Speed up to safe interactions

The effects of intersection design and road users' behaviour on the interaction between cyclists and car drivers

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1. Introduction

1.1. Background

1.1.1. Safety of cyclists at intersections

Globally, more than half of the 1.35 million fatalities in road traffic crashes are among vulnerable road users (in 2016; WHO, 2018). In the EU countries, more than 2,000 cyclists were fatally injured in 2016 (European Commission, 2018). In this report the European Commission provided data that showed that 42% of the fatalities among cyclists occurred in rural area. These data also revealed that of the fatalities among cyclists, 28% occurred at intersections. In ‘cycling countries’ Denmark and the Netherlands, this share is respectively 65% and 48%. An explanation for this higher share is that cyclists and motorised traffic meet each other at intersections as a result of crossing paths whereas they are physically separated from each other at road sections (Schepers et al., 2017b). Intersections are considered to be critical points in the road network as a result of conflicting traffic movements (Antonucci et al., 2004; Madsen & Lahrmann, 2017; Richard, Campbell & Brown, 2006). In a relatively short time frame, road users need to perform various manoeuvres while approaching and driving through intersections (e.g. checking the priority setting, choosing the right direction and interacting with other road users).

Although more cyclists get injured in crashes occurring at intersections in urban areas than in rural areas (see also Table 1.1), crashes in which a cyclist is involved in rural areas have more serious consequences for cyclists (Ministerie van Infrastructuur en Waterstaat / BRON, 2019). Dutch data reveal that at rural intersections 24% of the registered casualties among cyclists sustain fatal injuries compared to 8% at urban intersections, see Table 1.1.[1] When looking at the injuries of cyclists in crashes with a motor vehicle, cyclists sustain head injuries relatively often compared to crashes without the involvement of a motor vehicle (Weijermars, Bos & Stipdonk, 2014). Weijermars, Bos & Stipdonk show that in the latter crash type, cyclists sustain relatively more hip and thigh injuries.

[1] In the Netherlands there are various problems with the registration of crashes, for a more detailed description see Chapter 3.

	Intersections on 50 km/h roads	Intersections on 80 km/h roads
Fatalities	217 (8%)	87 (24%)
Seriously injured (MAIS2+)	2,508 (92%)	277 (76%)
Total	2,725 (100%)	364 (100%)

Table 1.1. Fatalities and seriously injured (MAIS2+) among cyclists in intersection crashes on 50 km/h urban and 80 km/h rural roads in the Netherlands in the period 2006-2009 (Source: Ministerie van Infrastructuur en Waterstaat / BRON, 2019).

The data presented in Table 1.1 consider the time period 2006-2009 and contains information on the location of the seriously injured (Maximum Abbreviated Injury Score of 2 and higher, MAIS2+). For the time period 2010-2018, it is not possible to disaggregate data on seriously injured (MAIS2+) into sub categories as presented in Table 1.1. Hospital data form the basis for information on seriously injured (Landelijke Basisregistratie Ziekenhuiszorg / Dutch Hospital Data, 2019). These data mainly contain information on injuries and almost no information on crash characteristics such as details about the crash site. As a result, data on seriously injured (MAIS2+) cannot be divided into sub categories such as age group, transport mode or intersection type (Weijermars et al., 2019). Weijermars et al. found that in the time period 2014-2018 the number of seriously injured (MAIS2+) in the Netherlands increased and resulted in approximately 21,700 seriously injured (MAIS2+) in 2018. Also, almost 15% of them are cyclists sustaining injuries in a crash with a motor vehicle. In approximately half of the fatal crashes occurring at intersections on 80 km/h rural roads in the period 2014-2018 one or more cyclists were involved (Ministerie van Infrastructuur en Waterstaat / BRON, 2019).

The data presented above show that safety problems exist in the Netherlands that are related to cycling in rural area, especially at intersections where cyclists meet with motorised traffic. In addition, rural roads appear to be relatively dangerous as 20% of the fatal and serious injury crashes occur at these roads whereas they form only approximately 4% of the network (RTL Nieuws, 2018; RTL Nieuws & Van Wee, 2018).[2] Furthermore, note that the

[2] This analysis was conducted by Van Wee from Delft University of Technology. In this analysis crash risk for 550 rural roads (speed limit 60 km/h or 80 km/h) and motorways (speed limit 100 km/h and 120 km/h) was determined based on crash data between 2014 and 2016 (both fatal and seriously injury crashes), traffic volume and road length. The findings showed that the crash risk of these rural roads was three times higher compared to motorways.

Dutch bicycle modal share is higher than anywhere else in the world. Although the bicycle infrastructure is of a high quality by international standards (Schaap et al., 2015; Schepers et al., 2017b), the Netherlands also has a substantial number of road deaths among cyclists because of its high volumes of cyclists. Further improving cycling safety by measures such as safer infrastructure is key to reaching the countries' road safety targets and is therefore the main focus of this study.

An explanation for the differences in injuries between urban and rural crashes may be found in the impact speed in a crash which is illustrated by Rosén & Sander (2009) and Jurewicz et al. (2016). At an impact speed of 50 km/h, more than 90% of the pedestrians survive a crash with a car compared to less than 50% at a speed of impact of 80 km/h (Rosén & Sander, 2009). Rosén, Stigson & Sander (2011) conducted a literature review on the fatality risk of pedestrians as a function of the impact speed of a car and concluded that "pedestrian fatality risk increased monotonically with car impact speed" (Rosén, Stigson & Sander, 2011, p. 32). Jurewicz et al. (2016) studied the relationship between impact speed and the probability of severe injuries for pedestrians (here: MAIS3+). Based on their findings, Jurewicz concluded that the critical impact speed for crashes involving a pedestrian and a motor vehicle is to be 20 km/h. At lower speeds, there is less kinetic energy released in a crash (Wegman & Aarts, 2006). Although this study investigated the relation between car impact speed and pedestrian fatality risk, these results may be applicable to cyclists as they are vulnerable road users too (Jurewicz et al., 2016). The results of Maki et al. (2003), Nie, Li & Yang (2015) and Peng et al. (2012) confirm that the chances of sustaining fatal injuries in a crash with a motor vehicle are comparable for cyclists and pedestrians. However, crash tests showed that the impact location (exact position of where the cyclist/pedestrian hits the vehicle) differs between cyclists and pedestrians, see Van Schijndel et al. (2012). This means that protection to be added to a vehicle in order to reduce injury severity may be different for pedestrians and cyclists. In order to reduce injury severity of vulnerable road users in a crash with a motor vehicle, it is of great importance to reduce driving speeds at intersections so impact speed might be lower in case a crash occurs. In addition to limiting the consequences for cyclists in a crash with a motor vehicle, it is also important to prevent crashes from happening: cyclists and drivers of motorised traffic should be able to interact with each other safely at rural intersections.

1.1.2. Importance of safe speed thresholds

In order to reduce the number of crashes and to limit the consequences of crashes, the Safe System approach can be adopted. The Safe System approach to road safety, such as Vision Zero in Sweden (Tingvall, 2003) and Sustainable Safety in the Netherlands (SWOV, 2018; Wegman, Aarts & Bax, 2008) advocates for an inherently safe road system (International Transport Forum, 2008). The Safe System approach strives to a road system that is designed to accommodate road users making errors and mistakes (see e.g. Salmon et al., 2010), thereby integrating the road user, the road and the vehicle. Infrastructure should be designed in such a way that road users can interact safely and, in case road users collide, the consequences are not serious. One key aspect of the Sustainable Safety approach is 'man is the measure of all things'; the capacities and limitation of the human being are taken as guiding factors (Wegman, Zhang & Dijkstra, 2010).

One way of taking into account the road user in intersection design is to determine safe speed thresholds (Jurewicz et al., 2016; Rosén & Sander, 2009; Rosén, Stigson & Sander, 2011). By setting speeds limits in accordance to the human body's tolerance, chances of surviving a crash for vulnerable road users colliding with motorised traffic may increase as impact speeds are lowered. As explained in the previous section, according to Jurewicz et al., the safe speed limit at intersections where both motorised traffic and vulnerable road users are present is 20 km/h. A new element of the study conducted by Jurewicz et al. was that they incorporated seriously injured in their analysis. This may enable safe behaviour and thereby safe interactions between road users at an intersection. As road design has the ability to affect road users' behaviour (see e.g. Montella et al., 2011; Theeuwes, Van der Horst & Kuiken, 2012; Van Driel, Davidse & Van Maarseveen, 2004), intersection design should be addressed in the context of road users' behaviour. The severity of encounters increases when road users differ in mass (vehicle related), protection (vehicle related) and speed (road users' behaviour related). These factors are identified as basic risk factors (Wegman & Aarts, 2006). Dutch roundabouts have proven to be relatively safe intersection solutions as there are fewer potential conflict points where cyclists and drivers of motor vehicles interact with each other and they enforce drivers to pass them with low driving speeds (Churchill, Stipdonk & Bijleveld, 2010; Elvik, 2003; Van Minnen, 1995). However, many intersections in Dutch rural area have been designed as priority (give-way) intersections or signalised intersections. The question arises why these intersection types have not been redesigned into roundabouts enabling safe interactions between motorised road users and vulnerable road users. As intersection design guidelines play a role in the design process of intersections (Boer, Grimmius & Schoenmakers, 2008; Weijermars & Aarts, 2010), the content of these design guidelines is of interest.

1.1.3. Attention to cycling, limited attention to rural cycling

In recent years, research addressed the safety of cyclists and other vulnerable road users more and more in order to come up with potential measures to reduce the number of casualties (for an overview see Mulvaney et al., 2015). There is a variety in the design of bicycle facilities especially in urban area, e.g. see DiGioia et al. (2017). Cycling facilities that separate cyclists from motorised traffic appear to be safer than facilities where they share the intersection together (Aldred et al., 2018; Madsen & Lahrmann, 2017; Thomas & DeRobertis, 2013). On the other hand, Elvik (2009) found an increase in the number of crashes between cyclists and drivers of motorised traffic when they are physically separated from each other. Elvik suggests that this may be explained by that this physical separation results in a lack of attention regarding to the other road user. Related to attention, other studies address the level of safety of one-way bicycle paths compared to two-way bicycle paths when applied at intersections (e.g. Räsänen & Summala, 1998; Schepers et al., 2011; Summala et al., 1996). These studies found that safety issues exist as car drivers have difficulties scanning (i.e. searching for cyclists to be present) one of the two cyclist driving directions as they do not expect them there to be present. Thereby the need for speed reduction of motorised traffic is being stressed as it improves the scanning strategy of drivers (e.g. Summala et al., 1996) and the outcome of crashes (e.g. Aldred et al., 2018; Rosén, Stigson & Sander, 2011). In the Netherlands, when bicycle paths parallel to the major road cross the minor intersecting road they can be bended out so that turning drivers have a better view on the bicycle path to look for cyclists (CROW, 2002; for more information is referred to Section 4.3.1).

In addition to research addressing cyclist safety in relation to the interaction with motorised traffic, attention is being paid to single bicycle crashes. This is a crash in which only a cyclist is involved and no motor vehicle (as a crash opponent), see e.g. Schepers et al. (2017a). Schepers et al. found that there is an increase in the number of these crashes in the Netherlands that may be explained by elderly cycling more. Another safety issue related to the interaction between motorised traffic and cyclists is a crash in which the cyclist 'disappears' in the blind spot of a truck or delivery van (SWOV, 2020). This occurs in two situations: a truck/van turns and crosses the bicycle path or a truck/van approaches a priority (give-way) intersection and crosses a separate bicycle path (SWOV, 2020). On average, less than ten fatalities were registered per year in the period 2008-2016. As the crash registration does not contain the vehicle's specific manoeuvre anymore, the size of this safety problem is unknown from 2017 on (SWOV, 2020).

Another topic related to cycling is the electric bicycle. The e-bike has become a popular bike in the Netherlands (Schaap et al., 2015). More and more e-bikes are sold where other bike types show declining sales numbers. 12% of the kilometres travelled by bicycle in the Netherlands were covered by e-bikes (Schaap et al., 2015). According to Schaap et al., the e-bike allows older people to stay mobile for a longer period of time. Also, commuters use the e-bike for traveling to work. Thereby they cycle distances two times longer compared to a regular bike. In the Netherlands, the number of kilometres travelled by bike is increasing (Schaap et al., 2015). According to Schaap et al. a large part of the increase in biking kilometres is due to the e-bike. People of 65 years and older are accountable for 46% of the kilometres travelled by e-bike (2.2 billion km, which is 12% of all bike kilometres; Kennisinstituut voor Mobiliteitsbeleid, 2019). They use the e-bike for shopping and leisure whereas people under 65 mainly use the e-bike for home-to-work commute. Distances travelled by e-bike are approximately 1.5 times longer compared to regular bikes (Kennisinstituut voor Mobiliteitsbeleid, 2019). The involvement of e-bikes in crashes is being registered by the police since 2013. The registration level is however unknown (SWOV, 2017). Based on the majority of European studies it can be concluded that the injuries cyclists sustain in crashes when cycling on a regular bike do not differ much from when cycling on an e-bike (see e.g. Fyhri, Johansson & Bjørnskau, 2019; Valkenberg et al., 2017; Verstappen et al., 2020; Weber, Scaramuzza & Schmitt, 2014; Weiss et al., 2018). In addition, Schepers et al. (2014) conducted a case–control study to both compare the likelihood of crashes needing treatment at the hospital's emergency department and the injury consequences for e-bikes and regular bikes in the Netherlands. The data were controlled for age, gender and the frequency of bike use. They found that cyclists on an e-bike were more likely to be involved in a crash for which they needed treatment at the emergency department than cyclists on a regular bike. Also, they found that the severity of crashes with e-bikes was comparable to the severity of crashes with regular bikes. This may sound surprising when considering the kinetic energy released in crashes: a higher speed results in more kinetic energy released which results in more severe injuries. However, there is not much difference in speed between e-bikes and regular bikes in the Netherlands (Kennisinstituut voor Mobiliteitsbeleid, 2019; Twisk et al., 2013; Van Boggelen, Van Oijen & Lankhuijzen, 2013; Westerhuis & De Waard, 2014). An exception is the study of Poos et al. (2017). Poos et al. studied cyclists that were brought into the accident and emergency department of a hospital. Their results show that cyclists using e-bikes sustain more severe and multiple injuries and also more serious brain injuries compared to cyclists using regular bikes (Poos et al., 2017). They found that almost none of the cyclists involved wore a bicycle helmet. Based on the results of a meta-analysis, both Høye (2018) and Olivier & Creighton (2017) found that the use of a helmet reduces head injury, serious head injury, facial injury and fatal head injury.

Although a vast and fast growing amount of research address cycling safety, the majority of this research address cycling in urban area. Little attention has been devoted so far to cycling safety in rural area and in particular to the interaction between cyclists and car drivers at rural intersections. However, at these intersections impact speeds may be higher than at urban intersections because of the higher speed limits, and consequently the speeds of vehicles. Also, there are differences in (options for) the design of infrastructure. So, it can be concluded there is a gap regarding the knowledge on the safety of cyclists at rural intersections. Another unknown aspect is related to the design of rural intersections and concerns the incorporation of safety in the actual design of those intersections. Also, there is not much knowledge on which factors play a role in the interaction between cyclists and car drivers at rural intersections including the mutual relation between those factors. Thereby, a conceptual model describing the interaction between these two road users seems to be lacking.

To conclude, the increasing number of casualties among vulnerable road users when interacting with motorised traffic is a disquieting development (WHO, 2018). At the same time, cycling is promoted as a solution for the arising mobility problems many countries and cities are facing in the (near) future (OECD/ITF, 2013). Also, technological developments such as the electric bicycle enables road users to bike larger distances (Kennisinstituut voor Mobiliteitsbeleid, 2019; Schaap et al., 2015; Van Boggelen, Van Oijen & Lankhuijzen, 2013). In almost half of the fatal crashes occurring at rural intersections a cyclist was involved. The studies mentioned above indicate that among these factors may be the behaviour of road users and the design of the intersection. It is therefore important to examine the factors that affect the interaction between cyclists and motorised traffic.

1.2. Aim, research questions and focus

The underlying societal aim of this study is to provide information needed to improve the road safety issues related to the interactions between cyclists and motorised traffic at rural intersections. More specifically, this thesis aims to provide information to make these interactions safer by examining how the factors *road users' behaviour* and *intersection design* play a role in the interaction between cyclists and car drivers at rural intersections. Therefore, the following research questions will be addressed in this research:

1. Which factors affect the interaction between cyclists and car drivers and the occurrence of crashes and its severity?
2. In what type of crashes at rural intersections are cyclists involved?
3. To what extent is safety incorporated in the actual intersection design on rural roads?
4. How do the presence and behaviour of a cyclist influence the behaviour of a car driver at rural intersections?

Although the behaviour of both the car driver and the cyclist may play a role, the empirical study in Chapter 5 focuses on the behaviour of the car driver. At rural intersections, cyclists need to give way to approaching motorised traffic. Cyclists are the ones who need to perform the evasive manoeuvre, in order words: they need to stop and let motorised traffic pass before they can continue their route. So drivers have right of way but it is unknown if and how they will react when they approach an intersection where cyclists could be present.

The empirical research in this dissertation is focused on Dutch intersections of 80 km/h rural roads intersecting with another 80 km/h rural road or a 60 km/h rural road. Intersections between two 60 km/h roads were not studied as fewer crashes occurred here (Ministerie van Infrastructuur en Waterstaat / BRON, 2019). Also, this research focuses on three- and four-arm intersections which means that roundabouts are left out as they are already relatively safe (Churchill, Stipdonk & Bijleveld, 2010; Elvik, 2003; Van Minnen, 1995). Another demarcation of this research is the focus on car drivers only (not on other motorised vehicles) in the interaction with cyclists. The reason is that a passenger car is the most dominant crash opponent for cyclists in rural intersection crashes (see Chapter 3 for a more detailed analysis). Other crash types such as blind spot crashes with trucks or vans appear to be less frequent at rural intersections.

1.3. Theory and methods; links between chapters

This section describes the main outlines of theory and methods used in this research. Each chapter contains a more detailed description of the theory and methods used. Chapter 2 answers the first research question and forms the theoretical framework for the following chapters of this dissertation. Based on an extensive literature review, a conceptual model is developed that describes the various factors that play a role in the interaction between cyclists and drivers of a motor vehicle at intersections. This model contains two main factors, namely *intersection design* and *road users' behaviour*. These factors will be studied in Chapter 4 and Chapter 5 respectively.

Chapter 3 addresses the second research question and provides the results of an explorative crash analysis study on crashes occurring at rural intersections. For this purpose, the crash database of registered crashes was analysed by selecting the data about crashes and casualties occurring at these intersections. In addition, a more detailed analysis of fatal intersection crashes was conducted in order to gain more insight in infrastructural characteristics that could not be extracted from the crash database. This descriptive study presents an overall picture of casualties occurring at rural intersections in the Netherlands. This chapter aims to provide essential background information to determine the focus of Chapter 4 and Chapter 5.

In Chapter 4 the third research question is addressed. This chapter presents the results of an interview study held among five provincial road authorities responsible for rural intersections. The interview focussed on general road safety problems, design dilemmas and the policy of road authorities on intersection design. In addition, a selection of recently reconstructed intersections was discussed in detail to gain insight in why various road design characteristics such as speed-reducing measures and bicycle crossing facilities were present or absent. Together with the results from Chapter 2 and Chapter 3, Chapter 4 generates input for the experimental study described in Chapter 5.

Chapter 5 deals with the fourth research question and shows the results of a driving simulator study. This study looks more closely into the interaction between cyclists and car drivers. The results of Chapter 2, Chapter 3 and Chapter 4 are used to determine which interactions need to be studied more closely. In a moving-base driving simulator participants drove a long stretch of a 80 km/h rural road with eight intersections. Three aspects of the interaction with cyclists were explored, namely how the number of cyclists, the cyclist's approach direction, and the cyclist's action affect speed behaviour and mental workload of car drivers approaching rural intersections. In addition, the effects of a speed-reducing measure on the interaction between cyclists and car drivers were examined.

Last, Chapter 6 gives an overview of the main findings of this dissertation and discusses the implications of these findings for policy makers and researchers.

The outline of this dissertation can be found in Figure 1.1 and shows the relation between the chapters. The arrows between the chapters stand for the results of a chapter being taking into account in another chapter. The first chapter forms the introduction to the research topic. Chapter 2 is the theoretical framework of this research. Chapter 3, Chapter 4 and Chapter 5 address the empirical research that was carried out. Chapter 6 is the concluding chapter.

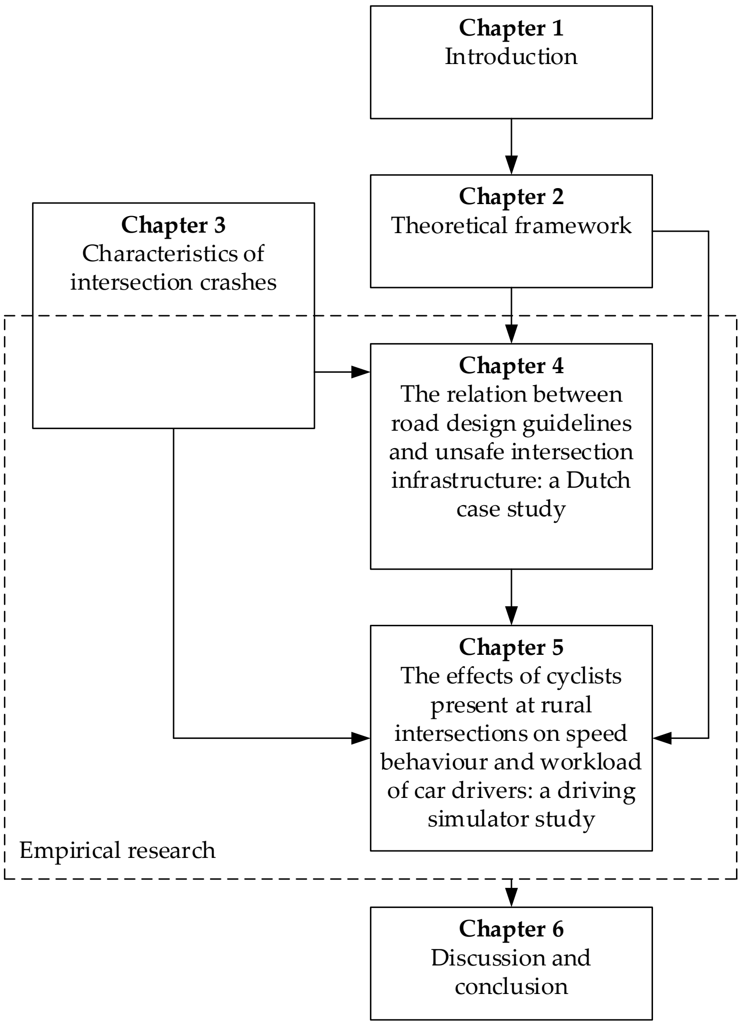

Figure 1.1. Visualisation of the dissertation outline.

2. Theoretical framework

2.1. Introduction

This chapter presents the theoretical framework of this research. For this purpose, an extensive literature review has been conducted. This theoretical framework is discussed using a conceptual model on the interaction between a cyclist and a driver of a motor vehicle. The present chapter both discusses the conceptual model and presents the literature relevant to this interaction. Section 2.2 gives an introduction to the conceptual model and describes the model's elements. Section 2.3 and Section 2.4 respectively discuss the effects of the two main factors *intersection design* and *road users' behaviour* on *interaction*. Section 2.5 deals with the interaction between a cyclist and a driver of a motor vehicle. Section 2.6 gives on overview of literature concerning an interaction leading to a crash. Section 2.7 is the concluding section of this chapter.

2.2. Conceptual model

2.2.1. Presentation of the conceptual model

Various models have been developed over the years to describe how road users behave in traffic (see for example Michon, 1985; Ranney, 1994; Weller & Schlag, 2006) but a model on the interaction between a cyclist and a car driver at a rural intersection seems to be lacking. Therefore, this section presents such a model that contains factors that have an effect on this interaction, see Figure 2.1. For the present study, this model is being applied to rural intersections. The model can also be applied to other intersections. In that case, the model's structure remains the same but the content (i.e. the values of the variables) of the model's elements may vary. For example, this model can also be applied to interactions between a cyclist and a driver of a motor vehicle at an intersection in urban area but it should be noted that some of the circumstances regarding urban intersections are different (e.g. lower speed limit, different traffic rules and different layout and environment of the intersection). And, road users may have different expectations regarding the traffic situation ahead (for more information is referred to Section 2.4.1) or exposure may differ (for more information is referred to Section 2.6). The same applies for the interaction between a cyclist and a driver of another motor vehicle (e.g. a truck) as the behaviour of these motor vehicles may differ compared to passenger cars (e.g. differences in mass or braking distance) and differences in impact when a crash occurs compared to a crash with a passenger car. The model is discussed in further detail in the coming sections.

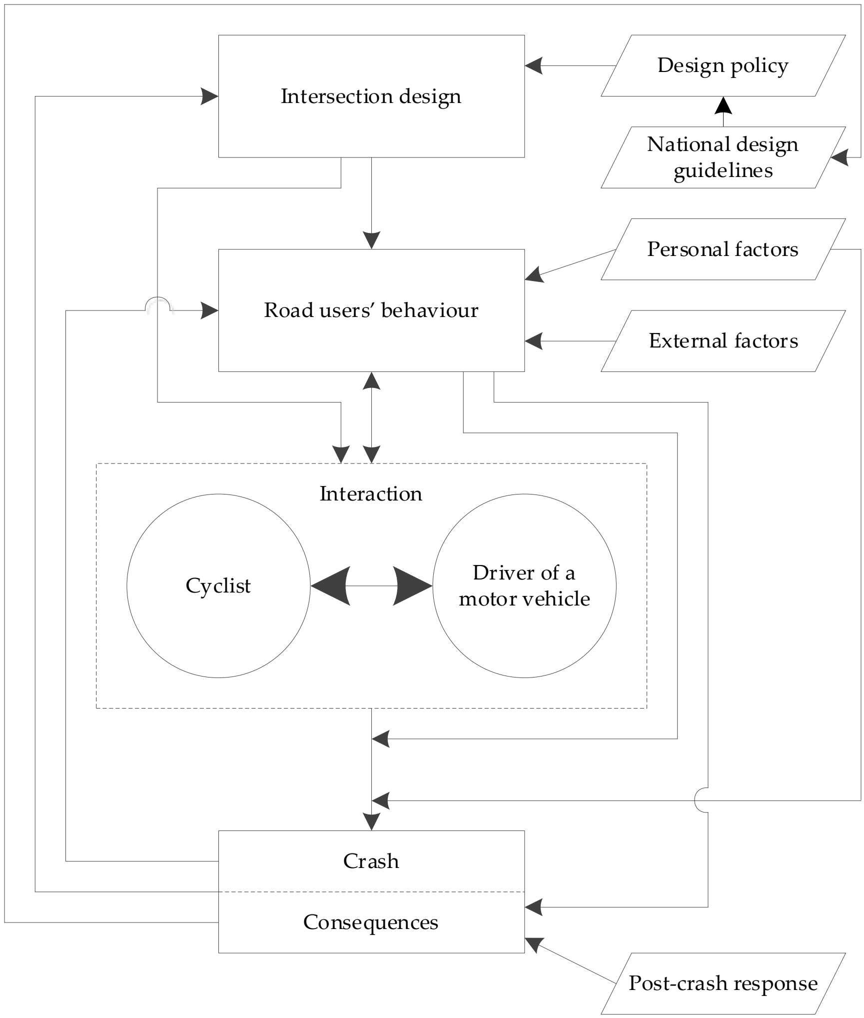

Figure 2.1. Conceptual model of the interaction between a cyclist and a driver of a motor vehicle at an intersection, and the relation with crashes and their corresponding consequences.

The upper part of the conceptual model consists of the two main factors affecting the interaction between a cyclist and a driver of a motor vehicle at an intersection, namely *intersection design* and *road users' behaviour*. The first factor *intersection design* concerns the layout of the intersection including the road environment, the road traffic signs and regulations. The second factor *road* *users' behaviour* is the behaviour of the road users involved in the interaction, thus the behaviour of the cyclist and the driver of a motor vehicle. When an interaction is successful, both road users continue their way. The lower part of the model describes the case that an interaction is not successful which results in a crash between the cyclist and driver of a motor vehicle and its corresponding consequences (i.e. damage to the vehicles as well as injuries).

The elements of the model as presented in Figure 2.1. can be linked to the basic risk factors speed, mass and protection (as described by Aarts & Van Schagen, 2006; Elvik, 2005). Table 2.1 shows which of the model's elements can be linked to the three basic risk factors.

	Basic risk factors		
	Speed	Mass	Protection
Intersection design	Yes	-	-
Road users' behaviour	Yes	-	-
Interaction	Yes	-	-
Crash and its consequences	Yes	Yes	Yes

Table 2.1. The relationship between the main elements of the conceptual model and the basic risk factors speed, mass and protection.

Intersection design can be linked to speed as the design of an intersection has an effect on speed, for example because speed-reducing measures influence speed. Also road users' behaviour has a relation with speed as it concerns the speed road users drive or cycle. The basic risk factor speed is related to interaction too. Regarding crash and its corresponding consequences, these two elements are related to all three basic risk factors. The relation between the model's elements and basic risk factors is further described in Sections 2.3, 2.4, 2.5 and 2.6.

Based on literature (as further described in the next sections) it can be concluded that the two main factors *intersection design* and *road users' behaviour* are being affected by other factors or determinants. *Intersection design* is being affected by *design policy* of a road authority whereas *road users' behaviour* is being affected by *personal factors* and *external factors*. Furthermore, *post-crash response* has an effect on the consequences of a crash. Although the main focus of this study is on the relations between *intersection design*, *road users' behaviour* and *interaction*, some attention is paid to these determinants as well. In the next sections, the model on the relation between *intersection design*, *road users' behaviour* and *interaction* is discussed. But first, Section 2.2.2 presents an overview of the model's elements including a functional description of the road users involved in the interaction and a description of crash occurrence.

2.2.2. Description of the model's elements

The conceptual model in Figure 2.1 contains various elements placed in boxes. The definitions of these elements as used in this dissertation will be explained below.

Intersection design
The factor *intersection design* concerns the layout of the intersection as well as the surrounding environment. Worldwide, there is a lot of variation in how rural intersections including biking facilities are designed: cyclists may have to cycle on the carriageway surrounded by motorised traffic or they have their own bicycle infrastructure thereby being separated from motorised traffic. The Netherlands is a country with a relatively well developed bicycle infrastructure with a high level of cycling safety (Schepers et al., 2017b). The environment varies a lot, from rural area to the build environment.

Next to roundabouts which are being left out of this dissertation, intersections on Dutch rural 80 km/h roads are designed as signalised intersections or priority (give-way) intersections. These intersections have a different road configuration: signalised intersections generally have one or two driving lanes for through traffic and priority (give-way) intersections only one (CROW, 2013).

Another difference between these two intersections is the number of potential conflict points: points where a cyclist and driver of a motor vehicle can collide with each other. In general, a signalised intersection has more potential conflict points compared to a priority (give-way) intersection because there are more lanes to be crossed. For more information is referred to Section 3.3.3.

