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Wegman, Fred; Schepers, Paul

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Safe System approach for cyclists in the Netherlands: Towards zero fatalities and serious injuries?

Fred Wegman [a], Paul Schepers [b]

[a] Delft University of Technology, Faculty of Civil Engineering and Geosciences, Delft, The Netherlands
[b] Rijkswaterstaat Water, Traffic and Living Environment, Utrecht University, Faculty of Geosciences, Utrecht, The Netherlands

ABSTRACT

More than one third of all road deaths in the Netherlands and more than two thirds of seriously injured casualties are cyclists. In recent years these shares have increased, despite the fact that the implementation of Safe System principles has been leading in road safety policy and has been successful in reducing the total number of road deaths. However, the annual number of fatalities among cyclists failed to decline and the number of injuries among cyclists has been increasing, especially in single-bicycle crashes. This raises the question why until now Safe System implementation has failed to contribute to the reduction of the number of casualties among cyclists. This question is urgent because of the goal to reduce the number of road deaths and serious traffic injuries in the Netherlands to (virtually) ZERO by 2050. This ambition is in line with the objectives of the European Union. The causes of the unfavourable developments in road safety for cyclists in the Netherlands and which problems require a solution are examined. This raises two questions: can improved implementation of Safe System measures reverse the negative trend, and can this result in ZERO cycling casualties in the future. The discussion involves investigating three dimensions: exposure, crash risk, and injury risk. The opportunities that technological developments may offer in future decades are also considered. It is concluded that Safe System implementation will include opportunities to make cycling considerably safer in the Netherlands. However, we face too many uncertainties to allow for developing scenarios that show how close the Netherlands will be to ZERO cyclists casualties.

1. Introduction

Cycling safety is a major issue in the Netherlands (Ministerie van Infrastructuur en Waterstaat, 2022). This may be related to the fact that the Netherlands is a country of cyclists. Cycling forms an important part of the Dutch road transport and the life of Dutch citizens. Cycling conditions in the Netherlands are excellent: short trip distances in cities, moderate climate, flat terrain, and high quality of cycling infrastructure. Policies of Dutch governments promote cycling: to and from work, to and from school, for recreation, and for sports. However, recent developments of cycling safety are alarming: the numbers of cycling deaths and serious injuries have been increasing in recent years whereas the Netherlands had experienced a reduction in total road fatalities for several decades (Aarts et al., 2022). Dutch road safety policy has set a target for 2050, which is in line with targets set by the European Union: zero road fatalities and serious injuries (Ministerie van Infrastructuur en Waterstaat, 2018). In other words: the Netherlands faces a serious challenge on cycling safety. The present study explores the backgrounds of the decline of cycling safety and investigates options to eliminate fatalities and serious injuries among cyclists in the Netherlands in the coming decades. More specifically, we examine why the Safe System approach has contributed to cycling safety much less than to road safety in general and how this approach can be made more successful in its contribution to the goal of ZERO bicycle casualties in 2050.

1.1. Road safety trends

Measured by the mortality rates, the Netherlands is one of the safest countries worldwide (ITF, 2022) and, like many other high-motorized countries, the Netherlands has made much progress over the years. Fig. 1 presents the total number of fatalities (1970–2020) at ten-year intervals for a selected number of countries. A substantial reduction can be observed in all countries.

Half of the countries – all European countries and Japan – reduced the number of road fatalities by 80 % or more in 50 years. This performance is even more impressive if we consider that the number of inhabitants and the number of kilometres travelled increased substantially over this period, implying that the rates (mortality rate per inhabitant and fatality rate per kilometre travelled) declined considerably. Although this trend was positive overall in the Netherlands, it was not the same for all traffic modes. According to official statistics the share of cyclist deaths in total road deaths doubled from 19 % in 1996 to 39 % in 2022.

The progress made in reducing the number of road fatalities in high-motorized countries during the past decade (2010–2020) has been less than in earlier decades (ITF, 2022). Concerning the development in the number of seriously injured the total picture is not very clear. First of all, we face the problem of different definitions of serious injuries in road crashes and, secondly, underreporting varied among countries, also in the European Union (European Commission, 2021a). However, some

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progress has been made in recent years, especially in the European Union. The EU decided to include serious injuries in its targets for 2030, as agreed upon in the Valletta declaration on road safety of 2017. The Union also agreed on a harmonized definition: a serious road injury is defined as a road traffic casualty with an MAIS (Maximum Abbreviated Injury Scale) score of 3 or higher (MAIS3+). It is estimated that for every life lost in the EU five more people suffer serious injuries (European Commission, 2021a). Tingvall et al. (2013) argued that by focussing on MAIS 3+ (mainly based on a threat-to-life approach), long-term consequences in AIS 1 and AIS 2, that might lead to impairments, are neglected. This is correct, but in accordance with definitions of the European Union and the Dutch Government we present MAIS 3 + figures in this paper.

1.2. The Dutch Safe System approach

The Safe System approach was launched in the Netherlands under the name Sustainable Safety (Koornstra et al., 1992), but we decided to depart from that name and to use the international term Safe System approach. As yet, two updates have been published (Wegman and Aarts, 2006; SWOV, 2018). The main idea of a Safe System approach is to create an environment for road users that eliminates or drastically reduces crash risk and, in case the elimination of crash risk is not (yet) realistic and crashes still occur, to reduce risks of serious injury (Wegman et al., 2022). The environment of the road user is first of all defined by the road infrastructure (including road sides) that should be adapted to the limitations of human capacity by proper road design. Secondly, it is defined by vehicles fitted with tools to simplify the human tasks and constructed to protect the vulnerable human being as effectively as possible. Thirdly road users are adequately educated, informed, and, whenever necessary, controlled. If crashes still occur, serious injury must be prevented. A Safe System involves a pro-active approach based on understanding inherent risks in road transport that should be prevented before crashes begin to occur. Finally, a shared responsibility exists amongst those who use roads and those who design, build and manage the transport system components (roads, vehicles, technologies, post-crash care). The Dutch Safe System approach is presented in more detail in Wegman et al. (2022).

The Safe System approach has been translated into a set of principles. After Koornstra et al (1992), also referred to as 'the purple book', the second version was published in 2005 in Dutch, and in English in 2006 (Wegman & Aarts, 2006), a third edition was published in 2018 (SWOV, 2018). The principles in these three different versions are very similar. The focus of the first two versions are on Safe System design only, the third edition adds two organizational principles: effective allocation of responsibility and learning and innovation in the traffic system (see SWOV, 2018; Wegman et al., 2022).

Strong emphasis (perhaps even its core) in the Dutch approach has been on creating a *Safe* Infrastructure (a *Safer* Infrastructure was no longer the goal) in which the most important lines of thought were (and are) to eliminate 'latent errors' in the system (or 'holes in the slices of cheese') (Reason, 1990) and to eliminate exposure to risk and crash risks. Speed management was a key element, including setting safe and credible speed limits supported by infrastructural measures. With respect to safe vehicles, it was decided to rely on international progress resulting from vehicle regulations drafted by the United Nations in Geneva (WP.29), European vehicle directives and results from EuroNCAP. Traffic enforcement (including campaigns) was also considered to be crucial, as long as far-reaching intelligent systems (such as alcolocks; alcohol ignition interlocks) are not effective (yet). Of the enforcement activities general deterrence was considered to be the main driver, supported by a significant increase in the objective probability of detection (the actual chance of being caught when committing an offence).

Implementation of interventions during the period 1998–2007 is well documented. In the publication 'Ten years of Sustainable Safety; Road Safety Assessment 1998-2007′ Weijermars and van Schagen (2009) reported on this issue in great detail. It was concluded (Weijermars & Wegman, 2011) that all measures together prevented 32 % to 34 % of the fatalities in 2007 than were expected without these measures. A cost-benefit analysis also indicated that the measures were cost beneficial (benefit-cost ratio 3.6:1). These outcomes show the benefits of the Dutch Safe Systems approach and its implementation to road safety. Mainly based on data of road fatalities, the researchers concluded that the full potential of Safe System had not been exploited. For that reason they recommended to implement more interventions in a more comprehensive way and to maintain a better quality of some interventions.

Weijermars et al. (2013) looked in more detail at the effects of the implementation of Sustainable Safety measures on serious road injuries.

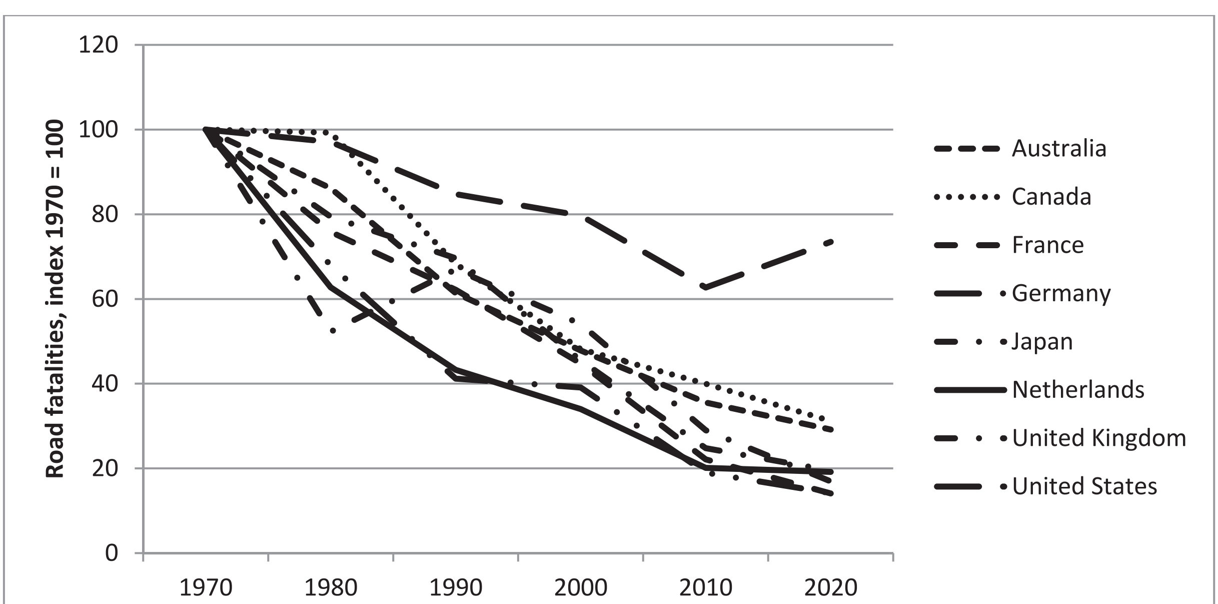

Fig. 1. Long-term trends in road fatalities 1970 – 2020 (index 1970 = 100) for a selected number of countries that made data available to the IRTAD-database from ITF.

The conclusion was that the number of serious road injuries in Dutch traffic decreased less than the number of fatalities. Firstly, this may be due to Sustainable Safety not only focusing on the prevention of crashes, but also on the severity of the injuries. A very critical component of Sustainable Safety is the lowering of impact speeds (Wegman et al., 2023). It is widely known that the lowering of impact speeds has a greater impact on the number of fatalities than on the number of serious injuries (Nilsson, 2004; Elvik, 2009; IRTAD, 2018).

