle facilities on commute mode share. Transportation Research Board 85th Annual Meeting. Transportation Research Board, Washington D.C.

Barten, M., Van Drunen, R., Herber, N., IJsselstijn, S., Nägele, R., Vissers, J., 2006. PROV 2005; Periodiek Regionaal Onderzoek Verkeersveiligheid (PRRSS 2005; Periodic Regional Road Safety Survey). Rijkswaterstaat, Delft.

Beck, R.R., 2009. Mountain bicycle acceleration and braking factors. Accident Reconstruction Journal 19 (4), 49-56.

Berends, E.M., Stipdonk, H.L., 2009. De Veiligheid van Voetgangers en Fietsers op 30km/uur-Erftoegangswegen (Pedestrian and Cyclist Safety on 30 km/h Access Roads). Institute for Road Safety Research, Leidschendam.

Bergström, A., Magnusson, R., 2003. Potential of transferring car trips to bicycle during winter. Transportation Research Part A 37 (8), 649-666.

Berveling, J., Derriks, H., 2012. Opstappen als het Kan, Afstappen als het Moet (Mounting if Possible, Dismounting if Necessary). Netherlands Institute for Transport Policy Analysis, Den Haag.

Bhatia, R., Wier, M., 2011. "Safety in Numbers" re-examined: can we make valid or practical inferences from available evidence? Accident Analysis and Prevention 43 (1), 235-240.

Birth, S., Pflaumbaum, M., Potzel, D., Sieber, G., 2009. Human Factors Guideline for Safer Road Infrastructure. World Road Association, Paris.

Bjørnskau, T., Year. Hypotheses on risk compensation. In: Proceedings of the Conference Road Safety in Europe and Strategic Highway Research Program (SHRP), Lille, France, pp. 81-98.

Brooks, J.O., Tyrrell, R.A., Frank, T.A., 2005. The effects of severe visual challenges on steering performance in visually healthy young drivers. Optometry and Vision Science 82 (8), 689–697.

Brown, S., 2009. Bicycle Tires and Tubes. Retrieved 16-9 2009, from http://www.sheldonbrown.com

Brüde, U., Larsson, J., 1992. Trafiksäkerhet i Tätortskorsningar (Road Safety at Urban Junctions). VTI, Linhköping.

Brüde, U., Larsson, J., 1993. Models for predicting accidents at junctions where pedestrians and cyclists are involved. How well do they fit? Accident Analysis and Prevention 25 (5), 499-509.

Brüde, U., Larsson, J., 2000. What roundabout design provides the highest possible safety? Nordic Road and Transport Research 12 (2), 17-21.

Buchanan, C., 1963. Traffic in Towns. Her Majesty's Stationery Office, London.

Buehler, R., Pucher, J., 2012. International Overview; Cycling Trends in Western Europe, North America, and Australia. In: Pucher, J., Buehler, R. eds. City Cycling. Massachusetts Institute of Technology, Cambridge.

Chorus, C.G., Arentze, T.A., Timmermans, H.J.P., 2008. A random regret-minimization model of travel choice. Transportation Research Part B: Methodological 42 (1), 1-18.

CIHI, 2012. The National Trauma Registry (NTR). Canadian Institute for Health Information, Ottawa.

Cohen, P.R., 1996. Getting What You Deserve from Data. IEEE Expert October, 12–14.

Consumer Safety Institute, 2011. Factsheet Fietsongevallen (Factsheet Bicycle Victims). Stichting Consument en Veiligheid, Amsterdam.

Corben, B., Senserrick, T., Cameron, M., Rechnitzer, G., 2004. Development of the Visionary Research Model. Monash University Research Centre, Clayton.

COST, 331, 1999. Requirements for Horizontal Road Markings - Final Report of the Action. Office for Official Publications of the European Communities, Luxembourg.

CROW, 1993. Tekenen voor de Fiets (Sign up for the Bike). CROW, Ede.

CROW, 2002. Handboek Wegontwerp Gebiedsontsluitingswegen; Publicatie 164c (Design Manual for distributor roads). CROW, Ede.

CROW, 2007. Design Manual for Bicycle Traffic. CROW, Ede.

Daniels, S., Brijs, T., Nuyts, E., Wets, G., 2009. Injury crashes with bicyclists at roundabouts: influence of some location characteristics and the design of cycle facilities. Journal of Safety Research 40 (2), 141-148.

Daniels, S., Nuyts, E., Wets, G., 2008. The effects of roundabouts on traffic safety for bicyclists: An observational study. Accident Analysis and Prevention 40 (2), 518-526.

Danish Road Directorate, 2000. Collection of Cycle Concepts. Kopenhagen.

Davidse, R., 2007a. Diepteonderzoek naar de Invloedsfactoren van Verkeersongevallen: Een Voorstudie (In-depth Study of the Road Crash Influence Factors: a Preliminary Study). Institute for Road Safety Research, Leidschendam.

Davidse, R.J., 2007b. Assisting the Older Driver; Intersection Design and In-Car Devices to Improve the Safety of the Older Driver. Institute for Road Safety Research, Leidschendam

De Geus, B., Vandenbulcke, G., Int Panis, L., Thomas, I., Degraeuwe, B., Cumps, E., Aertsens, J., Torfs, R., Meeusen, R., 2012. A prospective cohort study on minor accidents involving commuter cyclists in Belgium. Accident Analysis and Prevention 45, 683-693.

De Hartog, J.J., Boogaard, H., Nijland, H., Hoek, G., 2010. Do the health benefits of cycling outweigh the risks? Environmental Health Perspective 118 (8), 1109-16.

De Waard, D., 1996. The Measurement of Drivers' Mental Workload. Groningen University, Groningen.

De Waard, D., Schepers, J.P., Ormel, W., Brookhuis, K.A., 2010. Mobile phone use while cycling: incidence and effects on behaviour and safety. Ergonomics 53, 30-42.

Den Brinker, B.P.L.M., Beek, P.J., 1996. Reading with magnifiers. Ergonomics 39 (10), 1231-1248.

Den Brinker, B.P.L.M., Daffertshofer, A., 2005. The IDED method to measure the visual accessibility of the built environment. International Congress Series 1282, 992-996.

Den Brinker, B.P.L.M., Smeets, J., Talens, H., Methorst, R., 2007. Veiliger fietsen op overzichtelijke routes (Safer cycling on comprehensible routes). Verkeerskunde 7, 24-29.

Derriks, H., Mak, P., 2007. IRTAD Special Report: Underreporting of Road Traffic Casualties. Ministry of Transport, Public Works and Water management, The Hague.

Dhondt, S., Macharis, C., Terryn, N., Van Malderen, F., Putman, K., 2013. Health burden of road traffic accidents, an analysis of clinical data on disability and mortality exposure rates in Flanders and Brussels. Accident Analysis and Prevention 50, 659-66.

Dijkstra, A., 2003. Infrastructurele Verkeersvoorzieningen en hun Veiligheidsaspecten (Road Factors and their Effect on Road Safety). Institute for Road Safety Research, Leidschendam.

Dijkstra, A., 2004. Rotondes met Vrijliggende Fietspaden ook Veilig voor Fietsers (Are Roundabouts with Separate Cycle Tracks also Safe for Cyclists)? Institute for Road Safety Research, Leidschendam.

Dill, J., Carr, T., 2003. Bicycle commuting and facilities in major U.S. cities: if you build them, commuters will use them. Transportation Research Record 1828, 116-123.

Dingus, T.A., Klauer, S.G., Neale, V.L., Petersen, A., Lee, S.E., Sudweeks, J., Perez, M.A., Hankey, J., Ramsey, D., Gupta, S., Bucher, C., Doerzaph, Z.R., Jermeland, J., Knipling, R.R., 2006. The 100-Car Naturalistic Driving Study, Phase II. NHTSA, Washington, DC.

Director of Environmental Services, 1998. London Cycle Network; Design Manual. Director of Environmental, Royal Borough of Kingston upon Thames, London.

Donges, E., 1978. A two-level model of driver steering behavior. Human Factors 20 (6), 691–707.

Dozza, M., Werneke, J., Fernandez, A., Year. Piloting the naturalistic methodology on bicycles. In: Proceedings of the International Cycling Safety Conference 2012, Helmond.

Eenink, R., Reurings, M., Elvik, R., Cardoso, J., Wichert, S., Stefan, C., 2008. Accident Prediction Models and Road Safety Impact Assessment: Recommendation for Using These Tools. Institute for Road Safety Research, Leidschendam.

Elvik, R., 2001. Area-wide urban traffic calming schemes: a meta-analysis of safety effects. Accident Analysis and Prevention 33 (3), 327-36.

Elvik, R., 2004. To what extent can theory account for the findings of road safety evaluation studies? Accident Analysis and Prevention 36 (5), 841-849.

Elvik, R., 2006. Laws of accident causation. Accident Analysis and Prevention 38 (4), 742-747.

Elvik, R., 2009. The non-linearity of risk and the promotion of environmentally sustainable transport. Accident Analysis and Prevention 41 (4), 849-55.

Elvik, R., 2010. Why some road safety problems are more difficult to solve than others. Accident Analysis and Prevention 42 (4), 1089-1096.

Elvik, R., 2011. Assessing causality in multivariate accident models. Accident Analysis and Prevention 43 (1), 253-264.

Elvik, R., Bjørnskau, T., 2005. How accurately does the public perceive differences in transport risks?: An exploratory analysis of scales representing perceived risk. Accident Analysis and Prevention 37 (6), 1005-1011.

Elvik, R., Høye, A., Vaa, T., Sørensen, M., 2009. The Handbook of Road Safety Measures. Emerald, Bingley.

Elvik, R., Mysen, A.B., 1999. Incomplete accident reporting: meta-analysis of studies made in 13 countries. Transportation Research Record 1665, 133-140.