Regarding the facilities for cyclists, it can be noted that cyclists have their own bicycle facilities: separate bike paths along the road sections and crossing facilities at the intersections. These bicycle facilities cross the main carriageway at the median island between the two driving directions. These crossing facilities can be one directional or two directional. Cyclists need to give way to the motorised traffic. For more information is referred to Section 2.4.1.

Road users' behaviour

The factor *road users' behaviour* concerns the behaviour of both the cyclist and the driver of a motor vehicle. Road users in their vehicles differ in their behaviour such as manoeuvrability (i.e. a cyclist may be more manoeuvrable than a driver of a motor vehicle) or stopping distance (i.e. a driver of a motor vehicle may need more distance to make a full stop).

Interaction between a cyclist and a driver of a motor vehicle

With the term interaction is in this dissertation referred to as a cyclist and a driver of a motor vehicle interacting with each other, the intersection and its environment during their approach to an intersection. At the intersection, the cyclist and the driver of a motor vehicle encounter each other where the bicycle path crosses the driver's lane. This point is called the potential conflict point. A conflict may occur when the cyclist and the driver of a motor vehicle encounter each other closely: the cyclist passes the potential conflict point some seconds before the driver of a motor vehicle arrives at that point or vice versa. So, they just miss each other. In other, conflict-free, situations there is more time between the cyclist passing the potential conflict point and the driver of a motor vehicle arriving at that point or vice versa. Related to the interaction between these two road users is the concept of the evasive manoeuvre. In these interactions, one road user can continue driving whereas the other needs to decide whether s/he is going to cross or to stop and give way to approaching road users. For a more detailed description is referred to Section 2.5. Crashes are the result of an interaction not being successful and are therefore considered separately.

The involved cyclist and driver

The model of interaction at rural intersections in Figure 2.1 concentrates on the interaction between two types of road users: a cyclist and a driver of a motor vehicle. In this model, the road users are considered together with their vehicles. So the two items *road user* and *vehicle* are considered as one entity whereas they are generally considered apart in the three item representation of the traffic system (i.e. road user, vehicle and road, see for example Elvik et al., 2009; Theeuwes, Van der Horst & Kuiken, 2012; Wegman & Aarts, 2006). This means that when a cyclist is addressed both the characteristics of the bicycle and the road user are considered together. A similar approach is applied to a driver of a motor vehicle. Although the design of vehicles may be relevant as well, the main focus of the conceptual model is on road users' behaviour and intersection design.

The reason for taking the road user and his vehicle as one entity is that the same person is a different road user in a motor vehicle compared to a road user on a bike because of the combination of his own characteristics and those of his vehicle. For example: an older person driving a passenger car is less vulnerable than when driving on a bike as s/he benefits from the characteristics of the passenger car such as regarding the stability of the vehicle (i.e. not being a balance vehicle like a bike) or the protection offered by the car during a crash (i.e. seat belt). In contrast, the following factors such as experience with the traffic situation and intersection, experience with the vehicle and knowledge of the traffic rules may also be important but they are not specifically for all cyclists or all drivers as a group. These factors are considered as personal factors and are described in Section 2.4.3. Below, a functional description of a cyclist and a driver of a motor vehicle is given.

A cyclist

A bicycle is a balance vehicle which implies that a cyclist needs to maintain a certain speed in order to ride stably and not to fall. The wind has a relatively large influence on the cyclist's course and speed. A bicycle has a relatively light mass and low speed. A cyclist can make a full stop within a relatively short distance because of the bicycle's relatively low mass and speed. On average, a cyclist on a conventional bike cycles at a speed of approximately 16 km/h (in the Netherlands, given the relatively well designed bicycle infrastructure; Twisk et al., 2013; Van Boggelen, Van Oijen & Lankhuijzen, 2013). Also, a cyclist is able to turn relatively quickly. When involved in a crash, a cyclist is relatively vulnerable as a bicycle does not offer protection (i.e. no passive safety measures such as an airbag). A helmet is the only protection a cyclist may have. In the Netherlands, a helmet is not mandatory and hardly used (SWOV, 2019).

A driver of a motor vehicle

A motor vehicle is a stable vehicle as a driver cannot fall over when driving at low speed or standing still. A passenger car has a relatively high mass and speed. As a result, a driver of a motor vehicle needs a relatively long braking distance when making a full stop. When being involved in a crash, the motor vehicle offers much protection to the driver such as by airbags and the safety belt but also due to the construction of the vehicle itself. There is one exception: the motor cycle. Motor cyclists are considered to be vulnerable because they are not protected by their vehicles (WHO, 2018).

Crash and its consequences
A crash is the result of an interaction not going well. When a cyclist and a driver of a motor vehicle collide with each other, the motor vehicle and/or the bicycle may get damaged and the cyclist and/or the driver may sustain injuries ranging from slight injuries to severe injuries or even fatal injuries. In the present study, a crash is referred to as the crash itself and its corresponding consequences.

2.3. Effect of intersection design

2.3.1. Effect of intersection design on road users' behaviour

According to the Sustainable Safety vision, the design of the infrastructure should be such that it leads to the desired behaviour of road users (SWOV, 2018). For example, when low speeds are desired at a certain road or intersection it should not be possible for road users to drive high speeds. Following the functionality principle, intersections at rural distributor roads are meant for exchanging traffic. This exchange should be facilitated such that this can be done safely, so low speeds when vulnerable road users and motorised traffic encounter each other (i.e. homogeneity principle, SWOV, 2018). So, the design of intersections has a relationship with the behaviour of road users. When discussing the relation between *intersection design* and *road users' behaviour*, the field of traffic psychology is to be considered. In general, traffic psychology deals with the behaviour of road users in traffic. Specifically, the field of ergonomics or human factors addresses the human in relation to the environment. In the case of road traffic this is the road user in relation to the road environment. The design of roads or intersections influences the behaviour of road user, in a positive way or in a negative way (Birth et al., 2008). Birth et al. describe that according to the human factors theory, road users can make errors at the operational level of the driving task (i.e. handling the vehicle by operating the gear and the brakes, maintaining the driving course). This can be the result of information lacking or that something in the interaction between a driver and the road is being misinterpreted. In order to minimise driving errors, it is important to take into account knowledge on road users' perception, information processing and decision making when designing intersections: its design should be self-explaining and user-friendly (Birth et al., 2008). This can be achieved by taking into account the three human factor 'rules' described by Birth et al. (2008). First, the road should give the driver enough reaction time to adapt their behaviour, namely at least four to six seconds. According to Birth et al. this is more than a normal stimulus reaction time as it also involves time for perception and decision. Facilitating road users with more time can be realised by reducing driving speeds at locations where road users interact with each other, thus at intersections. It appears that there is a relation between time and the probability of a dangerous traffic situation occurring (see e.g. Houtenbos, 2008; Näätänen & Summala, 1976; Summala et al., 1996). Second, the road must offer the driver a safe field of view. A monotonous periphery, optical misguidance or eye-catching objects along the road should be avoided as much as possible (Birth et al., 2008). And third, roads have to follow the drivers' perception logic. Based on experience and recent perceptions, drivers build up a certain expectation and orientation logic that have an effect on their perception and reaction (Birth et al., 2008). In other words, road users pay attention to those spots along the road where they expect the information to be present that they need (i.e. traffic signs or the presence of other road users) (Ranney, 1994; Theeuwes & Hagenzieker, 1993; Theeuwes, Van der Horst & Kuiken, 2012).

In relation to the last 'rule' on the road meeting the drivers' perception logic, a road or an intersection should be designed such that its design meets the expectations of road users which results in road users automatically showing safe driving behaviour. This concept of self-explaining roads was introduced by Theeuwes & Godthelp (1995). Consistency in road design leads to situations that are recognisable for road users whereas continuity in road design leads to a road course being predictable (SWOV, 2018; Wegman, Aarts & Bax, 2008). As a result, this may lead to fewer errors and more predictable behaviour of road users. In the Dutch Sustainable Safety vision this is referred to as the predictability principle (SWOV, 2018; Wegman, Aarts & Bax, 2008). The Sustainable safety vision developed a set of principles that can be used in achieving an inherent safe traffic system. These principles have a relation with the behaviour of road users, for example by designing roads in such a way that it meets the predictability principle. A predictable road layout and road course facilitate road users in having the right expectations so that they can anticipate the traffic situation ahead. When intersections look more or less the same (i.e. consistency in design), road users know what to expect regarding for example the right of way situation and the presence of other road users. It appears that expectancy issues exist at two-directional bicycle crossings. At these crossings, it appears that cyclists coming from the 'unexpected' direction are seen less by drivers intending to cross the bicycle crossing compared to cyclists coming from the 'expected' direction. The expected direction is when cyclists ride in the same direction as motorised traffic in the lane closest to the bicycle path does. The unexpected direction is the direction that is added to a bicycle path and is the direction in which cyclists ride opposite to the direction of motorised traffic in the lane closest to the bicycle path. It appears that drivers intending to enter the main road by turning right have difficulties in detecting cyclists coming from the right (Räsänen, Koivisto & Summala, 1999; Räsänen & Summala, 1998; Schepers et al., 2011; Summala et al., 1996) which results in an increase in crash risk for cyclists. At one-directional bicycle crossings these issues do not exist which results in a fewer problematic interactions between drivers of motor vehicles and cyclists.

Not only does intersection design have an effect on the behaviour of drivers of a motor vehicle, it also affects the behaviour of cyclists. It appears that it is more demanding for cyclists to cross a major road compared to a minor road which may be explained by the complexity of the traffic situation (Räsänen & Summala, 1998). A median island where cyclists can stand still may reduce this complexity by lowering the task demands as suggested by Schepers et al. (2011). This median island enables cyclists to cross the major road in two phases: first, the driving direction from the left and second, the driving direction from the right (Van Boggelen et al., 2011). More specifically, when the median island is designed in such a way that the cyclist is forced to look in the direction of approaching traffic. By doing so, a cyclist has a better view on the approaching traffic.

Another principle of the Sustainable Safety vision is the homogeneity principle (SWOV, 2018; Wegman, Aarts & Bax, 2008). Especially in medium and high speed situations large differences in speed, direction and mass should be avoided. Regarding safe driving behaviour, driving speeds may be the most important behaviour as speed is related to the likelihood of getting involved in a crash as well to the consequences of a crash (i.e. injuries; see e.g. Aarts & Van Schagen, 2006; Rosén, Stigson & Sander, 2011). It appears that in addition to speed enforcement, drivers' speed choice is affected by the characteristics of the road environment, namely the cross sectional profile, alignment and the surrounding road environment. The wider the road or the less curvy the road or the less bushes and trees in the environment, the higher the speed (see for an overview e.g. Aarts et al., 2006; Martens, Comte & Kaptein, 1997). It is therefore of great importance that a self-explaining road encourages drivers to adopt the appropriate speed. This means that speed limits should be credible, in other words: road users find the speed limit reasonable with respect to the characteristics of the road, the road environment and the driving conditions (Fildes & Lee, 1993; Goldenbeld & Van Schagen, 2007). Research shows that road users comply to the speed limit better when speed limits are credible (Goldenbeld and Van Schagen, 2007, Van Nes et al., 2008).

In addition to road design having an effect on road users' behaviour, the presence of an intersection itself has an effect on speed too. When drivers approach an intersection, it appears that they reduce their speed somewhat as a form of compensating behaviour because they experience high workload (Harms, 1991; Houtenbos, 2008; Montella et al., 2011). Mental workload is defined as "the specification of the amount of information processing capacity that is used for task performance" (De Waard, 1996, p. 15). Their workload increased as a result of higher processing demands (Harms, 1991; Stinchcombe & Gagnon, 2010; Teasdale et al., 2004; Theeuwes, Van der Horst & Kuiken, 2012). Driving an intersection is considered to be a complex task for road users as drivers need to perform a lot of tasks and as a result, drivers adapt their behaviour. Also the mental workload of cyclists increases when cycling in more complex traffic situations (Boele-Vos, Commandeur & Twisk, 2017; Vlakveld et al., 2015). An increased mental workload of road users means that the driving task becomes more mentally demanding for drivers. The model developed by De Waard (1996) describes mental workload and task performance as a function of task demand. With increasing task demand mental workload increases and affects task performance at some point. Workload should not be confused with distraction. The difference between them is that distraction occurs when a competing task is present whereas workload may change because of the primary driving task (Schaap et al., 2013).

2.3.2. Effect of intersection design on interaction

Intersection design determines the conditions under which road users can interact with each other. Regarding bicycle facilities on intersecting roads and at intersections, there is a lot of variety around the world. There are countries in which cyclists do have to share the road with motorised traffic so they interact with each other constantly. Also, there are countries where cyclists have their own cycling facilities where interactions are limited to those locations where both paths cross. It is safer for cyclists to have bicycle paths (i.e. physically separation from motorised traffic) compared to roads where cyclists do not have their own facilities (see e.g. Harris et al., 2013). Implementing bicycle paths limits the number of interactions between these two road users. Regarding the situation in the Netherlands, cyclists are not allowed on rural 80 km/h roads but instead they have their own bicycle facilities (i.e. bike paths) next to the road (CROW, 2013). Cyclists and drivers of a motor vehicle interact with each other at intersections where bike paths cross the carriage way at-grade. At signalised intersections, the Dutch road design guidelines prescribe that it is not allowed for conflicting paths of cyclists and motorised traffic to have a green phase at the same time. At priority (give-way) intersections, motorised traffic has right of way over cyclists wanting to cross the main intersecting road which is communicated to road users by traffic signs and road markings (CROW, 2013). Cyclists on bike paths parallel to the main intersecting road thereby crossing the minor road at crossings that are out-bended (i.e. at a distance 10 to 15 metres from the intersection), need to give right of way to motorised traffic. Cyclists have right of way over motorised traffic at crossings that are not out-bended (i.e. at a distance of 5 metres from the intersection) (CROW, 2013).

Regarding cyclists wanting to cross the main carriageway, a design characteristic that enables a less complex interaction for cyclists is a median island. According to Schepers et al. (2011) this may lower task demands as was described above. Without a median island, the interaction task for a cyclist involves interacting with traffic coming from both driving directions at the same time. The median island enables a cyclist to deal with drivers of motor vehicle from one driving direction at a time. Also, a cyclist can wait safely at the median island before crossing the second driving direction (Van Boggelen et al., 2011). Similar to the concept of a median island (i.e. dividing the interaction task into several smaller interaction tasks) is the creation of space between the carriageway and the bicycle crossing. This enables drivers wanting to enter the main carriageway to deal with cyclists first and to cross the bicycle path before reaching the main carriageway. In between, they can wait safely (Kuiken & Schepers, 2017).

Another design element that affects the interaction between a cyclist and a driver of a motor vehicle is the presence of speed-reducing measures. Summala et al. (1996) found that at lower speeds achieved by speed-reducing measures, drivers scanned the other driving direction more often and were therefore able to interact with traffic coming from this direction. Speed reduction such as speed humps enables less complex interactions for both cyclists and drivers of a motor vehicle as there is more time to interact with each other. Another benefit of lower driving speeds is that it is easier for road users to estimate the speed of approaching traffic and therefore to decide whether to cross or not. Especially at high speeds, it appears to be hard to estimate the speed of approaching vehicles which makes it difficult to choose a gap that is suitable for crossing (Elvik, 2015; Oxley et al., 2005; Sun et al., 2015). Results from a Dutch evaluation study showed that plateaus that were applied at rural intersections improved road safety (Fortuijn, Carton & Feddes, 2005). Fortuijn, Carton & Feddes found that at signalised intersections the number of injured road users decreased with approximately 40-50%. It should be noted that in addition also speed enforcement by cameras was applied at these intersections. At priority (give-way) intersections a reduction of approximately 35% in the number of injured road users was accomplished.

2.3.3. Effect of design policy of road authorities on intersection design and the role of national design guidelines

Now we have seen that *intersection design* influences *road users' behaviour* at an intersection, it raises the question why not every intersection is designed in such a way that it enforces safe behaviour. So that road users are able to interact with each other safely on inherent safe infrastructure. The stages on the ladder of knowledge utilisation may be useful for finding an explanation (Bax, 2011). This ladder describes how knowledge can be used, from receiving the information only (thus without incorporating it) to implementing the research findings that on its turn results in effects. It appears that road authorities, responsible for intersection design on rural roads, do make efforts to adopt the results but they do not adopt the results in their choices and decisions they make (i.e no influence on the policy outcomes; Bax, 2011).

Especially in the Netherlands, road authorities started to develop their own design policies in which the national design guidelines formed the basis (Boer, Grimmius & Schoenmakers, 2008; Weijermars & Aarts, 2010). However these design policies do not propose designs that are desired to create an inherent safe infrastructure. In addition to road safety other topics in these design policies are the environment, costs, space, throughput of vehicles. So, safety is not the only aspect road authorities have to take into account. Although road authorities state that the national design guidelines are useful, they also say that it is not always possible to stick to these guidelines (Boer, Grimmius & Schoenmakers, 2008; Weijermars & Aarts, 2010). Contextual factors (e.g. space available and costs) make that national design guidelines are not being followed (completely) and that they have to make other decisions than what is described in these guidelines or they even make an own set of guidelines (Boer, Grimmius & Schoenmakers, 2008; Weijermars & Aarts, 2010). How much road safety is being taking into account by a road authority, may be related to their ambitions for road safety suggested Bax et al. (2015).

It is allowed to deviate from the national road design guidelines developed by CROW. The Dutch road design guidelines for rural roads are not obligatory as in rules or law. This results in a variety in designs without the so-needed consistency (see e.g. Theeuwes & Godthelp, 1995). Another drawback of the road design guidelines is that they do not meet the criteria for an Sustainable Safe infrastructure. This is related to the process of how the road design guidelines are developed in which multiple interests play a role, for example road safety and throughput. Sometimes priority is given to other interests than road safety which results in guidelines containing proposed designs that do not meet the criteria for a Sustainable Safe infrastructure. The striking example is safe driving speeds. As was described earlier (see Section 2.3), speeds play an important role in crash occurrence and injury severity. However, speed reduction at rural intersections are presented as an option instead of being mandatory (CROW, 2013). This makes rural intersection with driving speed higher than 30 km/h potentially dangerous situations for vulnerable road users (Jurewicz et al., 2016).

2.4. Effect of road users' behaviour

2.4.1. Effect of road users' behaviour on interaction

One important type of road users' behaviour is driving speed as was already described in the previous section. Driving speeds at rural intersections which are relatively high affect the interaction between road users not only in the crash phase (i.e. high kinetic energy released, see also Section 2.4.3) but also in the pre-crash phase. There is less time to interact with other roads users when driving at high speeds. When drivers slow down while approaching an intersection, there is more interaction space which is defined by Houtenbos as 'the time that is available for both road users to negotiate their way across the intersection' (Houtenbos, 2008). Silvano, Koutsopopoulos & Ma (2016) also found that the speed of car drivers played a role in interactions even though this study focuses on interactions between car drivers and cyclists at roundabouts. This study also found that the proximity of the cyclist to the roundabout (i.e. conflict area) affected the yielding behaviour of car drivers. Silvano, Koutsopopoulos & Ma found that drivers yielded for cyclists when they were within 20 meters to the conflict area. This may be explained by the finding that drivers see cyclists at an intersection as an overt latent hazard (Vlakveld, 2011). It was found that cyclists' unpredictability and vulnerability affected drivers' behaviour as a result of the negative impact on their perceived behaviour control (Basford et al., 2002). For example, drivers may reduce their speed and wait till there is an appropriate moment to pass the cyclist. This may be true especially in situations where cyclists do not have the right of way (Hoekstra & Houtenbos, 2013). Driving with lower speeds may also affect drivers' perception (Rogers, Kadar & Costall, 2005). At low speeds, drivers tended to also look at objects along the road, whereas at higher speeds, drivers mainly focused on the direction in which they were heading. Drivers' perception may be related to expectancy, because it appears that drivers do not detect objects at unexpected locations or see them later (Theeuwes & Hagenzieker, 1993).

Above was discussed that design affects expectations of road users at two-directional bicycle crossings. As a road user acts in a certain way because of his expectations, having wrong expectations may induce a behaviour that is not suitable for the interaction with another road user. In the example of this type of bicycle crossing, wrong expectations lead to car drivers only looking in one direction to see if bicycles are present. As s/he does not look in the 'unexpected' direction, a cyclist coming from this direction is not being detected in time or not being detected at all (Räsänen, Koivisto & Summala, 1999; Räsänen & Summala, 1998; Schepers et al., 2011; Summala et al., 1996). Summala et al. (1996) found that drivers mainly focused on approaching cars coming from the left and thereby failed to see cyclists that approached from the right early enough. Apparently drivers have a visual search strategy that concentrates on detecting the more frequent and major dangers. They less concentrate on visual information on less frequent dangers (e.g. cars from the right poses no threat to them and cyclists approaching from the right). Summala et al. (1996) found that speed-reducing measures changed drivers' visual search behaviour in favour of the cyclists approaching from the right. This can be explained because of the speed-reducing measures created more time to focus on each direction. Although the Netherlands is a country in which cyclists are a very common feature in everyday life and are generally expected to be present, the above mentioned problems regarding expectations are present in the Netherlands as well (see e.g. Schepers & Voorham, 2010). Kovácsová et al. (2018) studied the interaction between a cyclist and a car from the cyclist's perception. Their aim was to study how cyclists anticipate potential hazards when they are approaching intersections. They suggested that crashes between cyclists and car drivers may not only occur because of perceptual errors but also due to having false assumptions about the future actions of the other road user. In their study they found that cyclists looked at the approaching car more than at the environment because this car is on collision course. They looked until the car was found no longer to be a hazard. After that, they looked at the road ahead.

In the previous section on intersection design, perception was addressed as it is being affected by intersection design. But perception also plays a role in the interaction as it is essential that both road users see each other and deal with each other. Thus, perception is an important aspect of interaction (Houtenbos, 2008). Not only regarding other road users but also regarding relevant elements from the road environment such as traffic signs or road markings that indicate which traffic rules apply. If a road user does not see another road user being present at or in the proximity of an intersection, a problem (i.e. a serious conflict or a crash) may occur. One of the reasons for a road user not detecting another road user may be found in the concept of looked-but-failed-to-see (Herslund & Jorgensen, 2003). A road user was looking in the right direction but did not really see the other road user.

Related to perception, there is the concept of situation awareness that plays a role as well. Situation awareness refers road users perceiving and understanding the traffic situation, now and in the near future (Endsley, 1995). When approaching an intersection, road users need to decide what to do: which actions and/or manoeuvres they need to undertake. Following the concept of situation awareness, road users make an estimation about the traffic situation they are in, now but also how this situation may be in the near future. Situation awareness appears not to be similar for road users according to Salmon, Young & Cornelissen (2013). In their study situation awareness from three different road users: drivers, motorcyclists and cyclists was explored. They hypothesised that different road users may interpret the same (contemporary) traffic situation differently. Salmon, Young & Cornelissen concluded that the three road user groups use different information when driving through the same road situation. Specifically at intersections, there are incompatibilities between drivers, motorcyclists and cyclists. Drivers were focussed on things in front of them whereas motorcyclists and cyclists were focussed on traffic around them. Salmon, Young & Cornelissen (2013) suggest that this could be the reason why drivers do not see cyclists or motorcyclists travelling next to them. So, there are differences in how a cyclist and a driver approaching the same intersection use different information in their decision which actions to undertake while approaching the intersection.

2.4.2. Effect of interaction on road users' behaviour

Taking part in traffic is not without any risk. Based on crash statistics, some roads are riskier than others, some transport modes are riskier than others. This is referred to as objective risk. However, there is also subjective risk (Chaurand & Delhomme, 2013). Subjective risk is the risk perceived by road users. It appears that, in general, there is a discrepancy between objective risk and subjective risk (Chaurand & Delhomme, 2013). Road users may consider a situation to be very dangerous whereas objectively seen this situation is not that dangerous, in other words: road users overestimate risk. But road users can also underestimate risk when they consider a situation not to be dangerous but in fact the situation is dangerous. According to Vlakveld, Goldenbeld & Twisk (2008) it appears that hazard experience plays a role in risk perception. Hazard experience is referred to as the emotions a person feels when seeing danger such as anxiety and stress.

Because cyclists perceive a certain level of risk, it has an effect on their behaviour but also on the bicycle facilities they prefer to use or avoid (Chataway et al., 2014; Sanders, 2015). Chaurand & Delhomme (2013) found that cyclists perceived more risk when interacting with a car than with another cyclist. Also they found that there is a difference in perceived risk regarding an interaction between drivers and cyclists. It appears that car drivers perceive the interaction with a cyclist to be less dangerous whereas cyclists perceive the same interaction to be more dangerous. Chaurand & Delhomme suggest that as a result drivers may not be as careful as they should be when interacting with a cyclist. For example, drivers may behave in a way that suits the level of risk they perceive but is not suitable for the objective level of risk of that traffic situation. According to Chaurand & Delhomme (2013), their findings on risk perception may be useful in explaining that miscommunications between cyclists and motorists as well as incorrect expectations about the behaviour of the other road user play an important role in crashes between motorised traffic and cyclists. Chaurand & Delhomme studied the interaction between cyclists and drivers in urban area, but their findings may be relevant for interactions in rural area as well. It could be that cyclists, although they consider interactions with drivers more dangerous than interactions with other cyclists, have an incorrect perception of the safety level of interacting with motorised traffic at rural intersections. And as a result, they behave less safe than they should behave, for example cross in front of an approaching vehicle instead waiting for it to pass.

2.4.3. Effect of personal factors on road users' behaviour and crash occurrence

Besides the effect of intersection design on road users' behaviour, there are other factors that affect road users' behaviour too. These factors are here referred to as personal factors. These factors may not be specific for the interaction between two road users at an intersection, but they have an effect on road users' behaviour in general. As it is almost impossible to discuss all personal factors in detail, a selection of the main factors has been made. Some of these factors are labelled as crash risk factors as they increase the risk of getting involved in a crash. Examples are driving under the influence, fatigue, lack of experience especially for novice drivers and distraction (SWOV, 2018; Wegman, Aarts & Bax, 2008). Regarding the two sociodemographic factors age and gender, research shows that young drivers tend to be involved in a crash more than middle-aged, more experienced, drivers are (De Craen, 2010). It appears that young drivers, because they are less experienced, do not have the same ability to predict how the traffic situation ahead may develop. So they are less capable to anticipate potential hazardous situations. On the other hand, older drivers may have functional limitations (i.e. physical and mental disabilities) such as being less capable of looking over their shoulder compared to younger drivers (Davidse, 2007a; Schepers et al., 2020; SWOV, 2015). Related to this is state awareness, in other words that a road user knows what s/he is capable of (i.e. task capability) (Davidse et al., 2010). Closely related to state awareness is risk awareness or hazard perception: a road user knows how dangerous the traffic situation is (i.e. task demand) (Davidse et al., 2010).

As was discussed earlier, the human factors approach concentrates on if a road user has the right expectations, is able to see what s/he needs to see, understands what s/he needs to do and is able to do that (Theeuwes, Van der Horst & Kuiken, 2012). However, it is the question if the road user is willing to do what s/he has to do in the traffic situation s/he is in, in other words if s/he is motivated to do so. In addition to what was described above about experience, another aspect of experience is being familiar with the intersection: does a road user approach and drive through this intersection for the first time or is s/he familiar with this specific intersection? It is the question if and how familiarity plays a role in crashes between cyclists and motor vehicles at rural intersections. What does it mean for the interaction when road users are (un)familiar with the intersection? Are they more alert or less alert when approaching and crossing the intersection?

2.4.4. Effect of external factors on road users' behaviour

In addition to personal factors, there are various external factors that affect road users' behaviour. Weather conditions (i.e. precipitation) and lighting conditions (i.e. low sun) influences driving behaviour (SWOV, 2012). An example is heavy rain. Because of heavy rain, road users have a less clear view on the traffic situation ahead. It appears that drivers drive slower and increase the following distance to their lead vehicle (Hogema, 1996; Agarwal et al., 2005 in

SWOV, 2012). Similar to personal factors, external factors may have an effect on road users' behaviour in general instead of being specifically relevant for the interaction between two road users at an intersection.

2.5. Interaction between a cyclist and a driver of a motor vehicle

When a road user approaches an intersection s/he interacts with the road environment, the intersection and the other road user. A visual representation by Van der Horst (1977, in Schaap, 2012) of this process for an individual driver can be found in Figure 2.2.

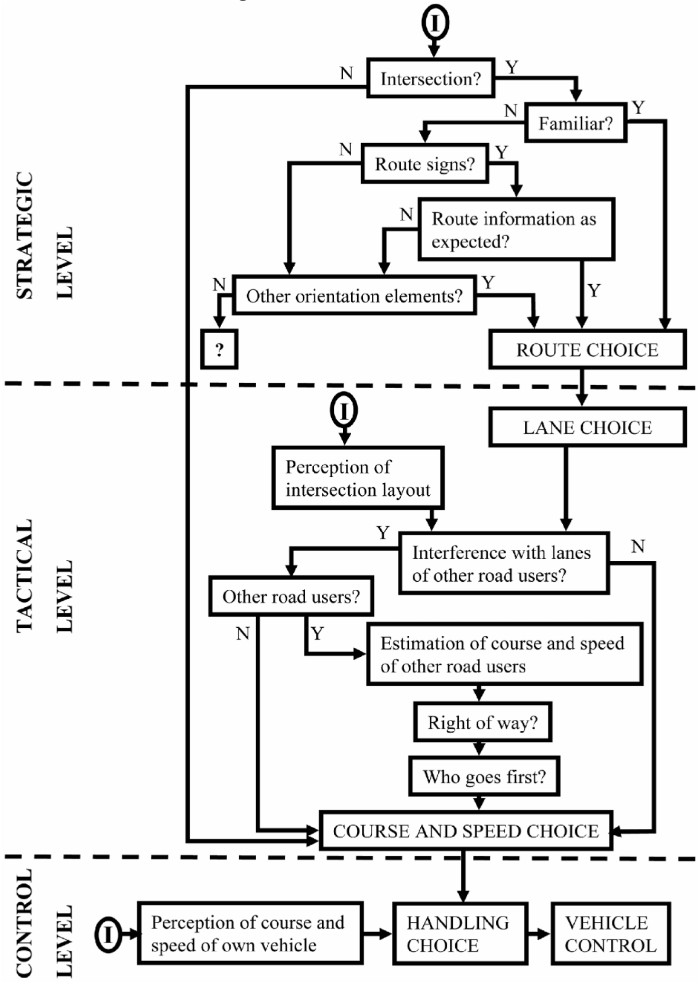

Figure 2.2. The three levels of the driving task when negotiating an intersection (Van der Horst (1977) in Schaap, 2012).

The model as presented above is based on the driving task classification by Michon (1985) into three levels: strategic (i.e. route choice), tactical (i.e. lane choice, course and speed choice) and control level (i.e. vehicle control), see Figure 2.2. At the strategic level, a road user looks for route signs and other orientation elements needed for his route choice. At the control level, a road user performs the handling task of the vehicle such as steering or braking. The interaction between two road users take place at the tactical level. At this level, road users look at the layout of the intersection to see if they will be going to interfere with lanes of other road users but also to see if other road users are present.