Secondly, and even more important for the current study, the Sustainable Safety vision lacked a focus on crashes not involving motor vehicles, mostly crashes involving cyclists. During the period 1993–2009, the number of serious injuries in crashes involving motorized vehicles decreased from 12 000 to 9 000 in the Netherlands, while serious injuries in crashes not involving motorized vehicles increased from 6 000 to 9 000. These trends continued in following years, so that by 2021 the majority (63 %) of seriously injured road users were casualties of crashes without motor vehicle involvement (Aarts et al., 2022). The main explanation given for this discrepancy is that many serious road injuries occur in crashes not involving motorized vehicles and that Sustainable Safety did not explicitly pay attention to these types of crashes (Weijermars et al., 2013). It is crucial to understand that the overwhelming majority (more than 90 %) of the crashes resulting in serious injuries not involving motorized vehicles are bicycle crashes and the far majority of these crashes are single-bicycle crashes.

1.3. Towards ZERO bicycle casualties

Dutch policy aims for ZERO road casualties (fatalities and serious injuries) in 2050 (Ministerie van Infrastructuur en Waterstaat et al., 2018). SWOV (Weijermars et al., 2018) estimated that an annual reduction of almost 11 % would yield approximately 20 road deaths in 2050. In the years 2000–2010, the average annual reduction was 4 %. This implies that the Netherlands needs to improve its performance considerably in future decades to arrive at (almost) ZERO in 2050.

Cycling safety presents an even greater challenge for the future. Not only can an upward trend for cyclist fatalities be observed in the past decade (+3%), but also an increasing share in road fatalities (from 32 % in 2013 to 36 % in 2021 and 39 % in 2022). Furthermore we can observe an upward trend in serious injuries (MAIS3 +) of 2.5 % annually. This means that cyclists form a very substantial part (71 %) of these serious injuries. A major part of these are cyclists injured in crashes without involvement of a motorized vehicle (Aarts et al., 2022).

This brings us to the main aim of this study: to describe how to reduce the number of cyclist casualties (fatalities and serious injuries) from the current numbers to ZERO in 2050. This research explores options for improvement of cyclist safety using the Safe System approach. It does not touch on topics such as cost-effectiveness, implementation issues, public acceptance of interventions, political support etc.

Obviously, the aim of ZERO bicycle casualties will not be reached without taking additional road safety measures, but it is of relevance to answer the question "What will the road transport system look like in 2050?" It is barely possible to predict exactly how road traffic will develop over the coming decades: transport of passenger and freight, individual motorized transport, active transport modes, public transport, petrol/diesel cars, plug-in hybrids and electric cars. How will climate change influence road transport and will future technologies offer options for sustainable and safe mobility? Also, will automated vehicles penetrate the market and which automation levels can be expected (SAE, 2021)? Transport technologies have drastically changed road traffic over the years (Annema, 2023) and will continue to shape the future of road transport. It is clear that developments will be different in the Netherlands (with its high densities of activities, high quality and heavily used road network, and high bicycle modal share) than in other countries like the US and Australia, or countries where currently motorized two wheelers are dominant (Asia, Latin America and Africa).

We shall introduce some assumptions as a starting point for this research: road traffic in 2050 will be a combination of motorized vehicles and active transport modes, mainly on the current road infrastructure. Using a scenario-approach it was made plausible that more automation will be applied, although it is not to be expected that the entire fleet in the Netherlands will be fully automated in 2050 (Milakis et al., 2017). It is expected that penetration of vehicle automation will be slower in the complex urban environment and that cycling will remain an important part of active modes.

To explore options for changing/improving road safety we use a simple, well-known model in road safety developed by Kåre Rumar from Sweden (1999), followed by Göran Nilsson (2004). They proposed to consider the size of the traffic safety problem as the product of three dimensions:

- exposure to risk (E);
- crash risk (C/E: number of crash per exposure);
- injury risk (I/C: number of people killed or injured per crash).

If we want to attain ZERO, at least one of these three dimensions should be ZERO. In 2050 this will not be exposure in terms of kilometres cycled. Currently, Dutch policies try to promote cycling for economic, social, environmental and health benefits. As it is relatively cheap, increases in accessibility, especially of city centres, has almost no impact on the environment because it produces no noise and no greenhouse gas emissions, and last but not least, it reduces the risk of all-cause mortality (Kelly et al., 2014, and de Hartog et al., 2010) showing that the health benefits outweigh the risks of being injured in a road crash.

This brings us to the next dimension: crash risk. It is helpful to make a distinction between fundamental risk factors in traffic and risk-increasing factors (Wegman & Aarts, 2006). Fundamental risk factors are inherent to road traffic and are a combination of factors such as speed and mass (and the resulting kinetic energy in a crash) combined with the vulnerability of the human body. Fundamental risk factors play a role in all crashes. In addition to fundamental risk factors we face risk-increasing factors caused by, or at least related to road users. These factors are, for example, lack of driving experience, use of psycho-active substances such as alcohol and drugs, illnesses and ailments, emotion and aggression, fatigue and distraction (Wegman & Schepers, 2023).

The vulnerability of the human body is to be considered a fundamental factor because it is of relevance for all crashes. The first line of defence to reach ZERO casualties is to eliminate exposure to risk (and as indicated above this is not the same as the exposure measured by the number of kilometres travelled) and crash risk. If this is successful, elimination of injury risk is no longer required anymore. But, because a guarantee of ZERO crash risk is highly unlikely, it is also necessary to work on the elimination of injury risk. This is illustrated in the Swiss Cheese model of crash causation (Fig. 2, Reason, 1990) in which many layers of defence should be created between hazard and crashes.

An ambition of ZERO casualties (or close to ZERO casualties) require ambitious interventions. But it is also necessary to describe the expected safety impacts of certain interventions in a quantitative way in order to be able to conclude how much certain packages of interventions will contribute to reach this goal. Enough knowledge, enough good data and evaluation results of interventions that improve safety of cyclists are key ingredients for underpinning ambitious policies. Two sections (4 and 5) discuss the (current) knowledge and whether it is strong enough, whereas Section 4 looks into the history and Section 5 looks into the future.

1.4. Research questions and organisation of this paper

This study focusses on cycling safety, and tries to answer three questions: why the implementation of Dutch Safe System was relatively unsuccessful for cyclists in the last few decades (RQ 1) and secondly whether the Safe System approach nevertheless presents enough

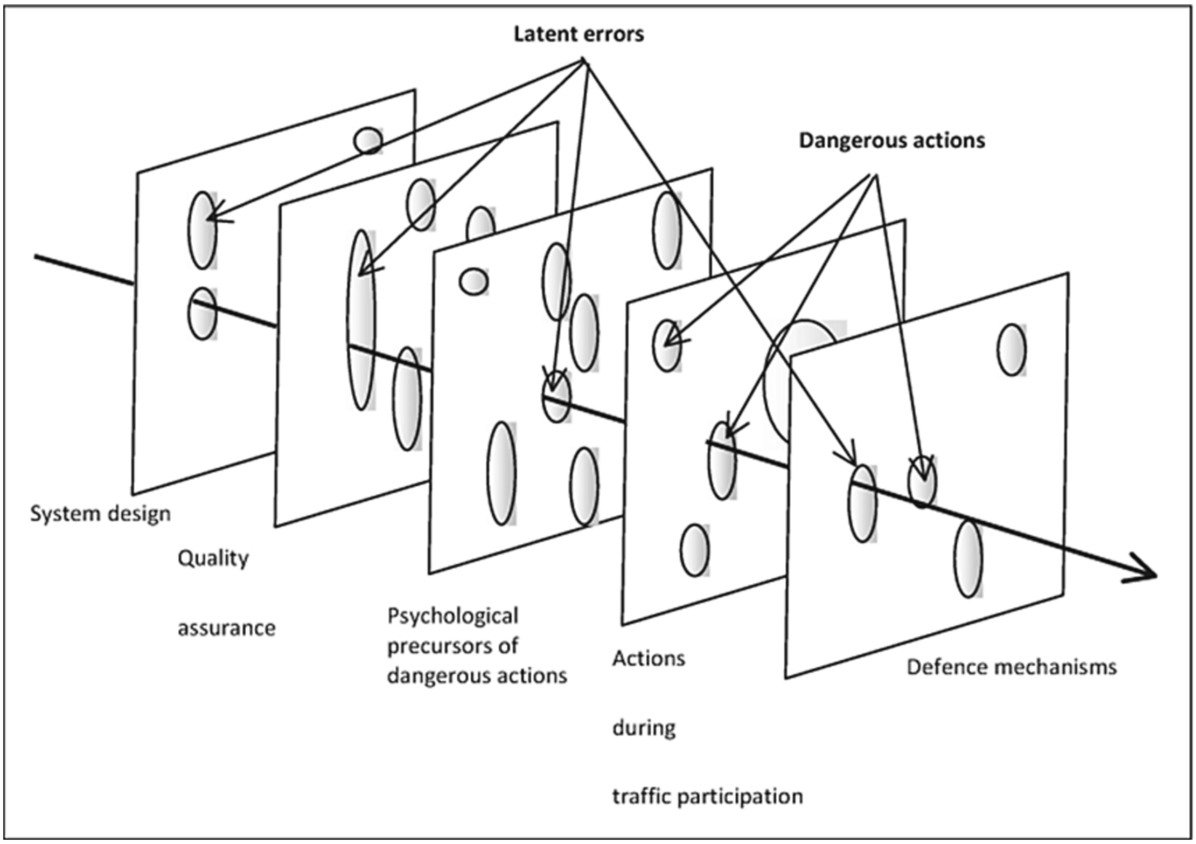

Fig. 2. The development of a crash (bold trajectory) as a result of latent errors and dangerous road user actions, also known as the Swiss Cheese model. Source: Wegman & Aarts, 2006 adapted from Reason, 1990.

opportunities for substantially reducing the number of cyclist casualties (RQ 2). The third question is how to reach ZERO casualties (fatalities and serious injuries) among cyclists in 2050 and how and how quantitative information can be used when developing policies (RQ 3).

This study approaches the issue from different angles. It starts with describing the road safety problem of cyclists (Sections 2 and 3), whereas Section 2 gives a broad outline of the problem and Section 3 discusses causes of bicycle crashes. Section 4 discusses the results of what has been done to reduce the number of bicycle casualties by implementing Safe System interventions (RQ 1). Section 5 deals with interventions, fitting in the Safe System approach, that could be considered in the coming decades (RQ 2). The manuscript closes with a Discussion (Section 6) and a set of conclusions and recommendations (Section 7). These two sections address the third research question (RQ 3).

2. Cyclists in the Netherlands

2.1. Bicycles, cyclists and bicycle facilities

On a population of 17.7 million Dutch inhabitants the total bicycle park is estimated to be around 23.4 million, and 15 % of bicycles (3.4 million) are estimated to be e-bikes (BOVAG-RAI, 2023). In the last few years about one million new bicycles have been bought annually, and 57 % of these new bicycles are e-bikes, and their share is increasing. Annually, a Dutch citizen travels about 1000 km by bike. Distance cycled per capita has hardly changed over the past decades (Schepers et al., 2021).