ETSC, 2012. Pedalling Towards Safety. European Transport Safety Counsil, Brussels.

EuroNCAP, 2012. European New Car Assessment Programme. Retrieved Oktober 28 2012, from http://www.euroncap.com/

European Commission, 2010. Towards a European Road Safety Area: Policy Orientations on Road Safety 2011-2020 (COM(2010) 389). Brussels.

EuroRAP, 2011. European Road Assessment Programme. Retrieved Oktober 28 2012, from http://www.eurorap.org/

Fabriek, E., De Waard, D., Den Brinker, B., 2010. Visuele Aspecten van Fietsvoorzieningen (Visibility of Bicycle Facilities). University of Groningen, Groningen.

FHWA, 2010. Highway Safety Manual. Federal Highway Administration, Washington, D.C.

Fietsersbond, 2011. Fietsrouteplanner (Bicycle Route Planner). Retrieved 20 December 2011, from http://www.fietsersbond.nl/fietsersbond-routeplanner

Fietsersbond, 2012. Het Nut van Bredere Banden (The Value of Wider Tires). Retrieved 10-08, from http://www.fietsersbond.nl

Fitzpatrick, K., Wooldridge, M.D., Tsimhoni, O., Collins, J.M., Green, P., Bauer, K., Parma, K.D., R., K., Harwood, D.W., Krammes, R., Poggioli, B., 1999. Alternative Design Consistency Rating Methods for Two-Lane Rural Highways; FHWA-RD-99-172. FHWA, Washington, D.C.

Floyd, F.J., Widaman, K.F., 1995. Factor analysis in the development and refinement of clinical assessment instruments. Psychological Assessment 7 (3), 286-299.

Ford, A., 2009. Modeling the Environment. Island Press, Washington D.C.

Frank, L., Hawkins, C., 2008. Assessing Travel and Environmental Impacts of Contrasting Levels of Vehicular and Pedestrian Connectivity: Assessing Aspects of the Fused Grid. Canada Mortgage and Housing Corporation, Ottawa.

Frendo, T., 2010. The Classification and Analysis of 300 Cycling Crashes that Resulted in Visits to Hospital Emergency Departments in Toronto and Vancouver. University of British Columbia, Vancouver.

Fuller, R., 2005. Towards a general theory of driver behaviour. Accident Analysis and Prevention 37 (3), 461-472.

Furth, P.G., 2012. Bicycling Infrastructure for Mass Cycling: A Transatlantic Comparison. In: Pucher, J., Buehler, R. eds. City Cycling. Massachusetts Institute of Technology, Cambridge.

Gårder, P., Leden, L., Pulkkinen, U., 1998. Measuring the safety effect of raised bicycle crossings using a new research methodology. Transportation Research Record 1636, 64-70.

Garson, G.D., 2012. Factor Analysis. North Carolina State University, Asheboro.

Gerrard, J., Rose, G., Lo, S.K., 2008. Promoting transportation cycling for women: the role of bicycle infrastructure. Preventive Medicine 46 (1), 55-59.

Gibson, J.J., 1961. The Contribution of Experimental Psychology to the Formulation of the Problem of Safety. In: Jacobs, H.H. ed. Behavioural Approaches to Accident Research. . Association for the aid of crippled children, New York.

Godthelp, H., Wouters , P.I.J., 1978. Koershouden voor fietsers en bromfietsers (Tracking ans steering control in cyclists and mopedists). Verkeerskunde 11, 537-543.

Goldenbeld, C., 1992. Ongevallen van Oudere Fietsers in 1991 (Crashes with Older Cyclists). Institute for Road Safety Research, Leidschendam.

Golob, T.F., 2003. Structural equation modeling for travel behavior research. Transportation Research Part B: Methodological 37 (1), 1-25.

Gommers, M.J.P.F., Bovy, P.H.L., 1987. Routekeuzegedrag en Netwerkgebruik (Route Choice and Network Use). Delft University of Technology, Delft.

Google, 2011. Google Maps and Google Earth. Retrieved 20 December 2011, from http://www.google.nl/maps and http://www.google.com/earth/

Google, 2012. Google Scholar. Retrieved 25-01 2012, from http://scholar.google.nl/

Habak, C., Casanova, C., Faubert, J., 2002. Central and peripheral interactions in the perception of optic flow. Vision Research 42 (26), 2843-2852.

Haddon, W., Jr., 1980. Advances in the Epidemiology of Injuries as a Basis for Public Policy. Public Health Reports 95 (5), 411-421.

Hagemeister, C., Tegen-Klebingat, A., 2011. Fahrgewohnheiten älterer Radfahrerinnen und Radfahrer. TÜV Media, Köln.

Hagenzieker, M.P., 1995. Bromfiets op de Rijbaan: Ongevallenstudie (Moped Riders on the Carriageway: Crash Study). Institute for Road Safety Research, Leidschendam.

Hägerstrand, T., 1970. What about people in regional science? Papers in Regional Science 24, 6-21.

Hakkert, A.S., Braimaister, L., 2002. The Uses of Exposure and Risk in Road Safety Studies. Institute for Road Safety Research, Leidschendam.

Hakkert, A.S., Gitelman, V., Vis, M.A., 2007. Road Safety Performance Indicators: Theory (Deliverable D3.6 SafetyNet). Institute for Road Safety Research, Leidschendam.

Hamann, C., Peek-Asa, C., 2013. On-road bicycle facilities and bicycle crashes in Iowa, 2007–2010. Accident Analysis and Prevention 56, 103-109.

Hatakka, M., Keskinen, E., Gregersen, N., Glad, A., 1999. Theories and Aims of Educational and Training Measures. In: Siegrist, S. ed. Driver Training, Testing and Licencing. Swiss Counsil for Accident Prevention, Bern.

Heemskerk, M., Wilson, K., Pavao-Zuckerman, M., 2003. Conceptual models as tools for communication across disciplines. Conservation Ecology 7(3): 8. 7 (3), 8.

Heesch, K.C., Garrard, J., Sahlqvist, S., 2011. Incidence, severity and correlates of bicycling injuries in a sample of cyclists in Queensland, Australia. Accident Analysis and Prevention 43 (6), 2085-92.

Heiman, G.W., 1999. Research Methods in Psychology. Houghton Mifflin Company, Boston, New York.

Heinen, E., Handy, S., 2012. Similarities in attitudes and norms and the effect on bicycle commuting: evidence from the bicycle cities davis and delft. International Journal of Sustainable Transportation 6 (5), 257-281.

Heinen, E., Maat, K., Van Wee, G.P., 2010a. Day-to-day choice to commute or not by bicycle. Transportation Research Record 2230, 9-18.

Heinen, E., Van Wee, B., Maat, K., 2010b. Commuting by bicycle: an overview of the literature. Transport Reviews 30 (1), 59-96.

Heinrich, H.W., 1931. Industrial Accident Prevention: A scientific approach. McGraw-Hill, New York.

Henson, R., Whelan, N., 1992. Layout and design factors affecting cycle safety at T-junctions. Traffic Engineering and Control 33, 548-551.

Herrstedt, L., 1979. Sikkerhed for Cyklister og Knallertkørere på Hovedfærdselsårer i Københavnsområdet (Safety for Cyclists and Moped Riders on the Main Traffic Arteries in the Metropolitan Region). Rådet for Trafiksikkerhedsforskning, Denmark.

Herslund, M.B., Jørgensen, N.O., 2003. Looked-but-failed-to-see-errors in traffic. Accident Analysis and Prevention 35 (6), 885-891.

Higgins, K.E., Wood, J., Tait, A., 1998. Vision and driving: selective effect of optical blur on different driving tasks. Human Factors 40 (2), 224–232.

Hole, G.J., Tyrrell, L., Langham, M., 1996. Some factors affecting motorcyclists’ conspicuity. Ergonomics 39 (7), 946-965.

Horrey, W.J., Wickens, C.D., Consalus, K.P., 2006. Modeling drivers' visual attention allocation while interacting with in-vehicle technologies. Journal of Experimental Psychology: Applied 12 (2), 67-78.

Houtenbos, M., 2008. Expecting the Unexpected; A Study of Interactive Driving Behaviour at Intersections. Institute for Road Safety Research, Leidschendam.

Hummel, T., 2001. Route Management in Safer Transportation Network Planning. Institute for Road Safety Research, Leidschendam.

Hunter, W.W., 2000. Evaluation of innovative bike-box application in Eugene, Oregon. Transportation Research Record 1705, 99-106.

Hunter, W.W., Harkey, D.L., Stewart, J.R., Birk, M.L., 2000. Evaluation of blue bike-lane treatment in Portland, Oregon. Transportation Research Record 1705, 107-115.

IMOB, 2011. Onderzoek Verplaatsingsgedrag Vlaanderen 2009-2011 (Travel Survey Flanders 2009-2010). Transportation Research Institute, Hasselt.

Jacobsen, P.L., 2003. Safety in numbers: more walkers and bicyclists, safer walking and bicycling. Injury Prevention 9, 205–209.

Janke, M.K., 1991. Accidents, mileage, and the exaggeration of risk. Accident Analysis and Prevention 23, 183-188.

Janssen, S.T.M.C., 1997. Functionele Eisen voor de Categorisering van Wegen (Functional Requirements for Road Classification). Institute for Road Safety Research, Leidschendam.

Jarjour, S., Jerrett, M., Westerdahl, D., Nazelle, A., Hanning, C., Daly, L., Lipsitt, J., Balmes, J., 2013. Cyclist route choice, traffic-related air pollution, and lung function: a scripted exposure study. Environmental Health 12 (1), 14.

Jensen, S.U., 1999. Pedestrian safety in Denmark. Transportation Research Record 1674, 61-69.