Regarding the interaction, the type of control at the intersection determines the conditions under which road users interact with each other. At signalised intersections, traffic signals determine which traffic flows are allowed to drive through and which traffic flows have to wait. Traffic signals can eliminate interactions between vulnerable road users and motorised traffic, i.e. by not giving them green light at the same time. Interactions still may occur when a road user runs the red light or when the traffic signals are out of order. At priority (give-way) intersections, traffic signs and road markings determine the priority setting. Compared to signalised intersections, priority (give-way) intersections leave more room for road users to judge the traffic situation by themselves in order to determine the appropriate behaviour. At these intersections, cyclists need to give way to motorised traffic when they want to cross the main carriageway. In these interactions, the driver of a motor vehicle can continue driving whereas the cyclist who needs to decide whether s/he is going to cross or to stop and give way to approaching drivers. So it is the cyclist in the first place who is the one to perform an evasive manoeuvre in order to avoid a crash from happening. To be more specific, the evasive manoeuvre of a cyclist is to stop and wait for approaching drivers to pass before crossing the drivers' lane. However, in case a cyclist fails (i.e. s/he crosses when s/he should not have), it is the driver who needs to perform the evasive manoeuvre such as braking in order to avoid a collision. The cyclist might be able to perform an evasive manoeuvre by himself/herself as well.

In the situation that a driver of a motor vehicle makes a turn thereby leaving the main carriageway or when she wants to enter the main carriageway, there is the possibility that s/he crosses a bicycle path situated parallel to the main carriageway. Depending on the type of bicycle crossing and the type of intersection, the driver of a motor vehicle has the right of way over cyclists on the bicycle path or s/he needs to give way to cyclists. With respect to the situation where the driver of a motor vehicle has the right of way, again it is the cyclist who needs to perform the evasive manoeuvre. In the situation that the driver of a motor vehicle needs to give way to cyclist, it is vice versa.

When deciding whether to cross or not, a road user makes an estimation on the course and speed of the other road users, see also Figure 2.2. Estimating the speed of another road user is difficult, especially when driving speeds are high (Elvik, 2015; Oxley et al., 2005; Sun et al., 2015). It appears that road users (i.e. pedestrians in most studies) have difficulties in estimating in estimating speed accurately. These studies found that road users underestimate high speeds of approaching motor vehicles, i.e. they consider the driving speed of the approaching car to be lower than the vehicle's actual speed. Oxley et al. (2005) concluded furthermore that road users seems to take a road-crossing decision primarily based on the distance between them and the approaching vehicle. The speed of the approaching vehicles is also taken into account but to a less extent.

2.6. From interaction to crash

When a cyclist and a driver of a motor vehicle approach each other at an intersection they can meet each other at the point where the bicycle path crosses the lane of the driver of a motor vehicle. This point is also called the potential conflict point. A conflict is "an observable situation in which two or more road users approach each other in space and time to such an extent that there is a risk of collision if their movements remain unchanged" (Van der Horst, 1990, p. 16). So, a conflict is a situation in which the cyclist and the driver of a motor vehicle are about to arrive at the potential conflict point at the same time. This may result in a crash unless the cyclist and/or the driver undertake an action so that they do not collide with each other.

Regarding the occurrence of crashes, it appears that crashes occur less often than conflicts. Hydén (1987) developed a pyramid shaped representation of all events occurring in traffic (see Figure 2.3) and presented all events that occur in traffic ranked by the relative rate of occurrence. The majority of encounters in traffic are undisturbed but only a small proportion of all encounters results in a crash. Of those crashes, fatal crashes occur less frequently compared to crashes in which there is only damage to the vehicle(s).

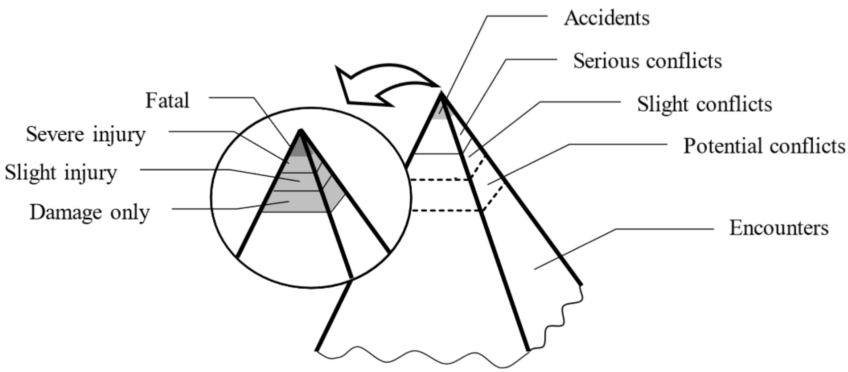

Figure 2.3. Representation of all events occurring in traffic with crashes occurring less frequently than undisturbed encounters (Laureshyn & Várhelyi, 2018; adopted from Hydén, 1987).

The likelihood of getting involved in a crash is related to the amount of travel and is called exposure. There are many ways for road users to travel, such as walking or travelling by bike, car, moped or public transport. Each transport mode has a different level of crash risk (Elvik et al., 2009). For example, crash risk for motorcyclists is thirteen times higher than crash risk for car drivers in the Netherlands (Stipdonk & Berends, 2008). Another aspect of exposure that is related to road users' crash risk is the mixture of transport modes, i.e. the relative proportions (Elvik et al., 2009). When there are more cyclists on the road network, the crash risk of each cyclist is lower compared to when there are only a few cyclists. This is called the 'safety in numbers' principle or effect: the more cyclists the lower the crash risk of cyclists (Brüde & Larsson, 1993; Elvik, 2013; Elvik & Bjørnskau, 2015; Jacobsen, 2003). However, Elvik & Bjørnskau (2015) warn that there are two important potential confounding factors. First, the characteristics of the cyclists and pedestrians, namely people who walk or cycle may have different characteristics compared to people who do not walk or bike. Second, the quality of pedestrian or cyclist infrastructure: high quality infrastructure may attract new pedestrians and cyclists which makes it more attractive (i.e. cost effective) to improve the infrastructure for pedestrians and cyclists. Also, it should be taken into account that not all relevant crashes were included in the studies on the safety in numbers effect as a result of the under-registration of crashes involving pedestrians and cyclists. For example, the registration rate of fatal crashes involving a bicycle in the Netherlands is 72% (Duivenvoorden et al., 2015) whereas the registration level of single-bicycle crashes in which a cyclist got seriously injured after falling or colliding with an object is approximately 4% (Reurings & Bos, 2009). Elvik & Bjørnskau (2015) conclude that it is unknown what the causal mechanism is behind the safety in numbers effect. They suggest that it might be related to the quality of interaction between cyclists or pedestrians and motorists: the more pedestrians and cyclists, the better motorised traffic is able to interact with them. Another important aspect that plays a role is the quality of the infrastructure (Wegman, Zhang & Dijkstra, 2010). In addition to increasing awareness with an increasing number of cyclists, the bicycle facilities themselves should be taken into account as well (Wegman, Zhang & Dijkstra, 2010). Cyclists and other vulnerable road users benefit from being able to use facilities that are separated from heavy and fast driving motorised traffic. In crashes with motorised traffic, vulnerable road users experience the high kinetic energy released and therefore may sustain serious injuries or even fatal injuries. In addition to being separated from motorised traffic, it is also important that the facilities for vulnerable road users themselves are designed safely. When falling or colliding with an obstacle, vulnerable road users are not protected by their vehicles as drivers of motorised traffic are. Their only protection may be a helmet. Small poles and objects higher than five centimetres are obstacles that might be harmful to cyclists on bicycle facilities (Boele-Vos et al., 2017). It is therefore important to design safe cycling facilities as safe cycling conditions on well-designed bicycle facilities have a positive effect on risk. This phenomenon is referred to as awareness-in-numbers (Wegman, Zhang & Dijkstra, 2010).

But what makes it that a crash occurs? This can be explained by Reason's (2000) model of the development of a crash. In this model a distinction is made between latent errors and active errors. Active errors are dangerous actions that can be linked to crashes directly. Latent errors are gaps in the traffic system that become contributory factors that cause a dangerous action resulting in a crash. So, a crash is the result of events in a chain that are not well adapted to each other (Reason, 2000). It is therefore important to solve these latent errors. An example is a road user colliding with oncoming traffic during the performance of an overtaking manoeuvre, in a curve on a single carriageway right in front of an intersection, late at night with poor lighting along the route. So, it is not a specific factor or circumstance but a combination of factors or circumstances that contributes to a crash (Boele-Vos et al., 2017; Grayson & Hakkert (1987) in Van der Horst, 1990; Wegman, Aarts & Bax, 2008). In an extensive literature review, Salmon et al. (2010) concluded that some road safety visions such as the Swedish Vision Zero and the Dutch Sustainable Safety consider human error no longer as the primary cause of crashes. Instead, human error is seen as the consequence of latent failures created by the system, i.e. the road user, road authority and government

(Salmon et al., 2010). As was explained in sections above, the Sustainable Safety vision therefore wants the traffic system to be designed by taking human factors as the primary focus so that the system prevents crashes from happening (SWOV, 2018).

As was mentioned above, a crash occurs because of a combination of factors or circumstances. Regarding those factors, a distinction can be made between factors that affect the likelihood of the occurrence of the crash and factors that could play a role in the severity of the crash (Davidse, 2007b; Evans, 1993). In the following sections, factors related to road users' behaviour and intersection design that play a role in the occurrence of intersection crashes are described. Also is described the effect that crashes have on intersection design and road users' behaviour.

2.6.1. Effect of road users' behaviour on crash occurrence and crash consequences

Speed is one of the three basic risk factors (Aarts & Van Schagen, 2006; Elvik, 2005). The two other basic risk factors are mass and protection. As was already described in Section 2.2.2, there is a large difference between a cyclist and a driver of a motor vehicle with respect to mass and protection. The effect of speed is twofold: not only does it affect the risk of being involved in a crash but it also affects the severity of a crash. Internationally, it is generally assumed that about a third of the fatal crashes is (partly) due to speeding or improper speeds (e.g. OECD/ECMT, 2006). However, it is difficult to determine precisely when speeding is the main cause, because often other factors in addition to speed also play a role in the occurrence of a crash. Especially for vulnerable road users, the consequences of a crash in terms of injury severity is affected by speed and the angle of impact (Jurewicz et al., 2016). Cyclists are not protected by their vehicle as drivers of motor vehicles (except motorcyclists) are protected by their vehicles. The only protection a cyclist may have is a helmet. Speed reduction of motorized traffic limits the adverse consequences that cyclists experience in potential conflicts (Reynolds et al., 2009; Rodarius, Mordaka & Versmissen, 2008; Rosén, Stigson & Sander, 2011; Van Hassel & De Lange, 2006; Wegman, Zhang & Dijkstra, 2010) because there is less kinetic energy released in a crash (Wegman & Aarts, 2006). In addition to high or improper speeds, the variety in speeds also plays a role. Large differences in speed leads to an increased crash risk (Aarts & Van Schagen, 2006). Therefore, road safety can also benefit from homogeneity of speeds (Van Nes, Brandenburg & Twisk, 2010).

In addition to speed there are more types of behaviour that have an effect on the occurrence of a crash. Examples are driving under the influence, fatigue, lack of experience especially for young driving and distraction (Wegman, Aarts & Bax, 2008). These factors are for this study categorised as personal factors and were discussed in Section 2.4.3.

2.6.2. Effect of crashes and crash consequences on intersection design

Traditionally, crashes and their severity are the main input for road safety research as well as the main motivation for road authorities to undertake action (Svensson & Hydén, 2006; Tarko et al., 2009). Especially high-risk locations, locations where many crashes occurred, urged the road authorities to treat these locations before they will treat other locations. However, there are problems concerning the use of crash data. First, the number of crashes declines. And second, there are problems regarding the crash data in crash database such as incompleteness of crash records and under registration of crashes (i.e. not every crash is being reported to the police and thus registered in the crash database). This creates the need for other ways to conduct road safety research and to prioritise locations for treatment. Therefore, safety research shifted from using direct measures such as crashes and crash severity to using surrogate measures of road safety (Tarko et al., 2009; Van der Horst, 1990). Surrogate safety measures are other measures than the number of crashes to describe the level of safety of a road section, an intersection or a road network. Moreover, surrogate safety measures are considered to be a rather proactive approach compared to the reactive character of crash analyses. Schaap (2012) classified the measures into two groups. The first group of surrogate safety measures describe how safe certain behaviour of single road users is, such as time to line crossing. The second group concerns measures describing the severity of a conflict between two road users, such as time to collision. Traffic conflicts are widely used as a surrogate safety measure because traffic conflicts are occurring more frequently than crashes (see Figure 2.3). A conflict is defined as 'a situation where two or more road users approach each other in time and space to such an extent that a collision is imminent if their movements remain unchanged' (Svensson & Hydén, 2006). Some studies suggest that findings from traffic conflict studies are considered to be beneficial for crashes as well (Dijkstra et al., 2010; Tarko et al., 2009).

In the relation between consequences of crashes and intersection design subjective and objective safety play a role. The layout of an intersection is being changed when that intersection appears to be unsafe for example when data points out that there is a safety problem. In this case, objective safety is being used as an argument for action, thus treatment of an intersection. But what should road authorities do if citizens claim that an intersection is unsafe and want the road authority to undertake action? Or what if a road authority wants to apply a safety measure which is scientifically proven to be safe but citizens do not want that measure? Instead, they want a measure of which research showed that this measure does not contribute to road safety. In these examples both objective safety and subjective safety play a role. It appears that there is tension between objective safety and subjective safety in politics (Vlakveld, Goldenbeld C. & Twisk, 2008).

2.6.3. Effect of crash consequences on national design guidelines

The national design guidelines in the Netherlands are developed (i.e. created for the first time or updated when they already existed) every three to twelve years (Schermers et al., 2013). In a working group consisting of experts from for example governments, interest groups and knowledge institutes, the guidelines are being developed based on consensus. According to Schermers et al. (2013), in this process is strived to develop guidelines to design roads as safe as possible. However, as scientific research on the safety effects of numerous designs and its elements is lacking, the guidelines are for a large part developed based on the expertise of the working group (Schermers et al., 2013). According to Schermers et al., in the development process of design guidelines scientific research is generally taken into account. This research can deliver new insights after studies have been conducted on certain road safety developments, such as an increase in the number of injured among certain road users groups (e.g. elderly cyclists).

2.6.4. Effect of crashes on road users' behaviour

Studies addressing the effect of the impact of crashes on road users' behaviour point out different results. Studies do not show a clear conclusion how the behaviour of road users is being affected after they sustained injuries in a crash. For example, Rajalin & Summala (1997) looked at the effect being involved in a fatal crash had on a driver's mileage, offences and self-reported driving behaviour. Almost half of the people that were involved in a fatal crash (thus the other road user died) had reduced their mileage in the year after the year of the crash. Injury severity played a role: seriously injured reduced their mileage more than people who were only slightly injured or did not have injuries at all. The number of offences three years before and three years after the crash was used to study if the drivers became more cautious. The results showed an increase in the number of offences per million kilometres. An interview with 37 drivers showed that 50% of drivers themselves stated that the crash had only a short effect (i.e. ranging from days to some months) on their driving behaviour and 25% said that the crash had a permanent effect. The majority said that the crash had an effect on their behaviour in traffic situations that looked similar to those of the crash. Also Vissers (1995) concluded that the effect is small and only temporary. In a study among young Dutch male drivers, it was found that these young male drivers did not change their behaviour permanently. An explanation may be that they believed that a crash is something that happens by accident and cannot be prevented. Furthermore, they considered themselves to be relatively invulnerable when driving in a car (Vissers, 1995). Also Chen & Guo (2015) found an temporary effect. They performed an analysis on data from the 100-car naturalistic driving study (Dingus et al., 2006) in which 51 crashes were analysed. Both the effects on driving behaviour and driving risk were studied. This first was measured by the probability of distraction (i.e. drivers' engagement in moderate and complex secondary tasks) and the latter by the number of safety-critical incidents and near crashes. The results showed that drivers were less engaged in secondary task after experiencing a crash, especially within 15 hours after the crash. However, after 50 hours of driving the effect had diminished. The results on driving risk showed that drivers were less involved in safety-critical incidents and near crashes in the time period after the crash, but again this effect was not permanent (Guo & Chen, 2015).

On the other hand, Ho et al. (2015) found an effect of a crash on the number of traffic offences. In the study, the number of traffic offences before and after a crash was studied in relation to severe road trauma. The results showed that road users who obtained serious injuries in a crash (i.e. admitted to the intensive care unit) conducted fewer traffic offences than before their crash. Only a small proportion of the road users did not change their behaviour in terms of the number of traffic offences.

2.6.5. Effect of post-crash response on crash consequences

In general, the interaction between cyclists and drivers of a motor vehicle at intersections is successful: they can continue their way after crossing the intersection. The majority of passages in traffic is undisturbed but only a small proportions of all passages results in a crash (Hydén, 1987). Especially in crashes in which road users sustain serious injuries, it is of great importance that they get the medical care they need as soon as possible. The injuries of a victim of a traffic crash may be fatal when the medical care does not arrive in time (Somers, 1983). So, post-crash response plays an important role.

Based on the results of a literature review, Noland (2004) showed that medical care has improved over the years because of new medical techniques and the introduction of trauma care systems. Also, the transport of injured road users to a hospital is an important element of trauma care. Noland concluded that new techniques and improvements in medical care caused a major reduction in fatalities. Clark, Winchell & Betensky (2013) studied traffic crash mortality of crashes in rural area. By comparing it to a lower crash mortality in urban area, Clark, Winchell & Betensky investigated whether this is affected by deficiencies in time delays, Emergency Medical Services or injury severity. From this study it was concluded that that mortality after injury in rural area may benefit more from measures that prevent crashes from happening and minimise the severity of injuries than from trying to further decrease the prehospital times (i.e. intervention by a trauma team at the crash site or in the hospital, see Clark, Winchell & Betensky, 2013).

In the Netherlands, since 1995 four trauma centres are created and trauma helicopters are introduced to deliver medical assistance at crash sites (ANWB, 2020). Sometimes, a victim is being transported by a trauma helicopter to the hospital.

2.7. Conclusion

The previous sections described various studies related to one or more aspects regarding the interaction between a cyclist and a driver of a motor vehicle at an intersection. It can be concluded that the interaction between these two road users is affected by *road users' behaviour* and *intersection design.* As a generic model describing this interaction seems to be lacking, a conceptual model has been developed. The model as proposed in Section 2.2 contains the main factors that influence the interaction between a cyclist and a driver of a motor vehicle. This model fits the scope of the research that is presented in this dissertation. Also, the model can be applied to interactions between these two road users at other intersections as this model is not limited to a specific intersection type or a specific type of interaction. The model can be applied to interactions at intersections in both urban and rural area, and to countries where the biking culture is dominant but also to countries in which biking is not a commonly used transport mode. Therefore, this model is considered to be a robust and generic model for describing the interaction between a cyclist and a driver of a motor vehicle at an intersection. Note that in the empirical research described in the next sections is referred to driver of a passenger car.

Especially in Chapter 5 as the experiment was conducted in a passenger car driving simulator.

When applying the proposed model there is an important aspect that should be kept in mind: the context. The model may work differently in different countries and in different circumstances. Thus, what is in the arrows or in the boxes may differ. For example, in countries in which the bicycle is a commonly used transport mode, drivers of a motor vehicle are used to interact with them in traffic and thus expect cyclists to be present in traffic. Whereas in countries or regions where only a slight part of the population uses a bike, drivers who are not confronted with them on a regular basis may not expect them to be present and may even be surprised when meeting them in traffic. Context also plays a role in intersection design and its corresponding bicycle facilities: cyclists may have their own facilities separated from the motorised traffic or they need to share the carriageway with motorised traffic.

Considering the conceptual model as presented above, the two main factors *intersection design* and *road users' behaviour* are further studied in the next chapters. Before studying these two factors, the characteristics of intersection crashes in rural area are explored by performing an analysis on the crash database. In Chapter 3 the results of this analysis are presented. Gaining insight into factors that have an effect on the occurrence of a crash is useful in order to come up with measures that could prevent those crashes from happening in the future (Davidse, 2007b; Sandin, 2009). The factor *intersection design* is studied in Chapter 4. From the literature it is known what safe conditions are for interactions between vulnerable road users and drivers of motorised traffic at intersections. But how does it work in the real world: are rural intersections designed in such a way that road users can safely interact with each other? Therefore, Chapter 4 focuses on the actual design of rural intersections and describes the factors that play a role in the (re)construction of an intersection. The factor *road users' behaviour* is studied in Chapter 5. Little is known about how cyclists affect driving behaviour of car drivers at rural intersections. Therefore, a driving simulator study was conducted to safely study the interaction between car drivers and cyclists. Chapter 5 presents the results of this study.

3. Characteristics of rural intersection crashes

3.1. Introduction

The previous chapter proposed a conceptual model on the interaction between a cyclist and a driver of a motor vehicle at an intersection consisting of two main factors *intersection design* and *road users' behaviour*. This chapter provides the results of a crash analysis on the characteristics of crashes occurring at rural intersections on Dutch 80 km/h rural roads. By performing such an analysis, background information is gained on crashes occurring at these intersections. The findings are used to determine more specifically where to focus on in the two remaining studies in Chapter 4 (focusing on the factor *intersection design*) and Chapter 5 (focusing on the factor *road users' behaviour*).

In the coming sections, the following can be found. Section 3.2 describes the method that was used to analyse the intersection crashes. In Section 3.3 the results of the analysis are presented. Last, in Section 3.4 the main findings are discussed.

3.2. Method

From Chapter 1 it is clear that there are safety issues between cyclist and motorised traffic at rural intersections. But the details are not known, for example what types of crashes occur and at what types of intersections do they occur. Therefore, the aim of analysing the database of registered crashes is to gain insight in the characteristics of crashes occurring at intersections on rural 80 km/h rural roads. The research questions are:

1. What types of crashes occur at those intersections?
2. What types of road users are involved in those crashes?
3. What are the design characteristics of those intersections?

3.2.1. Analysis of the database of registered crashes

Crash database

For answering research question 1 and research question 2, the database of registered crashes (BRON) was used (Ministerie van Infrastructuur en Waterstaat / BRON, 2019). Research question 3 needed a different approach, see for more information Section 3.2.2. Police registration forms are input for this database. After a crash happened, a police registration form is produced.

In case of a severe crash or if there is an indictable violation of the highway code, a police charge is made on top of the registration form (Management Assistance Group, 1995; Vis et al., 2011). As not every crash is reported to the police, the BRON database only contains the registered crashes. Regarding the registration of crashes, two issues play a role, namely the registration of crashes as such and the distribution among the crashes. The registration level appears to depend on the severity of crashes as well as the road users involved. First, fatal crashes have a higher registration level than slight injury crashes and property damage only (PDO) crashes. Second, the registration level appears to be higher in case motor vehicles are involved compared to crashes in which vulnerable road users are involved. Regarding the registration rate of cyclists, this level is the lowest irrespective of the severity of the crash (Van Norden, Goldenbeld & Weijermars, 2011, p. 78).

For the present crash analysis, fatal crashes and serious injury (MAIS2+) crashes were analysed. Only those crashes were selected that occurred at intersections in rural area. By setting the variable 'speed limit' to 80 km/h, intersections with at least one intersecting road with a speed limit of 80 km/h were taken into account. This speed limit refers to the speed limit of the intersecting road; there may be a lower speed limit at the intersection itself. The other intersecting road can be a minor road (60 km/h) or another major road with a speed limit of 80 km/h. In the analysis, data from two time periods was used, namely 2006-2009 and 2010-2018 (for more information is referred to Appendix 1). The various subsets of data regarding serious injury (MAIS2+) crashes presented in the following sections are only to be made with data from the time period 2006-2009, originating from the BRON database of registered crashes. As a result of multiple changes such as in the registration method and the data sources, more recent data on seriously injured (MAIS2+) nowadays originate from hospitals (Landelijke Basisregistratie Ziekenhuiszorg / Dutch Hospital Data, 2019). As these data form the basis for information on seriously injured (MAIS2+), they contain almost no information on crash characteristics. Data on fatal crashes from the time period 2010-2018 is added to provide more recent insights in the safety issues at rural intersections. Appendix 1 describes the implications of using less recent data.

An important aspect of crash data is the registration level. It appears that in 2010, the registration level of fatalities in road crashes appeared to be much lower compared to the previous years. The registration level was approximately 95% (mid-nineties) and 90% in the period 2006-2009 and dropped to 84% in 2010 (Vis et al., 2011). Vis et al. found that the lower registration level seemed to be correlated with the new forms the police used for recording crash characteristics and the implementation of a new police information system. Compared to the old registration forms used by the police, these new forms did not contain those information required to be a solid basis for road safety research.

Additional research regarding the registration level of fatalities in the database with registered crashes showed that the fatalities that were not included were mainly cyclists (Reurings & Bos, 2009; 2011). These cyclists did not collide with a motor vehicle but appear to fall, collide with another cyclist or collide with an object (i.e. single-bicycle crashes). These crashes were not recorded by the police and thus not included in the crash database. The same applies for crashes in which cyclists sustain serious injuries but the registration level of these crashes is much lower compared to fatal crashes. The registration level of single-bicycle crashes in which a cyclist got seriously injured after falling or colliding with an object is approximately 4% (Reurings & Bos, 2009). Reurings & Bos also found that the registration level of motor vehicle crashes in 2008 was 59% whereas it was assumed previously to be more than 80%.

Glossary

Within this crash analysis, the following definitions were used (based on the definitions of International Transport Forum, 2009):

- *Road crash* – an event on a public road that occurred in traffic and resulted in damage to objects and/or injury to people and involved at least one moving vehicle;
- *Fatality* – a casualty who died as a result of the crash within 30 days after the crash occurred;
- *Fatal crash* – a crash with at least one fatality;
- *Seriously injured casualty* – a road user who is admitted to the hospital for at least one night and has a minimum Maximum Abbreviated Injury Score (MAIS) of 2, and does not die within 30 days after the crash occurred (Reurings & Bos, 2009);
- *Serious injury crash* – a crash where no one was killed but where at least one road user had to be admitted to the hospital for at least one night and has a minimum MAIS of 2 (Reurings & Bos, 2009).

In the definition of seriously injured casualties, the Maximum Abbreviated Injury Score (MAIS) is used. MAIS is an international measure and refers to the most severe ('maximum') injury of all injuries of a casualty. Examples of injuries with a MAIS of 2 and more are concussions and fractures. Since 2009, MAIS2+ is used to determine seriously injured in the Netherlands. Until 2009, a definition was used which defined a seriously injured casualty as an 'in-patient': a road crash casualty who had to be admitted to the hospital for at least one night. However, an in-patient is not necessarily seriously injured but can be admitted to the hospital for observation only (Reurings & Bos, 2009).

Using MAIS enables an international comparison of traffic casualties between countries in Europe (Broughton et al., 2008). Another advantage of using severity assessments from the hospital injuries is the sharp boundary between seriously injured with MAIS2+ and seriously injured with MAIS3+. For these groups, the underreporting coefficients are known. In Europe, serious injuries are defined as MAIS3+ as it was not feasible for each country to use MAIS2+ whereas it was for the Netherlands. Using a boundary on MAIS2+ resulted in a number of killed and severely injured that is approximately fifteen times higher than the number of killed only (Broughton et al., 2008). Using MAIS3+, the number of killed and severely injured is approximately six times higher. Polinder et al. (2015) found that using MAIS2+ in the Netherlands captured approximately 80% of the burden of road traffic injuries expressed in disability adjusted life years (DALYs). By using MAIS3+, this is only 54%. Thus, seriously injured with MAIS2+ account for a large proportion of the burden of road traffic injuries in the Netherlands.

Exposure data

In this chapter, several intersection types on the 80 km/h roads are addressed. For a solid comparison, the application of exposure data is favoured over the absolute number of crashes. In road safety research, exposure data is used in comparisons of the safety levels of different entities, such as road categories or transport modes. There are several possibilities for expressing the level of exposure (e.g. number of cars or road length); distance travelled by road users in traffic (also known as mobility) is generally used in road safety research (Bijleveld, 2008). In the Netherlands, data on the distance travelled are collected via a travel survey (Ministerie van Verkeer en Waterstaat / Rijkswaterstaat, 2010). However, this information is not disaggregated in various road categories which means that there is no information available on distance travelled on 80 km/h rural roads including intersections.

For comparing various intersection (control) types, an appropriate unit of exposure is the number of intersections. An important source for characteristics of the Dutch road network is the National Road Database (NRD) accessible by using the GIS application ArcMap (published by ESRI, 2011). In the National

Road Database, the road network is described by road segments and junctions (e.g. end of a no-through road or a location with traffic exchange). Intersections and roundabouts are not single items in the database but consist of several road segments and junctions. Regarding roundabouts, the National Road Database contains the variable 'roundabout' which enables the extraction of the number of roundabouts (as was done by Churchill, Stipdonk & Bijleveld, 2010). Unfortunately, there is no variable indicating intersections. A search query on the National Road Database in order to distract the number of intersections on 80 km/h rural roads did not appear to be feasible as the intersections consist of many road segments but not in a uniform way. Thus, it was not possible to define an intersection in terms of road segments. Hence, the National Road Database did not provide the number of various intersection types. Therefore, relevant literature was used, namely the findings of Marchesini (2009) and (Dijkstra et al., 2010). Marchesini and Dijkstra et al. examined the relationship between observed crashes and simulated conflicts at intersections by using a micro simulation model calibrated with real crash data. Both studies were applied to a Dutch regional network which consisted of signalised and priority intersections both three- and four-arms. Although the studies concerned a network consisting of several road categories including 80 km/h rural roads, both studies provide insight into the number of crashes and conflicts as well as conflict and crash risk of several intersection (control) types.

3.2.2. Detailed analysis of fatal intersection crashes

In addition to the analysis of the database with registered crashes, a more detailed analysis of fatal intersection crashes was conducted. The aim was to gain insight in infrastructural characteristics that could not be extracted from the crash database. The research question to be answered is the third research question presented above: 'what are the design characteristics of intersections where fatal crashes occurred?'. Several general variables were collected using police registration forms, a virtual visit of the crash sites and information about the crashes on the Internet. In some cases, there were no speed limit signs visible on the images of Google Street View and therefore a chart (in Dutch: Maximum snelheden kaart) containing the speed limits was used in addition (Rijkswaterstaat, 2011). The collected variables were:

- road users involved;
- posted speed limits;
- intersection type (e.g. three or four-arms);
- intersection control type (e.g. signalised intersection);
- crash type (e.g. side-impact).

For the detailed analysis, three additional sources were used namely the police registration forms, a virtual visit of the crash sites and information about the crashes on the Internet. First, the registration forms of all fatal intersection crashes in 2008 were collected which resulted in registration forms of 66 registered fatal crashes. Serious injury crashes could not be included as registration forms were available for fatal crashes only. Second, for each crash additional information on the crash site was gathered, mainly on design characteristics of the infrastructure. Therefore, the crash site was located by using Google Maps and Google Street View. Google Street View allowed for visiting the crash site virtually and appeared to be useful when checking for example traffic signs indicating that an intersection is a crossing or an on-ramp. Third, the Internet was searched for additional images of the crashes. On so-called crash websites and on websites of newspapers, additional information on several crashes was found. These websites contained videos and photos made by amateur and (semi)professional photographers shortly after the crash occurred. The images showed the crashed vehicles still present at the crash site, police investigating the crash site and sometimes even emergency services doing their job. In general, the photos and videos were taken from a proper distance (e.g. casualties are not identifiable). The Internet was searched using the following key words: 'crash' (translated in Dutch) and name of the city or village mentioned on the registration form. In addition, a time frame was selected, namely within one month after the crash date.