With some 1,000 kms cycled per capita per year, the Netherlands is a frontrunner: in 2014–2017 the annual distance cycled was about 50 % higher than in the second country, Denmark, and ten times higher than in the US and in the European countries with the lowest bicycle use (Schepers et al., 2021; Buehler et al., 2020). The mode share for cycling for all trips is 26.8 % for the Netherlands (Goel et al., 2022) and this is two to three times higher than for the countries with the next highest shares.

Average bicycle use fails to show some major shifts. The aging population and the fact that the elderly continue to cycle longer, are the reasons why an increasing proportion of the total distance cycled is by the elderly, see Fig. 3. In 2021 nearly half of the total distance travelled was covered by cyclists older than 50 years of age. This trend is particularly important for road safety as older cyclists are particularly vulnerable if they are involved in a crash. In addition, bicycle use is growing in large cities while decreasing in rural areas (Harms et al., 2014).

We can observe a growing variety in bicycle types (traditional bike, sports bike, racing bike, e-bike, cargo-bike, fatbike, bike transporting children etc.) in Dutch traffic. This is relevant to road safety because of the different characteristics of these different bicycle types, such as different cycling speeds and related risks.

With a share higher than 90 %, classic bicycles without or with electric pedal support were dominant in traffic on cycle paths in the Netherlands approximately one decade ago (de Groot-Mesken et al., 2015). Recent data is not available, but observations in traffic suggest a growing share of non-classic bicycles, especially e-bikes. Some speed pedelecs can also be observed, although their numbers - almost 30 000 - are small in comparison with the 3.4 million e-bikes (BOVAG-RAI, 2023).

It is estimated that over a quarter of the total number of bicycle kilometres were travelled on e-bikes (KiM, 2020). And this share is growing, especially the kilometres travelled by older (>65 years) cyclists. There are also a growing numbers of non-standard bicycles, each with a small share. For example, the Netherlands had about 125,000 cargo bikes used to transport goods or children in 2021 (Wolff and

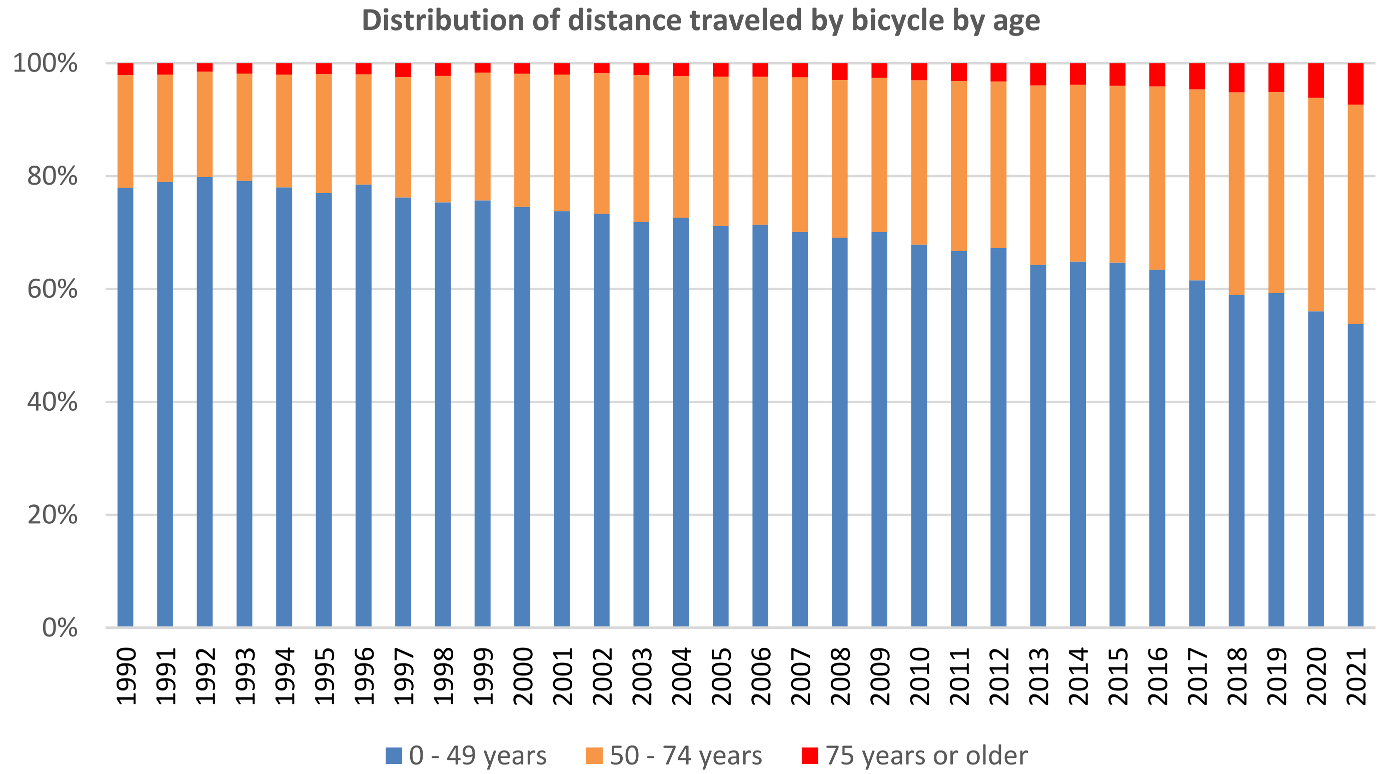

Fig. 3. Distribution of distance cycled by age group according to the Dutch National Travel Survey (edited by SWOV with estimate for bicycle use young children).

Knigge, 2022). Mopeds with a 25 km/h speed limit have a substantial share as well, but their sales and their numbers have been declining since the introduction of a mandatory helmet use on January 1, 2023.

The Netherlands is not only a country of bicycles, but, consequently, also of bicycle facilities. A distinction can be made between cycle streets (motorized vehicles allowed, but advised to behave as guests), stand-alone cycle tracks, physically separated cycle tracks and visually separated bicycle lanes). National Statistics report about 140,000 km of paved road length and 38,000 km of cycle tracks. See Fig. 4 for an impression of cycling and cycle facilities in the Netherlands.

2.2. *Bicycle crashes and casualties*

It is useful to provide some more general information on crashes and injuries for a good understanding of road safety problems of cyclists in the Netherlands as a basis for design policies and interventions to reach ZERO cyclist casualties in 2050.

One of the differences among countries is the definition of a bicycle crash. In the Netherlands a road crash is defined as a collision or incident on a public road (or a private road to which the public has right of access) that results in damage to objects and/or injury to people and that involves at least one vehicle in motion. Please note that this is not necessarily a motorized vehicle. The last part of this definition is very

Fig. 4. Photographs of some bicycle facilities and cyclists (clockwise): cycle street ('car as a guest'), fietsstraat, cargo-bike, turbo roundabout with separated bicycle tracks, urban cycle track, bicycle box, and fatbike.

important for cyclists, because this means that single-bicycle crashes are considered to be traffic crashes in the Netherlands. This is not the case in every country in the world. The United States, for example, defines an incident only as a road crash if one or more motorized vehicles are involved, meaning that single-bicycle crashes are not defined as a road crash.

In the Netherlands, serious road injuries are defined as casualties who have been admitted to hospital with road injuries with a severity of 3 or higher on the medical injury scale AIS (MAIS3+), and who have not died within 30 days after the crash. The number of seriously injured cyclists has shown a mostly upward trend in recent decades. In 2021, 71 % of the seriously injured road casualties in the hospital registration were cyclists.

Based on information in Section 2.1., it will not come as a surprise that the share of cyclists in crash statistics in the Netherlands is not only high, but also higher than in any other country worldwide (see for example ITF, 2022).

In the year 2022, 39 % of all Dutch road fatalities were cyclists and 30 % were car occupants. If we consider the last few decades, it is remarkable that the number of car occupant fatalities came down from 600 in 1996 to 200 in 2022, whereas the number of cyclist fatalities remained at approximately the same level in the same period (see Fig. 5).

Almost one in three of the cyclist fatalities was an e-bike rider. As yet there is no convincing evidence whether riding an e-bike is more hazardous than riding a regular bike after controlling for age and gender: some studies do and others do not report an increased risk for e-bike riders. This is remarkable considering that e-bike riders travel faster than traditional cyclists, and higher speeds are associated with higher risks. It is documented (Fishman & Cherry, 2016 and KiM, 2020) that the e-bike contributes to older people continuing to cycle into old age and also to cycling more frequently and longer distances. Thus, paradoxically – and unlike car drivers – the older, more vulnerable cyclists travel more kilometres (see also Fig. 3). It is recommended to carry out more research on whether e-bikers travel under lower risk conditions than cyclists on other bicycles.

Fatality rates for cyclists can be estimated by dividing the annual number of fatalities by the yearly travel distance (kms). Although data quality and comparability is problematic for international comparisons (e.g. Castro et al., 2018) we can conclude with reasonable certainty that the Netherlands has one of the lowest cyclist fatality rates, if not the lowest. Unfortunately, we must conclude that a relatively low risk (per kilometre travelled) when combined with relatively many kilometres travelled and with a high proportion of elderly cyclists (associated with a high proportion of e-bikes) results in a substantial road safety problem in the Netherlands. It is an increasingly dominant road safety problem, both for fatalities and for serious road injuries.

Casualty rates among older cyclists in particular are growing. "The sharpest rise in traffic fatalities was seen among cyclists aged 75 years and over" was the heading of Statistics Netherlands' press release publishing 2022-data on road fatalities. Table 1 presents the age distribution of fatalities for several age groups and two travel modes: car occupants and cyclists.

The age distributions of cyclist and car occupant fatalities are completely different: 85 % of all cyclist fatalities are older than 50 and 51 % are older than 75 years of age. In contrast for car occupants: 60 % are younger than 50 years and 40 % are older than 50 years of age.

Head and brain injuries are rather common among cyclists. Based on data (2011–2016) from Statistics Netherlands (Weijermars et al., 2019) it was estimated that 64 % of all cyclist fatalities sustained head and/or brain injury and this percentage is 82 % for children (0–11 years). Almost one-third of all cyclists with serious injuries after a crash have sustained head or brain injury. In bicycle crashes involving motorized vehicles, the share of cyclists sustaining head or brain injury was as high as 47 % and in bicycle crashes without involvement of motorized vehicles, over a quarter of cyclists suffered from head or brain injury (28 %). Head and brain injury indicates brain injury in 86 % of the cases, while the remaining 14 % concern injury to the head without damage to the brain.

2.3. *Single crashes vs. crashes with one other party involved*

According to Dutch hospital data, over 80 % of all seriously injured cyclists (MAIS3+) were involved in crashes without motorized vehicles, most of these being single-bicycle crashes (Aarts et al., 2022). According

Table 1
The number of fatalities in the Netherlands in 2022; total, cyclists and car occupants.