Jensen, S.U., 2008. Safety effects of blue cycle crossings: a before-after study. Accident Analysis and Prevention 40, 742-750.

Johnson, B., Murphy, C., 2013. Sustainable Transportation in the Netherlands: Unbundling. Retrieved 15 januari 2013, from http://wiki.coe.neu.edu/groups/nl2011transpo/

Johnson, C.A., Keltner, J.L., 1983. Incidence of visual field loss in 20,000 eyes and its relationship to driving performance. Archives of Ophthalmology. 101 (3), 371-375.

Jones, D.E.H., 1970. The stability of the bicycle. Physics Today 23 (4), 34-40.

Kahneman, D., Tversky, A., 1979. Prospect Theory: An Analysis of Decision Under Risk. Econometrica 47 (2), 263-291.

Karkhaneh, M., Naghavi, M., Rowe, B.H., Hagel, B.E., Jafari, N., Saunders, L.D., 2008. Epidemiology of bicycle injuries in 13 health divisions, Islamic Republic of Iran 2003. Accident Analysis and Prevention 40 (1), 192-9.

KiM, 2011. Mobiliteitsbalans 2011 (Mobility Balance 2011). Netherlands Institute for Transport Policy Analysis, Den Haag.

Kim, J.K., Kim, S., Ulfarsson, G.F., Porrello, L.A., 2007. Bicyclist injury severities in bicycle–motor vehicle accidents. Accident Analysis and Prevention 39 (2), 238-251.

KNMI, 2009. Zonsopkomst en Zonsondergang (Sunrise and Sunset). Retrieved 6-3 2009, from http://www.knmi.nl

Koning, G.J., Bovy, P.H.L., 1980. Route-Analyse - Een Vergelijking van Model- en Enquêteroutes van Automobilisten in een Stedelijk Wegennet (Route Analysis - A Comparison of Model- and Survey Routes of Drivers in an Urban Road Network). Delft University of Technology, Delft.

Kooijman, J.D., Meijaard, J.P., Papadopoulos, J.M., Ruina, A., Schwab, A.L., 2011. A bicycle can be self-stable without gyroscopic or caster effects. Science 332 (6027), 339-42.

Koornstra, M.J., Mathijssen, M.P.M., Mulder, J.A., Roszbach, R., Wegman, F.C.M., 1992. Naar een Duurzaam Veilig Wegverkeer (Towards Sustainably Safe Road Traffic). Institute for Road Safety Research, Leidschendam.

Kortstra, J.R.A., Schoone-Harmsen, M., 1987. Een Analyse van Éénzijdige Verkeersongevallen en van Ongevallen Buiten de Openbare Weg (An Analysis of Single-Vehicle Accidents and Accidents Outside Public Roads). Stichting Consument en Veiligheid, Amsterdam.

Kroon, P.O., 1990. Bicycle Accidents in Gothenburg 1983-1984. Gothenburg University, Gothenburg.

Kruijer, H., Den Hertog, P., Klein Wolt, K., Panneman, M., Sprik, E., 2013. Fietsongevallen in Nederland; Een LIS Vervolgonderzoek naar Ongevallen met Gewone en Elektrische Fietsen (Bicycle Crashes in the Netherlands; A Study on Crashes with Classical and Electrical Bicycles). VeiligheidNL, Amsterdam.

Kwan, I., Mapstone, J., 2004. Visibility aids for pedestrians and cyclists: a systematic review of randomised controlled trials. Accident Analysis and Prevention 36 (3), 305-312.

Langley, J.D., Dow, N., Stephenson, S., Kypri, K., 2003. Missing cyclists. Injury Prevention 9 (4), 376-379.

Larson, A.M., Loschky, L.C., 2009. The contributions of central versus peripheral vision to scene gist recognition. Journal of Vision 9 (10), 6 1-16.

Larsson, J., 2008. Trafikskador 1998–2005 Enligt Patientstatistik (Traffic Injuries 1998–2005, According to Patient Statistics). VTI, Linköping.

Leibowitz, H.W., Owens, D.A., 1977. Nighttime driving accidents and selective visual degradation. Science 197 (4302), 422-3.

Leibowitz, H.W., Post, R.B., 1982. The Two Modes of Processing Concept and Some Implications. In: J. Beck, ed. Organization and Representation in Perception. In: Beck, J. ed. Organization and Representation in Perception. Lawrence Erlbaum, Hillsdale, pp. 343–363.

Lemmink, K.A.P.M., Dijkstra, B., Visscher, C., 2005. Effects of limited peripheral vision on shuttle sprint performance of soccer players. Perceptual and Motor Skills 100 (1), 167-175.

Leveson, N., 2004. A new accident model for engineering safer systems. Safety Science 42 (4), 237-270.

Lewis-Evans, B., De Waard, D., Brookhuis, K.A., 2011. Speed maintenance under cognitive load – Implications for theories of driver behaviour. Accident Analysis and Prevention 43 (4), 1497-1507.

Ley, P., 1972. Quantitative Aspects of Psychological Assessment. Duckworth, London.

Li, G., Braver, E.R., Chen, L., 2003. Fragility versus excessive crash involvement as determinants of high death rates per vehicle-mile of travel among older drivers. Accident Analysis and Prevention 35 (2), 227-235.

Lie, A., Tingvall, C., 2002. How do Euro NCAP results correlate with real-life injury risks? A paired comparison study of car-to-car crashes. Traffic Injury Prevention 3 (4), 288–293.

Liu, X., Shen, D., Huang, J., 1995. Analysis of bicycle accidents and recommended countermeasures in Beijing, China. Transportation Research Record 1487, 75-83.

Lord, D., Mannering, F., 2010. The statistical analysis of crash-frequency data: a review and assessment of methodological alternatives. Transportation Research, Part A 44 (5), 291–305.

Lord, D., Washington, S.P., Ivan, J.N., 2005. Poisson, Poisson-gamma and zero-inflated regression models of motor vehicle crashes: balancing statistical fit and theory. Accident Analysis and Prevention 37 (1), 35-46.

Loschky, L.C., McConkieb, G.W., Yang, J., Miller, M.E., 2005. The limits of visual resolution in natural scene viewing. Visual Cognition 12 (6), 1057-1092.

Lusk, A.C., Furth, P.G., Morency, P., Miranda-Moreno, L.F., Willett, W.C., Dennerlein, J.T., 2011. Risk of injury for bicycling on cycle tracks versus in the street. Injury Prevention 17, 131-135.

Martens, M.H., Fox, M.R.J., 2007. Do familiarity and expectations change perception? Drivers' glances and response to changes. Transportation Research Part F: Traffic Psychology and Behaviour 10 (6), 476-492.

McFadden, D., 1974. Conditional Logit Analysis of Qualitative Choice-Behaviour. In: Zarembka, P. ed. Frontiers in Econometrics. Academic Press, New York, NY, pp. 105–142.

McGee, H.W., Hanscom, F.R., 2006. Low-Cost Treatments for Horizontal Curve Safety. Federal Highway Administration, Washington.

McKenna, M.T., Michaud, C.M., Murray, C.J.L., Marks, J.S., 2005. Assessing the burden of disease in the United States using disability-adjusted life years. American Journal of Preventive Medicine 28 (5), 415-423.

Meijaard, J.P., Papadopoulos, J.M., Ruina, A., Schwab, A.L., 2007. Linearized dynamics equations for the balance and steer of a bicycle: a benchmark and review. Proceedings of the Royal Society A 463 (2084), 1955-1982

Melief, W.B.A.M., Gorter, K.A., 1998. Slechtzienden en Blinden in Nederland (Visually Impaired and Blind People in the Netherlands). Verwey-Jonker Instituut, Utrecht.

Miaou, S.P., 1994. The relationship between truck crashes and geometric design of road sections: Poisson versus negative binomial regressions. Accident Analysis and Prevention 26, 471-482.

Michon, J.A., 1985. A Critical View of Driver Behavior Models. What Do We Know, What Should We Do? In: Evans, L., Schwing, R.C. eds. Human Behavior and Traffic Safety. Plenum Press, New York.

Ministry of Infrastructure and the Environment, 2008. Road Safety Strategic Plan 2008-2020; From, for and by Everyone. the Netherlands., The Hague.

Ministry of Infrastructure and the Environment, 2009. Cycling in the Netherlands. The Hague.

Ministry of Infrastructure and the Environment, 2012. Brief Verkeersdoden 2011, IENM/BSK-2012/53959 (Letter on 2011 Road Deaths). The Hague.

Mokhtarian, P.L., Chen, C., 2004. TTB or not TTB, that is the question: a review and analysis of the empirical literature on travel time (and money) budgets. Transportation Research Part A 38 (9–10), 643-675.

Moore, J.K., Kooijman, J.D.G., Schwab, A.L., Hubbard, M., 2011. Rider motion identification during normal bicycling by means of principal component analysis. Multibody System Dynamics 25 (2), 225-244.

Moudon, A.V., Lee, C., Cheadle, A.D., Collier, C.W., Johnson, D., Schmid, T.L., Weather, R.D., 2005. Cycling and the built environment, a US perspective. Transportation Research Part D 10 (3), 245-261.

Näätänen, R., Summala, H., 1974. A model for the role of motivational factors in drivers' decision-making. Accident Analysis and Prevention 6 (3–4), 243-261.

Niewöhner, W., Berg, F.A., 2005. Gefährdung von Fußgängern und Radfahrern durch rechts Abbiegende Lkw (Endangerment of Pedestrians and Cyclists by Right-Turning Lorries). BASt, Bergisch Gladbach.

Nyberg, P., Bjornstig, U., Bygren, L.O., 1996. Road characteristics and bicycle accidents. Scandinavian Journal of Social Medicine 24 (4), 293-301.

Nygårdhs, S., Fors, C., Eriksson, L., Nilsson, L., 2010. Field Test on Visibility at Cycle Crossings at Night. VTI, Linköping.