After following this procedure, 15 of these 66 fatal intersection crashes appeared not to be relevant. Crashes at crossings (where there is no possibility for exchanging traffic) and on-ramps were excluded as well as crashes on road sections. These locations were considered to be different compared to the intersection types studied here as other manoeuvres are performed. When using Google Street View for searching the crash site, in two cases temporary roadside memorials (e.g. flowers, letters and cuddly toys) were found on the images indicating the location of a fatal crash. However, it is possible that these memorials belong to another crash. In a few cases, the information on the registration form was not sufficient enough to determine the precise location of the crash site and on the Internet no additional information was found. These crashes were excluded as well.

From the remaining relevant crashes (N = 51), several general variables were collected using the three sources mentioned above. The variables were related to the road users involved, the type of crash they were involved in and the intersection (control) type. In some cases, there were no speed limit signs visible on the images of Google Street View and therefore a chart (in Dutch: Maximum snelheden kaart) containing the speed limits was used in addition (Rijkswaterstaat, 2011). The collected variables were:

- road users involved;
- posted speed limits;
- intersection type (e.g. three or four-arms);
- intersection control type (e.g. signalised intersection);
- crash type (e.g. side-impact).

In addition, each crash site was assessed to determine if the intersection meets the requirements for a sustainably safe infrastructure. Therefore, the presence of several characteristics which should be present at intersections was obtained. The assessment is based on a study on quality aspects of a sustainably safe road infrastructure conducted by Dijkstra (2003). In this study, several requirements additional to the Sustainable Safety vision (SWOV, 2018; Wegman, Aarts & Bax, 2008) were suggested for road sections and intersections at 80 km/h distributor roads. According to Dijkstra, several measures strongly related to serious crashes should be applied to intersections. Dijkstra formulated the following requirements that were assessed here:

- left turn lane at three- and four-arm intersections;
- pedestrian/cycling facilities (e.g. median treatment for pedestrians and cyclists);
- roundabouts or speed-reducing measures.

3.3. Results

In this section, the answers to the three research questions are presented. Section 3.3.1 describes the type of crashes occurring at the intersections. The road users involved in those crashes are described in Section 3.3.2. Section 3.3.3 and Section 3.3.4 focus on the design characteristics of the intersections.

3.3.1. Types of intersection crashes

At intersections on 80 km/h rural roads in the Netherlands, side-impact crashes were the predominant crashes for both fatal and seriously (MAIS2+) crashes, respectively 68%-70% and 59% (see Table 3.1). Head-on crashes were the second-most frequently occurring crashes, 12%-13% for fatal crashes and 19% for serious injury (MAIS2+) crashes. The results showed the majority of crashes seemed to involve more than one road user (i.e. low percentage of single-vehicle crashes).

	Fatal crashes		Serious injury (MAIS2+) crashes	Measure of severity
	2006-2009	2010-2018	2006-2009	2006-2009
Side-impact	191 (70%)	208 (68%)	762 (59%)	0.20 ± 0.01
Head-on	35 (13%)	36 (12%)	252 (19%)	0.12 ± 0.02
Rear-end	10 (4%)	14 (5%)	132 (10%)	0.07 ± 0.02
Pedestrian	10 (4%)	6 (2%)	13 (1%)	0.43 ± 0.10
Single-vehicle*	25 (9%)	41 (13%)	136 (11%)	0.16 ± 0.03
Total	271 (100%)	305 (100%)	1295 (100%)	

Table 3.1. Number of registered fatal and serious injury (MAIS2+) crashes per crash type at intersections on 80 km/h rural roads in the Netherlands in the period 2006-2009 and 2010-2018 (Source: Ministerie van Infrastructuur en Waterstaat / BRON, 2019). The measure of severity represents the proportion fatal crashes of all serious casualty crashes (fatal + serious injury (MAIS2+) crashes) and was calculated for the time period 2006-2009. As both the number of fatal crashes and serious injury (MAIS2+) crashes contain an error, the measure of severity does as well and is therefore expressed by the error $\sigma_\alpha = \sqrt{(x1x2^2+x1^2x2)/(x1+x2)^2}$.

The measure of severity is used to distinguish the severity of crash types (see Table 3.1). This measure is calculated by dividing the number of fatal crashes by the sum of the number of fatal crashes and serious injury crashes. By doing so, it is assumed that the registration rates of the crash types are not different. The results show that crashes in which a pedestrian is involved are the most severe. A possible explanation is the vulnerability of pedestrians (Rosén, Stigson & Sander, 2011). The second-most severe crash type is a side-impact crash. An explanation may be the construction of the vehicles and the vulnerability of cyclists involved in side-impact crashes. At intersections on 80 km/h rural roads, it is possible that side-impacts occur in situations where the driving speeds are up to 80 km/h. However, EuroNCAP criteria for vehicles are 50 km/h which means that vehicles are not constructed for high-speed impacts (Wegman & Aarts, 2006). According to Wegman & Aarts, it is not expected that side-airbags will provide the needed protection in crashes with impact speeds higher than 50 km/h. In contrast, cyclists or (light) moped riders involved do not benefit from the construction of their transportation mode. Therefore, high impact speeds are harmful to vulnerable road users (Rodarius, Mordaka & Versmissen, 2008; Rosén, Stigson & Sander, 2011; Van Hassel & De Lange, 2006; Wegman, Zhang & Dijkstra, 2010).

3.3.2. Road users involved in intersection crashes

In crashes occurring at rural intersections, the highest number of casualties is among vulnerable road users. Pedestrians, cyclists, (light) moped riders and motorcyclists account for 60% of the fatalities and 50% of the seriously injured (see Table 3.2). Of all vulnerable road users, cyclists form the largest group. Regarding road users of motorised traffic, car occupants account for 37% of the fatalities and 45% of the seriously injured (MAIS2+). The category 'other transport modes' includes drivers of the more heavy traffic (i.e. buses and lorries) and have a relatively small share in the number of casualties. Also, this category includes casualties among mobility scooters and microcars. These casualties should be counted as vulnerable road users too as they are less protected by their vehicle than motorists and have less mass and speed compared to motorised traffic.

	Fatalities	**Seriously injured (MAIS2+)**
Pedestrian	10 (4%)	13 (1%)
Bicycle	87 (31%)	276 (19%)
(Light) moped	27 (10%)	193 (14%)
Motorcycle	42 (15%)	230 (16%)
Passenger car	103 (37%)	632 (45%)
Other*	9 (3%)	73 (5%)
Total	278 (100%)	1,417 (100%)

Table 3.2. The transport mode of the casualties in intersection crashes on 80 km/h rural roads in the Netherlands in the period 2006-2009 (Source: Ministerie van Infrastructuur en Waterstaat / BRON, 2019). * Transport mode category 'other' includes delivery van, bus, lorry, and other transport modes such as mobility scooter and microcar.

The crash opponents for fatalities and seriously injured (MAIS2+) are presented in Table 3.3. The crash opponents are classified into three groups, namely the crash opponent was a passenger car, another vehicle or there was no other vehicle involved. For vulnerable road users, the majority of fatalities (52-60%) and of the seriously injured (MAIS2+; 60-77%) collided with a passenger car. The majority of passenger car occupants collided with passenger cars (in case of seriously injured (MAIS2+)) and with other vehicles than passenger cars (in case of fatalities). A small percentage of the fatalities and seriously injured (MAIS2+) occurs without the presence of another vehicle.

	Fatalities by crash opponent			Seriously injured (MAIS2+) by crash opponent		
	Passenger car	Other vehicle	No vehicle	Passenger car	Other vehicle	No vehicle
Pedestrian	6 (60%)	4 (40%)	0 (0%)	10 (77%)	3 (23%)	0 (0%)
Bicycle	49 (56%)	36 (41%)	2 (2%)	202 (73%)	66 (24%)	8 (3%)
(Light) moped	14 (52%)	12 (44%)	1 (4%)	136 (70%)	52 (27%)	5 (3%)
Motorcycle	25 (60%)	14 (33%)	3 (7%)	139 (60%)	51 (22%)	40 (17%)
Passenger car	39 (38%)	47 (46%)	17 (17%)	358 (57%)	199 (31%)	75 (12%)
Other*	5 (56%)	2 (22%)	2 (22%)	32 (44%)	32 (44%)	9 (12%)

Table 3.3. Fatalities and seriously injured (MAIS2+) by crash opponent at intersections on 80 km/h rural roads in the Netherlands in the period 2006-2009 (Source: Ministerie van Infrastructuur en Waterstaat / BRON, 2019). * Transport mode category 'other' includes delivery van, bus, lorry, and other transport modes such as mobility scooter and microcar.

Involvement of cyclists in intersection crashes

From the crash statistics in Table 3.4, it appeared that cyclists were involved in 46% of the fatal crashes and in 21% of the serious injury (MAIS2+) crashes. Regarding the latter it should be noted that these concern an older time period, however more recent data on serious injury (MAIS2+) crashes cannot be disaggregated at this level (see for more information Section 3.2.1). The majority of crashes involving a cyclist were side-impact crashes, respectively 80% of the fatal crashes and 77% of the serious injury (MAIS2+) crashes. In the Netherlands, the bicycle is a relatively frequently used transport mode (Harms, Bertolini & te Brömmelstroet, 2014; Kennisinstituut voor Mobiliteitsbeleid, 2019; Lynam et al., 2005; Schepers et al., 2017a). At Dutch rural intersections, vulnerable road users are accommodated by facilities such as cycle paths and crossing facilities. Cyclists are referred to as vulnerable road users as they are less physically protected by their bicycle than motorists are by their vehicles for example and have less mass and speed compared to motorised traffic (Reynolds et al., 2009; Wegman, Zhang & Dijkstra, 2010; Wegman & Aarts, 2006).

	Fatal crashes (N=305)		Serious injury (MAIS2+) crashes (N=1,295)	
	No cyclist involved	Cyclist involved (1 or more)	No cyclist involved	Cyclist involved (1 or more)
Side-impact	97	111	548	214
Head-on	26	10	212	40
Rear-end	11	3	120	12
Pedestrian	6	0	13	0
Single-vehicle*	24	17	125	11
Total	164	141	1,018	277
Total (%)	54	46	79	21

Table 3.4. Involvement of cyclists in registered fatal crashes at intersections on 80 km/h rural roads in the Netherlands in the period 2010-2018 (Source: Ministerie van Infrastructuur en Waterstaat / BRON, 2019). And the involvement of cyclist in serious injury (MAIS2+) crashes in the period 2006-2009 (Landelijke Basisregistratie Ziekenhuiszorg / Dutch Hospital Data, 2019). *Single-vehicle crashes also includes crashes with parked cars and other objects but they are very rare.

Age of casualties in intersection crashes

In Table 3.5, the age of fatalities and seriously injured (MAIS2+) in rural intersection crashes is presented. For fatalities, road users of 60 years and older seem to be a little overrepresented compared to other age groups. 51% of the fatalities and 25% of the seriously injured (MAIS2+) was 60 years or older. 9% of the fatalities and 15% of the seriously injured (MAIS2+) was under 18. In intersection crashes, young road users seem to get seriously injured whereas older road users seem to get fatally injured. In comparison, 24% of the Dutch population was under 20 years whereas 20% of the Dutch population was 60 years and older (CBS Statline, 2019).

	Fatalities	Seriously injured (MAIS2+)
0 - 11	3 (1%)	23 (2%)
12 - 17	21 (8%)	180 (13%)
18 - 24	24 (9%)	216 (15%)
25 - 29	10 (4%)	92 (6%)
30 - 39	22 (8%)	160 (11%)
40 - 49	31 (11%)	211 (15%)
50 - 59	26 (9%)	174 (12%)
60 - 74	55 (20%)	200 (14%)
75+	86 (31%)	161 (11%)
Total	278 (100%)	1,417 (100%)

Table 3.5. Casualties by age group in crashes at intersections on 80 km/h rural roads in the Netherlands in the period 2006-2009 (Source: Ministerie van Infrastructuur en Waterstaat / BRON, 2019).

Involvement of a car in intersection crashes

As was shown above, the majority of fatalities and seriously injured (MAIS2) were involved in a crash with a passenger car. When looking at the distribution of crashes over the time of day, there seems to be an increase in crashes during the morning and afternoon peak period (Figure 3.1). The distribution of serious injury (MAIS2+) crashes over the time of day seems to be more or less similar to the distribution of fatal crashes, except for the morning peak period: there are relatively more serious injured (MAIS2+) than fatalities. A similar result was found by Isaksson-Hellman (2012).

To study the serious injury (MAIS2+) crashes in more detail, the involvement of a car in these crashes is displayed in Figure 3.2. As there is more traffic during the peak periods, there seem to be more serious injury (MAIS2+) crashes in which a passenger car was involved. As there are also cyclists and pedestrians (going to work or to school), this may explain the increase of crashes in which no car was involved. With the lower registration rate of crashes without a motor vehicle (see Section 3.2.1) in mind, the real number of seriously injury (MAIS2+) crashes is higher than the registered number.

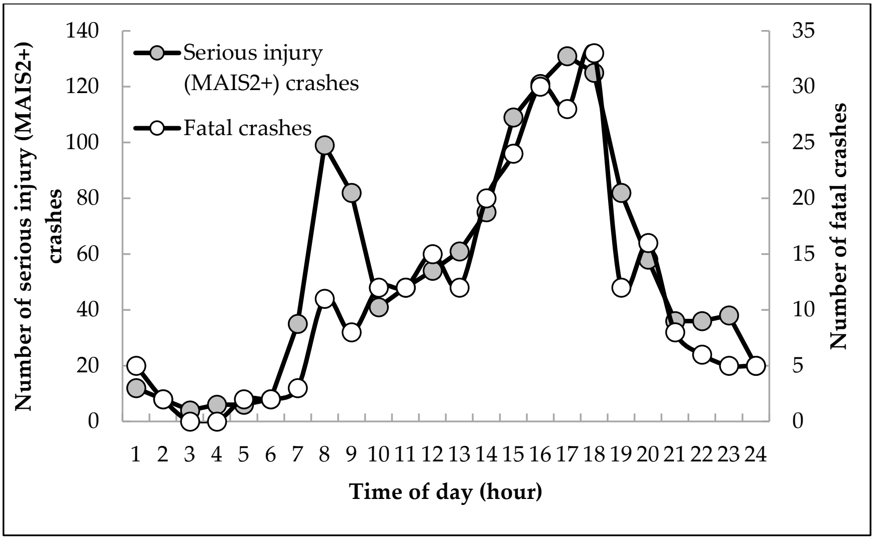

Figure 3.1. Distribution over the time of day for casualty crashes at intersections on 80 km/h rural roads in the Netherlands in the period 2006-2009 (Source: Ministerie van Infrastructuur en Waterstaat / BRON, 2019).

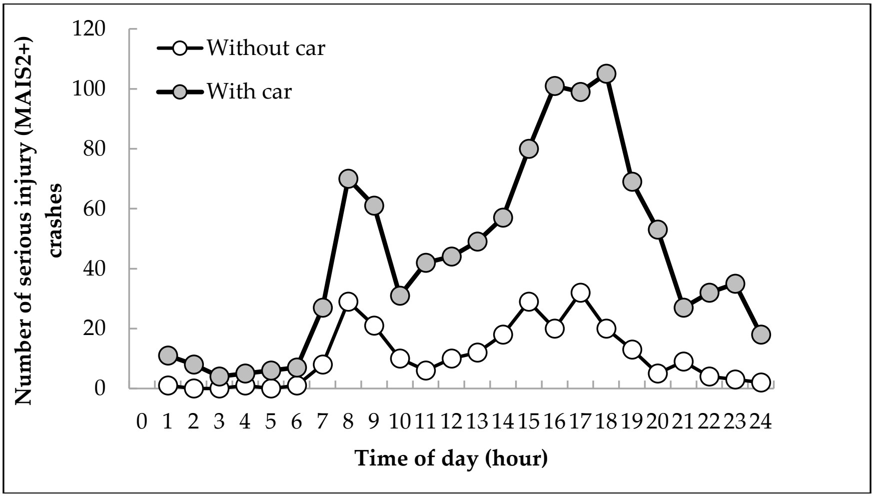

Figure 3.2. Distribution of serious injury (MAIS2+) crashes at intersections on 80 km/h rural roads in the Netherlands in the period 2006-2009 with and without a passenger car over time of day (Source: Ministerie van Infrastructuur en Waterstaat / BRON, 2019).

The relatively high number of seriously injured (MAIS2+) may be explained by looking at the age of the casualties (see also the previous section). Among young casualties, there are relatively more seriously injured (MAIS2+) than fatalities. For elderly, this is vice versa: there are relatively more fatalities than seriously injured (MAIS2+). During the morning peak, schools start around the same time whereas there is more variation in the time of schools ending. Thus, during the morning peak the number of young people in traffic is relatively higher than during the afternoon peak.

3.3.3. Intersection types

In the Dutch rural road network, various types of intersections exist, such as roundabouts, signalised intersections and priority (give-way) intersections. Stop-controlled intersections are rare. From the crash database information was obtained referring to the intersection being a roundabout, a three-arm or four-arm intersection. Unfortunately, the distribution of intersection crashes over intersection control types (i.e. priority (give-way) or signalised) cannot be obtained. A relatively small proportion of casualties occurred at roundabouts: only 2% (6 out of 278) of all fatalities and 3% (42 out of 1,417) of all seriously injured (MAIS2+) that occurred at rural intersections (see Table 3.6). At three-arm intersections, 45% (126 out of 278) of the fatalities and 43% (621 out of 1,417) of the seriously injured (MAIS2+) occurred. Approximately 53% of the fatalities and of the seriously injured (MAIS2+) occurred at four-arm intersections.

	Fatalities (N=278)			**Seriously injured (MAIS2+) (N=1,417)**		
	3-arm intersection	4-arm intersection	round-about	3-arm intersection	4-arm intersection	round-about
Pedestrian	7 (6%)	3 (2%)	0 (0%)	7 (1%)	6 (1%)	0 (0%)
Bicycle	40 (32%)	47 (32%)	0 (0%)	145 (23%)	122 (16%)	9 (21%)
(Light) moped	12 (10%)	15 (10%)	0 (0%)	94 (15%)	97 (13%)	2 (5%)
Motorcycle	18 (14%)	20 (14%)	4 (67%)	110 (18%)	108 (14%)	12 (29%)
Passenger car	45 (36%)	56 (38%)	2 (33%)	238 (38%)	378 (50%)	16 (38%)
Other*	4 (3%)	5 (3%)	0 (0%)	27 (4%)	43 (6%)	3 (7%)
Total	126 (100%)	146 (100%)	6 (100%)	621 (100%)	754 (100%)	42 (100%)

Table 3.6. Number of registered casualties by their transport mode at intersections on 80 km/h rural roads in the Netherlands in the period 2006-2009 (Source: Ministerie van Infrastructuur en Waterstaat / BRON, 2019). * Transport mode category 'other' includes delivery van, bus, lorry, and other transport modes such as mobility scooter and microcar.

Table 3.6 also shows the transport modes of the casualties. At both three- and four-arm intersections, approximately one third of fatalities occur among cyclists and passenger occupants. At roundabouts, fatalities were found among motorcyclists and passenger car occupants. Regarding the seriously injured (MAIS2+), the two main groups are cyclists and passenger car occupants. At roundabouts, the two main groups of seriously injured (MAIS2+) were motorcyclists and passenger car occupants.

Roundabouts appear to be an effective treatment in reducing the number of casualties and crashes (Churchill, Stipdonk & Bijleveld, 2010; Elvik, 2003; Van Minnen, 1995) as roundabouts force drivers to reduce their driving speeds. Another advantage is that roundabouts have a relatively low number of potential conflict points compared to three- and four-arm intersections (see Figure 3.3). Irrespective of the traffic volume at these intersections, the number of potential conflict points indicates the level of safety. The higher the number of potential conflict points, the more unsafe an intersection will be (Dijkstra, 2014).

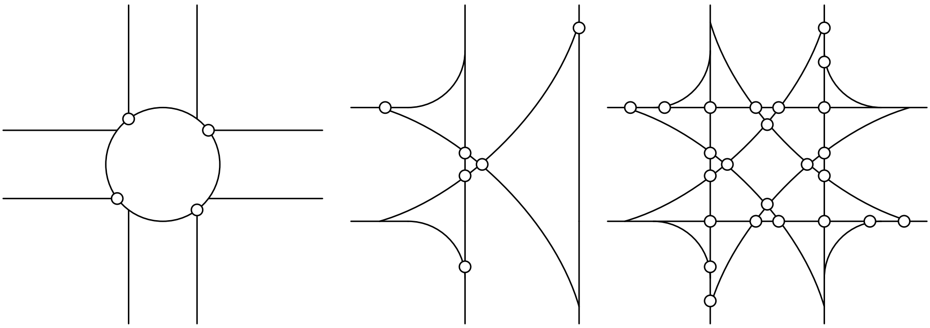

Figure 3.3. The potential conflict points of motorised traffic at a roundabout and at a three-arm and a four-arm intersection.

The schematic representation of potential conflict points in Figure 3.3 only concerns the potential conflict points of motorised traffic. Potential conflict points between vulnerable road users (mainly cyclists, light mopeds and mopeds) and motorised traffic are presented in Figure 3.4. Regarding all intersection control types, the number of potential conflict points for vulnerable road users crossing the intersection depends on the number of lanes to be crossed. Vulnerable road users crossing one arm of a roundabout have two potential conflict points with motorised traffic compared to three at a priority (give-way) intersection with a left turn lane. At signalised intersections, vulnerable road users might have the most potential conflict points as there are generally more driving lanes to be crossed for both driving directions (i.e. vehicles entering or exiting the intersection). For example, one right turn lane, one left turn lane, one lane straight ahead and one or two lanes of motorised traffic leaving the intersection.

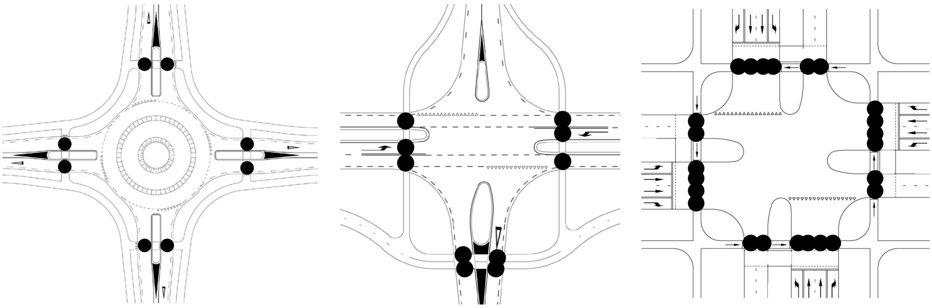

Figure 3.4. The potential conflict points between crossing vulnerable road users and motor vehicles at a roundabout, priority (give-way) and signalised intersection (adapted from CROW, 2013).

The finding that at four-arm intersections more crashes occur than at three-arm intersections corresponds to the results of Dijkstra et al. (2010). From Table 3.7, it appears that at four-arm intersections more crashes per intersection occur compared to three-arm intersections. Dijkstra et al. looked at all crashes between motor vehicles including PDO crashes. Although this latter crash type was not studied here, the results gained insight into the distribution of crashes among intersection type.

	Number of intersections	Number of crashes	Crashes per intersection
3-arm intersections	415	166	0.4
4-arm intersection	154	206	1.3

Table 3.7. Calculated number of crashes per intersection type for both signalised and priority intersections (adapted from Dijkstra et al., 2010).

Regarding the intersection control type, signalised intersections have higher traffic volumes than non-signalised intersections (Marchesini, 2009). The higher the traffic volumes, the higher the number of crashes and conflicts (Dijkstra et al., 2010). Dijkstra et al. found that four-arm signalised intersections have the highest crash risk and three-arm signalised intersections have the highest conflict risk. The risks calculated by Dijkstra et al. are presented in Table 3.8.

	Crash risk (number of crashes per million vehicles)	Conflict risk (number of conflicts per 1,000 vehicles)
Priority intersections		
3 arms	137	119
4 arms	193	142
Signalised intersections		
3 arms	216	155
4 arms	364	113

Table 3.8. Crash and conflict risk for various types of intersections (Adapted from Dijkstra et al., 2010).

3.3.4. Fatal crashes in more detail

In addition to the analysis of the registered crashes in the crash database, the fatal intersection crashes in 2008 were further analysed in more detail. By examining the police registration forms and a virtual visit of the crash site, extra information was collected compared to the analysis of the crash database which was presented in the previous sections.

In 2008, 66 fatal crashes were registered at intersections on 80 km/h rural roads. Fifteen crashes had to be excluded since the crash was not a fatal crash (n=1), the crash site was not at an intersection (n=9) or the location was unknown (n=5). The characteristics of the remaining 51 rural intersection crashes are described below.

Intersection types

The majority of the intersection crashes occurred at priority (give-way) intersections whereas only four occurred at signalised intersections (see Table 3.9).

	Fatal crashes
Priority (give-way) intersection	44 (86%)
Signalised intersection	4 (8%)
Intersection without any designated priorities	2 (4%)
Roundabout	1 (2%)
Total	51 (100%)

Table 3.9. Number of fatal crashes at intersections on 80 km/h rural roads per intersection type in the year 2008 (Source: police registration forms).

For each intersection, the posted speed limit, intersection control type and the number of arms were determined. The dataset contained 29 three-arm intersections and 21 four-arm intersections (see Table 3.10). The single roundabout had four arms. The majority of crashes occurred at intersections having two intersecting roads with a speed limit of 80 km/h (59%). Sixteen crashes occurred on intersections with one intersecting road with a speed limit of 80 km/h and one with a speed limit of 60 km/h.

	80-80 km/h		**80-60 km/h**		**80-50 or 80-30 km/h**	
	3 arms	4 arms	3 arms	4 arms	3 arms	4 arms
Priority (give-way) intersection	16	10	8	6	2	2
Signalised intersection	1	0	0	2	1	0
Intersection without any designated priorities	1	1	0	0	0	0
Roundabout	0	1	0	0	0	0
Total	18	12	8	8	3	2

Table 3.10. Intersection control type and the posted speed limit of the 51 fatal crashes at intersections on 80 km/h rural crashes in 2008 (Source: registration forms and Street View).

Types of intersection crashes

The findings regarding type of crash showed that 77% of the crashes are side-impacts (see Table 3.11). In addition, when considering the information in Table 3.12 indicating that the majority of the crashes was coded as 'not giving way to other road user', it is not a surprise that side-impact crashes were the predominant crash type at intersections. At an intersection, rules supported by signs and markings assign who has right of way and who has to give way facilitating that road users do not meet each other at the same time at the same place. But if something goes wrong, it is almost inevitable that two road users collide as their paths cross each other at the intersection.

	Fatal crashes
Side-impact	39 (77%)
Head-on	4 (8%)
Rear-end	3 (6%)
Single-vehicle	1 (2%)
Fixed-object	3 (6%)
Parked	0 (0%)
Pedestrian	1 (2%)
Total	51 (100%)

Table 3.11. Type of crash of the fatal crashes at intersections on 80 km/h rural roads based on the information coded by the police on the registration form for the year 2008 (Source: registration forms).

	Fatal crashes
Not giving way to other road user	35 (69%)
Crashing into vehicle in front	4 (8%)
Running the red light	3 (6%)
Crashing against pedestrian on carriageway	1 (2%)
Leaving own lane	5 (10%)
Overtaking vehicle in front	3 (6%)
Total	51 (100%)

Table 3.12. Number of fatal crashes at intersections on 80 km/h rural roads and their manoeuvres based on the information coded by the police on the registration form for the year 2008 (Source: registration forms).

Concerning the overtaking crashes, the three crashes have in common that a motorcyclist is overtaking a vehicle which suddenly makes a left turn at the intersection. In five crashes, road users left their lanes and crashed into objects (e.g. tree or signpost) or ended in a ditch. From three crashes the police registered that one road user must have run the red light which caused that the two road users crashed. In four crashes, a road user collided with the vehicle in front and in one crash a car driver suddenly encountered a pedestrian on the carriageway.

Road users involved

In the 51 intersection crashes, 51 road users got fatally injured. Approximately 31% of the fatalities was a cyclist and approximately 29% was a car driver (see Table 3.13). Another 33% was a powered two-wheeler rider (i.e. (light) moped or motorcycle). In total, approximately 67% of the fatalities was a vulnerable road user (i.e. was not protected by the vehicle compared to for example car occupants).

	Fatal crashes
Pedestrian	1 (2%)
Bicycle	16 (31%)
(Light) moped	8 (16%)
Motorcycle	9 (18%)
Car	15 (29%)
Delivery van	0 (0%)
Lorry	0 (0%)
Bus	0 (0%)
Other modes	2 (4%)
Total	51 (100%)

Table 3.13. The transport mode of the fatally injured road users at intersections on 80 km/h rural roads coded by the police on the registration form for the year 2008 (Source: registration forms).

Of the sixteen fatalities among cyclists, thirteen (80%) were involved in a crash in which they crossed the major road and were hit by an approaching passenger car, truck or van. The other three were involved in a crash in which the motor vehicle driving on the minor road was about to enter the major road thereby not giving way to the cyclists on the bicycle path that was crossed.

Intersection design at the crash sites

Each crash site was assessed by a virtual examination of several design characteristics. Fifty out of the 51 crash sites (98%) did not have speed-reducing measures applied to the intersecting roads (see Table 3.14). The only crash site where driving speeds were reduced was the single roundabout in the dataset. At one crash site out of the 50 crash sites without speed-reducing measures, an optically instead of a physically raised intersection was applied. Second, it appeared that most of the crash sites that do not have diverging lanes for left turns did not have separated driving directions as well. At approximately 31% of the intersections, driving directions were separated. The majority of the intersections did not have the driving directions separated. Also, in approximately 77% (67% + 10%) of the crash sites there seemed to be free access for agricultural traffic which indicated that in addition to motorised traffic slower driving and/or heavy agricultural traffic can be present. Road users may want to overtake agricultural traffic which is not always allowed; traffic signs are placed to inform road users if overtaking is allowed or not.

	Crash sites of fatal crashes
Speed-reducing measures	
Yes (n=1: roundabout)	1 (2%)
No (n=1: optically raised intersection)	50 (98%)
Total	51 (100%)
Diverging lane for left turn	
Yes (n=2: as well as for right turn)	15 (29%)
Partially, not at crash site	5 (10%)
No	31 (61%)
Total	51 (100%)
Separation of driving directions	
Yes	16 (31%)
Partially, at one side only	3 (6%)
No	32 (63%)
Total	51 (100%)
Limited access	
Yes (n=7: parallel road present)	12 (24%)
Partially, agricultural vehicles permitted	5 (10%)
No	34 (67%)
Total	51 (100%)

Table 3.14. Design characteristics of the crash sites of the 51 fatal crashes at intersections on 80 km/h rural roads in 2008 (Source: Street View).