Age groups	< 25y	25 – 50y	50 –75y	>75y	Total
Total	111	149	216	269	745
Cyclist	26	18	98	148	290
Passenger car	46	83	44	48	221

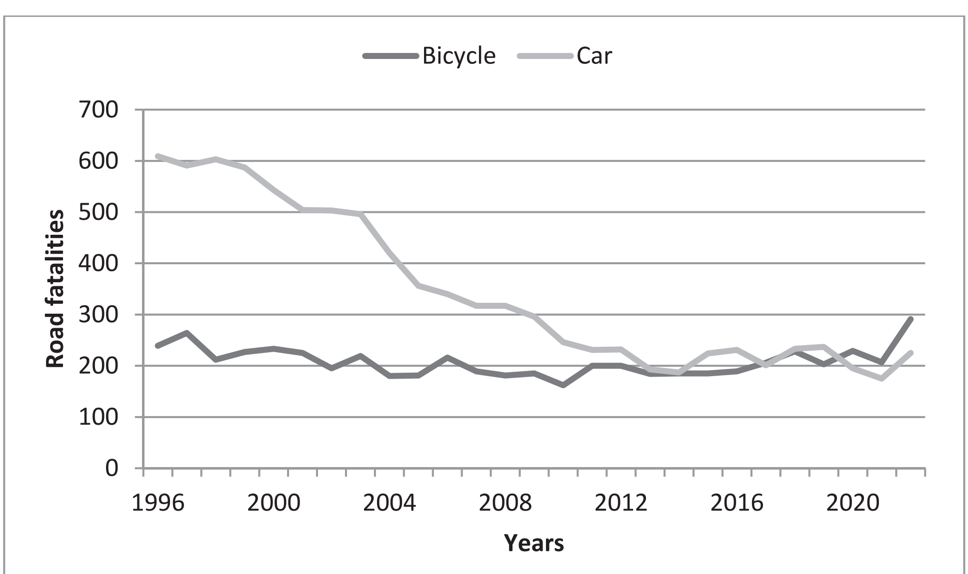

Fig. 5. Development of the number of road fatalities for car occupants and cyclists (1996 – 2022).

to two international reviews, the proportion of single-bicycle crashes among cyclist casualties treated at emergency departments or having been admitted to hospital after a crash ranges from 50 % to 95 % across countries. This range has remained fairly constant over time (Schepers et al., 2015; Utriainen et al., 2023).

It is important to understand that fatal bicycle crashes differ from bicycle crashes resulting in (serious) injury. Some data from the Netherlands illustrate this (Aarts et al., 2022): 55 % of all fatalities amongst cyclists in 2021 were in a collision with a motorized vehicle and 45 % were not. However, 18 % of seriously injured casualties were in a collision with a motorized vehicle and 82 % in other crash types.

To conclude: measured by the number of bicycles per capita or the modal share of cycling and the number of kilometres travelled we may conclude that worldwide the Netherlands is a cycling champion. However, this is also reflected in the official crash data. While the cyclist fatality rate is low by international standards, the high amount of bicycle use results in a considerable share of cyclists in road fatalities (40 %) and extremely high share in serious injuries (71 %). Cycling safety is mainly a problem of older cyclists (85 % of all cyclist fatalities are over 50 years old, 51 % are older than 75 years). Official police statistics and hospital registrations are not very informative about crash causes, about crash types or circumstances of crashes. The next section provides more information on that issue.

3. Causes of bicycle crashes

This section describes cycling safety in the context of the Safe System approach and provides a foundation with knowledge about causes of bicycle crashes.

3.1. Crash causes and their connection with the Safe System approach

Underreporting of crashes in official police registration is a known problem worldwide, in the European Union and in the Netherlands (WHO, 2018, ETSC, 2018, Aarts et al., 2022). It is also known that the less severe the consequences of a crash, the lower the reporting rate, and that the underreporting rate for cyclists is higher than for any other transport mode, especially when no motorized vehicle is involved (Shinar et al., 2018). This culminates in a dramatically low 4 % reporting rate of single-bicycle and bicycle-bicycle crashes in the Dutch police registration (Reurings & Stipdonk, 2011). Even with a more complete registration of bicycle crashes, crash causation studies based on police-reported crashes cannot result in valid and reliable results. As Shinar rightfully stated (Shinar, 2019), it is not a police task to determine the causes of a crash, but to determine whether and to what extent a traffic offence has been committed (illegal behaviour) and who was the guilty or the innocent party in the crash. This information is also used to determine whether behaviour was inappropriate and if a person involved could be held liable for the crash consequences. Therefore, it is not surprising that "human error" emerges as a cause in 90 % of the databases based on police registration of crashes. Furthermore, it is common practice for the police to record only factors present at the crash scene (Hauer, 2020). It is also of interest to understand Hauer's analysis of crash causation based on a new definition that links causes to remedial actions ("*A Crash cause is a circumstance or action that, were it different, the probability of crashes to occur and/or their severity would be different*"). This point of view is not completely new as the distinction between direct crash causes (immediately prior to a crash) and latent factors (or system failures) was already made decades ago by Treat et al. (1979) and Wagenaar and Reason (1990). And this is exactly the point made by Hauer: when we want to improve road safety there is no need to restrict efforts to direct crash causes only, but also to identify and eliminate 'latent errors' in the system. By doing so, it is expected that the result will be a departure from *a single cause of a crash only* (as reported by the police in many crash forms) and from the *90 % human factor-idea* (Shinar, 2019).

Therefore, if we accept Hauer's definition, for 'action' we could include all the slices of the Swiss cheese model as proposed by Reason (1990), including the slices not related to human behaviour just before a crash. The Swiss cheese model was visualised by Wegman & Aarts (2006) to illustrate the Safe System approach; this is also in line with the approach developed by Leveson (2011). See for example her book 'Systems thinking applied to safety' and her model called STAMP (Systems-Theoretic Accident Model and Processes). This is an accident causality model based on systems theory and systems thinking as used in industry and elsewhere (see for example Zhang et al., 2022).

The perspective on crash causes as presented here is a founding layer for developing the Safe System approach in the Netherlands. This view seems to be accepted these days (see for example ITF/OECD, 2008), but it was sacrilegious in the early nineties when 'blaming the human being' was the dominant way of thinking based on the idea that more than 90 % of road crashes were caused by humans and their errors.

3.2. Bicycle crash types

If we want to learn more about factors and circumstances of road crashes and their consequences we can look for crash patterns and classify/categorize them. This results in a taxonomy of crash patterns. Due to the underreporting and bias problem of bicycle crashes in official police data, this should be done by using other methodologies like in-depth studies. Several attempts have been made for crashes with cyclists (e.g. Schepers & Klein Wolt, 2012, Boele-Vos et al., 2017, Ohlin et al., 2019). They worked with different types of databases, different selection of crashes (age groups, crash types) different severities of injuries etc and research methods ranging from a site inspection of the crash location to interviews with casualties. These approaches have resulted in a different perspective on the problem of cycling safety. The dominant picture confirms the results from the Netherlands: serious injuries are primarily the result of single-bicycle crashes, fatal crashes are mostly crashes with motorized vehicles, and to a far lesser extent single-bicycle crashes and crashes with other vulnerable road users. Last but not least, crashes with motorized vehicles are more serious for cyclists than other crash types (Schepers et al., 2015).

In-depth research by Boele-Vos et al. (2017) yielded important insights on crash types involving cyclists and some of their characteristics. The research arrived at eight crash types of cyclists aged 50 and over who were involved in a single-bicycle crash or a collision with another road user travelling at a low speed (pedestrian, cyclists, moped rider or light-moped rider). See Table 2.

The researchers added some characteristics to each crash type: which specific groups were involved (e.g. age group, gender, type of bicycle) and which common contributory factors were involved (e.g. behaviour of other road users, discontinuity of road design, unusual road design, saddle too high, sight restriction etc.). This type of information is very rich when it comes to 'direct causes', but it also gives great insights into

Table 2
Identified crash types of cyclists aged 50 and over who were involved in a single-vehicle crash or a collision with another road user travelling at a low speed (pedestrian, cyclists, moped rider or light-moped rider); Source Boele-Vos et al., 2017).

Cyclist loses balance while riding or stopping and dismounting on a slope
Cyclist veers off course unintentionally and hits the kerb or runs off the road
Cyclist encounters unexpected road furniture (e.g. bollard) on the bicycle track or carriageway
Distracted cyclist veers off course and collides with oncoming traffic or runs off the road
Cyclist underestimates the complexity of the traffic situation
Cyclist does not give or get given right of way in a traffic situation with a restricted sight distance
Cyclists misunderstand each other's intentions while overtaking
Cyclist ends up in an unforeseeable situation that was created by someone who was not taking part in traffic

the challenges ahead when developing countermeasures to eliminate 'latent errors' in the road transport system. The study of Boele-Vos et al. (2017) used a small sample size and worked with a relatively narrow focus. It is recommended to carry out more of this type of studies to add to our understanding of crash causation. Studies using results from naturalistic cycling are also recommended to increase the understanding of causes of bicycle crashes and policies to increase cycling safety (Dozza & Werneke, 2014).

Schepers & Klein Wolt (2012) studied *direct causes* (causes observed just prior to a crash) of single-bicycle crashes using information from a questionnaire filled out by cyclists treated at Emergency Care Departments in the Netherlands. Answers were used to categorize crashes according to a crash typology based on literature on single-bicycle crashes. The results were compared and discussed to arrive at a final categorization (percentages of the single-bicycle crashes in the sample between brackets):

- Infrastructure-related crashes (58 %)
- Collisions with an obstacle (12 %) or riding off the road (21 %)
- Slippery road surface (18 %)
- Loss of control due to uneven road surface or loose object (7 %)
- Cyclist-related crashes (45 %)
- Loss of control at low speed, e.g. while (dis)mounting (16 %)
- Loss of control due to forces on the front wheel or handlebars (8 %)
- Loss of control due to riding behaviour (21 %)
- Bicycle malfunction (5 %)
- Other or unknown (12 %)

3.3. Latent bicycle crash and injury factors

Using the above described crash typologies and theoretical knowledge on bicycle stability and biomechanics, we can identify latent bicycle crash and injury factors. Recent studies (Ohlin et al., 2019, and overview by Utriainen et al., 2023) by and large confirm the findings of Schepers & Klein Wolt (2012), although, because of the different settings and methods used, other researchers find different distributions.

Two factors are critical. First of all, and as all cyclists know, bicycles are balance vehicles: losing balance can happen just like that. Anything may make you lose control and fall off the bike, or be involved in a collision with a fixed object, another cyclist or with a motorized vehicle. A cyclist can lose control when braking inadequately, when correcting a travel course abruptly, or when mounting or dismounting. An uneven or slippery road can result in a fall. An experienced rider can balance a forward-moving bicycle by turning the front wheel in the direction of an undesired lean, i.e., steering to the right when falling to the right, and vice versa. This moves the ground-contact points underneath the rider (Kooijman et al., 2011), but will only function if the front wheel in particular maintains grip. Cyclist behaviour, such as drinking and cycling or being distracted by texting while cycling, may disrupt balance control and thereby increase risk, particularly single-bicycle crash risk. In addition, the behaviour of other road users, for example other cyclists on a cycle track or fast moving motorized vehicles at an intersection can easily result in a crash and also in serious injury.