OECD, 2008. Towards Zero: Ambitious Road Safety Targets and the Safe System Approach. Organisation for Economic Cooperation and Development, Paris.

OECD, 2012. Cycling Safety: Key Messages. Organisation for Economic Cooperation and Development, Paris.

Ormel, W., Klein Wolt, K., Den Hertog, P., 2008. Enkelvoudige Fietsongevallen (Single-Bicycle Crashes). Stichting Consument en Veiligheid, Amsterdam.

Othman, S., Thomson, R., Lanner, G., 2009. Identifying critical road geometry parameters affecting crash rate and crash type. Annals of Advances in Automotive Medicine 53, 155-65.

Owens, D.A., Andre, J.T., 1996. Selective visual degradation and the older driver. IATSS Research 20, 57-66.

Owens, D.A., Tyrrell, R.A., 1999. Effects of luminance, blur, and age on night time visual guidance: a test of the selective degradation hypothesis. Journal of Experimental Psychology: Applied 5 (2), 115–128.

Parkin, J., Wardman, M., Page, M., 2007. Models of perceived cycling risk and route acceptability. Accident Analysis and Prevention 39 (2), 364-371.

Previc, F.H., 1998. The neuropsychology of 3-D space. Psychological Bulletin 124 (2), 123-64.

Pucher, J., Buehler, R., 2008. Making cycling irresistible: lessons from the Netherlands, Denmark and Germany. Transport Reviews 28 (4), 495-528.

Pucher, J., Buehler, R., 2012. Integration of Cycling with Public Transportation. In: Pucher, J., Buehler, R. eds. City Cycling. Massachusetts Institute of Technology, Cambridge.

Pucher, J., Dill, J., Handy, S., 2010. Infrastructure, programs, and policies to increase bicycling: an international review. Preventive Medicine 50, S106-25.

Quddus, M.A., 2008. Modelling area-wide count outcomes with spatial correlation and heterogeneity: an analysis of London crash data. Accident Analysis and Prevention 40, 1486-1497.

Ranney, T.A., 1994. Models of driving behavior: A review of their evolution. Accident Analysis and Prevention 26 (6), 733-750.

Räsänen, M., Koivisto, I., Summala, H., 1999. Car driver and bicyclist behavior at bicycle crossings under different priority regulations. Journal of Safety Research. 30, 67–77.

Räsänen, M., Summala, H., 1998. Attention and expectation problems in bicycle–car collisions: an in-depth study. Accident Analysis and Prevention 30 (5), 657-666.

Reurings, M.C.B., 2010. Hoe Gevaarlijk Is Fietsen in het Donker (How Dangerous Is Cycling in Darness)? Institute for Road Safety Research, Leidschendam.

Reurings, M.C.B., Bos, N.M., 2011. Ernstig Verkeersgewonden in de Periode 1993-2009 (Serious Road Injuries between 1993 and 2009). Institute for Road Safety Research, Leidschendam.

Reurings, M.C.B., Jansen, T., Eenink, R., Elvik, R., Cardoso, J., Stefan, C., 2005. Accident Prediction Models and Road Safety Impact Assessment: A State-of-the-Art. Institute for Road Safety Research, Leidschendam.

Reynolds, C.C., Harris, M.A., Teschke, K., Cripton, P.A., Winters, M., 2009. The impact of transportation infrastructure on bicycling injuries and crashes: a review of the literature. Environmental Health 8, 47.

Rietveld, P., Daniel, V., 2004. Determinants of bicycle use: do municipal policies matter? Transportation Research Part A 38 (7), 531-550.

Rijkswaterstaat, 2010. Mobiliteitsonderzoek Nederland 2009 (The Netherlands National Travel Survey 2009). Ministry of Infrastructure and the Environment, Delft.

Rijkswaterstaat, 2011a. Actuele Hoogtekaart Nederland (Height Map Netherlands). Retrieved 20 December 2011, from http://www.ahn.nl

Rijkswaterstaat, 2011b. Snelhedenkaart (Speed map). Retrieved 20 December 2011, from http://www.maximumsnelheden.info/kaart.php

Robberstad, B., 2005. QALYs vs DALYs vs LYs gained: what are the differences, and what difference do they make for health care priority setting? Norsk Epidemiologi 15 (2), 183-191.

Robinson, D.L., 2005. Safety in numbers in Australia: more walkers and bicyclists, safer walking and bicycling. Health Promotion Journal Australia 16 (1), 47-51.

Rodarius, C., Mordaka, J., Versmissen, T., 2008. Bicycle Safety in Bicycle to Car Accidents. TNO Science and Industry, Delft.

Roelofs, T., 1997. Image Enhancement for Low Vision. Technical University Eindhoven, Eindhoven.

Rogers, S.D., Kadar, E.E., Costall, A., 2005. Gaze Patterns in the Visual Control of Straight-Road Driving and Braking as a Function of Speed and Expertise. Ecological Psychology 17 (1), 19-38.

Rosén, E., Stigson, H., Sander, U., 2011. Literature review of pedestrian fatality risk as a function of car impact speed. Accident Analysis and Prevention 43 (1), 25-33.

Rumar, K., 1999. Transport Safety Visions, Targets and Strategies: Beyond 2000. European Transport Safety Council, Brussels.

Rumar, K., Marsh, D.K., II, 1998. Lane Markings in Night Driving: A Review of Past Research and of the Present Situation. University of Michigan, Transportation Research Institute, Michigan.

Sakshaug, L., Laureshyn, A., Svensson, Å., Hydén, C., 2010. Cyclists in roundabouts—Different design solutions. Accident Analysis and Prevention 42 (4), 1338-1351.

San Diego State University, 2012. SafetyLit; Injury Prevention Literature Update & Archive Database. Retrieved 15-01, from http://www.safetylit.org/

Schepers, J.P., 2006. Evaluatie van de Maatregel Voorrang Fietsers van Rechts (Evaluation of the Legislation Change Right of Way for Cyclists entering from the Right). Rijkswaterstaat, Rotterdam.

Schepers, J.P., 2008. De Rol van Infrastructuur bij Enkelvoudige Fietsongevallen (The Role of Infrastructure in Single-bicycle Crashes). Rijkswaterstaat, Delft.

Schepers, J.P., 2010. Fiets-Fietsongevallen (Bicycle-Bicycle crashes). Rijkswaterstaat, Delft.

Schepers, J.P., 2012. Does more cycling also reduce the risk of single-bicycle crashes? Injury Prevention 18 (4), 240-5.

Schepers, J.P., Agerholm, N., Amoros, E., Benington, R., Bjørnskau, T., Dhondt, S., De Geus, B., Hagemeister, C., Loo, B.P.Y., Niska, A., 2013a. An international review of the hidden problem of single-bicycle crashes (SBCs). Routes-Roads (Accepted for publication).

Schepers, J.P., Den Brinker, B.P.L.M., 2011. What do cyclists need to see to avoid single-bicycle crashes? Ergonomics 54 (4), 315-27.

Schepers, J.P., Hagenzieker, M.P., Methorst, R., Van Wee, G.P., Wegman, F., 2013b. A conceptual framework for road safety and mobility applied to cycling safety. Accident Analysis and Prevention, In press.

Schepers, J.P., Heinen, E., 2013. How does a modal shift from short car trips to cycling affect road safety? Accident Analysis and Prevention 50 (1), 1118–1127.

Schepers, J.P., Kroeze, P.A., Sweers, W., Wust, J.C., 2011. Road factors and bicycle-motor vehicle crashes at unsignalized priority intersections. Accident Analysis and Prevention 43 (3), 853-61.

Schepers, J.P., Vermeulen, W., 2012. Ontwikkeling en Doelstelling Ernstig Gewonden (Development of the Number of Serious Road Injuries and the Target). Rijkswaterstaat Centre for Transport and Navigation, Delft.

Schepers, J.P., Voorham, J., 2010. Oversteekongevallen met Fietsers (Crossing Accidents with Cyclists). Rijkswaterstaat, Delft.

Schieber, F., Schlorholtz, B., McCall, R., 2008. Visual Requirements of Vehicular Guidance. In: Castro, C. ed. Human Factors of Visual and Cognitive Performance in Driving. CRC Press, Boca Raton.

Schneider, A., Hommel, G., Blettner, M., 2010. Linear regression analysis: part 14 of a series on evaluation of scientific publications. Deutsches Ärzteblatt International 107 (44), 776.

Schnüll, R., Lange, J., Fabian, I., Kölle, M., Schütte, F., Alrutz, D., Fechtel, H.W., Stellmacher-Hein, J., Brückner, T., Meyhöfer, H., 1992. Sicherung von Radfahrern an städtischen Knotenpunkten. BASt, Bergisch Gladbach.

Schoon, C.C., 2000. Verkeersveiligheidsanalyse van het Concept-NVVP; Deel 1: Effectiviteit van Maatregelen (Road Safety Analysis of the Concept NVVP; Part 1: Effectiveness of Measures). Institute for Road Safety Research, Leidschendam.

Schoon, C.C., 2006. De Problematiek van Rechtsafstaande Vrachtauto's (The Problem of Right-Turning Lorries). Institute for Road Safety Research, Leidschendam.

Schoon, C.C., Blokpoel, A., 2000. Frequentie en Oorzaken van Enkelvoudige Fietsongevallen (Frequency and Causes of Single-Bicycle Accidents). Institute for Road Safety Research, Leidschendam.

Schoon, C.C., Doumen, M.J.A., De Bruin, D., 2008. De Toedracht van Dodehoekongevallen en Maatregelen voor de Korte en Lange Termijn (The Circumstances of Blind Spot Crashes and Short- and Long-Term Measures). Institute for Road Safety Research, Leidschendam.