3.4. Discussion

3.4.1. Overview of the main results

The aim of the analysis of fatal and serious injury (MAIS2+) crashes presented in this chapter was to provide background on the main characteristics of crashes occurring at intersections on 80 km/h rural roads in the Netherlands. Therefore, the database of registered crashes was analysed as well as the registration forms of fatal crashes. The latter analysis proved to be a valuable supplement. The examination of crash sites revealed the intersection control types, which was not possible to obtain from the crash database.

The crash analysis of fatal and serious injury (MAIS2+) rural intersection crashes on 80 km/h rural roads revealed that:

- 68-70% of the fatal crashes and 59% of the serious injury (MAIS2+) crashes was a side-impact;
- 60% of the fatalities and 50% of the seriously injured (MAIS2+) was a vulnerable road user. Cyclists form the largest group, respectively 31% and 19% of the fatal and serious injury (MAIS2+) crashes;
- the majority of the fatalities and the seriously injured among vulnerable road users collided with a passenger car;
- in 46% of the fatal crashes and 21% of the serious injury (MAIS2+) crashes a cyclist was involved;
- 90% of the fatal crashes and 77% of the serious injury (MAIS2+) crashes in which a cyclist was involved was a side-impact;
- 45% of the fatalities and 43% of the seriously injured (MAIS2+) occurred at three-arm intersections. 53% of the fatalities and 53% of the seriously injured (MAIS2+) occurred at four-arm intersections.

The detailed examination of fatal crashes that occurred in 2008 showed that:

- 86% occurred at priority (give-way) intersections;
- 77% was a side-impact;
- 69% was coded as ‘not giving way to other road user’;
- 67% was a vulnerable road user. Cyclists form the largest group as 31% of the fatalities was a cyclist;
- 98% of the intersections did not have speed reduction;

Both analyses showed similar results regarding the high involvement of vulnerable road users (i.e. mainly cyclists) and the high proportion of side-impact crashes. The analysis of fatal crashes provided more insight in the infrastructural characteristics which couldn't be obtained adequately from the database of registered crashes.

Overall, the results indicate two important issues relating to safety. First, the majority of crash sites did not meet the requirements for a sustainably safe infrastructure (as proposed by Dijkstra, 2003). Following the Sustainable Safety vision, traffic situations in which vulnerable road users and fast-driving motorised traffic share the same space in traffic should not exist. Because these situations do exist, it will result in encounters between these two road user groups that will lead to crashes in which casualties occur. The intersections studied in this chapter did not have speed-reducing measures. Therefore, the posted speed limits are higher than the safe speeds that were identified by Jurewicz et al. (2016). This raises questions on why road authorities do not apply speed reduction knowing that speed is a key factor for road safety (Aarts & Van Schagen, 2006), and are they aware that these intersections are unsafe? Schepers et al. (2011) found that the presence of a raised bicycle crossing or another speed-reducing measure was negatively related to crashes in urban area in which a motor vehicle that left or entered the minor road crashed into a cyclist on the main road and thus having right of way. Second, there are indications that the interaction between road users does not go well, especially between vulnerable road users and motorised traffic. The fatal crash analysis showed that 80% of the cyclists crossed the major road and were hit by an approaching motor vehicle. The results did not show safety problems related to vulnerable road users being present in the blind spot of a truck or van. In interactions, drivers having right of way or phasing a green light have expectations regarding other road users crossing the intersection (Houtenbos, 2008; Sandin, 2009). Do car drivers expect cyclists to always wait for them to pass by or are they aware that sometimes a cyclist decides to cross in front of them leading to critical situations?

3.4.2. Limitations

In this chapter, a crash analysis was conducted using the database of registered crashes. A disadvantage concerning the registration of crashes is the under registration: not every crash is being recorded. This means that the database of registered crashes does not contain all crashes that occurred. And because of a new registration method by the police from 2010 onwards, insufficient information on crashes is available in order to be able to perform solid road safety analyses. In this study, only crash data till 2009 could be used. Crash analyses are helpful in the process of selecting measures to be implemented. It is therefore necessary to collect enough detail on crashes such as the design of intersections (i.e. infrastructural characteristics such as speed-reducing measures) and the driving behaviour of the road users involved. Besides enough detail on crashes, another important component of solid crash analyses is exposure data. Exposure data such as the number of intersections can be used to point out the relative risks. For the present study, exposure data was almost not available.

A limitation of this analysis concerns the lack of information on driving speeds. Speed affects crash severity and the likelihood of being involved in a crash (Aarts & Van Schagen, 2006). Unfortunately, there were no speed measurements at rural intersections available to include in the analysis. However, driving speeds at rural intersections being close to the speed limit of 80 km/h are harmful to cyclists and other vulnerable road users in case they end up colliding (Rodarius, Mordaka & Versmissen, 2008; Rosén, Stigson & Sander, 2011; Van Hassel & De Lange, 2006; Wegman, Zhang & Dijkstra, 2010).

3.4.3. Implications for the empirical research of Chapter 4 and 5

The findings presented in this chapter have implications for the empirical research presented in Chapter 4 and Chapter 5. First, the results of this chapter showed that there are safety issues regarding cyclists and motorised traffic interacting with each other at rural intersections. Although various insights were retrieved from the data on crashes, what exactly happened at those intersections did not become clear. What about the road users, did they see each other and how did they react on each other? And to what extent did the design of the intersection play a role? The results of the fatal crashes analysis showed that these crashes occurred at intersections that not have speed-reducing measures applied to them. This might be a coincidence but it raises questions regarding the design of these intersections. What is the policy of road authorities regarding rural intersections where cyclists are present? Is it common to apply speed-reducing measures? So, for the study in Chapter 4 it is important to focus on the design of rural intersections in relation to the design policy of road authorities. The second implication concerns the interaction between the cyclist and car driver itself. What makes it that cyclists and motorised traffic collide when cyclists try to cross the carriageway? In this situation, cyclists need to give way to the motorised traffic. In other words, the evasive manoeuvre is to be done by the cyclist: the cyclist decides when to cross or to wait a car to pass by. Drivers of approaching cars can proceed driving when approaching an intersection as they have right of way. But what effect does approaching an intersection with cyclists have on the behaviour of drivers? Do they expect the cyclist to wait for them to pass by or do they anticipate that the cyclist may behave in such a way that the driver needs to adjust his/her behaviour? Chapter 5 should therefore focus on this part of the interaction between cyclists and drivers of approaching cars.

4. The relation between road design guidelines and unsafe intersection infrastructure: a Dutch case study[3]

4.1. Introduction

In an inherent safe traffic system, serious injury crashes do not exist. As speed is a key factor for road safety (Aarts & Van Schagen, 2006), the vehicles and the infrastructure should be made inherent safe. Vehicles should have a certain level of crashworthiness (by e.g. airbags, seat belts, crumple zone). At roads and intersections, driving speeds should be limited so that if a crash occurs impact speeds are low. Safe System approaches such as Vision Zero (Tingvall, 2003) and Sustainable Safety (Wegman & Aarts, 2006) prescribe to apply safe speeds that matches the traffic situations with its road users involved, see for example Jurewicz et al. (2016). To meet this safe speed, the speed limit of 80 km/h, which is common on Dutch rural intersections, should be lowered to 50 km/h or even 30 km/h when vulnerable road users are present at the intersection. A good example of a safe intersection is the roundabout. At well-designed roundabouts, speeds are automatically reduced in order to pass. This raises the question roundabouts and intersections with speed-reducing measures are not yet the standard.

It is not that the design principles as presented by Sustainable Safety have not found their way into the road design guidelines. In the Dutch road design guidelines, various keywords of the sustainable safety vision are present. However, it is questionable if these principles have been included completely. Knowing that speed is the most important factor for road safety, it is surprising that speed-reducing measures at rural intersections are not mandatory according to the Dutch road design guidelines but optional. Also, the Dutch road design guidelines and manuals do not have the same legal status as the Dutch Road Traffic Act which means that road authorities can decide to not use the guidelines. How safe are these guidelines and how are these design guidelines being used? And what does this mean for intersection layout in the real world?

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[3] This chapter is based on a conference proceeding: Duivenvoorden, C.W.A.E. & Kroon, E.C.M. (2011). *Een interviewstudie onder wegbeheerders naar de veiligheid en het ontwerp van kruispunten op 80 km/u wegen*. Paper presented at Nationaal Verkeerskunde Congres, 2 November 2011, Nieuwegein.

It appears that regional road authorities do not always design roads according to the guidelines and manuals. There are not many studies that have investigated specifically if and how road authorities use road design guidelines. The majority of studies, as was concluded by Bax (2011), had a wider scope and focused on the use of knowledge of road safety as published in for example scientific journals (see e.g. Department for Transport, 2008). A Dutch study showed that the main reason for road authorities to not use design manuals is that the situation is considered to be deviant and does not allow to follow the guidelines (Boer, Grimmius & Schoenmakers, 2008; Weijermars & Aarts, 2010). Sometimes, road authorities deviate from the guidelines as they do not agree with certain guidelines or as they believe that the guidelines do not lead to the safest situation (Weijermars & Aarts, 2010). What are the consequences for road safety? Another Dutch study showed that when a priority (give-way) or signalised intersection was favoured over a roundabout, the intersection crossing was not raised (Doumen & Weijermars, 2009). Thus, the use of speed-reducing measures at rural intersections is limited. Knowing that speed is a key factor for road safety, one could question if road authorities fully understand the consequences of their chosen intersection layout.

Previous studies of for example Boer, Grimmius & Schoenmakers (2008) and Weijermars & Aarts (2010), although limited in number, have shown that road authorities do not always use road design guidelines but it is unknown what the consequences for road safety are. Therefore, the aim of the present case study on rural signalised and priority (give-way) intersections on 80 km/h distributor roads is to examine the use of intersection design guidelines as well as how road safety is being incorporated in real world intersection designs. The research question are:

1. Are the intersection designs as described in the intersection design guidelines safe?
2. How do road authorities use the design guidelines?
3. How do road authorities incorporate safety in intersection design?

4.2. Method

4.2.1. Interviewees

For the Dutch case study, five provincial road authorities were selected. Four of these road authorities were selected based on the road length of 80 km/h rural roads of their road network and the number of casualty crashes at intersections on their 80 km/h rural roads (see Table 4.1). The number of casualty crashes was used as an indicator for the level of intersection unsafety whereas a larger road length was used as an indicator for the amount of intersections in the road network. Together, these two variables might indicate the level of experience of road authorities with safety problems of intersections of 80 km/h rural roads. The fifth road authority (the province of Zuid-Holland) was questioned as the province was known for applying speed-reducing measures at rural intersections whereas this was not done in other provinces.

	Casualty crashes		**Road length 2008 (km)**	
	number	rank	km	rank
Gelderland*	284	1	1,049	1
Noord-Brabant*	192	2	511	3
Limburg	142	3	375	9
Overijssel*	111	4	655	2
Noord-Holland*	111	4	458	6
Friesland	104	6	507	4
Zuid-Holland*	73	7	463	5
Utrecht	58	8	295	12
Zeeland	53	9	331	11
Drenthe	52	10	353	10
Groningen	51	11	415	8
Flevoland	42	12	435	7

Table 4.1. Road length in 2008 (km) and the number of casualty crashes (2006-2008) at intersections on 80 km/h rural roads in the Netherlands (Ministerie van Infrastructuur en Waterstaat / BRON, 2019). The selected provinces are marked with an asterisk (*).

4.2.2. Interviews

The road authorities were interviewed in a face-to-face interview which was held in Dutch as the interviewees were Dutch. Each interview took approximately one and a half hour. The interview consisted of a structured list of questions in order to assure the comparability of the data among the road authorities interviewed. The interview schedule was designed according to the procedure as described in Kumar (2005, p.137-140). The interviews were held in 2011.

The interview consisted of two parts. The first part contained general questions on intersections whereas the second part of the interview addressed eight selected intersections in a more in-depth way. First, the questions focussed on general road safety problems, design dilemmas, policy on intersection design and how road authorities figure out that there are safety problems or other issues at intersections on their road network. Second, specific problems and dilemmas for each intersection selected were discussed as well as if other intersection designs considered and why certain infrastructural characteristics are present or absent. Therefore, photos of selected intersections from Google Street View were brought into the interviews. In total, seven characteristics were listed which originate from the Dutch Road Design Manual (CROW, 2013):

- presence of speed-reducing measures;
- presence of left turn lane. At priority (give-way) intersections a left turn lane is preferred;
- presence of limited access (e.g. for agricultural traffic);
- presence of physically separate driving directions near the intersection;
- presence of bended cycling facility for cyclists crossing the minor road;
- presence of bicycle crossing in two phases for cyclists crossing the major road. Physically separated driving directions near the intersection creates the possibility for a bicycle crossing in two phases;
- absence of right turn lane. At priority (give-way) intersections no right turn lane is preferred whereas at signalised intersections a right turn lane could be preferred with respect to traffic volumes.

Furthermore, the road authorities were questioned on which factors (e.g. limited space or high implementation costs) affecting intersection design played a role in their decision making. These factors were written down on cards including several blank cards for new factors. The interviewees were asked to choose factors that were affecting intersection design and to add new factors on blank cards if applicable. Next, the interviewees were given the task to rank the chosen factors into three categories from having a small, medium or large effect on intersection design. These categories were outlined on a A3 formatted scheme. Factors which were not applicable were not placed on the scheme. During the second part of the interview, the interviewee was asked again to perform the task of selecting and ranking factors for each intersection discussed (see next section).

4.2.3. Selection of intersections for in-depth questions

The second part of the interview addressed a discussion of several selected intersections. For that purpose, intersections were selected that were recently reconstructed so that information about the reconstruction process of these intersections was still top of mind at the road authorities. Four intersection categories were considered, namely three-arm signalised intersections, four-arm signalised intersections, three-arm priority (give-way) intersections and four-arm priority (give-way) intersections. The main road was a distributor road whereas the intersecting road could be a distributor or an access road. Roundabouts were not addressed as roundabouts were considered to be safe already.

From each category, two intersections were selected which resulted in eight intersections per province. For the selection of eight intersections per province, provincial policy plans were consulted which contained lists of (re)construction projects of road sections and intersections. Intersections from finished projects were selected and if necessary supplemented with projects still in the execution stage. By selecting these projects, it was possible to not only question the problems but also applied solutions. Another benefit was a bigger chance of the availability of recent pictures on the intersections obtained from Google Street View.

4.2.4. Analysis

The answers given to the questions asked during the interviews were collected and summarised. The results have a descriptive character. No statistical analyses were performed as the numbers of cases were too low. Therefore, the following sections present the results in a descriptive way.

4.3. Results

4.3.1. Analysis of design guidelines

Various elements of the design guidelines that are dealt with in the interviews originate from the Road Design Manual. This Road Design Manual consists of four parts of which one focuses on rural distributor roads, the road category studied here (CROW, 2002). These design standards distinguish three intersection types: roundabouts, priority (give-way) intersections and signalised intersections appropriate for 80 km/h rural roads. However, roundabouts will not be discussed as they are not part of the study. Regarding the other two intersection types, various design elements are presented here. Subsequently, cycling facilities, right and left turn lanes, speed-reducing measures, limited access and separated lanes are discussed. First, in the next section it is explained when a priority (give-way) intersection or a signalised intersection is applied.

Road type and intersection control type

On the distributor roads, two types of road section are distinguished based on lane configuration. The Road Design Manual addresses 'road type I' and 'road type II'. Road type I has a dual carriageway (2x2 lane configuration) whereas road type II has a single carriageway (2x1 lane configuration). The distinction is made based on traffic volume and capacity. If (expected) traffic volume exceeds the level of 3,200 PCE (personal car equivalent) per hour for both driving directions (transverse profile), road type I is to be applied over road type II (CROW, 2002). Regarding the type of control at the intersection, priority (give-way) intersections are only allowed to be applied on road type II whereas traffic signals need to be applied to intersections on road type I (CROW, 2002). According to the Handbook, 'the design of a signalised intersection is as much as possible similar to a priority (give-way) intersection' (CROW, 2002, p 191). In the next sections, only the differences between these two types of intersections are described.

Cycling facilities on minor roads

Cycling facilities on 80 km/h rural roads physically separate cyclists from motorised traffic. These facilities enable cyclists and moped riders to cross the minor road. At priority (give-way) intersections, cyclists on the bicycle path parallel to the main road have right of way over motorised traffic if the bicycle path is within five metres of the intersection. According to the Road Design Handbook (CROW, 2002), this situation is acceptable if the road to be crossed is an access road without traffic volumes that are exceptionally high and if the bicycle path is a one-way track. It is preferred to construct the bicycle path in red asphalt and to raise it. According to the Handbook, it is safer for cyclists and moped riders to not have right of way over motorised traffic (CROW, 2002). Therefore, the bicycle path needs to be bended out so that the bicycle path is constructed within ten to fifteen metres of the intersection. However, it is not forbidden to not bend out the bicycle path. At signalised intersections, conflicts between cyclists and motorised traffic are not allowed according to the Road Design Handbook. Therefore, these road users do not have green at the same time. The cycling facility is not bended out.

Cycling facilities on main roads with separated carriageways

In principle, road sections of rural distributor roads have separated driving directions. However, it is possible to not have separated driving directions. Cycling facilities for crossing the main road at priority (give-way) intersections are related to the presence of separated carriageways. It is possible to convert the separated driving directions into a separated carriageway at the intersection. From a road safety point of view, the Road Design Manual strongly advises against a wide carriageway separation of 15-20 metres. According to the Road Design Handbook, separating carriageways allows cyclists and moped riders to cross the main road in two phases. The carriageway separation requires a minimum width of 3 metres for cyclists to cross. Moreover, it highlights the presence of an intersection and allows for placing roadside furniture. The latter requires a minimum width of 2.10 metres. In order to avoid overtaking manoeuvres by vehicles by using the left turn lane, the carriageway separation needs to physically enclose the left turn lane. The length of a carriageway separation is determined by the length of the left turn lane. According to the Road Design Handbook, signalised intersections always have 'a (small) carriageway separation' which has similar requirements and advantages as those on priority (give-way) intersections. However, the Handbook does not compel separated carriageways at the intersections. This applies for priority (give-way) intersections as well.

Right and left turn lanes

Left turn lanes separate decelerating left turning traffic from the continuing through traffic and therefore avoid blockages on the through lane. At priority (give-way) intersections, left turns have to be constructed whereas right turn lanes are inappropriate with respect to road safety. Right turn lanes are not desired as they can visually block the view of drivers on through traffic which are blocked by right turning traffic. However, the Handbook does not forbid right turn lanes. According to the Road Design Handbook, a left turn lane increases the size of an intersection which forces crossing traffic to cross a larger distance. However, this disadvantage is much smaller than the advantages of a left turn lane being present. At signalised intersections, the presence of right turn lanes is not an issue. Traffic control does not allow road users from both the main and minor road to enter the intersection at the same time which means there is no risk of vehicles blocking a road user's view. The lane configuration for turning and through traffic depends, amongst others, on traffic volume, with a maximum of two lanes for turning traffic and three for through traffic.

Speed-reducing measures

The design speed for rural distributor roads is 80 km/h. The Road Design Handbook describes that a speed of 80 km/h at intersections is too high from a safety point of view. The preferred speed is 50 km/h which requires the need for speed-reducing measures. However, speed-reducing measures are not mandatory. As it is undesired to bend out lanes, two other options are speed enforcement and plateaus with a length of at least 5 metres. Plateaus can be applied several metres in front of the intersection which is preferred or at the intersection itself. The effects on road safety of a plateau on the minor road are smaller compared to those on the main road as is written down in the Road Design Handbook.

Limited access

The Road Design Handbook advises to exclude slow motorised traffic, such as agricultural vehicles. For road type I, it is always necessary to exclude this type of road users. However, the Handbook does not describe in much detail how slow motorised traffic should be treated if excluded from the rural distributor road (e.g. parallel road).

Summarizing

The previous sections described several design elements of intersections, both priority (give-way) and signalised. It appears that the Handbook gives options for certain issues. However as the guidelines do not have a legal status; road authorities can deviate from it. There are no consequences if road authorities decide to apply less safe solutions or design elements not according to the Handbook. For example, it is therefore possible to not bend out cycling facilities although this is a less safe solution than to bend out. Another issue that arises from studying the guidelines is that scientific references are not present. Considering the same example again of not bending out a cycling facility: the Handbook does not provide results from scientific studies (e.g. a crash analysis) that one option is safer than another option. It is therefore questioned if road authorities are able to make a conscious decision between two (or more) options when they are not provided with information on the safety level of the presented options. The next sections provide further details on the interviews held with five provincial road authorities. Within the interviews, the road authorities were questioned about the usage of guidelines as described in the Road Design Handbook.

4.3.2. How do road authorities use the road design guidelines?

The road authorities were asked on their policy regarding intersections and intersection design. The five provinces did not have a documented intersection policy, such as criteria for determining the type of the intersection to be constructed. All provinces acknowledged that roundabouts were the safest intersection type. However local circumstances such as traffic flow and available space affected the choice for a roundabout. Regarding the application of traffic signals, in general the road authorities did not remove traffic signals once they were applied. One province used to have a unique position as they had a policy regarding the use of speed-reducing measures (plateaus) whereas the other four provinces did not apply any speed-reducing measures. Results from an evaluation study showed that the plateaus improved road safety (Fortuijn, Carton & Feddes, 2005). However, another policy was set out which resulted in no more new plateaus at reconstructed intersections.

Road design guidelines as developed by CROW were used by the road authorities. However, each road authority said to have developed own guidelines or standard designs (e.g. for intersections, road sections or roundabouts). A reason given for developing own guidelines is that the guidelines developed by CROW are not sufficient (e.g. too theoretical as it describes the design on a relatively high level of detail) and therefore not appropriate to use when designing the intersection in detail. Therefore, the provincial guidelines developed were based on the CROW guidelines but expanded with detailed information on (intersection) design. These documents describe the design of intersections in detail such as the angle of the curves, the width of the carriageway and of the pedestrian and cyclist facilities, height of the kerbside, details of the markings on the road, etcetera. Besides an extensive description of all the details of the intersection, drawings are included as well.

4.3.3. The in-depth analysis of intersections

In total, 22 intersections from four provinces were discussed during the interviews, namely two thee-arm signalised intersections, six four-arm signalised intersections, six three-arm priority (give-way) intersections and eight four-arm priority (give-way) intersections. For one province it was not feasible to select intersections recently reconstructed. Originally, eight intersections per road authority were planned to discuss in further detail. For one province, only seven appropriate intersections were found. And during the interviews it appeared that nine intersections selected were inappropriate for the present study as these intersections were reconstructed into a roundabout.

At intersections on 80 km/h rural road, several problems related to road safety were experienced as was mentioned by the road authorities. The listed problems are presented in Table 4.2. In twelve out of 22 intersections, problems with vulnerable road users, namely cyclists, were reported. The largest share concerned conflicts between turning motorised traffic and cyclists where the motorised traffic left the major road and entered the minor road. Here, eight intersections suffered from problems with the presence of cyclists. Some of these intersections were situated on a school route. In four other cases, problems occurred with cyclists crossing the intersection however not by making use of the bicycle crossing. Safety problems between motorised traffic were reported as well, such as side-impact crashes where a right turning vehicle blocked the view for another road user on the minor road wanting to enter the major road. As a result, this other road user was not able to see other road users approaching.

	Solution
Conflicts between turning vehicles and bicycles (N = 8)	Red asphalt on bicycle path while crossing minor road; one not red
Crossing cyclists (N = 4)	Adjusted bicycle crossing while crossing major road
Capacity or changes in traffic flow (N = 4)	Adjusted traffic signal control
Road safety (N = 2)	Applying traffic signals
Illegal overtaking manoeuvres or experienced difficulties while turning (N = 2)	Removal of left or right turn
Absence of perpendicular connection (N = 1)	Perpendicular connection with minor road
Use and design (N = 1)	Adjusted right of way situation

Table 4.2. Listed problems and their corresponding solutions as described by the provincial road authorities.

In addition to road safety issues, several dilemmas were experienced with respect to the design of the intersection such as unobtrusive intersections, design of intersections being too wide which might cause high driving speeds, overtaking manoeuvres at left-turn lanes and cycle paths too close to the road. Related to the design of the intersection, at four intersections problems arose with respect to capacity or traffic flow because of changes in the road network (adding or removing road sections or intersections) or in the environment (new destinations generating more traffic). At these signalised intersections, it was solved by adjusting the settings of the traffic signal control.

In Table 4.2, also the solutions of the provinces are presented. In two cases, the intersection was completely reconstructed, namely from a priority (give-way) intersection into a signalised intersection. In the other cases, smaller reconstructions were applied such as adjusting the traffic signal control at four intersections in order to solve problems with capacity, traffic flow or road safety (crashes). For example, the removal of a permitted conflict with cyclists or the application of separated driving directions.

At twelve intersections, bicycle facilities were adjusted such as applying red asphalt to the bicycle path crossing the minor road (where cyclists have right of way) and sometimes raising the bicycle path as well (see Table 4.2). At other intersections, a median island was installed in order to accommodate a bicycle crossing or a left turn lane. The application of a median island was believed to reduce driving speeds as well. By way of contrast, at one intersection the left turn lane was removed to make space for a median island aiming to avoid overtaking manoeuvres thereby using the left turn lane. At several intersections, the right of way situation for cyclists or motorised traffic was changed.

One province used to have a unique position as they had a policy regarding the use of speed-reducing measures (plateaus) whereas the other four provinces did not apply any speed-reducing measures. Results from an evaluation study showed that the plateaus improved road safety (Fortuijn, Carton & Feddes, 2005). At signalised intersections the number of injured road users decreased with approximately 40-50% but at these intersections also speed enforcement by cameras was applied. At priority (give-way) intersections the application of plateaus reduced the number of injured road users with approximately 35%. However, another policy was set out which resulted in no more new plateaus at reconstructed intersections.

4.3.4. Factors affecting intersection design

Regarding the final design of the intersections, the road authorities were asked which factors played a role in the realisation of the intersections. Road safety was the most important factor according to the road authorities (see Table 4.3). A distinction is made between the top five for all 22 intersections together and for priority (give-way) intersections and signalised intersections respectively. Besides road safety, the factors implementation costs and neighbours were ranked in the top five for both intersection control types. Apart from that, other factors were present in the top five.

	All intersections (N = 22)	**Priority (give-way) intersections (N = 14)**	**Signalised intersection (N = 8)**
1	Road safety (2.32)	Road safety (2.36)	Road safety (2.25)
2	Implementation costs (1.27)	Traffic volume (1.43)	Neighbours (1.88)
3	Traffic volume (1.23) Traffic flow (1.23)	Implementation costs (1.36)	Traffic flow (1.14)
4	Space (0.91)	Neighbours (1.14)	Implementation costs (1.00) Space (1.00) Aesthetics (1.00)
5	-	Uniformity (0.93)	-

Table 4.3. Various factors and their average score on the level of influence (range 0 to 3).

The authorities did not mention that budget affected the final intersection design. Early in the process of planning of the reconstruction, the budget required was determined and planned. Moreover, one province mentioned that budget was not experienced to be a problem as the overall finances were sufficient.

4.3.5. Examination of intersection characteristics

Subsequently, seven characteristics of the reconstructed intersections were discussed (see Table 4.4) by using pictures from Google Street View. The results showed that speed-reducing measures were never applied. A left turning lane was present at all signalised intersections whereas it was less common at priority intersections. Limited access was applied at the intersecting roads in 50% of the signalised intersections whereas there were fewer priority intersections with limited access. The same applied for physically separated driving directions at intersections. Bended bicycle paths were almost never applied whereas the application of a bicycle crossing in two phases was more common. The last characteristic was the presence of a right turning lane. A right turning lane was present at almost all signalised intersections whereas it was less applied at priority intersections.

	Priority (give-way) intersections		**Signalised intersections**	
	3 arms (N = 6)	4 arms (N = 8)	3 arms (N = 2)	4 arms (N = 6)
Speed-reducing measures	0 (0 %)	0 (0%)	0 (0%)	0 (0%)
Left turning lane	2 (33.3%)	2 (25%)	2 (100%)	6 (100%)
Limited access	0 (0%)	1 (12.5%)	1 (50%)	3 (50%)
Separated lanes	0 (0%)	1 (12.5%)	1 (50%)	3 (50%)
Bended bicycle path	1 (16.7%)	0 (0%)	0 (0%)	0 (0%)
Bicycle crossing in two phases	3 (50%)	1 (12.5%)	1 (50%)	3 (50%)
Presence of right turning lane	1 (16.7%)	2 (25%)	2 (100%)	5 (83.3%)

Table 4.4. Presence of measures at priority (give-way) and signalised intersections.

4.3.6. What are the consequences for road safety?

The road authorities were asked if they performed evaluations on reconstructed intersections in order to check if the reconstructed intersection has improved the situation. Only one respondent stated to perform evaluations on those intersections that were reconstructed using evaluation techniques such as crash analyses, measuring driving speeds or based on contact with the police or road users (e.g. an online questionnaire). Though, all provincial road authorities recorded crash statistics of their road network in order to for example develop a top list of the most unsafe locations and conducted traffic counts and speed measurements. These detection loops for the traffic counts and speed measurements were located on road sections only. In general, it appears that road authorities do not structurally perform road safety evaluations on intersections that were reconstructed.

4.4. Discussion

4.4.1. Overview of the main results

In the present study, a case study on rural intersection design was conducted. The road design manual regarding intersections was analysed (research question 1) and provincial road authorities were interviewed about the usage of road design guidelines (research question 2) and intersection design (research question 3). The analysis of the design guidelines showed that the CROW Handbook (CROW, 2013) describes several (safe and less safe) options for intersection characteristics. From a road safety point of view, speed reduction is beneficial as it reduces impact speeds in case of a crash. In the road design guidelines as presented in the Handbook however, speed-reducing measures are not recommended. Also, road authorities appeared to develop own guidelines or deviated from the existing guidelines which is possible as the guidelines do not have a legal status. The reason is that they consider the guidelines developed by CROW to be not appropriate when designing intersections in detail. The provincial guidelines that were developed by the road authorities are based on the CROW guidelines but contain detailed information on (intersection) design. Developing own guidelines did not lead to safer intersections designs compared to the national design guidelines as in both guidelines the application of speed-reducing measures is not mandatory.

The in-depth analysis of rural intersections confirmed that less safe solutions or design elements are chosen for rural intersections. Based on the findings of this study it can be questioned if road authorities were able to make a conscious decision regarding safe intersection design. Although the road authorities stated to take road safety into account as the most important factor influencing intersection design (i.e. they all ranked road safety first), other factors may be more important when it comes to intersection design. Here, the issues of self-reporting bias and socially desirable answers given by the interviewees may be present. However, this research method was chosen as no other method was considered to be appropriate to obtain these results. This may be explained by that speed-reducing measures may be considered to lead to a loss in traffic flow or that they are not considered to be appropriate to be used on rural distributor roads. The results of the in-depth discussion of intersections showed that in twelve out of 22 intersections safety problems between cyclists and motorised traffic occurred. Especially at these intersections where cyclists and motorised traffic encounter each other, it is important to apply speed reduction (Jurewicz et al., 2016). However, the examination of the characteristics of the 22 intersections revealed that speed-reducing measures were never applied. The speed limit remains 80 km/h and speed measurements were not conducted at intersections, which means that the actual driving speeds at intersections were unknown. However, for vulnerable road users it is of great importance that driving speeds are low (e.g. Jurewicz et al., 2016; Reynolds et al., 2009; Rosén, Stigson & Sander, 2011). Jurewicz concluded that the critical impact speed for crashes involving a pedestrian and a motor vehicle is 20 km/h.