The second factor is that a cyclist – a vulnerable road user - is unprotected in a crash or fall,protection by wearing a helmet being the only exception. Bicycle helmets may substantially prevent serious brain trauma (Høye, A., 2018a). As many bicyclists, know, even a minor fall, for example when mounting or dismounting – at a really low speed - can result in serious injury, especially for elderly cyclists (Schepers, et al., 2020).

3.4. Crash causes in the context of the aim of ZERO bicycle casualties

What do we know about the problems to be tackled and about defining the main approaches to move in the direction of ZERO? Firstly, three crash types should be distinguished, each of which requires its own strategy to prevent its occurrence:

- Crashes with motor vehicles;
- Single-bicycle crashes;
- Crashes with other vulnerable road users.

Secondly, because we aim for ZERO, we have to engineer a Safe System by making the whole road network safe for all cyclists, and all behaviours. Thirdly, as we learned from a systems approach we have to install 'redundant barriers' to prevent safety problems in case one barrier fails to function. From this perspective it is also necessary to eliminate risk increasing factors, and not only to reduce these factors. We could capture our lines of thought to address reaching ZERO cyclist casualties as follows:

Crashes with motor vehicles: the main approach is to ensure that cyclists are separated (in time and space) from heavy and fast-moving motorized vehicles at intersections and road sections. In case separation is not an option, the second approach is speed reduction by infrastructural measures and/or by fitting motorized vehicles with advanced systems to reduce impact speeds under 30 km/h and to detect cyclists in time. The third approach is to protect against brain/head injury.

Single-bicycle crashes: the main approach is to offer high-quality cycling facilities, to prevent falls off the bicycle, to create an obstacle free cyclist environment (bollards, kerbs, parked vehicles and dooring – opening a vehicle door into the path of a cyclist etc.), to make safe verges for cyclists and to maintain cycling facilities on a regular basis to prevent uneven and slippery road surface. The second line is stabilizing bicycles. The third line is to offer protection to cyclists in case they fall.

Crashes with other vulnerable road users. The interaction between cyclists and other vulnerable road users needs to be safe by providing sufficient space (wide enough tracks) and time to each group and by reducing speed differences between cyclists and other vulnerable road users. For a bicycle crash casualty, the crash mechanism may closely resemble a single-bicycle crash and for that reason provide protection in case of falling.

4. Safe system approach: Also safe for cyclists?

About 10–15 years ago, it became clear that the Dutch Safe System approach did not pay sufficient attention to the safety problems of cyclists and to serious injuries (see for example Weijermars and van Schagen, 2009; Weijermars, et al., 2013). Nevertheless, it is of interest to explore what has already been accomplished for cyclists. So, this section looks back in time and deals with RQ 1.

The three main types of crashes involving cyclists (see Section 3) are crashes with motor vehicles, single-bicycle crashes and crashes with other vulnerable road users. The Dutch Safe System approach paid explicit attention to the first crash type, but did not address the other two crash types. In other words: no specific countermeasures were developed and implemented in the Dutch Safe System approach to mitigate these crash types.

A strong focus has been on speed management (called the homogeneity principle), relying heavily on redesigning the infrastructure and lowering impact speeds to 'tolerable levels'. This was expected to improve safety for vulnerable road users, and this was certainly the case for collisions between vulnerable road users and motorized traffic, as was shown in the evaluation of Safe System (Weijermars & Wegman, 2011). However, when good quality injury data became available (Reurings & Bos, 2009), the first signal was given that our Safe System approach was not comprehensive and effective enough. A second important finding was that the number of seriously injured cyclists was increasing and many of these injuries occurred in crashes not involving motorized vehicles. The majority of these crashes were single-bicycle crashes. The evaluation study of Safe System implementation showed that the reduction in the total number of fatalities was 4.5 % per year (1996–2009) and only 0.2 % in the number of seriously injured. In the same period the reduction in cyclist fatalities was about 2 % per year while in seriously injured cyclists hardly any change could be observed. Weijermars et al. (2013) analysed this discrepancy and concluded that an overarching concept in the Dutch approach was speed reduction and that speed reduction is more successful for more severe crashes (fatal crashes) than for injury crashes. This is supported by Nilsson's power law (Nilsson, 2004). Weijermars et al. (2013) developed a version of the five Sustainable Safety principles especially for bicycle crashes not involving motorized vehicles. These crash types are single-bicycle crashes and crashes with other vulnerable road users. At first sight, the five principles (Table 3) proposed by Weijermars et al. (2013) seem to be adequate for dealing with the second and third crash types of cyclists (single-vehicle crashes and crashes with other vulnerable road users). However, we recommend a more detailed approach, that addresses all three crash types for cyclistst, to all components of the road transport system (especially roads), and include this approach in Dutch road safety strategies and action plans.

Safe infrastructure and safe and credible/acceptable/reasonable speed limits were the core Safe System elements in the Netherlands. One of the main characteristics of this approach is speed reduction when motorized vehicles and vulnerable road users, pedestrians and cyclists, share the same physical space. The impact speed should be as low as possible. The findings of Jurewicz et al. (2017) suggest that at an impact speed of 50 km/h, the probability of MAIS3+ is 80 % for pedestrians, at 30 km/h it is 20 % and at 20 km/h 10 %. In other words: the probability of being seriously injured is drastically reduced when impact speeds are reduced, though it will still fall short of ZERO.

The assumption behind the design of 30 km/h-zones is that a motorized vehicle driving at 30 km/h will brake just prior to a collision, resulting in an impact speed lower than 30 km/h. This presupposes that the driver of a motorized vehicle detects the cyclist and brakes prior to the impact. There is no guarantee that this will in fact be the case. In Safe System thinking it is preferred to make vulnerable road users safety independent of the driver's performance and of whether or not a driver detects a cyclist (or a pedestrian) and responds by breaking to reduce the impact speed.

The second option, also fitting perfectly well in the Safe System approach, was to reduce crash injury in collisions with motorized vehicles by (physical) separation whenever impact speeds are greater than 30 km/h. This implies giving cyclists their own route instead of a separated parallel cycle track or cycle lanes along the same road (Schepers et al., 2013). This enables separation of cyclists and motorized vehicles at higher speeds at a network-level. Schepers calls this concept 'unbundling'. His conclusion is that this will have positive safety effects in the Dutch context. The approach also reduces cyclists' exposure to noise and air pollution. It can be implemented by constructing large traffic-calmed areas with shortcuts, standalone paths, and bicycle streets for cyclists, and (where feasible) grade-separated intersections such as bicycle tunnels to connect traffic-calmed areas.

Table 3
Development of the five Sustainable Safety principles for bicycle crashes not involving motorized vehicles (Source: Weijermars et al., 2013).

Principle	Development for bicycle crashes without motorized vehicles
Functionality	Various types of facilities may also be distinguished for bicycles, depending on their function (flow or exchange/residence).
Homogeneity	It may be studied whether cyclists should also be separated among themselves with respect to speed, and, possibly, mass, volume and manoeuvrability as well.
Predictability	To what extent are cycling facilities designed for easy recognition by cyclists and to what extent are their expectations with respect to road surface, road layout and behaviour of other road users correct?
Forgivingness	It may be investigated whether the infrastructure for cyclists, the bicycle and the cyclists could be made more forgiving.
State awareness	State awareness among cyclists may be investigated, specifically with respect to alcohol.

Evidence indicates that physically separated cycle tracks are safer than visually separated cycle lanes (van Petegem et al., 2021; Thomas and DeRobertis, 2013). These researchers emphasize that adequate intersection treatments for cycle tracks are required (e.g. bicycle signal heads with exclusive phase, and well-designed ending of a cycle track before an intersection). Also dooring should be prevented by preventing curbside parking along cycle tracks and -lanes. Cyclists and motorized traffic should be physically separated not only at road sections, but also at intersections. If that is not a realistic option, we have to fall back on reducing speeds at intersections to a maximum of 30 km/h.

All intersections where cyclists and motorized vehicles meet should be designed in such a way that the design imposes a lower speed in the urban setting and in the rural setting (Duivenvoorden, 2021). Intersection design from a Safe System perspective is captured in Dutch design guidelines (CROW, 2013; CROW, 2021). Two options for a safe intersection design are possible: a roundabout or a four-/three-leg intersection with speed reduction to a maximum of 30 km/h by using speed humps just before the intersection, or a raised intersection. Studies show that intersections are safer after implementation of traffic lights (Elvik, 2009), but this type of solution does not fit well in a Safe System approach. Conflicts at (too) high speed are still possible if a red light is ignored or if there are partial conflicts in the traffic signal scheme. Several road design and traffic engineering solutions can help reduce crash risks at intersections (see for example, Schepers et al., 2011). It is 'normal practice' to slow down motorized vehicles at rural intersections by roundabout-design in the Netherlands, but sufficient speed reduction at four-/threeleg intersection is not yet common practice (Duivenvoorden, 2021).

Another problem for cyclists at intersections is the so-called blind-spot of trucks and certain vans. When a truck turns right and a cyclist on its right goes straight ahead, the cyclist moves through the blind spot where the truck driver's direct sight of the cyclist is obscured. In these encounters the cyclist continuing straight ahead has priority. Many cyclists expect to be given priority but the truck driver is not always assisted sufficiently by his mirrors and/or camera system to prevent a collision. Eliminating this type of conflict is possible by simply eliminating this type of manoeuvre. In other words, by preventing trucks and cyclists from meeting or by designing intersections in such a way that cyclists cannot be in the driver's blind spot, e.g. by positioning a bicycle crossing at least 2 m away from the intersection area (Schoon et al., 2008). Other options (better mirror systems, cameras, convex mirrors placed at the intersection) are not appropriate in a Safe System approach, as we make ourselves dependent on how well truck drivers use their mirrors and cameras.

During the last decades separation of cyclists and fast-moving motorized vehicles has been 'normal practice' in the Netherlands, both in built-up areas and in rural areas. Consequently, locations, for example, where cyclists use the same space as motorized traffic on rural collector/distributor roads (with a 80 km/h speed limit) are rare. But, creating more separated facilities for cyclists was more a part of implementing strategies to promote (safe) cycling than part of Safe System implementation.