Schubö, A., 2009. Salience detection and attention capture. Psychological Research 73 (2), 233-243.

Servaas, M., 2000. The Significance of Non-Motorised Transport for Developing Countries. Interface for Cycling Expertise, Utrecht.

Shinar, D., 2007. Traffic Safety and Human Behavior. Elsevier, Amsterdam.

Siddiquia, C., Abdel-Atya, M., Choi, K., 2012. Macroscopic spatial analysis of pedestrian and bicycle crashes. Accident Analysis and Prevention 45, 382 - 391.

Slop, M., Van Minnen, J., 1994. Duurzaam Veilig Voetgangers- en Fietsverkeer (Sustainable Safe Pedestrian and Cycle Traffic). Institute for Road Safety Research, Leidschendam.

Sobel, M.E., 1982. Asymptotic Intervals for Indirect Effects in Structural Equations Models. In: Leinhart, S. ed. Sociological Methodology. Jossey-Bass, San Francisco, pp. 290-312.

Sobel, M.E., 1988. Direct and Indirect Effect in Leaner Structural Equation Models. In: Long, J.S. ed. Common Problems/Proper Solutions: Avoiding Error in Quantitative Research. Sage, Beverly Hills, CA, pp. 46-64.

Sobhani, A., Young, W., Logan, D., Bahrololoom, S., 2011. A kinetic energy model of two-vehicle crash injury severity. Accident Analysis and Prevention 43 (3), 741-754.

Southworth, M., 2005. Designing the walkable city. Journal of Urban Planning and Development 131 (4), 246-257.

Statistics Denmark, 2013. Traffic Accidents. Retrieved 31 January 2013, from http://www.dst.dk/

Statistics Netherlands, 2011. Statline. Retrieved 20 December 2011, from http://www.cbs.nl

Steyvers, F.J., De Waard, D., 2000. Road-edge delineation in rural areas: effects on driving behaviour. Ergonomics 43 (2), 223-238.

Stipdonk, H., Reurings, M., 2012. The effect on road safety of a modal shift from car to bicycle. Traffic Injury Prevention 13 (4), 412-21.

Summala, H., Lamble, D., Laakso, M., 1998. Driving experience and perception of the lead car’s braking when looking at in-car targets. Accident Analysis and Prevention 30 (4), 401-407.

Summala, H., Pasanen, E., Räsänen, M., Sievänen, J., 1996. Bicycle accidents and drivers' visual search at left and right turns. Accident Analysis and Prevention 28 (2), 147-153.

SWOV, 2010a. Factsheet Young Novice Drivers. Institute for Road Safety Research, Leidschendam.

SWOV, 2010b. Factsheet Zones 30: Urban Residential Areas. Institute for Road Safety Research, Leidschendam.

SWOV, 2011a. Cognos. Retrieved 20 December 2011, from http://www.swov.nl

SWOV, 2011b. Factsheet Road fatalities in the Netherlands. Institute for Road Safety Research, Leidschendam.

SWOV, 2012. Factsheet Attention problems behind the wheel. Institute for Road Safety Research, Leidschendam.

Terry, H.R., Charlton, S.G., Perrone, J.A., 2008. The role of looming and attention capture in drivers’ braking responses. Accident Analysis and Prevention 40 (4), 1375-1382.

Teschke, K., Harris, M.A., Reynolds, C.C., Winters, M., Babul, S., Chipman, M., Cusimano, M.D., Brubacher, J.R., Hunte, G., Friedman, S.M., Monro, M., Shen, H., Vernich, L., Cripton, P.A., 2012. Route infrastructure and the risk of injuries to bicyclists: a case-crossover study. American journal of public health 102 (12), 2336-43.

Theeuwes, J., Godthelp, H., 1995. Self-explaining roads. Safety Science 19 (2–3), 217-225.

Theeuwes, J., Hagenzieker, M.P., 1993. Visual Search of Traffic Scenes: On the Effect of Location Expectations. In: Gale, A.G., Freeman, M.H., Haslegrave, C.M., Smith, P., Taylor, S.P. eds. Vision in Vehicle IV. Elsevier Science, Amsterdam: .

Thomas, B., DeRobertis, M., 2013. The safety of urban cycle tracks: A review of the literature. Accident Analysis and Prevention 52, 219-227.

Thompson, B., Diamond, K.E., McWilliam, R., Snyder, P., Snyder, S.W., 2005. Evaluating the quality of evidence from correlational research for evidence-based practice. Exceptional Children 71 (2), 181-194.

Tingvall, C., Haworth, N., 1999. Vision Zero - An ethical approach to safety and mobility. 6th ITE International Conference Road Safety & Traffic Enforcement: Beyond 2000. Melbourne.

Toet, A., Kooi, F.L., Bijl, P., Valeton, J.M., 1998. Visual conspicuity determines human target acquisition performance. tical Engineering 37 (7), 1969-1975.

Toft, Y., Dell, G., Klockner, K.K., Hutton, A., 2012. Models of causation: safety. Safety Institute of Australia, Tullamarine, Victoria.

Turano, K.A., Massof, R.W., Quigley, H.A., 2002. A self-assessment instrument designed for measuring independent mobility in RP patients: generalizability to glaucoma patients. Investigative Ophthalmology and Visual Science 43 (9), 2874-81.

Van Boggelen, O., Janssen, R., Everaars, J., 2005. Effect Toename Fietsaandeel op de Verkeersveiligheid (Road Safety Effects of an Increase of Cycling in the Modal Split). Transport Research Centre, Rotterdam.

Van Boggelen, O., Schepers, J.P., Kroeze, P.A., Van der Voet, M., 2011. Fietsberaadpublicatie 19: Samen Werken aan een Veilige Fietsomgeving (Collaborating to Improve Cycling Safety). Fietsberaad, Utrecht.

Van de Kaa, E.J., 2010. Prospect theory and choice behaviour strategies: review and synthesis of concepts from social and transport sciences. European Journal of Transport and Infrastructure Research 10 (4), 299-329.

Van der Horst, A.R.A., 1990. A Time Based Analysis of Road User Behaviour in Normal and Critical Encounters. Delft University of Technology, Delft.

Van Haeften, M., 2010. Het Kijkgedrag van Automobilisten en Fietsers bij Kruispunten met een Tweerichtingsfietspad (Viewing Behaviour of Drivers and Cyclists at Intersections with a Two-Way Cycle Track). University of Groningen, Groningen.

Van Loon, A., 2001. Evaluatie Verkeersveiligheidseffecten 'Bromfiets op de Rijbaan' (The Road Safety Impact of Moped Riders on the Carriageway). Rijkswaterstaat, Rotterdam.

Van Minnen, J., 1990. Ongevallen op Rotondes (Crashes at Roundabouts). Institute for Road Safety Research, Leidschendam.

Van Norden, Y., Bijleveld, F.D., 2011. Referentieprognose van de Verkeersveiligheidsverkenning 2020 (Reference Prognosis for the Road Safety Outlook 2020). Institute for Road Safety Research, Leidschendam.

Van Oijen, J., Lankhuijzen, R., Van Boggelen, O., 2013. Feiten over de Elektrische Fiets (Facts about Electrically Assisted Bicycles). Fietsberaad, Utrecht.

Van Schijndel-de Nooij, M., 2012. SaveCAP A Joint Project To Protect Cyclist and Pedestrians. TNO, Helmond.

Van Wee, B., 2009. Verkeer en Transport (Traffic and Transport). In: Van Wee, B., Anne Annema, J. eds. Verkeer en Vervoer in Hoofdlijnen (Outlining Traffic and Transport). Coutinho, Bussum.

Van Wee, B., Maat, K., 2003. Land-use and transport: a review and discussion of Dutch research. European Journal of Transport and Infrastructure Research 3 (2), 199-218.

Van Wee, B., Rietveld, P., Meurs, H., 2006. Is average daily travel time expenditure constant? In search of explanations for an increase in average travel time. Journal of Transport Geography 14 (2), 109-122.

Van Wee, G.P., Hagenzieker, M.P., Wijnen, W., 2012. Which indicators to include in the ex ante evaluations of the safety effects of policy options? Gaps in evaluation and a discussion based on an ethical perspective. Transport Policy, Accepted for publication.

Vandenbulcke-Plasschaert, G., 2011. Spatial Analysis of Bicycle Use and Accident Risks for Cyclists. Université catholique de Louvain, Louvain.

Veisten, K., Sælensminde, K., Alvær, K., Bjørnskau, T., Elvik, R., Schistad, T., Ytterstad, B., 2007. Total costs of bicycle injuries in Norway: correcting injury figures and indicating data needs. Accident Analysis and Prevention 39 (6), 1162-1169.

Viner, D., 1991. Accident Analysis and Risk Control. Derek Viner Ltd, Melbourne.

Vis, A.A., Dijkstra, A., Slop, M., 1992. Safety effects of 30 km/h zones in the Netherlands. Accident Analysis and Prevention 24 (1), 75-86.

Vlakveld, W.P., 2005. Jonge Beginnende Automobilisten, hun Ongevalsrisico en Maatregelen om dit terug te Dringen (Young Novice Drivers, their Crash Risk and Preventive Measures). Institute for Road Safety Research., Leidschendam.

Vlakveld, W.P., Goldenbeld, C., Twisk, D.A.M., 2008. Beleving van Verkeersonveiligheid (Perception of Lack of Traffic Safety). Institute for Road Safety Research, Leidschendam.

Vlakveld, W.P., Louwerse, W.J.R., 2011. De Relatie tussen Road Protection Scores (RPS) en het Slachtofferrisico op Wegvakken van Provinciale Wegen in Utrecht (The Relation between Road Protection Scores (RPS) and the Casualty Rate at Road Sections in the Province of Utrecht). Institute for Road Safety Research, Leidschendam.