4.4.2. Limitations

A limitation of the study is the size of the case study, namely the number of provincial road authorities interviewed and the number of rural intersections analysed in detail. The selection of provinces was based on the road length of 80 km/h rural roads and the number of casualty crashes at intersections on their 80 km/h rural roads on their road network. The design policy of the road authorities was not input for this selection. In theory, it is possible that road authorities were selected who may be quite alike as they have design policies in which speed-reducing measures are not being applied to rural distributor intersections. As the provinces are spread around the country, it is unlikely that the results found are to be linked to the uniqueness of the location of the provinces.

5. The effects of cyclists present at rural intersections on speed behaviour and workload of car drivers: a driving simulator study[4]

Abstract

Objective: *The objective was to gain insight into how the number of cyclists, the cyclist's approach direction, and the cyclist's action affect the speed and mental workload of drivers approaching rural intersections. In addition, the effects of a speed-reducing measure on the interaction between cyclists and motorized traffic were examined.*
Methods: *An experiment was conducted in a moving-base driving simulator. Thirty participants completed 3 runs each in 3 conditions: a baseline, a plateau, and a chicane condition. Participants drove an 80 km/h rural distributor road with 8 intersections. Eight cyclist scenarios were developed varying in the number of cyclists and the direction from which they approached the participants' lane. The Peripheral Detection Task was used to measure workload objectively and continuously.*
Results: *A plateau ahead of the intersection resulted in drivers entering the bicycle crossing with lower driving speeds but did not result in less serious potential conflicts compared to intersections without the speed-reducing measure. With respect to the presence of cyclists, drivers approaching the intersection without cyclists reached a minimum speed at a greater distance from the bicycle crossing compared to approaching the intersection with multiple cyclists in the baseline condition. At intersections with plateaus, drivers drove slower when encountering multiple cyclists compared to no cyclists. At intersections without the speed-reducing measure, drivers drove slower, decelerated stronger, and decelerated at a shorter distance to the bicycle crossing when encountering a suddenly crossing cyclist compared to a yielding cyclist.*
Conclusions: *Although drivers have the right of way at rural intersections, drivers' speed behavior was affected by the number and action of cyclists. From a road safety point of view, driving speeds at rural intersections need to be further reduced to limit the seriousness of potential conflicts between cyclists and motorized traffic.*

Keywords: *driving behavior, speed, mental workload, intersection, rural, cyclist, safety, driving simulator, peripheral detection task.*

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5.1. Introduction

Rural intersection crashes represent an important traffic safety problem. In both the United States (in 2011; NTHSA, 2013) and European Union countries (in 2009; Pace et al., 2011), approximately 40% of all intersection fatalities occurred in rural areas. Noteworthy is the relatively high involvement of cyclists in intersection crashes. Of all cyclist fatalities, 31 and 39% respectively occurred at intersections in the United States (NHTSA, 2013) and the European Union countries (Candappa et al., 2011). In The Netherlands, a country with a high level of cycling, cyclists were involved in 30% of all fatal crashes and 20% of all serious injury crashes occurring at rural intersections (2006-2008; Ministerie van Infrastructuur en Waterstaat / BRON, 2019). Because the majority of these crashes were side impacts with passenger cars, the present study addresses the interaction between motorized traffic and cyclists at rural intersections.

Speed reduction of motorized traffic limits the adverse consequences that cyclists experience in potential conflicts (Reynolds et al., 2009; Rodarius, Mordaka & Versmissen, 2008; Rosén, Stigson & Sander, 2011; Van Hassel & De Lange, 2006; Wegman, Zhang & Dijkstra, 2010) because there is less kinetic energy released in a crash (Wegman & Aarts, 2006). Speed reduction may also affect drivers' perception (Rogers, Kadar & Costall, 2005). At low speeds, drivers tended to also look at objects along the road, whereas at higher speeds, drivers mainly focused on the direction in which they were heading. Drivers' perception may be related to expectancy, because it appears that drivers do not detect objects at unexpected locations or see them later (Theeuwes & Hagenzieker, 1993). This might explain the safety issues of cyclists coming from an unexpected direction (Herslund & Jorgensen, 2003; Räsänen & Summala, 1998; Schepers et al., 2011). At lower speeds achieved by speed-reducing measures, drivers' visual search changed because drivers scanned the unexpected direction more often (Summala et al., 1996). Expectancy might also play a role in the safety in numbers phenomenon. Drivers appear to be less likely to collide with cyclists if more people cycle (Jacobsen, 2003), because drivers might adapt their behavior by, for example, reducing their speed when they expect to encounter cyclists (Rudin-Brown & Jamson, 2013).

When approaching intersections, drivers reduce their speed somewhat (Harms, 1991; Houtenbos, 2008; Montella et al., 2011), which can be partially explained by drivers experiencing a higher workload as a result of higher processing demands (Harms, 1991; Stinchcombe & Gagnon, 2010; Teasdale et al., 2004). In complex traffic situations, drivers' cognitive capacity is unable to keep up with the task demands (Elvik, 2006). Drivers perform compensatory behaviors (i.e., speed reduction) to control the complexity. Interacting with cyclists at rural intersections may increase complexity and workload even more; Vlakveld (2011) has suggested that cyclists at an intersection can be identified as an overt latent hazard to drivers. Drivers' behaviors appeared to be influenced by the cyclists' unpredictability as a result of the negative impact on their perceived behavior control (Basford et al., 2002), especially in situations in which cyclists did not have the right of way (Hoekstra & Houtenbos, 2013). Variations in workload can be measured by adding a subsidiary task to the primary driving task (Brown & Poulton, 1961). When drivers' performance on the subsidiary task worsens, the primary task becomes more demanding.

From the above-mentioned studies it is unknown how the number of cyclists, the direction from which a cyclist approaches, or the cyclist's unexpected action influences speed behavior and mental workload of drivers approaching rural intersections. This study aims to gain insight in the effects of these 3 aspects on speed behavior and mental workload of drivers approaching rural intersections. First, it was hypothesized that workload would increase when a cyclist is present compared to intersections without cyclists. Workload would increase even more at intersections with multiple cyclists, which would also result in a speed reduction. Second, we hypothesized that drivers' workload would increase and speed would decrease in situations in which the cyclist approached from the expected direction, because drivers would scan this direction as opposed to the unexpected direction. Third, we hypothesized that drivers would respond to a suddenly crossing cyclist by reducing speed and an increase in workload in order to avoid colliding with the cyclist, even at intersections with speed-reducing measures.

5.2. Method

5.2.1. Participants

Thirty participants, 23 males and 7 females, completed the experiment (M = 50 years, SD = 12.4, range 24–65 years). They drove approximately 20,350 km a year (SD = 8,201; range 7,000–40,000 km). All participants were paid €45 plus a reimbursement of travel expenses.

5.2.2. Apparatus

The experiment was conducted in the moving-base driving simulator of TNO, which is based on a 6 degrees of freedom platform. The mock-up was a BMW 318 with normal controls and was placed in front of a cylindrical screen with a total horizontal viewing angle of 180° (Van der Horst & Hogema, 2011). The motion range of the moving base was 0.8 to 1.0 m for translation (all axes) and 48 to 51° for rotation (around any axis). Motion cueing consisted of onset translation cues by means of high-pass-filtered translations derived from the vehicle model. This was augmented by road feel components consisting of low-pass-filtered noise signals on the motion heave and roll.

5.2.3. Road Environment

The route was a 17.5 km long stretch of 80 km/h rural distributor road with 8 intersections: 4 signalized and 4 priority (give-way) intersections (see Figure A1, Appendix 1). The priority (give-way) intersections were situated on a single carriageway and had one intersecting lane, whereas the signalized intersections were situated on a dual-carriageway road. At each intersection, 2 bicycle crossings were present: one ahead of and one behind the intersection, both at a distance of 17 m from the middle of the intersection. Participants encountered cyclists at the first bicycle crossing only. Because the onset of yellow or red could affect driving behavior, traffic signals showed the green light only. No traffic was driving in the same direction as the participants. Participants drove on the major road and therefore had right of way to traffic on the minor road. A run in the simulator lasted approximately 12 min.

5.2.4. Design

The design of the experiment was a within-subject design. The participants completed 3 runs, each representing one of the 3 conditions tested: baseline, plateau, and chicane conditions (see Figure A1, Appendix 1). The order of these conditions was randomized. The plateau was 14 m long (CROW, 2007). The chicane was an out-bended lane (S-shaped curve) based on the design concepts of roundabouts (i.e., a wide median island bended the intersecting roads outwards, forcing drivers to slow down). Both speed-reducing measures were situated 70 m upstream from the bicycle crossing. At 50 m upstream, a warning sign and a mandatory speed limit sign (50 km/h) were present.

Eight different cyclist scenarios were developed varying in the number of cyclists and the direction from which they approached the lane in which the participant drove (see Figure 5.1). The order of these scenarios was randomized over the 8 intersections per run to avoid learning effects and over both the priority and signalized intersections to eliminate effects of intersection control type on the results. To examine the effects of the presence of cyclists, the cyclist scenarios were classified into 3 groups: no versus one or more cyclists (no cyclist, right, double right, and multiple), right versus left approach (right and left), and expected versus unexpected action (right and crossing). Scenarios left + parallel and opposite were developed to increase the variety in cyclist configuration but were not analyzed.

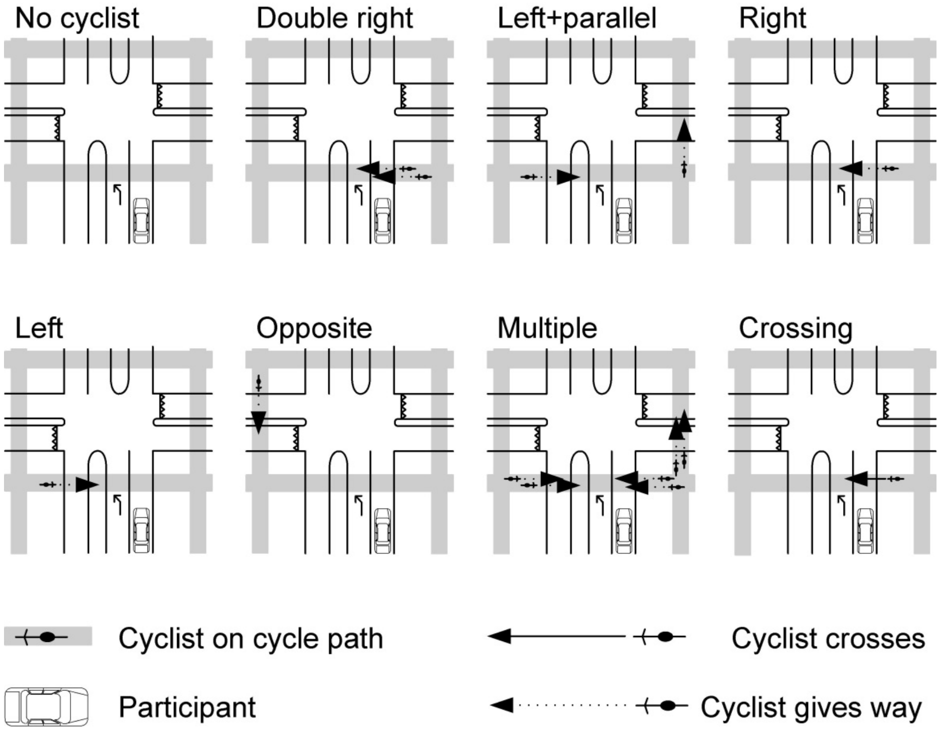

Figure 5.1. Overview of the 8 bicycle scenarios that each participant encountered per run

Yielding cyclists were programmed to decelerate while approaching the main carriageway in order to indicate that they would yield. They stopped a couple of meters from the participants' lane. In the crossing scenario, one simulated cyclist approaching from the right stopped in order to give right of way, but when the participants approached the cyclist crossed suddenly in front of the participants. This cyclist started crossing the participants' lane when the participants were approximately 5 s away and left the participants' lane before the participants entered the bicycle crossing

5.2.5. Peripheral Detection Task

During the experiment in the driving simulator, the Peripheral Detection Task (PDT) was used to measure cognitive workload objectively and more or less continuously (Van der Horst & Martens, 2010). Participants wore a head-mounted PDT headband with a red light emitting diode (i.e., worn such that the road view was not occluded) and a microswitch attached to the index finger of their dominant hand (see Figure A2, Appendix 2). The stimulus (i.e., the light emitting diode being switched on) was presented within the visual periphery of the participant. The interval between the stimuli was a uniform random distribution with a variation between 3 to 5 s. Each stimulus was presented during 1 s or until the microswitch was pressed. If participants responded within 2,000 ms after the stimulus onset, the reaction time was collected. If the microswitch was not pressed within this time frame, the signal was counted as a missed signal. PDT reaction times below 100 ms were counted as a missed signal as well because it is not likely that participants responded that quickly. Average reaction time and percentage of missed signals were used as indicators for workload (Van der Horst & Martens, 2010).

5.2.6. Data Collection and Statistical Analysis

The study consisted of 2 phases, namely, determining an effective speed-reducing measure (phase 1) and examining the effects of the presence of cyclists on speed behavior and mental workload for the baseline and an effective speed-reducing measure (phase 2). In phase 1, the selection of an effective speed-reducing measure was based on the empirical distribution of average driving speeds in the last 200 m to the bicycle crossing. In addition, average speed at bicycle crossing (km/h) was used to examine whether and how driving speed was affected by the speed-reducing measure. Furthermore, post encroachment time (PET, s) was used to determine the seriousness of the interaction in the crossing scenario. The PET described the time between the rear end of the bicycle leaving and the left front of the passenger car entering the position on the road where the paths of the bicycle's rear end and passenger car's left front crossed (based on the definition of PET in Van der Horst, 1990). The smaller the PET, the more serious the consequences of the interaction were assumed. Main effects for condition were analyzed using a repeated measures analysis of variance.

For phase 2, the following dependent variables were determined for speed behavior over an interval of 200 m upstream of each bicycle crossing: minimum driving speed (km/h), maximum deceleration (m/s^2), distance to bicycle crossing of minimum driving speed (m), and distance to bicycle crossing of maximum deceleration (m). For mental workload, average PDT reaction time (ms) and percentage of missed PDT signals (%) were collected. These variables were analyzed with a repeated measures 2-way analysis of variance with 2 within-subject factors: condition with 2 levels (i.e., baseline and an effective speed-reducing measure) and cyclist scenario with 6 levels (i.e., cyclist scenarios no cyclist, right, double right, multiple, left, and crossing). If the interaction between condition and cyclist scenario was found to be significant, the hypotheses concerning specific differences in cyclist scenarios in the 2 conditions were tested as contrasts using the Bonferroni correction. In total, we examined 10 contrasts for each dependent variable: 5 for the baseline condition and the same 5 for the plateau condition. The 5 contrasts were (1) no cyclist versus right, (2) no cyclist versus double right, (3) no cyclist versus multiple, (4) right versus left, and (5) right versus crossing. The assumptions of normality (i.e., Kolmogorov-Smirnov test) and sphericity (i.e., Mauchly's test) were checked. In case this latter assumption was violated, the degrees of freedom were adjusted by using the Greenhouse-Geisser correction factor ε. Effect sizes were reported using the partial eta squared and were considered to be small (η_p^2 = .01), medium (η_p^2 = .06) or large (η_p^2 = .14) (Cohen, 1988).

5.3. Results

5.3.1. Phase 1—Selecting an Effective Speed-Reducing Measure

The empirical distribution showed that the plateau appeared to be more effective in reducing driving speed than the chicane (see Figure 5.2). For example, approximately 45% of the drivers in the plateau condition drove less than 50 km/h compared to approximately 20% in the chicane condition. In the next sections, the effects of the plateau on speed behavior and workload are discussed. Average speed at bicycle crossing was significantly lower in the plateau condition than in the baseline condition, $F(1,29) = 198.84$, $p < .001$ (η_p^2 = 0.87, N = 30). Drivers drove approximately 62 km/h when entering the bicycle crossing in the plateau condition, whereas they drove approximately 80 km/h in the baseline condition. In the crossing scenario, PET was determined to describe the seriousness of the potential conflict between the cyclist and driver (see Table A1, Appendix 1). PET did not significantly differ between the baseline condition and the plateau condition, $F(1,29) = 0.31$, $p = .585$ (η_p^2 = 0.01, N = 30).

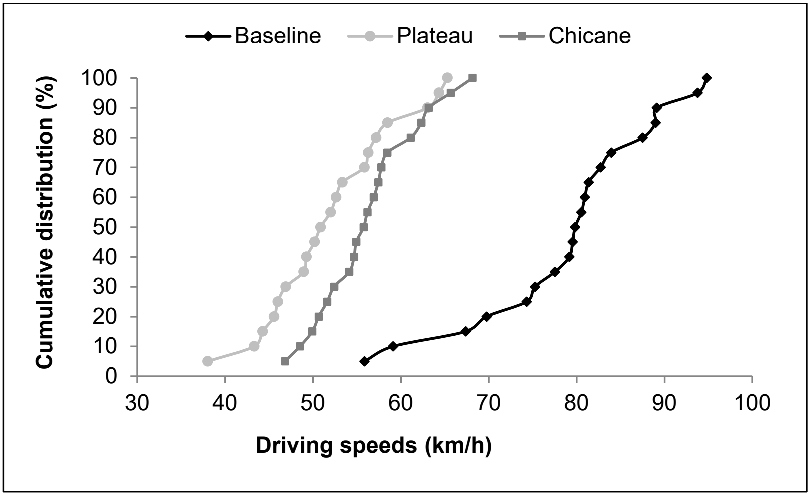

Figure 5.2. Empirical distribution of the average driving speeds for the baseline, plateau, and chicane conditions in the last 200 m from the bicycle crossing, N=30.

5.3.2. Phase 2—Effects of the Presence of Cyclists

Here, we analyzed the effects of the presence of cyclists on speed behavior and workload. The interaction effect was significant at the .05 level or lower for all dependent variables except the percentage of missed PDT signals (see Table A2, Appendix 1). The results of the contrasts are presented in Table A3 (Appendix 1).

5.3.3. No Versus One or More Cyclists

The contrasts showed a significant difference in speed behavior for the baseline condition. Distance to bicycle crossing minimum driving speed differed between approaching the intersection without cyclists compared to the intersection with multiple cyclists (p = .030). When approaching the intersection without cyclists, drivers' minimum speed was reached at approximately 153 m compared to 105 m when approaching the intersection with multiple cyclists. For workload, the contrasts did not show significant differences in the baseline condition between the scenario without cyclists compared to scenarios with one or more cyclists. At intersections with a plateau, minimum driving speed significantly differed between approaching the intersection without cyclists compared to the intersection with multiple cyclists (p = .003). Drivers approaching the intersection without cyclists drove approximately 39 km/h compared to approximately 31 km/h when approaching the intersection with multiple cyclists. For workload, the contrasts did not show significant differences between the scenario without cyclists compared to scenarios with one or more cyclists.

5.3.4. Right versus Left Approach

In the baseline condition, no significant differences were found for the variables on speed behavior and mental workload between drivers approaching the cyclist coming from the right compared to the cyclist coming from the left. In the plateau condition, no significant results for speed behavior and mental workload were found.

5.3.5. Expected versus Unexpected Action

Drivers approaching the cyclist yielding reached a minimum driving speed that was higher compared to approaching the suddenly crossing cyclist in the baseline condition (p = .009). Minimum driving speed was respectively 72 km/h and approximately 53 km/h. In addition, drivers approaching the suddenly crossing cyclist decelerated more strongly than when approaching the cyclist yielding (p = .003), respectively 4.1 and 0.6 m/s^2. In addition, maximum deceleration was reached at a shorter distance to the bicycle crossing at intersections when facing the suddenly crossing cyclist compared to the cyclist yielding (p < .001), namely, approximately 51 and 144 m. The contrasts showed no significant results for variables on speed behavior and workload in the plateau condition.

5.4. Discussion

5.4.1. Main Results

In phase 1 of this study, the plateau appeared to be more effective in speed reduction than the chicane. At intersections with a plateau, drivers entered the bicycle crossing with lower speeds compared to the baseline condition. Lower driving speeds are beneficial for road safety (for both motorized traffic and cyclists); however, the driving speeds obtained were still higher than the suggested safe speeds (Jurewicz et al., 2016; Rosén & Sander, 2009). The plateau ahead of the intersection did not result in less serious potential conflicts between the participants and the crossing cyclist. Because we meant to induce serious encounters between the participants and the crossing cyclist, we programmed the crossing cyclist to start crossing the participants’ lane when the participants were approximately 5 s away. This result should therefore be interpreted carefully.

In phase 2, 3 aspects of the presence of cyclists (i.e. number of cyclists, approach direction, and action) were examined. Regarding the number of cyclists (i.e., none, one, or more), drivers approaching the intersection without cyclists reached a minimum speed at a greater distance to the bicycle crossing compared to approaching multiple cyclists in the baseline. However, in both situations drivers' minimum speed was reached at more than 100 m to the bicycle crossing. In this respect, there were no differences close to the bicycle crossing between intersection approaches without cyclists and multiple cyclists. After passing a plateau, drivers drove slower when approaching multiple cyclists compared to no cyclists. The reduction in driving speed was not accompanied by an increase in workload, which does not suggest an increased difficulty of the intersection driving task as found by Harms (1991).

With regard to the approach direction of the cyclist (i.e., right versus left), no significant differences in speed behavior or workload were found between these 2 cyclist scenarios in both the baseline and plateau conditions. At first sight this does not seem to be in line with previous results, because from studies on cyclists' approach direction in urban areas it is known that safety issues exist with cyclists coming from the unexpected direction (e.g. Herslund & Jorgensen, 2003; Räsänen & Summala, 1998; Schepers et al., 2011). However, these results were found in traffic situations in which cyclists had the right of way, whereas the present study concerned traffic situations in which cyclists had to yield. Thus, drivers only needed to take action if cyclists disobeyed the traffic regulations.

At intersections without a speed-reducing measure, drivers drove slower, decelerated stronger, and decelerated at a shorter distance to the bicycle crossing when encountering the suddenly crossing cyclist compared to the yielding cyclist. Apparently, drivers felt the need to take action when the cyclist disobeyed the traffic regulations. Björklund and Aberg (2005) suggested that drivers rely not only on formal traffic rules but also on informal traffic rules, which are, for example, based on other drivers' behaviors (i.e., suddenly crossing). At intersections with speed-reducing measures, no significant differences in speed behavior and mental workload were found between drivers approaching the cyclist yielding compared to the cyclist suddenly crossing. The speed-reducing measure might have enabled the appropriate driving conditions for dealing with cyclists disobeying the traffic regulations.

5.4.2. Limitations

Because the Netherlands has a high level of cycling, Dutch drivers may have become used to interact with cyclists (Schepers & Voorham, 2010; Wegman, Zhang & Dijkstra, 2010), which would be in line with both the safety in numbers phenomenon (i.e. an increasing number of cyclists resulting in a declining risk; Jacobsen, 2003) and the awareness in numbers principle (i.e. welldesigned facilities result in lower risk; Wegman, Zhang & Dijkstra, 2010). Still, it is possible that participants did not look in the cyclist's direction at all or looked but failed to see (Herslund & Jorgensen, 2003). We assumed that the participants saw the cyclists. However, we did not measure visual scanning behavior. In future research, participants' viewing direction could be monitored with the aid of eye-tracking equipment, but this would not determine whether participants actually saw the cyclist.

Second, participants encountered cyclists at the bicycle crossing ahead of the intersection only because of practical considerations with regard to the duration of the experiment. In addition, no bicycle crossings on the minor road (e.g. see Phillips et al., 2011; Räsänen, Koivisto & Summala, 1999; Summala et al., 1996) were used to keep participants from making turns in order to avoid simulator sickness (e.g. see Stoner, Fisher & Mollenhauer, 2011).

A third possible limitation relates to the traffic situation in which participants were confronted with the cyclist who initially appeared to give way but suddenly crossed. In the experiment, this occurred in one out of 8 intersections. However, we do not know to what extent this reflects the actual frequency in real traffic.

A final limitation may be the selection bias regarding the research population (i.e., participants from a participant database). Generalizing the results obtained in this study to the driving population (in The Netherlands) should be done carefully.

6. Conclusions, discussion and implications

6.1. Overview of the main results

The underlying societal aim of this study is to provide information needed to improve the road safety issues related to the interactions between cyclists and motorised traffic at rural intersections. More specifically, this thesis aims to provide information to make these interactions safer by examining how the factors *road users' behaviour* and *intersection design* play a role in the interaction between cyclists and car drivers at rural intersections. The research in this dissertation focuses on the interaction between cyclists and car drivers at a rural intersection. The following research questions were addressed:

1. Which factors affect the interaction between cyclists and car drivers and the occurrence of crashes and its severity?
2. In what type of crashes at rural intersections are cyclists involved?
3. To what extent is safety incorporated in the actual intersection design on rural roads?
4. How do the presence and behaviour of a cyclist influence the behaviour of a car driver at rural intersections?

The intersections studied in this dissertation are four-arm intersections in rural area having at least one intersecting road with a speed limit of 80 km/h. Two types were studied. The first intersection type is a priority (give-way) intersections where the other intersecting road is a minor road (i.e. rural access road) with a speed limit of 60 km/h. The second intersection type is a signalised intersection where the other intersecting road was another major road (i.e. rural distributor road) with a speed limit of 80 km/h. The cycling facilities along 80 km/h rural roads physically separates cyclists from motorised traffic. On 60 km/h rural roads cyclists share the carriageway with motorised traffic. At intersections, cyclists can cross the main carriageway by making use of dedicated crossing facilities which are one-directional or two-directional. These bicycle facilities cross the main carriageway at the median island between the two driving directions. Cyclists need to give way to the motorised traffic.

The first question was answered in Chapter 2 by developing a conceptual model based on literature on the interaction between a cyclist and a driver of a motor vehicle at an intersection. This model also addressed the relation with crashes and their corresponding consequences. There are two main factors affecting the interaction, namely *road users' behaviour* and *intersection design*.

Intersection design influences the interaction between road users as it sets the conditions under which they interact with each other but it also affects *road users' behaviour* which can be explained from the traffic psychology perspective. On its turn, these main factors are influenced by several determinants such as the national design guidelines and personal factors.

In Chapter 3 the second research question was addressed. Here, the characteristics of crashes occurring at intersections on 80 km/h rural roads were investigated by performing a crash analysis on the BRON database of registered crashes in the Netherlands (Ministerie van Infrastructuur en Waterstaat / BRON, 2019). In addition, a detailed analysis was conducted on the fatal crashes of one year to obtain insight in the infrastructural characteristics of the crash sites that could not be obtained from the crash database. At rural intersections, the predominant crash type is the side-impact. Regarding the crashes at these intersections in which a cyclist was involved, the results show that the majority of these crashes is a side-impact as well. The fatal crash analysis showed that the majority of the cyclists crossed the major road and were hit by an approaching motor vehicle. The results did not show safety problems related to vulnerable road users being present in the blind spot of a truck or van. When involved in a crash, the main crash opponent for cyclists is the passenger car. The crash database did not provide details on the crash sites such as the specific design characteristics of the intersection including the cycling facilities. Therefore a detailed analysis of the fatal crashes was conducted by looking up the crash sites on Google Street View using the information about the crash site location registered on the police registration forms. This detailed analysis showed that the almost 90% of the crash sites was a priority (give-way) compared to less than 10% at signalized intersections. None of the intersections investigated did have speed-reducing measures. Given the relatively high number of crashes between a driver of a motor vehicle and a vulnerable road user, especially cyclists, the interaction between these two road users groups is a serious road safety problem. According to the Sustainable Safety vision, traffic situations in which vulnerable road users and fast-driving motorized traffic share the same space in traffic should not be allowed. The reason is that these situations will result in encounters between these two road user groups leading to crashes in which casualties occur.

The third research question was answered in Chapter 4. An interview study was conducted among road authorities responsible for 80 km/h rural roads. This study focused on the use of national design guidelines, their own design policy and their design choices in practice. It was found that the national design guidelines do propose less safe intersection designs as speed-reducing measures are not mandatory. This may result in high driving speeds that are not considered to be appropriate from a safety point of view (Jurewicz et al., 2016). Furthermore, the results show that road authorities develop their own design guidelines which they base on the national road design guidelines. These road authorities stated that road safety is the most important factor that played a role in the design of the intersections. However, the analysis of intersections reconstructed shortly before the interviews showed that the road authorities chose to implement intersection designs that can be considered potentially unsafe because at none of these intersections speed-reducing measures were applied. By doing so, motorised traffic is enabled to drive through an intersection with high driving speeds. This raises the question if road authorities are able to make a conscious decision regarding safe intersection design, especially since the road design guidelines do not oblige speed-reducing measures. This study showed that this leads to potentially unsafe intersection designs.

In Chapter 5 the fourth research question was addressed. In a moving-base driving simulator study, participants in a passenger car approached various intersections with and without speed-reducing measures. It was studied how the number of cyclists present at an intersection, their approach direction and their action (i.e. giving way versus suddenly crossing) affected the driver' speed behaviour and mental workload. The results showed that of the two speed-reducing measures tested, the plateau (i.e. a longer speed hump) was the most effective in speed reduction compared to the chicane. Although the plateau reduced driving speeds to a large extent, the driving speeds obtained were still higher than the suggested safe speeds (Jurewicz et al., 2016; Rosén & Sander, 2009). Also, the results show that drivers' speed behaviour was affected by the number and action of cyclists crossing although these drivers had the right of way at the intersections. To be more specific, it appeared that at intersections with plateaus, drivers drove slower when they encountered an intersection where multiple cyclists were present compared to an intersection where no cyclist was present. The cyclist's approach direction (i.e. left versus right) did not have an effect whereas other studies found safety issues related to cyclists coming from the unexpected direction. This can be explained by the drivers having right of way over the cyclists. In other words, drivers only needed to take action if cyclists disobeyed the traffic regulations. At intersections without a speed-reducing measure, drivers drove slower, decelerated stronger, and decelerated at a shorter distance to the bicycle crossing when encountering a cyclist who suddenly crossed compared to encountering a cyclist that yielded. At intersections with speed-reducing measures, drivers' speed behaviour and mental workload did not differ between approaching the cyclist yielding compared to approaching the cyclist suddenly crossing. The speed-reducing measure might have enabled the appropriate driving conditions for dealing with cyclists disobeying the traffic regulations. Although the speed-reducing measures lowered the driving speeds of the drivers, their driving speeds and impact speeds were still higher than the suggested safe speeds.