Cycle tracks should also be wide enough in order to contribute to the prevention/reduction of crashes between cyclists and single-bicycle crashes (see for example Boele-Vos. et al, 2017). This is the third crash type identified in Section 3. Fietsberaad, the Dutch bicycle council, has recently published a recommendation to increase the minimum width of cycle tracks that may be incorporated into a future update of the Design Manual for bicycle traffic (CROW, 2022). Recent research on cyclists' lateral position while meeting, common variations between cyclists' steering behaviour, vehicle width and circumstances showed that the former recommended minimum width of 150 cm is insufficient for safe meeting manoeuvres at two-way cycle tracks (Schepers et al., 2023). Research by CROW and Sweco showed that while 56 % of cycle tracks met the earlier recommendations in the current Design Manual for bicycle traffic (CROW, 2016), only 42 % meets the new recommendations by CROW (2022). These means that the majority of Dutch cycle tracks are insufficiently wide for safe cycling. The Safe System approach did not explicitly provide for sufficiently wide cycle tracks, because it was not an issue in road safety until many tracks began to be increasingly crowded. However, the problem will gain importance if cycling continues to grow in the larger Dutch cities at the same explosive rate and space to widen cycle tracks is difficult to find (Harms et al., 2014). A more varied vehicle mix on cycle tracks may also present a challenge, e. g. by more wider cargo bikes and speed differences caused by tampered electric bicycles. Further research is needed on the safety impacts of this changed reality in the Netherlands.

The final crash type that deserves attention is that of single-bicycle crashes. To prevent single-bicycle crashes was not an explicit aim of the Dutch Safe System approach and no evaluation results on this topic are currently available. This crash type also includes run-off-road crashes, whose interaction with cycle track width has already been discussed above. Schepers & Klein Wolt (2012) discovered that running-off-the-road is not only a problem for motorized vehicles, but also for cyclists: they estimated that about 20 % of cyclists with serious injuries in Accident & Emergency departments were involved in a run-off-road crash. Schepers and Den Brinker (2011) found the visibility of cycle tracks' edges to play a role in run-off road cycle crashes. This resulted in new recommendations on the installation of edge lines on cycle tracks outside urban areas in the current Design Manual for bicycle traffic (CROW, 2016). Implementation has taken off to a limited extent. Although, it has been a long tradition in the Netherlands to eliminate obstacles for cyclists (poles, bollards, kerbs, etc.) to crash into, this issue remains as new obstacles are placed on cycle tracks. Obviously given the data on this topic, current measures seem to be insufficient.

Interventions to address single-bicycle crashes should certainly be included in the Safe System approach in the Netherlands. Applying the Safe System forgivingness principle (if human beings make an error, the road environment should be forgiving for that error) to cycling safety problems systematically (preventing run-off-the road and safe road-sides), could consist of support when mounting and dismounting (especially for elderly riders), providing a smooth and clean surface, etc.

The evidence, mainly from the Netherlands, presented in this section on the safety impact of all interventions implemented in or outside the framework of the Safe System approach, demonstrates that we have learned a significant amount about cycling safety. However, this knowledge is not comprehensive and looks rather fragmented. Consequently, we are not fully able to assess the safety effects of Safe System implementation in the last decades in terms of the reduction in the number of cycle casualties. We recommend further evaluation research to understand better how exactly to improve our performance.

5. Safe System components for further improvements in cycling safety

In this section four promising areas are presented for further improvement of cyclist road safety in the Netherlands (reducing crash risk and injury risk), in relation with the three main crash types: with motorized vehicles, single-bicycle crashes and crashes with other vulnerable road users. This section deals with RQ 2. The four areas discussed are: safe infrastructure (5.1), safe vehicles (5.2), safe behaviour addressing risk-increasing factors (5.3), and introducing crash helmets for cyclists (5.4).

5.1. Safe infrastructure

There is a strong evidence that well-designed bicycle facilities reduce risks for cyclists (e.g. Wegman et al., 2012). Evidence is mainly coming from separation of cyclists and motorized traffic and from speed management. Large 30 km/h zones have been an important part of the Dutch Safe System approach since its inception. Major parts of the urban network (access roads) are 30 km/h zones these days (Weijermars and van Schagen, 2009). In recent years there has been a public and political debate to include some distributor roads as well or to even make 30 km/h the default within built-up areas. A major discussion is on how to redesign roads and streets with a distributor/collector function (with a current speed limit of 50 km/h) into roads and streets with a 30 km/h speed limit (CROW, 2023). Just changing the speed limit is not considered an effective solution (van Schagen et al., 2004), but infrastructural speed reducing measures on these streets and roads is a challenge and may not receive sufficient support from the public and other stakeholders such as emergency services. Another option could be to apply Intelligent Speed Assistance (see Section 5.2.),

Because Dutch road safety policy aims is to reduce all road casualties, including bicycle casualties, to ZERO, it is to be recommended to make the Safe System approach more comprehensive and include policies to address the three crash types involving cyclists. It is concluded that crashes between motorized vehicles and cyclists (crash type 1) were and are well covered. The new focus needs to be on the other two types: single-bicycle crashes and crashes between vulnerable road users. The new focus does not necessarily require redefining the existing Safe System principles. The four design principles for safe infrastructure (functionality, homogeneity, predictability and forgivingness) can largely be used when developing interventions to reduce crash and injury risks of cyclists. For example, physical forgivingness is relevant for motorized vehicles leaving the road, but also for single-bicycle-crashes. However, the interventions to make cycling safe by designing new infrastructure and by adapting existing infrastructure should address more strictly and more systematically all three types of cycle crashes.

In other words: Safe System still seems to guide us in the right direction, and it is not to be expected that future interventions will be completely different from interventions in the past, but the scale and the quality of them should be improved (relating to crash type 1). Furthermore, crash types 2 and 3 deserve to be equally treated in importance to crash type 1. For example, where the approach could previously lead to the recommendation of building a cycle track to separate cyclists from motorized traffic to prevent type 1 crashes, future attention will need to focus also on the quality of the cycle track to prevent type 2 and 3 crashes. More and more research results come available on how to reduce risks for cyclists on all three crash types by infrastructure improvements (e.g., Hoogendoorn, 2017), but more research is needed in this area.

A promising step is the third version of Sustainable Safety (SWOV, 2018) because this document identifies single-bicycle crashes and crashes between vulnerable road users as a priority (page 32/33). It reads:

"Aim: Cyclists do not fall, do not hit obstacles and are physically protected in case something goes wrong. Types of solutions within the traffic system and for the road user, again with an increasing amount of freedom for unsafe choices and thus a decreasing level of Sustainable Safety:

1. Obstacle-free, spacious and skid-resistant bicycle infrastructure: create a bicycle infrastructure that is forgiving and therefore free from slippery substances (loose sand/gravel/leaves), obstacles, and vertical edges and ridges that can cause cyclists to lose their balance, fall, and injure themselves. Additionally, create a bicycle infrastructure that is wide enough to provide cyclists the space for natural lateral movement and is sufficiently skid-resistant to prevent cyclists from slipping in bends.
2. Physical protection of the cyclist: as long as the road infrastructure and the road environment do not offer sufficient protection against injuries in the event of a crash, protective cycling gear provides some level of protection to the cyclist."

The conditions as described under 1. should cover the complete length of the infrastructure for cyclists for crashes that can be prevented through the design and maintenance of infrastructure. This approach should become part of a more intensified asset management and maintenance planning for road authorities on a regular basis. As many road authorities in the Netherlands follow a risk-based approach it is recommended to redefine safety performance indicators (SPIs) for roads and to develop an assessment tool to describe the safety quality (focussing on the three crash types) of bicycle infrastructure for example a Dutch CycleRAP-tool, such as the tool as defined under the Strategic Plan for Traffic Safety (Kennisnetwerk, 2023). But also more operational characteristics have to be addressed, such as winter maintenance to remove snow and ice, or autumn maintenance to remove slippery wet leaves, mud etc.

For condition 2, Bjurström (2020) investigated the extent to which new cycle track pavement may absorb the impact in the event of a fall to prevent injuries similar to pavements applied under playground equipment. Shock absorbing pavements appeared to reduce the impact on the body compared to a fall on a conventional asphalt pavement, but no pavement is close to meeting the Swedish Transport Administration's goal of a HIC (Head Injury Criterion) value of 1000 for falls from 1.5 m. Problematic for wider application was its limited durability.

Cycle tracks in the Netherlands seem to be used more extensively by a variety of users with different speed profiles (city bikes, racing bikes, cargo bikes, fatbikes etc.). And a new phenomenon can be observed: bicycle congestion. It is not fully understood how design characteristics (such as width of a track, intersection solutions, etc.), bicycle volumes, composition of the bicycle fleet etc. are correlated to risks. It is therefore recommended to make this a topic for research.

5.2. Safe vehicles: Motorized vehicles and bicycles

Partially or fully automated (motorized) vehicles will further penetrate in road traffic, although it is not predictable how this will deploy during the coming decades (the road towards full automation is uncertain and unclear) and it is not evident if and how cyclists will benefit from these developments. Generally speaking, ITS and ADAS have made cars safer, but the effect of the various systems differs greatly (SWOV, 2019). The research community agrees on a couple of general statements related to safety effects of ITS/ADAS: systems that intervene are usually more effective than systems that inform or warn; see for example the results of a study on Intelligent Speed Adaptation (Lai et al., 2012). ISA requires adequate road signs and signals that cars can read or an accurate digital map of speed limits as a prerequisite for reducing impact speeds for collisions between motorized vehicles and cyclists. In a Safe System approach, that aims for ZERO, it seems to be inevitable to use the so-called intervening ISA-variant: with a good functioning intervening ISA-variant we shall have positive safety effects (Lai et al., 2012)) and we don't make ourselves dependent on if and how drivers decide to slow down, if necessary. When assessing the effects, the possibility of a change in drivers' behaviour (behavioural adaptation) should be taken into account (Rudin-Brown and Jamson, 2013) in order not to overestimate (theoretical) effects. Behavioural adaptation should be included in all impact studies, also as a means to learn how systems are actually used by road users.

Many more ITS/ADAS-systems are available and will penetrate the market in the future, but a strong focus can be observed on improving safety of passengers of motorized vehicles, and not so much on protecting vulnerable road users. An exception to be mentioned is the EuroNCAP rating system. In EuroNCAP cars will gain additional points if they have an autonomous emergency braking (AEB) system, which recognises pedestrians and cyclists, and not just other motorized vehicles. Kullgren et al. (2023) found AEB to prevent bicycle-motor vehicle crashes in daylight and twilight, while AEB needs to improve to become effective in darkness.

Silla et al. (2017) identified five systems which were near-production and have good potential to improve cycling safety: Blind Spot Detection (BSD), Bicycle to Vehicle communication (B2V), Intersection Safety (INS), Pedestrian and Cyclist Detection System + Emergency Braking (PCDS + EBR) and VRU Beacon System (VBS). All these systems focus on the first crash type of cyclists: collisions between a cyclist and a motorized vehicle. The researchers carried out a safety impact assessment. The presented results are encouraging, but it is not realistic to expect that these systems will have major impacts on road safety and will make other interventions unnecessary. Furthermore, we have doubts that market forces alone will result in high penetration rates. Additional action, for example by regulators, may be needed to speed up the development and employment of ITS applications for improved cycling safety.

The following example illustrates the potential of ITS. Rural access roads in the Netherlands carry mixed traffic and have a 60 km/h speed limit. Obviously, this is a compromise that doesn't meet Safe System principles, as the impact speed of a motorized vehicle can easily be too high. Perhaps ITS can help to find a solution: assume a bicycle to vehicle communication (BVC) system combined with a so-called intervening ISA of 30 km/h wherever a motorized vehicle and a cyclist are in close vicinity. Prototype development and marketing are essential to make this successful.