Vlassenroot, S., Molin, E., Kavadias, D., Marchau, V., Brookhuis, K.A., Witlox, F., 2011. What drives the acceptability of intelligent speed assistance (ISA)? European Journal of Transport and Infrastructure Research 11 (2), 256-273.

Vlek, C., Jager, W., Steg, L., 1997. Modellen en strategieën voor gedragsverandering ter vermindering van collectieve risico's (Models and strategies for behavioural change in order to reduce collective risks). Nederlands tijdschrift voor de Psychologie 52, 174-191.

Wachtel, A., Lewiston, D., 1994. Risk factors for bicycle-motor vehicle collisions at intersections. ITE Journal 64 (9), 30-35.

Wagenaar, W.A., Reason, J.T., 1990. Types and tokens in road accident causation. Ergonomics 33 (10-11), 1365-1375.

Wang, Y., Nihan, N., 2004. Estimating the risk of collisions between bicycles and motor vehicles at signalized intersections. Accident Analysis and Prevention 26, 313-321.

Wang, Y.Z., Thibos, L.N., Bradley, A., 1997. Effects of refractive error on detection acuity and resolution acuity in peripheral vision. Investigative Ophthalmology and Visual Science 38 (10), 2134-43.

Wedderburn, R.W.M., 1974. Quasi-likelihood functions, generalized linear models, and the Gauss-Newton method. Biometrika 54, 439-447.

Wegman, F.C.M., Aarts, L.T., 2006. Advancing Sustainable Safety; National Road Safety Outlook for 2005–2020. Institute for Road Safety Research, Leidschendam.

Wegman, F.C.M., Aarts, L.T., Bax, C., 2008. Advancing sustainable safety: national road safety outlook for the Netherlands for 2005–2020. Safety Science 46 (2), 323-343.

Wegman, F.C.M., Zhang, F., Dijkstra, A., 2012. How to make more cycling good for road safety? Accident Analysis and Prevention 44 (1), 19-29.

Weijermars, W.A.M., Dijkstra, A., Doumen, M.J.A., Stipdonk, H.L., Twisk, D.A.M., Wegman, F.C.M., 2013. Duurzaam Veilig, ook voor Ernstig Verkeersgewonden (Sustainable Safety, also for Severely Injured Casualties). Institute for Road Safety Research, Leidschendam.

Weijermars, W.A.M., Wegman, F.C.M., 2011. Ten years of Sustainable Safety in the Netherlands. Transportation Research Record 2213, 1-6.

Welleman, A.G., Dijkstra, A., 1988. Veiligheidsaspecten van Stedelijke Fietspaden (The safety of Urban Bicycle Tracks). Institute for Road Safety Research, Leidschendam.

Weller, G., Schlag, B., 2007. Driver Behaviour Model; RIPCORD-INSEREST Deliverable D8. Technische Universität Dresden, Dresden.

Wierda, M., Brookhuis, K.A., 1991. Analysis of cycling skill: a cognitive approach. Applied Cognitive Psychology 5 (2), 113-122.

Wijk, M., 2008. Handboek voor Toegankelijkheid (Manual for Accessibility). Reed Business Elsevier, London/Amsterdam.

Wilde, G.J.S., 1982. The theory of risk homeostasis: implications for safety and health. Risk Analysis 2 (4), 209-225.

Wilmink, I., Janssen, J., Jonkers, E., Malone, K., Van Noort, M., Gerdien Klunder, G., Rämä, P., Sihvola, N., Kulmala, R., Schirokoff, A., Lind, G., Benz, T., Peters, H., Schönebeck, S., 2008. Socio-economic Impact Assessment of Stand-alone and Co-operative Intelligent Vehicle Safety Systems (IVSS) in Europe. TNO, Delft.

Winters, M., Teschke, K., 2010. Route preferences among adults in the near market for bicycling: findings of the cycling in cities study. American journal of health promotion 25 (1), 40-7.

Winters, M., Weddell, A., Teschke, K., Year. Is evidence in practice? A review of driver and cyclist education materials with respect to cycling safety evidence. In: Proceedings of the Transportation Research Board 92nd Annual Meeting.

Wood, J.M., Owens, D.A., 2005. Standard measures of visual acuity do not predict drivers' recognition performance under day or night conditions. Optometry and Vision Science 82 (8), 698-705.

Xing, Y., Handy, S.L., Mokhtarian, P.L., 2010. Factors associated with proportions and miles of bicycling for transportation and recreation in six small US cities. Transportation Research Part D 15, 73-81.

Zacharias, J., 2005. Non-motorized transportation in four Shanghai districts. International Planning Studies 10 (3-4), 323-340.

Zeegers, T., 2010. Ongevallen met Oudere Fietsers (Crashes of Older Cyclists). Fietsersbond, Utrecht.

Zegeer, C.V., Stewart, J.R., Huang, H., Lagerwey, P., 2001. Safety effects of marked versus unmarked crosswalks at uncontrolled locations; analysis of pedestrian crashes in 30 cities. Transportation Research Record 1773, 56-68.

Zwipp, H., Ernstberger, A., Groschupf, V., Günther, K.P., Haase, M., Haasper, C., Hagemeister, C., Hannawald, L., Juhra, C., Leser, H., 2012. Prevention of road accidents involving non-motorized traffic participants (pedestrians and cyclists) in Germany. Der Unfallchirurg 115 (6), 554.

Summary: A safer road environment for cyclists

This thesis is focused on the question how the road environment (road design and network characteristics) affects road safety for cyclists through effects on risk and exposure to risk. This question is relevant because government agencies in many countries aim to improve road infrastructure safety for cyclists to decrease the substantial health burden due to cyclist injuries. This concerns both collisions with motor vehicles which regularly result in fatal injuries as well as single-bicycle crashes (falls or obstacle collisions) in which many cyclists incur serious injuries. The research questions formulated in this thesis address three main topics. The first subject is about how the road environment affects travel behaviour and exposure. The second is about its effect on crash risk (injury risk is only marginally addressed). The third topic is the relationship between exposure and risk, because both may affect one another.

One of the innovative aspects of this thesis is that it contains studies related to all three topics (exposure, risk and their relationship), aiming to increase the knowledge of how the road environment contributes to or helps to prevent bicycle crashes. Most research is restricted to one of the three issues. *Chapter 1* describes a conceptual framework which combines exposure to risk, risk, and the relationship between them. The framework's three determinants for travel behaviour are locations of activities; resistances (generalized transport costs); needs, opportunities, and abilities. Crash and injury consequences are modelled by the three 'safety pillars': infrastructure, road users and the vehicles they use. The framework's link between risk and exposure is important because of the 'non-linear relationship' between these two, i.e. risk tends to decrease as exposure increases. Finally, the framework has a link from (perceived) risk to resistance because perceived risk plays a role in travel behaviour, e.g. a road user may prefer driving over cycling because cars are perceived to be safer. The remainder of this summary is organized according to the three research topics.

The road environment may encourage or discourage cycling which affects exposure to risk. It depends on the relationship between exposure and risk to what extent the number of road traffic casualties is affected. *Chapters 2 and 3* focus on the following research question: *How does a modal shift from short car trips to cycling affect road safety?* To answer this question, Crash Prediction Models (CPMs) were developed for Dutch municipalities. Models were also developed for single-bicycle crashes which was not done before. As single-bicycle crashes are under-reported by the police, the study also included another data source: self-reported crashes from a questionnaire study. It was found that cyclists are less likely to be involved in a severe single-bicycle crash in municipalities with a high amount of cycling. The volumes of cyclists and motor vehicles before and after a hypothetical modal shift were entered into the CPMs to estimate the road safety effects. The results suggest that, under conditions such as in Dutch municipalities, transferring short trips made by cars to bicycles does not change the number of fatalities, but increases the number of serious road injuries. The rise in the number of serious road injuries is due to high numbers of severe single-bicycle crashes. The effect of a modal shift is dependent on the age of the population in which the shift is concentrated, i.e. more favourable for young and less favourable for older drivers. Furthermore, the results suggest that it may be possible to influence the effect of a modal shift by measures specifically affecting cyclists' risk.

Chapter 4, 5, and 6 are focused on road design and crash risk. *Chapters 4* describes a study conducted to answer question 3a: *How is the design of unsignalized priority intersections related to bicycle–motor vehicle crashes?* In this study, the safety of cyclists at unsignalized priority intersections within built-up areas is investigated. Failure-to-yield crashes recorded at unsignalized intersections were classified into two types based on the movements of the involved motorists and cyclists:

- type I: through bicycle related collisions where the cyclist has right of way (i.e. bicycle on the priority road);
- type II: through motor vehicle related collisions where the motorist has right of way (i.e. motorist on the priority road).

The probability of each crash type was related to its relative flows and to independent variables using negative binomial regression. The results show that more type I crashes occur at intersections with two-way bicycle tracks, well-marked, and reddish coloured bicycle crossings. Type I crashes are negatively related to the presence of raised bicycle crossings (e.g. on a speed hump) and other speed reducing measures. The accident probability is also decreased at intersections where the cycle track approaches are deflected between 2 and 5m away from the main carriageway. No significant relationships are found between type II crashes and design factors such as the presence of a raised median.

Chapter 5 focuses on research question 3b: *What single-bicycle crash types can be distinguished and can these be related to infrastructure?* A literature search showed that only a few studies addressed single-bicycle crashes (i.e. a fall or obstacle collision). These studies and theories were used to develop a draft categorization of single-bicycle crash types. The typology was tested using a survey among bicycle crash victims treated at Emergency Care Departments. The results indicate that about half of all single-bicycle crashes are related to infrastructure: the cyclist collided with an obstacle (1ai), rode off the road (1aii), the bicycle skidded due to a slippery road surface (1bi), or the rider was unable to stabilize the bicycle or stay on the bike because of an uneven road surface (1bii). The first two categories happen due to the cyclist inadvertently taking a dangerous riding line, while the last two happen under more direct influence of the road surface conditions. Crash types related to the cyclist are loss of control at low speed (2a), due to forces on the front wheel (2b), or poor or risky riding behaviour (2c). Bicycle defects (3) contribute to a small group of crashes. Finally, some cyclists fall because of an external force such as a gust of wind (4).