In conclusion, this thesis proposes a new generic model that can be used to describe the interaction between cyclists and car drivers at rural intersections. This model contains two key elements that play a role in this interaction, namely *road users' behaviour* and *intersections design*. Changing the design of intersections directly influences the behaviour of car drivers at an intersection and the interaction between them and cyclists. Based on existing literature it was already known that speed reduction is essential for safe interactions between cyclists and drivers of a motor vehicle. The experimental study conducted in this thesis added new knowledge on the interaction because this study showed that drivers, who drove at lower speeds, were able to deal with a cyclist disobeying the traffic regulations by not giving way to the car driver. In practice, the results of the interview study conducted show that speed-reducing measures are hardly implemented at rural intersections in the Netherlands. Road authorities are not enforced to do so as speed reduction is not mandatory according to the guidelines (CROW, 2002). To be more specific, road authorities are not obliged to use the road design guidelines. From this research it can be concluded that from a safety point of view it is not desirable that the intersection design guidelines present speed-reducing measures as being optional instead of mandatory. So, this thesis confirms that *road users' behaviour* and *intersections design* are two key elements that play a role in the interaction between cyclists and drivers of a motor vehicle at rural intersections. By designing intersections in such a way that drivers are able to approach and drive through the intersection with relatively high speeds, safe interactions between vulnerable road users and motor vehicles cannot be enabled. It is therefore essential to create safe circumstances for cyclists when crossing rural intersections. The first is to eliminate the possibility of interacting with motorised traffic. The second is to lower the driving speeds of motorised traffic so that cyclists and drivers of a motor vehicle can safely interact with each other at rural intersections. As a result, this leads to safer circumstances for cyclists and motorised traffic because impact speeds are lower if a crash occurs. In interactions at rural intersections, the cyclist crossing the major road needs to conduct the evasive manoeuvre, in other words s/he has to stop and give way to approaching motorised traffic as the motorised traffic has right of way. So, besides speed reduction other design measures should be taken as well that help cyclists cross the intersection safely. For example, a median island that enables cyclists to cross the major road in two phases. Also, the bicycle path at the median island between the two driving directions should be bended out in order to force cyclists to look in the direction motor vehicles approach. The traffic situation should be designed such that cyclists know what traffic situation they are in, that they know what to expect and how to behave. The measures suggested focus on making the crossing of the intersection less complex (i.e. lower speeds of motorised traffic and therefore more time to make a decision).

6.2. Discussion: interpretation of the results

Five topics will be discussed here as each of these topics play a role in the interpretation of the results. They have in common that they have the potential to contribute to improve the understanding of the interaction between a driver of a motor vehicle and a cyclist at rural intersections. The five topics are research from the cyclists' perspective, reliable crash data, safety in the design guidelines, technological developments and the Dutch context of the results.

6.2.1. Research from the cyclists' perception

In this research, the interaction between a cyclist and a car driver at rural intersections was studied by using a driving simulator. This simulator enabled a detailed analysis of effects on the behaviour and mental workload of participants being a driver in a passenger car. However, this driving simulator was not suitable to measure the effects on the behaviour and mental workload of participants being a cyclist. So, no information was obtained on how cyclists approach and cross a rural intersection and how an approaching motor vehicle may affect their behaviour and mental workload. It is to be expected that the interaction between cyclists and drivers of a motor vehicles can be studied more extensively when a cycling simulator is used to gain insight from the cyclist perspective. Another research method that could gain insight in the interaction between cyclists and drivers is observing the interaction in real life. In naturalistic driving and naturalistic cycling studies, various cameras mounted in the vehicle or on the cyclist or bicycle provide information on the interaction from the point of view of the driver and cyclist. It is thereby essential to collect information on the intersection design as well (e.g. by mounting cameras on lightning poles for a bird's eye view) because intersection design affects road users' behaviour (see e.g. Aarts et al., 2006; Martens, Comte & Kaptein, 1997; Räsänen & Summala, 1998; Schepers et al., 2011). In order to understand why sometimes a cyclist does not give way to motorized traffic but crosses right in front of them, it would be interesting to study the reasons for this behaviour. How do they perceive the interaction with motor vehicles at rural intersections? And what will be additional (design) measures that enable a safe crossing for cyclists? In addition, it would be worthwhile to study if the behaviour of cyclists on e-bikes differ from cyclists on regular bicycles in interactions with drivers of a motor vehicle in order to investigate what the implications are for rural intersections design.

6.2.2. Reliable crash data

Part of this research is a crash analysis of rural intersection crashes. For a crash analysis, it is essential to use reliable crash data. In the analysis conducted, data from two time periods was used, namely 2006-2009 and 2010-2018. The various subsets of data regarding serious injury (MAIS2+) crashes were only to be made with data from the time period 2006-2009, originating from the BRON database of registered crashes. Because of multiple changes such as in the registration method and the data sources, data on seriously injured (MAIS2+) from the period 2010-2018 originates from hospitals.

Since 2010, the registration level of crashes dropped dramatically (Vis et al., 2011). Because of using hospital data for information on seriously (MAIS2+) injured, it was not possible to disaggregate these data. This makes it impossible to conduct a reliable crash analysis at a disaggregated level, which is a disturbing development and a shame for the Netherlands. It is to be expected that when crash data is made suitable for analyses at an disaggregated level again, the development of cyclist safety at rural intersections could be monitored and analysed again. To do so, also exposure data needs to be available and of good quality. Although the crash data used dates back ten years ago, this does not mean that the topic is not relevant. Weijermars et al. (2018a) show that the number of fatalities in the Netherlands in the period 2008-2017 decreases. However, on the short term (i.e. comparing the year 2017 with the years 2014-2016) the number of fatalities increases. And, over the last decade the number of seriously injured (MAIS2+) increases with almost 2% per year (Weijermars et al., 2018a). With the renewed attention for road safety in politics (Ministerie van Infrastructuur en Waterstaat et al., 2018), this dissertation can contribute to the discussion how to tackle the numbers of crashes and casualties (i.e. especially among cyclists) occurring at rural intersections. It is therefore essential to have reliable crash data. One way to obtain these data is to combine the information from the crash registration by the police (i.e. detailed crash site characteristics) with the information from the hospital data (i.e. detailed injury characteristics). This will allow future research to focus on statistical comparisons between variables to find out if, for example, certain road users groups are overrepresented (or underrepresented) as compared to other road users groups.

6.2.3. Safety in the design guidelines

In this dissertation critical remarks were made regarding the design guidelines used by road designers and road authorities when designing new intersections or reconstructing existing intersections. These guidelines propose intersections designs that can be considered not safe as speed-reducing measures are not recommended. This implies that designs based on prevailing design guidelines for rural intersections will result in unsafe intersections, that is to say: create conditions in which fast moving motor vehicles will kill or seriously injure cyclists when a crash occurs. This should not be accepted from a road safety point of view. This problem does not exist (or should not exist) when using a well-designed roundabout on which travel speeds of motor vehicles when entering or leaving a roundabout with relatively low speed (Churchill, Stipdonk & Bijleveld, 2010; Elvik, 2003; Van Minnen, 1995). However, it is to be realized that design guidelines take into account other topics besides road safety as well, such as traffic flow or capacity. From the guidelines it does not become clear which trade off has been made regarding road safety and these other topics. Although speed reduction seems to lead to an increase in the time to drive through the intersection, Fortuijn, Carton & Feddes (2005) found that it also leads to positive effects such as smaller critical gaps for traffic wanting to enter the major road or adjustments in the traffic signal control (e.g. shorter yellow time). Future research should further address what the consequences are for traffic flow when the safety level of the intersection designs in the guidelines is increased. Another aspect of intersection design in relation to road safety is uniformity. For intersections to be predictable for road users it is essential that rural intersections have a uniform layout. Regional differences in the layout of rural intersections in a country should be avoided. Overall, it is important that road authorities are able to use design guidelines that contain the information they need in their process of designing safe intersections. The design guidelines should contain detailed information on intersection design, preferably accompanied by results from scientific research. The information and knowledge presented in the guidelines should make road authorities more aware when making choices in the design process.

6.2.4. Technological developments

Another topic that is relevant and widely researched nowadays is technological developments in vehicles and infrastructure. On the one hand there are Advanced Driver Assistance Systems (ADAS) that may help drivers to keep their vehicle in the lane (i.e. lane keeping system) or to drive at a certain speed thereby keeping an appropriate distance to their lead vehicle (i.e. adaptive cruise control). On the other hand technology focuses on automated driving where the driver handles the control of the vehicle over to the vehicle. The interaction between cyclists and drivers of a motor vehicle at rural intersections may benefit from technology that helps a driver to detect a cyclist when the driver failed to detect the cyclist in time. Or from technology that enables autonomous emergency braking (see e.g. Cicchino, 2017) for a crossing cyclist when the driver has not reacted yet. In general, the technological developments focus on vehicles rather than bicycles. It would be worthwhile to study if technology also has the potential to help cyclists in the interaction with motorised traffic. Another topic that should be paid attention to is how road users are going to use these technologies (i.e. to use as they are supposed to be used), what the effects are on the interaction with other traffic and if there may be rebound effects (i.e. are cyclists going to cross in front of motorised traffic because automated vehicles are going to stop anyway?). It is not clear how fast technology will develop over the years and what their benefits will be (Shiwakoti, Stasinopoulos & Fedele, 2020; Tillema, Moorman & Kansen, 2020). Another important aspect of technology is the way how it is being used by road users. It may lead to behavioural adaptation and undesired side-effects as is shown in various studies, such as Hoedemaeker & Brookhuis (1998), Miller & Boyle (2019), Rudin-Brown & Parker (2004). During driving road users may perform non-driving related tasks or drivers may use their ADAS in traffic situations their ADAS is not designed for (Dutch Safety Board, 2019). Also, upcoming technological developments do not rule out that changes to the intersection design need to be made. It is therefore of great importance to start making intersections inherently safe instead of waiting till technology may be ready.

6.2.5. Dutch context of the results

The studies in this dissertation focus on the interaction between cyclists and car drivers in the Netherlands. This country is known for its cycling culture and its well-developed cycling infrastructure. Conclusions drawn from Dutch studies cannot be easily translated to other countries; it should be done carefully. An example may be roundabouts. Multiple Dutch studies conclude that they are relatively safe, both for motorised traffic and for cyclists (see e.g. Churchill, Stipdonk & Bijleveld, 2010; Elvik, 2003; Van Minnen, 1995) whereas a different result was found in for example Belgium (see e.g. Daniels, Nuyts & Wets, 2008). These differences may be explained by infrastructural differences. Although these studies have a rather Dutch character, the basic principles of the results are not limited to the Netherlands but they are applicable to other countries. By reducing the driving speeds of motorised traffic, both cyclists and drivers will benefit from not only the extra time they have to interact with each other but also from the less serious consequences in case they collide. Also two other aspects can be applied elsewhere, namely the physical separation between cyclists and fast moving motorised traffic at road sections and the high quality of cycling infrastructure. In the discussion of Safety in Numbers (i.e. drivers appear to be less likely to collide with cyclists if more people cycle, see e.g. Brüde & Larsson, 1993; Elvik, 2013; Elvik & Bjørnskau, 2015; Jacobsen, 2003) sometimes the quality of cycling infrastructure seems to be forgotten (Wegman, Zhang & Dijkstra, 2010). Cycling safety does not only improve when drivers have the right expectations regarding cyclists to be present but also the quality of the bicycle infrastructure affects the safety of cyclists. Although local conditions differ within countries and between countries, these two basic principles of the Sustainable Safety vision and Safe System approach are applicable universally, because laws of Newton and the vulnerability of the human body are universal. Thus, when considering the interaction between cyclists and drivers of a motor vehicle it is important to not only separate them physically on road sections but also to apply physical speed reducing measures at intersections.

6.3. Implications for the road traffic system

In a road traffic system, road users make mistakes and commit violations, as was illustrated by the Swiss Cheese model of Reason (2000) in Chapter 2. According to the Safe System approach, including the Sustainable Safety vision, it is important to create a road traffic system that matches the human capabilities and limitations of road users. By applying a human factors perspective, thus adjusting the road traffic system to the road users' capabilities and limitations, the occurrence of human error can be reduced. Therefore, the following implications are presented below.

6.3.1. Implications for those who develop the design guidelines

Intersection design should facilitate safe interactions between cyclists and drivers of a motor vehicle but the current intersection design guidelines do not accommodate this. Now that governments are stimulating cycling because of reasons related to health and environment, it is essential that the quality of cycling facilities improves in order to make cycling safe, also in rural areas. When looking at the current guidelines (see CROW, 2013) it can be concluded that the cycling facilities described are unsafe facilities. At priority (give-way) and signalised intersections speed-reducing measures are presented as options that can be considered. From the safety perspective of vulnerable road users, this can result in serious safety issues. In comparison, at Dutch roundabouts cycling facilities are relatively safe because roundabouts enforce motorised traffic to slow down (Churchill, Stipdonk & Bijleveld, 2010; Elvik, 2003; Van Minnen, 1995). At roundabouts, the safest situation for cyclists is to give way to motorised traffic instead of having right of way (Dijkstra, 2005). This is the recommendation in Dutch design guidelines and standard practice.

It is therefore essential that the design guidelines incorporate the perspective of vulnerable road users in order to facilitate safe interactions between vulnerable road users and motorised traffic. The current guidelines should be updated in order to recommend intersection designs that automatically enforce safe behaviour and that if crashes occur they do not result in serious injuries for cyclists.

As pointed out throughout this dissertation, speed reduction for motorised traffic is an essential element to create more time for interacting with other road users and to also limit the consequences of a crash (i.e. less kinetic energy released). This will not only make the interaction between cyclists and drivers of a motor vehicle easier but also between drivers. From a safety point of view, intersections should be made as safe as possible. Dutch roundabouts are proven to be a relatively safe intersection type (Churchill, Stipdonk & Bijleveld, 2010; Elvik, 2003; Van Minnen, 1995). When it is the case that a roundabout cannot be applied, speed-reducing measures need to be applied such as the speed hump or plateau. These measures should reduce driving speeds to speeds considered to be safe speeds for interactions between motorised traffic and vulnerable road users and is also similar to the speed reduction accomplished by roundabouts. From a safety point of view for vulnerable road users, 20 km/h is considered to be a safe speed by Jurewicz et al. (2016). This safe speed threshold is lower in comparison to the previous study of Rosén, Stigson & Sander (2011) as it is based on both fatalities and seriously injured instead of only fatalities. It is essential that drivers of motor vehicles are made aware of these measures instead of being surprised by them. In order to start slowing down on time, it is essential that drivers know that they are approaching an intersection where they have to slow down. Also, it is important that drivers are given enough time between the first notification (i.e. by road signs) of the intersection being ahead and the speed hump or plateau so that they can reduce their speed gradually when approaching an intersection. Finally, speed reducing measures should be designed in such a way that safe driving speeds (and impact speeds) will be the result.

Besides the speed-reducing measures, there are additional design principles that, although they were not studied in this dissertation, should be taken into account. Two-phase bicycling crossings enable cyclists to cross each driving direction separately (Van Boggelen et al., 2011). This makes crossing the carriageway easier and gives the opportunity to wait for a passing motor vehicle safely. Such crossings appears to be beneficial for elderly (Davidse, 2007a). Also, for bicycle crossings at the main carriageway where the cyclists need to give way to motorised traffic, the bicycle path at the median island between the two driving directions should be bended out in order to force the cyclist to look in the direction a motor vehicle approaches. This makes it harder for a cyclist to cross the carriageway at high speed when there is no traffic approaching but the safety benefits outweigh this drawback. For the bicycle crossings at the minor roads where the cyclists have priority over motorised traffic, the following principles should be taken into account. From a safety point of view, the same principle of a two-phase crossing should be applied here for motorised traffic. When approaching the intersection, the bicycle crossing is to be crossed before the main carriageway is reached. A driver first needs to pay attention to vulnerable road users crossing before needing to pay attention to the carriageway. It is thereby essential that there is enough space for a motor vehicle to stand still between the bicycle crossing and the carriageway so that the driver is able to deal with the bicycle crossing first before having to deal with the carriageway. For motorised traffic that has left the main carriageway and approaches the bicycle crossing where cyclists have the right of way, it is essential that their path is perpendicular to the bicycle crossing. By doing so, drivers have a good view on the bicycle path whereas at a smaller angle they need to look more over their shoulder to be able to see cyclists approaching. Important for all bicycle crossings is that it should be clear to drivers from which direction cyclists can be expected. Still, it is possible that a cyclist fails to stop -on purpose or by accident- and performs a crossing manoeuvre when s/he should not have. When drivers are aware of cyclists being present, they may anticipate the interaction ahead. In case of a failing cyclist, it is the driver who can try to avoid a crash. Also, drivers always need to be aware of cyclists disobeying the traffic rules and driving on the wrong side.

If new Dutch intersection design guidelines are developed, it is important that these guidelines are detailed enough so that road designers and policy makers can work with it. In the process of updating the guidelines, road designers should be part of it to check if the designs are detailed enough. Also, choices to be made in the process should be based on human factors knowledge and research so that the guidelines contain designs that match the capabilities of road users and are proven to be safe instead of believed to be safe. Furthermore, the process should be transparent so that it is clear why certain choices were made. It is worthwhile to study if the design guidelines should have a legal status so that policy makers and road designers are obliged to use them.

6.3.2. Implications for those who make use of the design guidelines

In this thesis, the questionnaire study with road authorities showed that road authorities stated to take road safety into account when making decisions regarding intersections to be reconstructed. In fact, they said road safety was the most important factor. But their recently reconstructed intersections revealed that the design of those intersections did not contain measures that reduced the driving speeds of motorised traffic to a safe level. It is remarkable that although they all acknowledge that roundabouts are the safest intersection type, they apply these other intersection designs and do not even try to adopt the principles of a roundabout (i.e. speed reduction and lowering the number of potential conflict points; see also Chapter 3). From a road safety perspective road designers and policy makers should strive to the safest intersection design possible. Also, it appeared that additional design guidelines were developed by the road authorities as they considered the national design guidelines not appropriate enough (e.g. level of detail). Despite the existing national design guidelines, almost every road authority feels the need to develop their own set of guidelines which may lead to inconstant intersection design. With the new national design guidelines as described in the previous section this should not be necessary nor possible anymore. Designers and policy makers should realise themselves that their designs directly affect the level of safety at rural intersections and that they have the ability to create safe traffic circumstances under which road users can interact with each other safely. Road authorities should therefore use these new design guidelines which will lead to safer intersections but also to consistent intersection design.

6.3.3. Implications for researchers

In the sections above, two implications for researchers were addressed. The first is to conduct research from the cyclists' perspective, for example by using a bicycle simulator to study the behaviour of cyclists. The second is to study the potential of technological developments (i.e. ADAS, emergency braking technology, automated driving technology) to help drivers of a motor vehicle and cyclists in their interactions.

Another implication for researchers is related to the technological developments that might be beneficial to improve interactions at rural intersections too. For example, new technology in vehicles is able to detect cyclists when a driver has not been able to or warn cyclists approaching an intersection that a vehicle is approaching too. It is worthwhile to study if these technologies are indeed able to improve the interaction between cyclists and drivers of a motor vehicle at rural intersections.

The last implication concerns cycling in rural area. The conceptual model as proposed in this dissertation broadened the existing but rather limited knowledge. When reviewing the literature available, it was noticed that the majority of the studies focused on cycling in urban area which is an challenging topic too. But with electric bikes enabling cyclists to travel longer distances, it is essential to also concentrate on cycling facilities in rural area. It is worthwhile to study how cycling in rural area should be facilitated. Should cyclists be present at these intersections at all? For urban networks, Schepers et al. (2013) concluded cycling safety is improved by unbundling, thus physically separating a cycling network for cyclists apart from motorised traffic. Unbundling at intersections in urban area can be realised by applying grade-separated intersections, for example a tunnel for bicyclists. In the sections above, various design principles were described that should be taken into account when updating the design guidelines. It is therefore worthwhile to study how the design principles presented can be worked out into designs that capture safe interactions between cyclists and drivers of a motor vehicle.

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Appendix 1. Implications of the data used

The empirical chapters of this dissertation consist of various data sources. In Chapter 3 data from the database of registered crashes BRON (Ministerie van Infrastructuur en Waterstaat / BRON, 2019) was used. The same applies for Chapter 4 in which also results from interviews with road authorities were used. Last, in Chapter 5 data from a driving simulator experiment were analysed. The data described and analysed in these chapters have in common that they are not recent data. In theory, the use of recent data could lead to different results and conclusions due to several reasons. These reasons can be linked to changes in the theories and empirical data used, to changes in the relations between variables or to changes in the responses given by interviewees or in the behaviour showed by participants. This Appendix describes what the implications are if recent data was used in these chapters.

Crash data from the BRON database of registered crashes (Chapter 3 and 4)
Data from seriously injury (MAIS2+) crashes occurring at intersections until 2009 were used. Chapter 3 also included an analysis of the crash sites of fatal crashes that occurred in 2008. Due to several changes in the registration of crashes by the police, the registration of crashes between 2010 and 2016 was less accurately compared to the period before 2010 (Rijkswaterstaat, 2018). This means that many characteristics of crashes were unknown as they were not recorded anymore. Weijermars et al. (2019) found that the number of crashes in which a cyclist and a motor vehicle were involved did not change much the last ten years. In addition, they found an increase of 24% in 2018 compared to the time period 2015-2017 (Weijermars et al., 2019). The results in Chapter 3 and Chapter 4 did not take into account the involvement of e-bikes. In 2006 only a small proportion (3%) of bicycles sold was an e-bike (Weijermars et al., 2018b) compared to 40% in 2018 (RAI/BOVAG/GfK, 2019).

So, changes in the empirical data used may result in slightly different results compared to the results reported in Chapter 3 and Chapter 4 if the same research was carried out these days. The exact numbers may be different but it would not lead to different conclusions. Especially the increase of the number of crashes between cyclists and motor vehicles stress the need to improve the interaction between cyclists and motor vehicles.

Data from the interviews with road authorities (Chapter 4)
The interviews discussed in Chapter 4 were held in 2011. Over the last years, there has been not much attention paid to road safety. The increasing number of fatalities and seriously injured in road traffic in the Netherlands caused renewed attention for road safety which lead to a new plan to tackle road safety issues till 2030 (Ministerie van Infrastructuur en Waterstaat et al., 2018). As already described above, there have been changes in the registered crash data in the last years. The number of road traffic fatalities and serious (MAIS2+) injured in the Netherlands seem to increase the last five years (Weijermars et al., 2019). This might cause the road authorities to pay more attention for road traffic casualties in rural area and for the safety level of their rural intersections compared to the time period of the interview study described in Chapter 4. With the Strategic Plan Road Safety in mind, road authorities may be more focused on road safety in rural area than before. This could lead to a different design policy and different design choices made compared to the past. However, changes in the Dutch national design guidelines (CROW, 2013) are not to be expected to occur overnight. Consequently, major changes in the actual design of rural intersections in the real world are not to be expected.

Concluding, if the study was carried out again these days, changes in empirical data and changes in responses given by road authorities may result in slightly different results. The increasing number of road traffic casualties may cause road authorities to pay more attention to the safety level of their rural roads. However, major changes in the national road design guidelines and the design policy of road authorities are not expected to be found if the study was conducted out these days.

Data from the driving simulator experiment (Chapter 5)
In 2012, the driving simulator study was conducted. In this study, driving behaviour of participants from the TNO participants database was analysed as they were driving a route with various rural intersections. The intersections studied in the experiment described in Chapter 5 do still exist and regulations concerning those rural intersections have not been changed.

So, it is not to be expected that results pointing in a different direction would be generated if the driving simulator experiment was to be conducted these days.

Appendix 2. Figures and tables from Chapter 5 which were published in an online supplemental

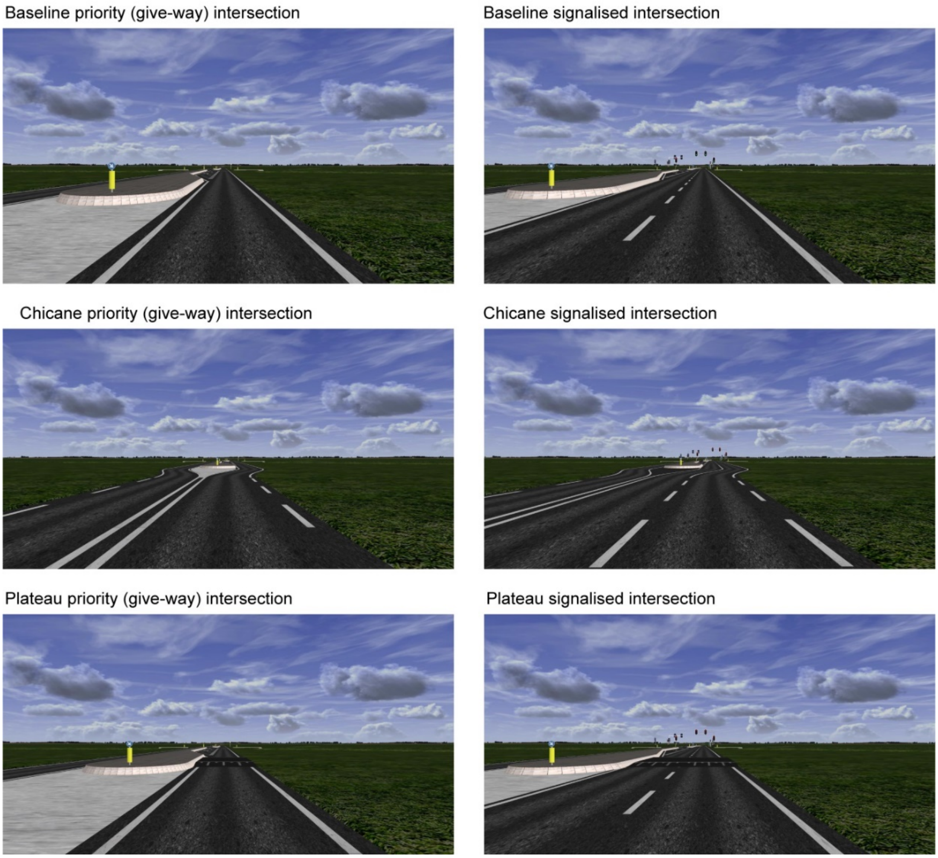


Figure A1. Screenshots of the baseline, plateau and chicane condition for both signalised and priority (give-way) intersections.

Figure A2. The head-mounted PDT headband with the red LED and the micro switch.

Table A1.
Mean (M) and standard deviation (SD) of variables on speed behaviour and workload for each cyclist scenario in the baseline and plateau condition.

		No cyclist		Right		Double right		Multiple		Left		Crossing	
		M	**SD**	**M**	**SD**	**M**	**SD**	**M**	**SD**	**M**	**SD**	**M**	**SD**
Baseline condition	Minimum driving speed (km/h)	75.6	12.1	71.6	15.6	74.5	16.1	68.0	20.3	73.0	15.2	53.4	21.9
	Maximum deceleration (m/s^2)	0.3	0.5	0.6	0.7	0.5	0.8	1.3	1.6	0.4	0.6	4.1	2.4
	Distance to bicycle crossing of minimum driving speed (m)	152.9	67.5	97.9	81.6	150.4	75.0	105.4	70.0	124.8	91.7	37.2	38.4
	Distance to bicycle crossing of maximum deceleration (m)	158.3	71.3	144.1	63.0	104.2	76.6	103.7	55.9	135.1	69.4	51.2	17.8
	PET (s)	-	-	-	-	-	-	-	-	-	-	1.1	0.9
	Average PDT reaction time	474.5	170.3	461.0	161.9	558.4	249.4	578.7	253.5	403.1	115.8	532.5	244.9
	Missed PDT signals (%)	12.8	28.6	10.3	23.5	12.5	20.2	25.0	28.3	10.0	23.0	31.9	26.9
Plateau condition	Minimum driving speed (km/h)	39.1	9.5	37.7	16.0	32.8	12.8	30.8	8.5	39.8	8.5	28.7	13.3
	Maximum deceleration (m/s^2)	2.7	1.9	2.3	0.9	3.1	1.8	3.4	1.8	2.6	1.9	3.3	1.9
	Distance to bicycle crossing of minimum driving speed (m)	90.9	32.1	75.2	42.0	67.9	34.5	77.8	19.6	86.4	39.4	44.5	31.1
	Distance to bicycle crossing of maximum deceleration (m)	125.3	39.0	97.0	39.8	122.0	44.8	114.4	19.9	133.9	34.8	64.4	41.2
	PET (s)	-	-	-	-	-	-	-	-	-	-	1.3	1.8
	Average PDT reaction time	526.6	176.9	696.9	261.2	521.9	167.2	634.1	293.9	579.4	245.5	663.9	259.3
	Missed PDT signals (%)	27.5	32.3	32.2	30.6	40.6	33.3	42.3	27.3	24.2	37.9	45.3	32.5

Table A2. Overview of the two-way ANOVA with main effects for cyclist scenario and condition, and an interaction effect. Results significant at the .05 level or lower are displayed in Italic and are marked with an *. An explanation for various numbers on N is that not for every participant a value of a variable could be obtained. For example, some participants missed all PDT signals resulting in the absence of a result for Average PDT reaction time.

	F	df	ε	p	η_p^2	N
Minimum driving speed (km/h)						
Scenario	18.75	3.61, 83.04	.72	*<.001**	.45	24
Condition	223.81	1, 23	-	*<.001**	.91	24
Scenario x condition	3.12	5, 115	-	*.011**	.19	24
Maximum deceleration (m/s²)						
Scenario	12.56	5, 70	-	*<.001**	.47	15
Condition	27.52	1, 14	-	*<.001**	.66	15
Scenario x condition	7.02	5, 70	-	*<.001**	.33	15
Distance to bicycle crossing of minimum driving speed (m)						
Scenario	15.13	5, 115	-	*<.001**	.40	24
Condition	20.43	1, 23	-	*<.001**	.47	24
Scenario x condition	4.28	5, 115	-	*.001**	.16	24
Distance to bicycle crossing of maximum deceleration (m)						
Scenario	11.05	5, 70	-	*<.001**	.44	15
Condition	.35	1, 14	-	.565	.03	15
Scenario x condition	3.82	5.70	-	*.004**	.21	15
Average PDT reaction time (ms)						
Scenario	2.78	5, 115	-	*.021**	.11	24
Condition	16.84	1, 23	-	*<.001**	.42	24
Scenario x condition	2.80	5, 115	-	*.020**	.11	24
Missed PDT signals (%)						
Scenario	10.30	5, 145	-	*<.001**	.26	30
Condition	26.41	1, 29	-	*<.001**	.48	30
Scenario x condition	.86	5, 145	-	.511	.03	30

Table A3. Overview of the results (*p* values) for the contrasts examined. Results significant at the .05 level or lower are displayed in Italic and are marked with an *.