The same is the case for the next important issue: cycle-related technologies for preventing single-bicycle crashes and injuries, especially for elderly cyclists. Several initiatives have been taken by Dutch researchers to make bicycles safer by using technology. One of these examples is SOFIE (Dubbeldam et al., 2017). Three design ideas have been proposed and are being tested: automatically adjustable saddle height, optimized frame and wheel geometry, and drive-off assistance in order to facilitate (dis)mounting. Another example is a tilting three-wheel bike, such as TRIS from Italy, or the Noordzij-bicycle in the Netherlands. These bikes have one rear wheel and two laterally closely positioned front wheels which is possible by tilting. A third example is the development by Delft University of Technology and a bicycle manufacturer being in the process of developing a smart steering support to prevent falling (Nieuwenhuizen and Schwab, 2017). A final remarkable development is research on a combination of a windscreen airbag and an automatic braking system, designed to protect cyclists and pedestrians in a collision with a vehicle (van Schijndel – de Mooij et al., 2011). Key to the innovation is an advanced sensing system to detect and recognise cyclists and pedestrians, also under poor lighting conditions.

It is too early to report on positive road safety effects in the Netherlands, but these are certainly promising developments. We are under the impression that these more or less isolated efforts from the research community as yet lack 'mass and power'. All these efforts result in the development of a prototype. These efforts deserve support to be scaled-up. It is recommended that Government (Netherlands and/or the European Union) takes a role.

5.3. Risk-increasing factors

The Safe System approach attempts to eliminate risk and one could argue that, if this is done properly, there is no need to address risk-increasing factors. But as it is unlikely that a total elimination of crash risks is feasible, it makes sense to eliminate risk-increasing factors, even if this were to be superfluous. Trying to eliminate risk-increasing factors does of course not imply that no or less attention should be given to eliminating basic risk factors.

An often raised question is if and how to deal with risky behaviour in a Safe System approach, because different interpretations are used of the 'shared responsibility' principle (e.g. ITF, 2016; Job et al., 2022). The very heart of Safe System thinking is the idea that human beings make errors and mistakes (unintentionally), are not always capable of performing their tasks as they should, and are not always willing to comply with rules and violate them intentionally (Wegman & Aarts, 2006). The Safe System approach tries to eliminate 'latent errors' (Reason, 1990) and make road safety independent of road user decisions as much as possible. This is being accomplished by laying responsibilities with those authorities and institutions that design, manage and use road transport, and with the individual road user. Road crashes are considered to be consequences of 'latent errors' rather than of human errors (see also Section 3). However, road users are supposed 'to accept responsibility for complying with the rules and constraints of the system': for example to use bike lights in darkness, wear a crash helmet, or don't drink and cycle. From this perspective it is legitimate to try to eliminate risky behaviour that results in serious crashes. Preferably, eliminating these risk-increasing factors should focus on interventions that tackle a safety problem fundamentally. From Safe System thinking it is preferred to tackle errors, mistakes and violations fundamentally, for example by installing seat-belt reminders, Intelligent Speed Assistance or alco-locks in vehicles rather than by more police enforcement and education.

Several risk-increasing factors for cyclists can be identified: cycling under the influence of alcohol, drugs or medicines, distracted or fatigued cycling, red light running, cycling in the dark without lights, not obeying right of way rules, riding at the wrong side of the road or cycle track. It is remarkable how little we know about prevalences and risks of these behaviours, perhaps with the exception of cycling under the influence of alcohol. At the same time we have some indication about cyclists not obeying rules in nowadays traffic and the effect of a combination of a behavioural campaign and enforcement to reduce that. For example, a Dutch campaign encouraged the use of bicycle lights. As a result, the number of fines for riding without bicycle lights rose from 50.000 in 2002 to 170.000 in 2004. Observational studies showed that the share of cyclists using a front light rose from 57 % to 73 % (Schepers, et al., 2019). Currently, 13 % of the cyclists do not use front lights and 18 % do not use rear lights in dark/dusk (Timmermans et al., 2022). To our best knowledge scientific studies on the effects of bicycle lights are lacking. An exception is a Dutch study from Kuiken & Stoop (2012). They found the risk of bicycle-motorized vehicle crashes in darkness to be reduced by 17 % when cyclists are using both front and rear bicycle lights. Yet another example: based on self-reported smartphone use, we may conclude that many cyclists use their smartphone, mainly for listening to music. This is especially the case for younger age groups (Stelling-Konczak et al., 2017). They found that 70 % of the cyclists aged 16 to 18 say they sometimes listen to music while cycling. Again, it is reasonable to think that this will increase risk, based on our knowledge about car drivers being distracted when using telephones or screens (e.g. Née et al., 2019). However, hardly anything is known about risk increase due to smartphone use by cyclists. It is recommended to carry out more research on the adverse impacts of risky behaviour of cyclists to underpin policies to prevent risk-increasing behaviour of cyclists.

As was mentioned earlier, it is well documented that use of alcohol use, certain drugs and certain medicines increase risk in traffic (European Commission, 2021b). Alcohol reduces reaction speed, worsens vehicle control and drivers are less alert. The mechanisms through which drugs and medicines affect the body differ greatly among drugs and medicines. There is no reason to believe cyclists respond differently to these substances, although this is not documented as well as for motorists. The legal alcohol limit for road users is 0.5 ‰ in the Netherlands, also for cyclists. The only exception is the lower limit of 0.2 ‰ for novice drivers and novice moped riders.

Alcohol use by cyclists is not measured in the Netherlands. Measurements in a pilot study between 5 pm and 8 am in the city centres of two cities in the Netherlands (The Hague and Groningen) provide a rough, non-representative estimation. They showed that on average 42 % of the tested cyclists had used more alcohol than legally allowed. The later in the evening/the earlier in the morning, the more cyclists were above the legal limit (0.5 ‰): up to 70 % of the tested cyclists after 01.00 am. This percentage is considerably higher among cyclists than among drivers.

Twisk & Reurings (2013) found that alcohol use is a risk-increasing factor for cyclists. The contributing role of alcohol is concentrated in the early morning of weekend days, with high proportions of injured cyclists who have used alcohol, and especially for single-bicycle crashes. This was not so much the case for elderly cyclists. But they concluded that darkness and fatigue also increased risks. The study did not allow assessment of the relative contribution of these (three) factors.

Based on this information we conclude that drinking and cycling in the Netherlands is a rather serious road safety issue. However, seems not to be regarded as a policy priority (yet). An important question is of course what would happen if strong policy were to be deployed on reducing drinking and cycling? It is not impossible that this would result in more drinking and driving, which could endanger potential crash opponents such as other cyclists in addition to car occupants. The traditional toolbox for reducing drinking and driving (reduction of alcohol consumption, introduction of lower legal limits, more enforcement using alcohol-checks and education/communication etc.) requires adaptation to become effective for Dutch cyclists. Policy innovations are recommended and these could also focus on reducing alcohol consumption in general to improve health (Room, et al., 2005). And maybe an alcolock for (electric) bicycles could be developed?

As the example of bicycle light use shows, we can generally conclude that enforcement on risky cycling behaviour can be effective. However, as indicated before, approaches and models developed for drivers of motorized vehicles cannot simply be copied.

We have to put in a caveat regarding the expected reduction in casualties of reducing risk-increasing factors. Risky behaviours such as riding without bicycle lights, distracted cycling and cycling under the influence are more common among younger age groups and less so among the older age groups (Krul et al., 2022; Rijkswaterstaat, 2023; Timmermans et al., 2022). This is of relevance because the group of older cyclists dominates the increase in fatalities and serious injuries (Section 2) while this group is already behaving relatively (compared to younger age groups) safely.

5.4. Crash helmets

Dutch cyclists generally don't wear a bicycle helmet, with the exception of sports and touring cyclists, as everyone can conclude when observing Dutch daily traffic. Helmets do not reduce crash risk, but injury risks. It could be argued that helmets fit perfectly well in a Safe System approach. Modifications to cars can reduce injury in a collision, but in single-bicycle crashes, a helmet is one of the few possible measures to prevent serious head injuries. When road safety data from 2022 was officially published, and the major problem of elderly cyclist fatalities became apparent, a public debate on bicycle helmets commenced. This discussion was fostered by several Dutch trauma surgeons partly based on their own research (Leijdesdorff, 2022) and their experiences as a surgeon.

In case of a fall or crash, the use of a bicycle helmet was found to reduce serious head/brain injury by 60 % and fatal head/brain injury by 71 % on average, while it is found that the protective effect is the same for children and adults (Høye, 2018a). Bicycle helmets are more effective in single-bicycle crashes than in collisions with motorized vehicles. Based on these findings SWOV (Weijermars, et al., 2019) made an estimate of the road safety effects if all Dutch cyclist wore a helmet. The estimate was based on the effectiveness as found by Høye (2018a), the number of head injuries (64 % of 190 fatalities – mean value of 2015–2017 - and 33 % of 13 000 serious injuries), and an assumed penetration of 100 %. This resulted in a reduction of 85 in the annual number of fatalities and of about 2500 seriously injured. This is equal to 16 % of all fatalities on Dutch roads. The majority of this reduction is among the elderly. Assuming we look at helmet wearing for people older than 70 years of age, the reduction in road fatalities would be around 50 (almost 10 % of all road fatalities in the Netherlands and 25 % of bicyclist fatalities).

If we accept the positive results of helmet wearing by cyclists, the question is how to achieve 100 % wearing rates by cyclists in the Netherlands? Basically we can distinguish two ways to increase wearing rates of helmets: on a voluntary and a mandatory basis. Wearing rates in countries where helmets are mandatory are higher (over 90 %) than in countries where they are not (max. 50 % for adults in Norway and 80 % of children) (Høye, 2018b). The results in Denmark are similar: from 6 % in 2004 to 50 % in 2022 on a voluntary basis (Olsson, 2023). Among cycling school children, helmet use has increased from 33 % in 2004 to 79 % in 2022 in Denmark.

It is argued that helmet legislation for cyclists may result in more high-risk behaviour(also known as risk compensation) and may deter people from cycling. Høye (2018a) reports that "most studies do not support the hypothesis that helmet use contributes to riskier cycling behaviour". The second issue (deterrence from riding a bicycle) resulted in rather heated debates, for example in Australia and Canada. Deterrence from cycling as a result of helmet legislation is a serious issue that should be considered carefully, because this is a regrettable side-effect. The reported results vary (Høye, 2018b, Olivier et al., 2018). Both systematic reviews concluded that the deterrence of a legal helmet obligation could have an adverse effect on cycling, but that it is not necessarily the case and will not necessarily be large or long-lasting. And finally, one should be very careful with transferring research results on this specific issue from one country to another, because impacts are dependent on local cycling conditions, culture and use of bicycles.