Question 3c is about the role of visibility of infrastructure in single-bicycle crashes: *What do cyclists need to see to avoid single-bicycle crashes?* This question is addressed *in Chapter 6*. To study the role of visual characteristics of the infrastructure, such as pavement markings, in single-bicycle crashes, a study in two steps was conducted. In Study 1, a questionnaire study was conducted among bicycle crash victims. Logistic regression was used to study the relationship between the crashes and age, light condition, alcohol use, gaze direction and familiarity with the crash scene. In Study 2, the image degrading and edge detection method (IDED-method) was used to investigate the visual characteristics of 21 of the crash scenes. The results of the studies indicate that crashes, in which the cyclist collided with a bollard or road narrowing or rode off the road, were related to the visual characteristics of bicycle facilities.

Chapter 7 focuses on network characteristics and cycling safety. It addresses the first research question: *How does network-level separation of vehicular and cycle traffic (unbundling) in urban networks affect road safety?* This is related to the distribution of traffic over space, one of the elements of travel behaviour. Bicycle-motor vehicle crashes are concentrated along distributor roads where cyclists are exposed to greater volumes of high-speed motorists than they would experience on access roads. This study examined the road safety impact of unbundling vehicular and cycle traffic in Dutch urban networks. Unbundling is operationalized as the degree to which cyclists use access roads and grade-separated intersections to cross distributor roads. The effect on the share of cycling in the modal split is also assessed as unbundling measures may affect the competitiveness of cycling compared to driving. The analyses were conducted using data of all Dutch municipalities with more than 50,000 inhabitants. Negative binomial regression was used to analyse the effect on the number of police-reported cyclist deaths and in-patients in bicycle-motor vehicle crashes. A mediation model was tested, with Structural Equation Modelling hypothesizing that unbundling corresponds positively with the cycling modal share via the length of car trips divided by those by bicycle. The results of this study suggest that unbundling improves cycling safety, and increases the share of cycling in the modal split (as a result of improved competitiveness of cycling in terms of trip length).

Chapter 8 discussed the main findings of the research conducted throughout the thesis and considered the implications. It can be concluded that cycling safety is affected by the road design. For instance, the studies described in *Chapters 4, 5, and 6* indicate that the design of bicycle tracks and intersections affect the likelihood of BMV and single-bicycle crashes. *Chapter 7* indicates that network characteristics are related to the likelihood of BMV crashes due its effect on the distribution of vehicular and cycle traffic over the network. This affects cyclists' exposure to high-speed vehicular traffic. The road environment may encourage or discourage cycling. For example, the study described in *Chapter 7* suggest that the measures taken for unbundling correspond positively with the modal share of cycling because trips become relatively shorter by bicycle then by car. In *Chapters 2 and 3* it is estimated that under conditions such as in Dutch municipalities, transferring short trips made by cars to bicycles does not change the number of fatalities, but increases the number of serious road injuries. *Chapter 8* discusses a number of uncertainties regarding the latter conclusion. A more favourable road safety impact can be expected if the modal shift would be induced by instance network-level separation or other safety-related measures than if it were induced by factors unrelated to safety (e.g. an increased gasoline price). The chapter discusses challenges for future research.

Samenvatting: Een veiligere wegomgeving voor fietsers

Dit proefschrift richt zich op de vraag hoe de wegomgeving (netwerk- en wegkenmerken) de verkeersveiligheid voor fietsers beïnvloedt via effecten op risico en blootstelling aan risico. Deze vraag is relevant omdat overheden in veel landen zich tot doel stellen om de veiligheid van weginfrastructuur voor fietsers te verbeteren om het letsel door fietsongevallen te reduceren. Het gaat daarbij zowel om aanrijdingen waarbij regelmatig doden te betreuren zijn als om enkelvoudige fietsongevallen (een val of botsing met een obstakel) waarbij veel slachtoffers ernstig gewond raken. De onderzoeksvragen die voor dit proefschrift zijn geformuleerd onderscheiden drie hoofdonderwerpen. Het eerste onderwerp richt zich op de vraag hoe de wegomgeving reisgedrag en blootstelling aan risico beïnvloedt. Het tweede onderwerp gaat over het ongevalsrisico (letselernst komt slechts marginaal aan bod). Het derde onderwerp gaat over de relatie tussen blootstelling en risico omdat beide elkaar kunnen beïnvloeden.

Een vernieuwend aspect van dit proefschrift is dat deze deelstudies omvat die zowel expositie, risico als de relatie tussen die twee adresseren om de kennis over hoe de wegomgeving fietsveiligheid beïnvloedt te vergroten. De meeste studies beperken zich tot één van drie onderwerpen. *Hoofdstuk 1* beschrijft een conceptueel model dat expositie, risico en hun relatie beschrijft. Het reisgedrag (verkeersvolumes, modaliteitskeuze en de verdeling van verkeer over de ruimte) waardoor verkeersdeelnemers aan risico worden blootgesteld is gemodelleerd met drie factoren, namelijk locaties van activiteiten, weerstand (gegeneraliseerde transportkosten) en de trits van behoeften, mogelijkheden en vermogens. Ongevalsrisico en letselernst zijn gemodelleerd op basis van infrastructuur, verkeersdeelnemers en voertuigen. Het model heeft een relatie tussen risico en expositie omdat het verband tussen beide niet lineair is, d.w.z. het risico neemt in het algemeen af naarmate de expositie toeneemt. Tot slot heeft het model een relatie tussen risico en weerstand omdat subjectieve veiligheid een rol speelt in reisgedrag. Een verkeersdeelnemer kan bijvoorbeeld kiezen voor de auto omdat autorijden als veiliger wordt beleefd dan fietsen. Het vervolg van de samenvatting is geordend volgens de drie onderzoeksvragen.

De wegomgeving kan fietsen stimuleren of ontmoedigen waarmee de blootstelling aan risico wordt beïnvloed. Het hangt van de relatie tussen expositie en risico af hoe het aantal verkeersslachtoffers wordt beïnvloed. Om meer inzicht in het verkeersveiligheidseffect te krijgen richten *Hoofdstuk 2 en 3* zich op de volgende onderzoeksvraag: *"Hoe beïnvloedt een vervanging van korte autoritten door fietsritten de verkeersveiligheid?"* Om deze vraag te beantwoorden zijn ongevalvoorspelmodellen, verder aangeduid als Crash Prediction Models (CPM's) ontwikkeld voor Nederlandse gemeenten. Er zijn hierbij ook modellen voor enkelvoudige fietsongevallen ontwikkeld (dat was nog niet eerder gebeurd). Vanwege de onderregistratie van enkelvoudige fietsongevallen door de politie is ook gebruik gemaakt van een andere bron (zelfgerapporteerde ongevallen uit een vragenlijstonderzoek). Het bleek dat fietsers een kleinere kans hadden om betrokken te raken bij ernstige enkelvoudige fietsongevallen in gemeenten met een hoog fietsgebruik. De volumes aan fiets- en autokilometers voor en na een hypothetische vervanging van korte autoritten door fietsritten werden in de CPMs ingevoerd om het effect op verkeersveiligheid te schatten. De resultaten wijzen erop dat, onder omstandigheden zoals in Nederlandse gemeenten, een vervanging van korte autoritten door fietsritten geen effect heeft op het aantal verkeersdoden maar leidt tot een toename van het aantal ernstig verkeersgewonden. Dat laatste komt door het hoge aantal fietsers dat ernstig gewond raakt bij enkelvoudige fietsongevallen. Het effect van de verandering in modaliteitskeuze hangt samen met de leeftijdsopbouw van de groep fietsers die van de auto overstapt op de fiets. Verder suggereren de resultaten dat het mogelijk is om de effecten van een vervanging van korte autoritten door fietsritten te beïnvloeden door maatregelen die specifiek effect hebben op het ongevalsrisico van fietsers.

Hoofdstuk 4, 5 en 6 richten zich op wegkenmerken en ongevalsrisico. Deelvraag 3a wordt behandeld in *Hoofdstuk 4* en gaat over fietsongevallen met motorvoertuigen: *Hoe zijn wegkenmerken van voorrangskruispunten (zonder VRI) gerelateerd aan fietsongevallen met motorvoertuigen?* Geregistreerde fietsongevallen werden verdeeld in twee groepen:

- type I: fietser op de voorrangsweg botst met motorvoertuig dat de voorrangsweg af- of oprijdt;
- type II: motorvoertuig op de voorrangsweg botst met fietser die de voorrangsweg oversteekt.

Bij type I heeft de fietser voorrang; bij type II de bestuurder van het motorvoertuig. De ongevalskans werd gerelateerd aan wegkenmerken en de aantallen fietsers en motorvoertuigen die betrokken konden zijn bij de betreffende ongevalsmanoeuvre, bijvoorbeeld bij type I fietsers op de voorrangsweg en motorvoertuigen die de voorrangsweg op- of afreden. De kans op type II ongevallen is verhoogd bij tweerichtingsfietspaden en (tegen de verwachting in) als de oversteekplaats goed gemarkeerd en rood is. De resultaten laten zien dat er minder type I-ongevallen zijn als er snelheidsremmers zijn toegepast om het verkeer dat de voorrangsweg op- of afrijdt te remmen. De ongevalskans is ook verlaagd als er een ruimte tussen de 2 en 5 m is tussen de voorrangsweg en het fietspad. Er werden geen significante verbanden gevonden tussen wegkenmerken en type-II ongevallen.