	No cyclist versus double right	**No cyclist versus right**	**No cyclist versus multiple**	**Right versus left**	**Right versus crossing**
Minimum driving speed (km/h)					
Baseline	1.000	1.000	.296	1.000	*.009**
Plateau	.438	1.000	*.003**	1.000	.112
Maximum deceleration (m/s^2)					
Baseline	1.000	1.000	.637	1.000	*.003**
Plateau	1.000	1.000	.701	1.000	1.000
Distance to bicycle crossing of minimum driving speed (m)					
Baseline	1.000	.116	*.030**	1.000	.121
Plateau	.101	.857	1.000	1.000	.081
Distance to bicycle crossing of maximum deceleration (m)					
Baseline	.288	1.000	.113	1.000	*<.001**
Plateau	1.000	.378	1.000	.154	1.000
Average PDT reaction time (ms)					
Baseline	1.000	1.000	1.000	1.000	1.000
Plateau	1.000	.092	1.000	.302	.399

Summary

It is a disquieting development that globally the number of casualties among vulnerable road users when interacting with motorised traffic is increasing. Although a vast and fast growing amount of research addresses cycling safety, the majority of studies address cycling in urban area. Little attention has been paid so far to cycling safety in rural area and in particular the interaction between cyclists and car drivers at rural intersections. Hospital data show that safety problems exist in the Netherlands that are related to cycling occurs in rural area, especially at intersections where cyclists meet with motorised traffic. The Safe System approach strives to a road infrastructure that is designed in such a way that road users can interact safely and, in case road users collide, the consequences are not serious. Lowering the speed limits and thereby driving speeds, may result in lower impact speeds in crashes. When impact speeds are in accordance to the human body's tolerance, chances of surviving a crash for vulnerable road users colliding with motorised traffic may increase. Hereby, the behaviour of road users and intersection design are important factors. The underlying societal aim of this study is to provide information needed to improve the road safety issues related to the interactions between cyclists and motorised traffic at rural intersections. More specifically, this thesis aims to provide information to make these interactions safer by examining how the factors *road users' behaviour* and *intersection design* play a role in the interaction between cyclists and car drivers at rural intersections Therefore, this thesis focuses on how the factors *road users' behaviour* and *intersection design* affect the interaction between cyclists and car drivers at rural intersections. The following research questions are addressed:

1. Which factors affect the interaction between cyclists and car drivers and the occurrence of crashes and its severity?
2. In what type of crashes at rural intersections are cyclists involved?
3. To what extent is safety incorporated in the actual intersection design on rural roads?
4. How do the presence and behaviour of a cyclist influence the behaviour of a car driver at rural intersections?

This research focuses on car drivers in the interaction with cyclists as the passenger car is the most dominant crash opponent for cyclists in rural intersection crashes. At rural intersections, cyclists need to give way to approaching motorised traffic. Cyclists are the ones who need to perform the evasive manoeuvre, in order words: they need to stop and let motorised traffic

pass before they can continue their route. So drivers have right of way but it is unknown if and how they react when they approach an intersection where cyclists could be present. Also, the empirical research is limited to Dutch intersections of 80 km/h rural roads intersecting with another 80 km/h rural road or a 60 km/h rural road. Specifically, the research focuses on three- and four-arm intersections; roundabouts are left out as they are already relatively safe.

Chapter 2 addresses the first research question and presents the theoretical framework of the thesis. Based on the existing literature, a generic conceptual model is developed which describes the various factors playing a role in the interaction between cyclists and drivers of motor vehicles at intersections. The model is presented on the next page.

Two main factors affect the interaction between a cyclist and a driver of a motor vehicle at rural intersections. The first is *road users' behaviour* and concerns the behaviour of both the cyclist and the driver of a motor vehicle when interacting with each other. The second is *intersection design* and represents the layout of the intersection including the road environment, road traffic signs and regulations. These two factors are related as intersection design affects road users' behaviour. By changing the design of intersections, the behaviour of the road users is affected and on its turn the interaction between these road users is being affected. One way to do so is to automatically enforce the desired behaviour (e.g. appropriate speed or looking direction). Also, these two factors are being affected by other factors or determinants such as the design policy of a road authority, the national design guidelines, personal factors and external factors. When an interaction is successful, both road users continue their way. But if not, it may lead to a crash between the cyclist and driver of a motor vehicle and its corresponding impact which is being described in the lower part of the model. Here, post-crash response plays a role.

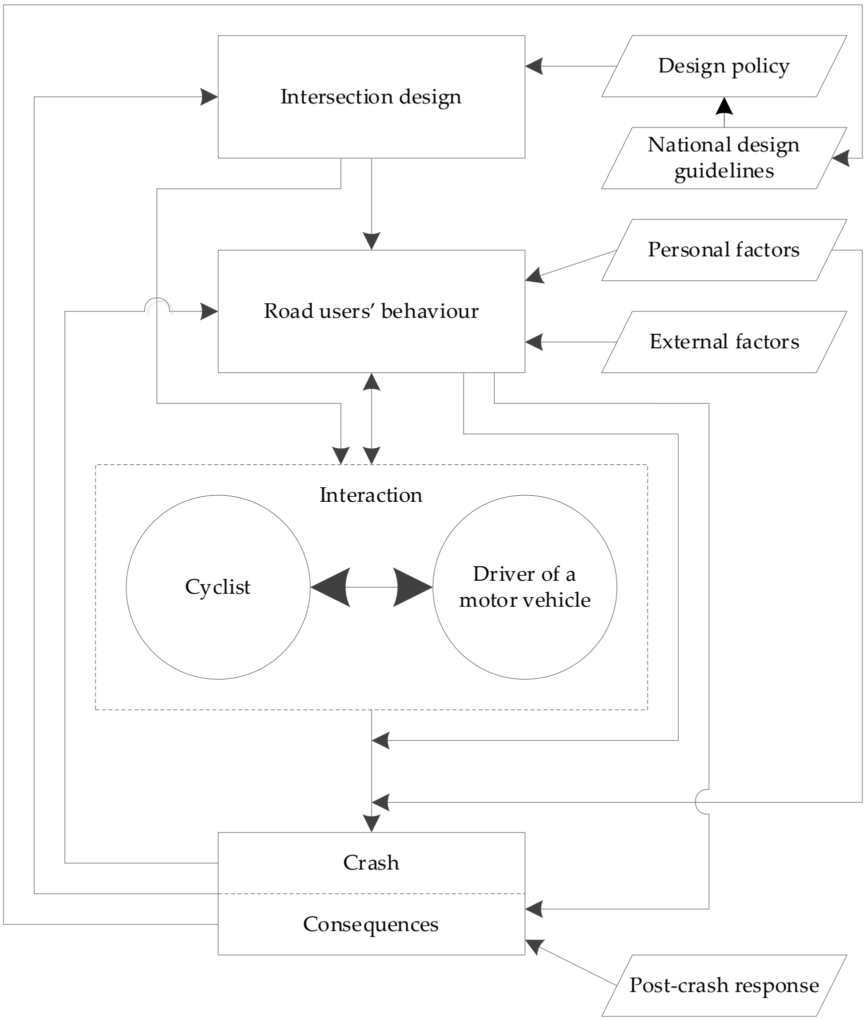


Figure. Conceptual model of the interaction between a cyclist and a driver of a motor vehicle at an intersection, and the relation with crashes and their corresponding impact.

The model presented is considered to be a robust and generic model for describing the interaction between a cyclist and a driver of a motor vehicle at an intersection. There is an important aspect regarding the application of the model, namely the context. The model may work differently in different countries and in different circumstances, so what is in the arrows or in the boxes may be different from what is presented in *Chapter 2*.

Chapter 3 answer the second research question by an explorative crash analysis study of the characteristics of rural intersection crashes. This descriptive study presents an overall picture of casualties occurring at rural intersections in the Netherlands and thereby provides essential background information to determine the focus of *Chapter 4* and *Chapter 5*. In order to do so, characteristics of fatal and seriously (Maximum Abbreviated Injury Score of 2 and higher, MAIS2+) crashes were collected from the database of registered crashes and from hospital data. The results show that the majority of the fatal crashes and serious injury (MAIS2+) crashes involving a cyclist were side-impact crashes. The passenger car is the predominant crash opponent of cyclists. Compared to car drivers, cyclists are not being protected by their vehicle and they have less mass and speed which makes them vulnerable in crashes with motorised traffic. Furthermore, the results of the detailed analysis of fatal rural intersection crashes showed that the majority occurred at priority (give-way) intersections. Only a small proportion occurred at signalised intersections. The examination of crash sites showed that none of the intersections had speed-reducing measures applied to the intersecting arms which makes it possible for motorised traffic to drive through the intersection with driving speeds higher than what is considered to be safe (30 km/h or even lower). Overall, two important conclusions can be drawn: the intersections studied did not meet the criteria for sustainably safe intersection design and that multiple interactions between cyclists and car drivers resulted in impacts leading to serious or even fatal injuries.

Chapter 4 concentrates on research question three whereby the focus is on the factor *intersection design*. In a Dutch case study the relation between intersection design and the road design guidelines was investigated. Road authorities were interviewed on the usage of the national road design guidelines and the actual design of recently reconstructed rural intersections. The results show that the road authorities which were interviewed considered the national design guidelines not to be appropriate when designing intersections which results in the development of own design guidelines. The reason is that they consider the guidelines developed by CROW to be not appropriate when designing intersections in detail. The guidelines they developed themselves are based on the national guidelines and contain detailed information on intersection design such the measures of the intersection elements and road markings. Developing own guidelines did not lead to safer intersections designs compared to the national design guidelines as both guidelines do not oblige the application of speed-reducing measures. The analysis of the design of multiple recently reconstructed intersections shows that these intersections contain solutions or design elements that can be considered less safe from a safety point of view although the road authorities stated to take road safety into account as the most important factor influencing intersection design. None of the reconstructed intersections discussed contain speed-reducing measures which means that motorised traffic can drive through the intersections with driving speeds higher than the safe speeds proposed for traffic situations involving vulnerable road users. Other factors may be more important when it comes to intersection design such as implementation costs or traffic flow.

Chapter 5 addresses the fourth research question which focuses on the factor *road users' behaviour*. In a moving-base driving simulator thirty participants drove three runs each presenting another condition: a baseline run, a run with plateaus applied at each intersection and a run with a chicane applied at the intersecting arm of each intersection. At the intersections, participants encountered cyclists. Therefore, eight cyclist scenarios were developed that varied in the number of cyclists, the direction from which they approached the participants' driving lane and their action (i.e. giving way versus suddenly crossing). Both driving behaviour and mental workload were measured in the experiment. This study focused on how the presence and behaviour of a cyclist affected the driver' speed behaviour and mental workload. The findings show that the plateau was more effective in reducing the drivers' speed than the chicane but the driving speeds obtained were still higher than the suggested safe speeds. When approaching the intersections, it appears that the number of cyclists and the action of the cyclists affected drivers' speed behaviour although these drivers had the right of way at the intersections. At intersections with plateaus, drivers drove slower when they encountered an intersection where multiple cyclists were present compared an intersection without cyclists. The approach direction of the cyclists did not have an effect on the behaviour of drivers which may be explained by the drivers having right of way over the cyclists. So, drivers only needed to take action if cyclists disobeyed the traffic regulations. At intersections without a speed-reducing measure, drivers drove slower, decelerated stronger, and decelerated at a shorter distance to the bicycle crossing when encountering a cyclist that suddenly crossed compared to encountering a cyclist that yielded. At intersections with speed-reducing measures, drivers' speed behaviour and mental workload did not differ between approaching the cyclist yielding compared to approaching the cyclist suddenly crossing. Although the speed-reducing measures lowered the driving speeds of the drivers, their driving speeds and impact speeds were still higher than the suggested safe speeds.

Chapter 6 summarises the results presented in the previous chapters and discusses them by giving an interpretation of the results. Also, implications for the road traffic system are presented. The generic model appeared to be useful for the interaction between cyclists and drivers of a motor vehicle at rural intersections but it can also be applied to other circumstances (e.g. other countries and urban intersections). Two key elements of this model are *road users' behaviour* and *intersections design*. Changing the design of intersections directly influences the behaviour of car drivers at an intersection and the interaction between them and cyclists. It was found that drivers, who approached intersections with lower speeds, were able to deal with a cyclist disobeying the traffic regulations by not giving way to the car driver of the motor vehicle. By designing intersections in such a way that drivers are able to approach and drive through the intersection with driving speeds in accordance to the safe speeds, safe interactions between vulnerable road users and motor vehicles are enabled. Uniformity in intersection design is thereby an essential aspect. It is essential to create safe circumstances for cyclists when crossing rural intersections. First, the possibility of interacting with motorised traffic should be eliminated. Second, driving speeds of motorised traffic should be lowered so that cyclists and drivers of a motor vehicle of motor vehicles can safely interact with each other at rural intersections. As a result, this leads to safer circumstances for cyclists and motorised traffic to collide with each other because of the lower impact speeds.

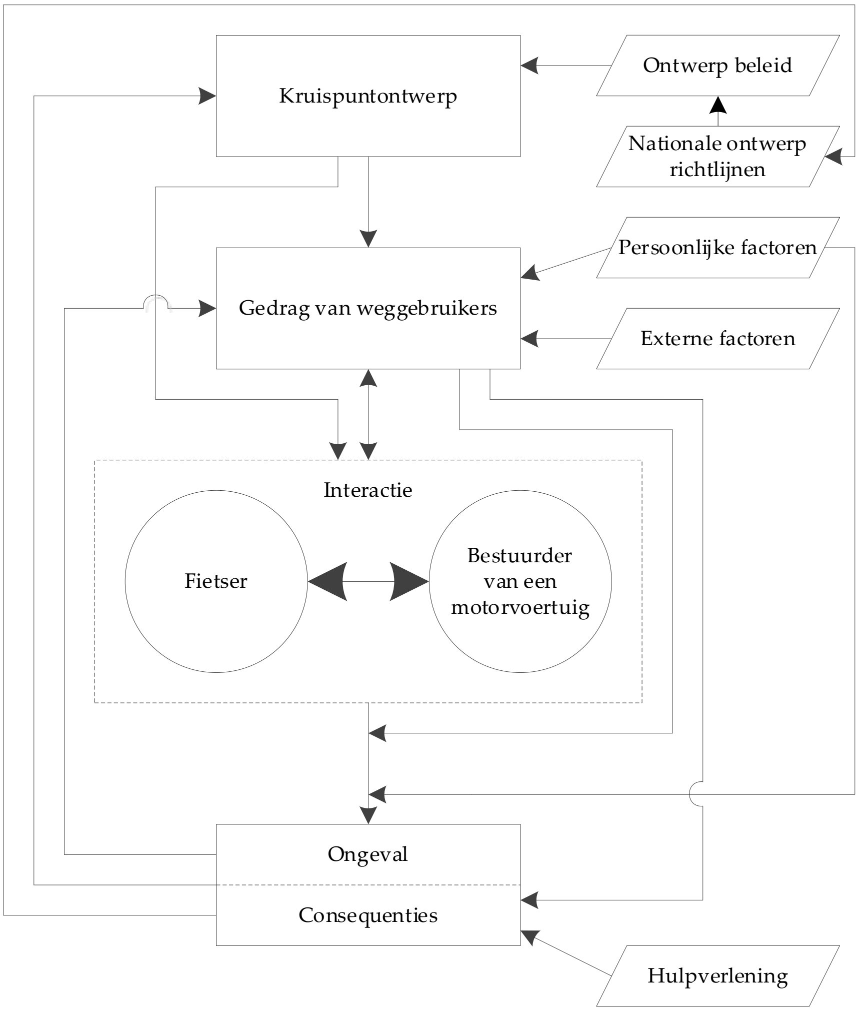
Samenvatting

Het aantal slachtoffers onder kwetsbare verkeersdeelnemers bij interacties met gemotoriseerd verkeer neemt toe wereldwijd en dat is een zorgelijke ontwikkeling. Er wordt veel onderzoek gedaan naar de veiligheid van fietsers maar het merendeel ervan heeft betrekking op fietsveiligheid in de bebouwde kom. Weinig onderzoek richt zich op fietsveiligheid in ruraal gebied en met name de interactie tussen fietsers en gemotoriseerd verkeer op rurale kruispunten is onderbelicht. Ziekenhuisgegevens laten zien dat er in Nederland problemen zijn ten aanzien van de fietsveiligheid in ruraal gebied; om specifiek te zijn op kruispunten waar fietsers en gemotoriseerd verkeer elkaar ontmoeten. De systeemaanpak van verkeersveiligheid (Engels: *Safe System approach*) streeft naar een zodanig ontworpen weginfrastructuur dat fietsers en gemotoriseerd verkeer op een veilige manier met elkaar kunnen omgaan. En dat, mocht er toch een ongeval gebeuren, weggebruikers er geen ernstig letsel aan overhouden. Het verlagen van de maximum snelheden en daarmee ook de gereden snelheden, kan resultaten in lagere botssnelheden in ongevallen. Wanneer botssnelheden zijn afgestemd op wat een menselijk lichaam kan verdragen (Engels: *human body's tolerance*), nemen de overlevingskansen voor kwetsbare verkeersdeelnemers in ongevallen met gemotoriseerd verkeer toe. Hoe weggebruikers zich gedragen én hoe het kruispunt is ontworpen zijn hierbij twee belangrijke factoren. Het onderliggende maatschappelijke doel van dit proefschrift is informatie verschaffen om verkeersveiligheidsproblemen aan te pakken die gerelateerd zijn aan de interactie tussen fietsers en gemotoriseerd verkeer op rurale kruispunten. Het doel van dit proefschrift is om informatie te geven waarmee deze interacties veiliger gemaakt kunnen worden. Hiervoor worden de factoren *gedrag van weggebruikers* en *kruispuntontwerp* bestudeerd. Dit proefschrift richt zich daarom op de rol van de factoren *gedrag van weggebruikers* en *kruispuntontwerp* in de interactie tussen fietsers en bestuurders van personenauto's op rurale kruispunten. De volgende vier onderzoeksvragen worden behandeld:

1. Welke factoren zijn van invloed op de interactie tussen fietsers en bestuurders van personenauto's, en het ontstaan van ongevallen en de ernst van die ongevallen?
2. In welke type ongevallen zijn fietsers betrokken op rurale kruispunten?
3. In welke mate is veiligheid meegenomen in het daadwerkelijke ontwerp van rurale kruispunten?
4. Hoe hebben de aanwezigheid en het gedrag van fietsers invloed op het gedrag van bestuurders op rurale kruispunten?

Dit onderzoek richt zich op bestuurders van personenauto's in de interactie met fietsers omdat personenauto's de meest voorkomende botsende partij zijn van fietsers in ongevallen op rurale kruispunten. Op deze kruispunten moeten fietsers voorrang verlenen aan naderend gemotoriseerd verkeer. Fietsers zijn diegenen die de vermijdingshandeling moeten verrichten, oftewel: zij moeten stoppen om het gemotoriseerd verkeer voor te laten gaan waarna ze hun weg kunnen vervolgen. Bestuurders van gemotoriseerd verkeer zijn in de voorrang op rurale kruispunten maar het is onbekend of en hoe zij reageren op de eventuele aanwezigheid van fietsers wanneer zij een dergelijk kruispunt naderen. Het uitgevoerde empirische onderzoek richt zich op Nederlandse kruispunten op rurale wegen waar een snelheidslimiet van 80 km/h geldt en die kruisen met een andere rurale weg met óf een snelheidslimiet van 80 km/h of van 60 km/h. De kruispunten die bestudeerd worden zijn drie- of viertaks-kruispunten; rotondes worden buiten beschouwing gelaten omdat deze al relatief veilig zijn.

Hoofdstuk 2 behandelt de eerste onderzoeksvraag. Dit hoofdstuk presenteert het theoretisch raamwerk van dit proefschrift. Er is een generiek conceptueel model gemaakt op basis van bestaande literatuur. Dit model beschrijft de verschillende factoren die een rol spelen in de interactie tussen fietsers en bestuurders van motorvoertuigen op kruispunten. Op de volgende bladzijde is het model weergegeven.



Figuur. Conceptueel model van de interactie tussen een fietser en een bestuurder van een motorvoertuig op een kruispunt, en de relatie met ongevallen en de daarbij horende consequenties.

Er zijn twee hoofdfactoren te onderscheiden die de interactie tussen een fietser en een bestuurder van een motorvoertuig beïnvloeden. De eerste is *gedrag van weggebruikers*; deze factor heeft betrekking op het gedrag van zowel de fietser als de bestuurder wanneer deze twee weggebruikers met elkaar interacteren. De tweede is *kruispuntontwerp* en beschouwt het ontwerp van het kruispunt inclusief de omgeving, verkeersregels en verkeerstekens. Deze twee factoren zijn gerelateerd aan elkaar omdat kruispuntontwerp het gedag van weggebruikers beïnvloedt. Aanpassingen in het kruispuntontwerp leiden tot aanpassingen in het gedrag van weggebruikers. Vervolgens wordt ook de interactie tussen deze twee weggebruikers beïnvloed. Een manier om dit te doen is het afdwingen van het gewenste gedrag (zoals de juiste snelheid of kijkrichting). Deze twee hoofdfactoren worden beïnvloedt door andere factoren of determinanten zoals het ontwerpbeleid van een wegbeheerder, nationale ontwerprichtlijnen, persoonlijke en externe factoren. In het geval van een succesvolle interactie kunnen beide weggebruikers hun weg vervolgen. Maar wanneer de interactie niet goed verloopt, kan het leiden tot een botsing tussen de fietser en de bestuurder van een motorvoertuig inclusief de daarbij behorende impact. De botsing en de impact worden beschreven in het onderste deel van het model. In dit deel van het model speelt de factor hulpverlening een rol.

Het gepresenteerde model wordt beschouwd als een robuust en generiek model voor het beschrijven van de interactie tussen een fietser en een bestuurder van een motorvoertuig. Bij de toepassing van het model is er belangrijk aspect dat in ogenschouw genomen moet worden, namelijk de context. Het model kan een andere invulling kennen wanneer het wordt toegepast in andere landen of in andere omstandigheden. Oftewel: de invulling van de pijlen en van de onderdelen kan anders zijn ten opzichte van wat is gepresenteerd in *Hoofdstuk 2*.

Hoofdstuk 3 behandelt de tweede onderzoeksvraag door middel van een exploratieve ongevallenanalyse naar de kenmerken van ongevallen die op rurale kruispunten gebeuren. Deze beschrijvende studie presenteert een overzicht van de slachtoffers van ongevallen op kruispunten in ruraal gebied in Nederland. Dit levert essentiële achtergrondinformatie die helpt bij het bepalen van de focus van *Hoofdstuk 4* en *Hoofdstuk 5*. Om dat te bereiken zijn kenmerken van fatale en ernstige (Maximum Abbreviated Injury Score of 2 and higher, MAIS2+) ongevallen verzameld uit de database met geregistreerde ongevallen en uit ziekenhuisgegevens. De resultaten laten zien dat de meerderheid van de fatale en ernstige (MAIS2+) ongevallen waarbij een fietser betrokken is een flankongeval is. De personenauto is de meest voorkomende botsende partij botspartner van fietsers. In vergelijking met bestuurders van personenauto's zijn fietsers niet beschermd door hun voertuig. Daarbij zijn ze minder zwaar en hebben minder snelheid waardoor ze kwetsbaar zijn in ongevallen met gemotoriseerd verkeer. In aanvulling laten de resultaten van de gedetailleerde analyse van fatale ongevallen op rurale kruispunten zien dat de meerderheid van deze ongevallen gebeurde op voorrangskruispunten. Een klein deel van de ongevallen gebeurde op met verkeerslichten geregelde kruispunten. De bestudering van de kruispunten waarop deze fatale ongevallen gebeurden, liet zien dat geen van de kruispunten snelheidsremmende maatregelen had. Dit maakt het mogelijk voor gemotoriseerd verkeer om de kruispunten te passeren met een snelheid die hoger is dan de snelheid die als veilig beschouwd wordt (30 km/h of zelfs lager). In zijn totaliteit kan worden gesteld dat er twee belangrijke conclusies getrokken kunnen worden: de bestudeerde kruispunten voldoen niet aan de criteria van een inherent veilig kruispuntontwerp en dat meerdere van de interacties tussen fietsers en bestuurders resulteerden in een ongeval met ernstig of zelfs fataal letsel.

Hoofdstuk 4 concentreert zich op de derde onderzoeksvraag die zich richt op de factor *kruispuntontwerp*. In een Nederlandse case studie werd de relatie tussen kruispuntontwerp en de wegontwerprichtlijnen onderzocht. In een interview werden wegbeheerders bevraagd over het gebruik van de nationale ontwerprichtlijnen en het daadwerkelijke ontwerp van rurale kruispunten waarvan het fysieke ontwerp niet lang daarvoor was aangepast. De resultaten laten zien dat de geïnterviewde wegbeheerders de nationale ontwerprichtlijnen van CROW minder toereikend vonden om een kruispunt in detail te ontwerpen. Als gevolg hiervan hebben ze zelf eigen ontwerprichtlijnen gemaakt. Deze zijn gebaseerd op de nationale richtlijnen en bevat detailleerde informatie over het kruispuntontwerp, zoals de maten van allerlei ontwerpelementen en markering. Het opstellen van eigen ontwerprichtlijn leidt niet tot een veiliger kruispuntontwerp in vergelijking met de nationale ontwerprichtlijnen. Beide richtlijnen stellen het toepassen van snelheidsremmende maatregelen niet verplicht. De analyse van recentelijk aangepaste kruispunten laat zien dat deze kruispunten ontwerpoplossingen of -elementen bevatten die minder veilig zijn bekeken vanuit een veiligheidsoogpunt ook al geven de wegbeheerders aan dat zij verkeersveiligheid als meest invloedrijke factor beschouwen die het kruispuntontwerp beïnvloedt. Geen van besproken kruispunten bevatte snelheidsremmende maatregelen. Dit betekent dat gemotoriseerd verkeer het kruispunt kan passeren met een snelheid hoger dan de veilig geachte snelheid behorende bij verkeerssituaties waar kwetsbare verkeersdeelnemers aanwezig zijn. Andere factoren zoals doorstroming of implementatiekosten lijken belangrijker te zijn wanneer het daadwerkelijke kruispuntontwerp wordt bepaald.

Hoofdstuk 5 behandelt de vierde onderzoeksvraag die betrekking heeft op de factor *gedrag van weggebruikers*. In een *moving-base* rijsimulator reden dertig proefpersonen drie ritten die elk een andere conditie representeerde: een rit die als *baseline* fungeerde, een rit waarbij op elk kruispunt een plateau was aangebracht en een rit waarbij er een chicane was aangebracht vlak voor het kruispunt. De proefpersonen kwamen op de kruispunten fietsers tegen. Hiervoor werden acht fietsers-scenario's opgesteld die varieerden in de hoeveelheid fietsers, de richting van waar ze de rijstrook van de proefpersoon naderden en hun actie (namelijk voorrang verlenen of plotseling voorlangs oversteken). In het experiment werd zowel rijgedrag als mentale werkbelasting gemeten. De studie richtte zich op hoe de aanwezigheid en het gedrag van de fietser het snelheidsgedrag en mentale werkbelasting van de bestuurder beïnvloedde. De resultaten laten zien dat het plateau effectiever was in het verlagen van de snelheid van de bestuurders dan de chicane. Desondanks was de gereden snelheid hoger dan de snelheid die vanuit een verkeersveiligheidsoogpunt wenselijk is. Het blijkt dat het aantal fietsers en de actie van de fietsers effect hebben op het snelheidsgedrag van bestuurders die het kruispunt naderen, ook al waren deze bestuurders in de voorrang. Op kruispunten met een plateau reden bestuurders langzamer als daar een meerdere fietsers waren in vergelijking als er geen fietsers waren. De aanrijrichting van fietsers bleek geen effect te hebben op het gedrag van bestuurders. Mogelijk is dit te verklaren doordat bestuurders in de voorrang waren. En hoeven zij alleen actie te ondernemen als fietsers de verkeersregels negeren. Op kruispunten zonder snelheidsremmende maatregelen reden bestuurders langzamer, decelereerden ze harder en decelereerden ze op kortere afstand tot de fietsoversteek wanneer zij een fietser naderden die plotseling overstak in vergelijking met een fietser die voorrang verleende. Op kruispunten met snelheidsremmende maatregelen was er geen verschil in snelheidsgedrag en mentale werkbelasting tussen het scenario met de plotseling overstekende fietser en het scenario waarbij de fietser voorrang verleende. Hoewel de snelheidsremmende maatregelen resulteerde in een lagere snelheid gereden door de bestuurders, zijn deze snelheden alsook de botssnelheden hoger dan de gewenste veilige snelheden.

Hoofdstuk 6 vat de resultaten van alle voorgaande hoofdstukken samen en bespreekt ze en geeft een interpretatie van de resultaten. Ook presenteert dit hoofdstuk de implicaties voor het verkeerssysteem. Het generieke model blijkt geschikt voor de interactie tussen fietsers en bestuurders van een motorvoertuig op rurale kruispunten maar het kan ook worden toegepast in andere omstandigheden (bijvoorbeeld andere landen of stedelijke kruispunten). De twee hoofdelementen van dit model zijn *gedrag van weggebruikers* en *kruispuntontwerp*. Wanneer het kruispuntontwerp wordt aangepast heeft dit direct invloed op het gedrag van bestuurders van een personenauto op een kruispunt en de interactie tussen hen en fietsers. Het bleek namelijk dat bestuurders die een kruispunt naderden met lage snelheid beter in staat waren om om te gaan met een fietser die de verkeersregels negeerde door de bestuurder geen voorrang te verlenen. Wanneer kruispunten op een zodanige manier worden ontworpen dat het voor bestuurders mogelijk is om met een veilige snelheid het kruispunt te naderen en te passeren, dan zijn veilige interacties tussen kwetsbare verkeersdeelnemers en gemotoriseerd verkeer mogelijk. Een belangrijk aspect hierbij is uniformiteit in het ontwerp van kruispunten. Het is essentieel om veilige omstandigheden te creëren voor fietsers die op rurale kruispunten moeten oversteken. Als eerste moet de mogelijkheid om te interacteren met gemotoriseerd verkeer zoveel mogelijk worden beperkt. Als tweede moet de gereden snelheid van gemotoriseerd verkeer omlaag zodat fietsers en bestuurders van gemotoriseerd verkeer op een veilige manier met elkaar kunnen interacteren op rurale kruispunten. Daarmee wordt ook bereikt dat fietsers en gemotoriseerd verkeer veiliger kunnen botsen vanwege de lage botssnelheden.

Dankwoord

Onvoorstelbaar maar waar: mijn proefschrift is klaar! Het ging niet zonder slag of stoot maar de mooie momenten doen de mindere vergeten. Ik ben trots op wat ik heb bereikt. Tijdens mijn promotietraject zijn veel mensen voor mij belangrijk geweest. Ik wil een aantal van hen in het bijzonder bedanken.

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Kirsten
Rijswijk, februari 2021

About the author

Kirsten Duivenvoorden was born on June 6th 1983 in Gouda. After graduating from the Jan van Egmond College in Purmerend in 2001, she went on to study Civil Engineering and Management at the University of Twente in Enschede. By taking a minor in Psychology during the Bachelor of Science programme, she was introduced to the field of traffic psychology. In her Master's programme, she specialised in Transport Engineering and Management and completed her study with an internship at TNO Human Factors in Soesterberg. Her Master thesis focused on the effects of roadside versus in-car speed support for a green wave on driving behaviour and workload. Kirsten obtained her Master of Science degree in 2007.

From 2007 till 2016, Kirsten worked as a researcher at SWOV Institute for Road Safety Research on various road safety projects related to road design and the behaviour of road users. From 2009 till 2016, she was a member of the SWOV in-depth road crash investigation team where she was responsible for the road inspections. In November 2008, Kirsten joined the Transport and Planning Department of the Civil Engineering and Geosciences faculty at Delft University of Technology as a PhD candidate.

Since 2016 Kirsten works as a traffic psychology/human factors advisor at Rijkswaterstaat, part of the Dutch Ministry of Infrastructure and Water Management. With great pleasure she works on many topics in which Human Factors aspects play a role, such as road works on motorways and smart mobility.

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