Hoofdstuk 5 richt zich op onderzoeksvraag 3b: *Welke typen enkelvoudige ongevallen kunnen worden onderscheiden en gerelateerd aan infrastructuur?* Een literatuuronderzoek liet zien dat slechts een beperkt aantal onderzoeken zich heeft gericht op enkelvoudige fietsongevallen. De uitkomsten van deze studies en theorie zijn gebruikt om te komen tot een typologie van enkelvoudige fietsongevallen. Deze is getoetst met een vragenlijstonderzoek uitgezet onder fietsslachtoffers behandeld op de spoedeisendehulpafdeling (SEH-afdeling) van een ziekenhuis. Uit het onderzoek blijkt dat ongeveer de helft van de enkelvoudige fietsongevallen is gerelateerd aan infrastructuur waarbij moet worden opgemerkt dat ongevallen meestal door een samenloop van factoren ontstaan. De volgende typen zijn gerelateerd aan infrastructuur: met een obstakel botsen (1ai), van de weg afrijden of tegen een trottoirband botsen (1aii), slippen door glad wegdek (1bi) of uit balans raken en vallen door kuilen of hobbels in het wegdek (1bii). Bij de eerste twee typen is ook sprake van een koersfout terwijl de laatste twee gebeuren onder directe invloed van de toestand van de verharding. Ongevalstypen die meer aan de fietser zijn gerelateerd zijn uit balans raken en vallen bij lage snelheden (2a), door krachten op het voorwiel (2b) of onhandig dan wel riskant rijgedrag (2c). Enkelvoudige ongevallen door defecten aan de fiets (3) vormen slechts een kleine groep. Tot slot was er een groep waarbij het slachtoffer viel door een externe kracht zoals windvlaag (4).

Onderzoeksvraag 3c gaat over de rol van het visuele ontwerp van infrastructuur bij enkelvoudige fietsongevallen: *In hoeverre speelt zichtbaarheid van infrastructuur een rol bij enkelvoudige fietsongevallen te voorkomen?* Onderzoek gericht op deze vraag wordt behandeld in *Hoofdstuk 6*. Om de rol van visuele kenmerken van infrastructuur zoals markeringen bij enkelvoudige fietsongevallen te bestuderen is een studie in twee fasen uitgevoerd. In studie 1 werd een vragenlijstonderzoek uitgevoerd onder slachtoffers van enkelvoudige fietsongevallen. Met logistische regressie werd het effect van aan visuele aspecten gerelateerde ongevalskenmerken onderzocht, namelijk leeftijd (ouderen hebben een verminderde visuele functie), lichtgesteldheid (licht versus donker), alcoholgebruik (dit tast o.a. de visuele functie aan), kijkrichting vlak voor het ongeval en bekendheid met de ongevalslocatie (i.v.m. verwachtingen over waar zich gevaren bevinden). In studie 2 werd de zogenaamde 'image degrading and edge detection' methode (IDED-methode) gebruikt. Daarmee werd de zichtbaarheid van kritische informatie (d.w.z. kritisch voor het voorkomen van het ongeval) op een selectie van 21 ongevalslocaties beoordeeld. De resultaten van beide studies suggereren zichtbaarheid van infrastructuur een rol kan spelen bij ongevallen waarbij de fietser met een obstakel botst of van de weg af rijdt.

Hoofdstuk 7 richt zich op netwerkkarakteristieken en fietsveiligheid en gaat in om de eerste onderzoeksvraag: *Hoe beïnvloedt scheiding van gemotoriseerd verkeer en fietsverkeer op netwerkniveau (ontvlechting) de verkeersveiligheid?* Dit is gerelateerd aan de verdeling van verkeer over de ruimte, één van de elementen van reisgedrag. Fietsongevallen met gemotoriseerd zijn geconcentreerd op het netwerk van gebiedsontsluitingswegen waar fietsers blootgesteld worden aan grotere volumes snelverkeer dan het geval zou zijn als ze op erftoegangswegen (of solitaire fietspaden) zouden rijden. In deze studie wordt het effect van ontvlechting in stedelijke netwerken op verkeersveiligheid onderzocht. Ontvlechting is hierbij geoperationaliseerd als de mate waarin fietsers door verblijfsgebieden fietsen en gebiedsontsluitingswegen ongelijkvloers kruisen (met fietstunnels en fietsbruggen). Het effect op het aandeel fietsgebruik in de modal split wordt ook onderzocht omdat ontvlechting de concurrentiepositie van de fiets kan versterken. De maatregelen voor ontvlechting (bijvoorbeeld afsluiting van een weg voor autoverkeer maar met een doorsteek voor fietsers) kunnen ervoor zorgen dat ritten per fiets korter zijn dan met de auto. De analyses worden uitgevoerd voor gemeenten met meer dan 50.000 inwoners. Negatieve Binomiale regressie is gebruikt om de relatie te onderzoeken met het aantal geregistreerde doden en ziekenhuisgewonden bij fiets-motorvoertuigongevallen. Er is met Structural Equation Modelling een mediatie-model getoetst om de hypothese te toetsen dat ontvlechting via de concurrentiepositie van de fiets bijdraagt aan het fietsaandeel in de modal split. De concurrentiepositie van de fiets is daarbij uitgedrukt als de lengte van korte ritten per auto gedeeld door de lengte van dezelfde ritten per fiets. De resultaten van de studie wijzen uit dat steden met een grotere mate van ontvlechting minder fietsslachtoffers hebben. De resultaten suggereren verder dat ontvlechting via een verbeterde concurrentiepositie van de fiets in lichte mate samengaat met een hoger aandeel fietsgebruik in de modal split.

In *Hoofdstuk 8* worden de belangrijkste bevindingen en implicaties van het proefschrift besproken. Geconcludeerd kan worden dat fietsveiligheid mede afhankelijk is van de wegomgeving. De studies beschreven in *Hoofdstuk 4, 5 en 6* laten zien wegkenmerken zoals het ontwerp van fietspaden en voorrangskruispunten de kans op fietsongevallen met motorvoertuigen en enkelvoudige fietsongevallen beïnvloeden. Het onderzoek beschreven in *Hoofdstuk 7* suggereert dat netwerkkenmerken gerelateerd zijn aan de kans op fietsongevallen met motorvoertuigen. De mate van ontvlechting van fiets- en gemotoriseerd verkeer beïnvloedt de blootstelling van fietsers aan gemotoriseerd snelverkeer. De wegomgeving kan fietsgebruik stimuleren of ontmoedigen. Bijvoorbeeld, de resultaten van de studie in *Hoofdstuk 7* suggereren dat de maatregelen voor ontvlechting het fietsgebruik kunnen bevorderen. In *Hoofdstuk 2 en 3* is geschat dat onder omstandigheden zoals in Nederlandse gemeenten een vervanging van korte autoritten door fietsritten geen invloed heeft op het aantal verkeersdoden maar wel leidt tot een toename van het aantal ernstig gewonden. *Hoofdstuk 8* bespreekt enkele onzekerheden bij die laatste conclusie. Een vervanging van korte autoritten door fietsritten zal een positievere impact hebben op de verkeersveiligheid als deze op gang gebracht is door maatregelen (zoals ontvlechting) die ook op zichzelf een positief verkeersveiligheidseffect hebben dan als deze veroorzaakt wordt door factoren die niet aan verkeersveiligheid zijn gerelateerd (bijvoorbeeld een stijging van de olieprijs). In het hoofdstuk worden uitdagingen voor toekomstig onderzoek besproken ten aanzien van de link tussen expositie en risico en andere onderzoeksvragen die nog open liggen en in toekomstig onderzoek opgepakt kunnen worden.

Curriculum Vitae

Paul Schepers was born on January 10th 1977 in Roosendaal and Nispen. After obtaining his Atheneum diploma from Norbertus college in Roosendaal in 1995 he began his study of geodetic engineering at Delft University of Technology where he earned his master's degree in 2001. In 1999 he also started studying psychology at Tilburg University. He worked as a trainee at Rijkswaterstaat (Department for civil engineering; Bouwdienst) since 2001. Rijkswaterstaat is the road authority for the Dutch motorway network. In 2003 he received his master's degree within the Division of Organizational Psychology at Tilburg University. Within Rijkswaterstaat Paul switched to the Department for Geo-information and ICT in 2003 and to the Centre for Transport and Navigation in 2005. Since then he has been working as a safety advisor for Rijkswaterstaat and for the Ministry of Infrastructure and the Environment. His work for the ministry is focused on policy issues, while the projects for Rijkswaterstaat are focused on safety management, human factors, and road design.

SWOV-Dissertatiereeks

In deze reeks zijn eerder verschenen:

Jolieke Mesken (2006). *Determinants and consequences of drivers' emotions.*

Ragnhild Davidse (2007). *Assisting the older driver: Intersection design and in-car devices to improve the safety of the older driver.*

Maura Houtenbos (2008). *Expecting the unexpected: A study of interaction behaviour at intersections.*

Frits Bijleveld (2008). *Time series analysis in road safety research using state space methods.*

Saskia de Craen (2010). *The X-factor; A longitudinal study of calibration in young novice drivers.*

Atze Dijkstra (2011). *En route to safer roads; How road structure and road classification can affect road safety.*

Charlotte Bax (2011). *Processes and patterns; The utilisation of knowledge in Dutch road safety policy.*

Willem Vlakveld (2011). *Hazard anticipation of young novice drivers; Assessing and enhancing the capabilities of young novice drivers to anticipate latent hazards in road and traffic situations.*

Sjoerd Houwing (2013). *Estimating the risk of driving under the influence of psychoactive substances.*

Henk Stipdonk (2013). *Road safety in bits and pieces; for a better understanding of the development of the number of road fatalities.*

ISBN: 978-90-73946-12-5