In case the public and political acceptance of mandatory helmet use by cyclists is low, a next-best option may be to start promoting helmet use on a voluntary basis. With gradually increasing voluntary use as in Denmark, attitudes toward an obligation may also change. A next step to be considered can be a legal obligation.

In summary, wearing a helmet while cycling reduces the risk of head and brain injuries, and this reduction is higher for more severe injuries. For safety reasons it is recommendable to wear a helmet while cycling and this intervention fits well into the Safe System approach, especially to prevent head/brain injuries in single-bicycle crashes. A helmet obligation could be more effective than encouraging voluntary wearing. Perhaps the latter may be needed to increase support in the Dutch society for an obligation. Helmet use by cyclists seems to be a very relevant contribution towards ZERO cycle casualties in the Netherlands.

6. Discussion

It is not unusual in policy making to set targets, as is the case with ZERO fatalities and seriously injured in the Netherlands in 2050. Perhaps the most famous example of recent years is the Paris Agreement on climate change from 2015. Its overarching goal is to hold "the increase in the global average temperature to well below 2 °C above pre-industrial levels" and pursue efforts "to limit the temperature increase to 1.5 °C above pre-industrial levels." This agreement is legally binding. All countries communicate actions they will take to reduce their greenhouse gas emissions and countries have to report on actions taken and progress made. A global stocktake will assess the collective progress. This approach is a result obligation that goes beyond an aspirational target (an effort obligation).

The European Union (and the Netherlands) work with aspirational targets. Transport Ministers agreed on halving the number of road deaths and serious injuries between 2020 and 2030 (European Commission, 2020). And the EU has reaffirmed its ambitious long-term goal, to move close to ZERO deaths by 2050. The Dutch Government (Ministerie van Infrastructuur en Waterstaat, Ministerie van JenV, IPO, VNG, et al., 2018) decided in line with this European ambition. However, this ambition is not legally binding. A Plan of Action 'proving' that this ambition is within reach is not available and EU-countries do not have a similar obligation as in the Paris Agreement (called Nationally Determined Contributions). SWOV (de Craen et al., 2022) published a scenario-study to see if and how the 2030-road safety target ('halving compared to 2020′) could be reached. The scenario-study was a combination of forecasting the number of road casualties that would occur in 2030, if no additional measures were taken, and forecasting with a set of additional measures. Their conclusion: "The target of a 50 % reduction of the number of road casualties by 2030 seems to be too ambitious". The effectiveness (measured in terms of crash and injury reduction) of working with policy targets is that as a response to disappointing forecasts, such as SWOV reported, additional measures should be developed and implemented. That is the mechanism as foreseen in the stocktaking of the Paris Agreement. But until now, for road safety target setting is far 'softer' worldwide, in the EU and in the Netherlands. Well-designed instruments and procedures are needed to make target setting really effective for reducing the number of road casualties. Additional interventions are required to reach the 2030-target in the Netherlands, if the prediction of SWOV is correct, and the same holds for 2050. This is especially the case for seriously injured and, as we learned, seriously injured are dominantly cyclists. It is evident that successful policies to reduce the number of cyclist casualties will be crucial for reaching ZERO casualties in the Netherlands in 2050.

The present research concludes that a variety of interventions to reduce crash risks and injury risks for cyclists can be taken, but a few problems must be tackled before meaningful quantitative assessments can be made (RQ 3): poor data, poor knowledge, poor understanding of implementation mechanisms. Furthermore, advocacy work should be done to increase public and political acceptance for certain interventions: for example, speed management, investments in cycling infrastructure and activities to increase helmet wearing are interventions that will only become a reality after effective advocacy campaigns.

Estimates of the number of road fatalities and seriously injured to be saved by interventions are based on three components: trendline developments (extrapolation), baseline developments (expectations about interventions that will occur in the future) and estimates of safety effects of interventions. Scenarios for the first two are theoretically possible, although we must understand that 2050 is really far in the future. And for meaningful extrapolation recent years were turbulent for road fatalities and seriously injured with impacts from COVID-19 (2020 and 2021) and the 2022-peak. But the main difficulties for high-quality estimates are due to a lack of data and a lack of knowledge of the safety impact of potential interventions.

The model of making these estimates is generic: $\Delta = T*P*E$, in which Δ is the estimated change in the number of casualties, T stands for the Target Group for a certain intervention (e.g. cyclist casualties on road stretches with a speed limit of 50 km/h), P is the penetration of an intervention (share of the target group affected by the intervention, for example lengths of cycle tracks along roads with a speed limit of 50 km/h) and E is the effectiveness of the proposed intervention (for example 50–60 % fewer bicycle crashes occur on distributor roads with cycle tracks compared to those with cycle lanes (van Petegem et al., 2021). Especially on E (effectiveness) we lack knowledge and on T the current data in the Netherlands is not available or not of a good quality. For P it is always possible to make estimates. But with the current status of data and knowledge we conclude that it is not justified to make assessments on whether the Netherlands is on track or not for reaching 2050 targets on cycling safety; based on recent developments and the 2030-results presented by SWOV (de Craen et al., 2022) one cannot be overly optimistic. But in any case, it is recommended to improve road safety data and continue with increasing knowledge on cycling safety.

It is complicated to develop effective interventions in case of poor understanding of causes of crashes. This is comparable to a doctor prescribing medication without having a medical diagnosis. The road safety research community seems to agree that the well-known'90-plus%' is poor driver behaviour, human failure or error' is not an adequate description of causes of crashes (see for example, Hauer, 2020, and Shinar, 2019). However, this '90-plus%' is dominating the views of many, inside the road safety community and outside. From in-depth studies, naturalistic driving studies, from surveys and interviews etc. we gain a lot more and better insights in causes of crashes (in which cyclists are involved). Furthermore, we recommend to stratify crash types of cyclists (Stipdonk, 2013, Boele-Vos et al., 2017 and Schepers et al, 2012) because the nature (and causes) of different crash types (collisions with motorized vehicles, single-bicycle crashes and crashes with other vulnerable road users) turned out to be completely different from what was the perception some decades ago and different crash types require different strategies to prevent them.

In general, external validity is a key issue to interpret research results. External validity is the extent to which findings of a study can be generalized to other settings, situations, countries etc. This is a very serious issue when it comes to safety of cyclists. The main reason is that the Netherlands is a kind of outlier when it comes to cycling and cycle facilities. Cyclists in the Netherlands are everywhere and need to be expected everywhere. Dutch drivers expect cyclists and they anticipate on that. In the Netherlands 'cyclists congestion' is discussed, and riding to travel to school or work, while it is the lonely cyclist riding for sports reasons in some other countries. Research results on the impact of introducing a legal obligation to wear a cycle helmet are from Australia or Canada, and perhaps not helpful when discussing introduction of legislation in the Netherlands: the cycling patterns and cultures differ enormously. However, sometimes results are applicable everywhere, for example when it comes to the safety effects of reducing impact speeds. And it can be argued that the Safe System principles (also to improve safety of cyclists) are rather universal, although the practical translation into interventions will be different.

This study doesn't pay much attention to implementation issues. When it comes to investments in road infrastructure it is a matter of political priority, of finding funding and of translating Safe System principles into effective interventions applied by (all!) road authorities. Vehicle safety and ITS/ADAS are far more complex themes from an implementation perspective. These themes have an international dimension, different stakeholders need to be lined up and it comes with the question how to increase penetration of effective interventions. And to make it somewhat more complicated: is it wisdom to wait for ITS/ADAS-interventions and not to invest in infrastructure? And who decides on that?

7. Conclusions and recommendations

There is certainly an urgency to increase the safety of cyclists, because the Netherlands aims to reduce the number of casualties to ZERO by 2050. The crash data shows that the annual number of traffic casualties has not decreased for over ten years and that the share of cyclist casualties is increasing. In other words, the negative trend of cycling safety (more casualties) needs to be reversed. This study illustrates clearly the many opportunities to improve the cycling safety in the Netherlands. The guiding principle should be to pay attention to each of the three main crash types (crashes between cyclists and motorized traffic, single-bicycle crashes and crashes between cyclists and other vulnerable road users).

A major problem in the Netherlands is the underreporting of crashes and the under-registration of crashes involving cyclists is dramatically high. This is a phenomenon that is not only reported in the Netherlands (ETSC, 2018). In addition, the official police registration of the causes of (bicycle) crashes does not give a good picture of the problem. This is also not specific to the Netherlands (Shinar et al., 2018). A number of specific studies have been carried out into the direct and latent causes of bicycle crashes in the Netherlands and into crash types, which provide a better insight into the causes of bicycle crashes. It is recommended that this research be repeated systematically and periodically.

Concerning RQ 1 (see section 1.4) it has been found that the Safe System approach in the Netherlands has had positive effects for fatalities, also among cyclists (Weijermans & van Schagen, 2009), but not for seriously injured cyclists (Weijermars, et al., 2013). One reason may be that no good analysis was available of cycling safety when designing Sustainable Safety, both due to lack of good data and lack of knowledge. For this reason, it is not unlikely that cycling safety in the description of the Safe System approach in the Netherlands as well as in the implemented policy injustifiably remained under the radar. Analysis of the existing Safe System principles shows that these are largely adequate for increasing cycling safety. Our conclusion when responding to RQ2 is therefore that the Safe System approach with the existing principles, provided that it also focuses on the problems of cyclists (the three crash types), will have positive safety effects. Dutch road design guidelines rely heavily on Safe System thinking and road designers are well trained with this vision. A more recognisable embedding in single-bicycle crashes and crashes with other vulnerable road users is a prerequisite for the long-term policy efforts needed to achieve ZERO cycling casualties.

It is recommended to focus on further completing a safe infrastructure with an emphasis on safe cycling infrastructure, on safe vehicles – both motorized vehicles and bicycles –, on a sharper emphasis on safe speeds and using ITS/ADAS applications. Because there is still much uncertainty about automation (what, when and how), it is recommended to keep working on a safe infrastructure, while waiting to see to what degree ITS/ADAS will contribute to solve the safety problems of cyclists. If ITS/ADAS helps at all, it will be for bicycle-motor vehicle crashes, but most probably not for single-bicycle crashes and crashes with other vulnerable road users. It is also recommended to address several risk-increasing factors.

With these new emphases, special attention is needed for the older cyclist. This is based on the prevailing view to allow older people to be socially active for as long as possible, and part of this is their mobility and use of the bicycle. But the crash/injury risk of the elderly is relatively high, and that can be reduced by applying the Safe System approach. An important component is developing a safe bicycle especially for the elderly, but also promote use of bicycle helmets and implement speed management, fitting in the Safe System approach.

Based on the knowledge about measures to reduce crash and injury risks and based on the idea that limiting bicycle mobility is not considered as an acceptable option to increase cycling safety, it is not possible to estimate whether ZERO bicycle casualties is a realistic possibility or will always remain a utopia. In other words: with today's knowledge it is not really possible to respond to RQ 3. With today's knowledge, it is implausible that ZERO is feasible or even to virtually ZERO. But the Safe System approach certainly offers starting points to substantially reduce risks of cyclists. Policies to achieve this reduction can be based on the Safe System approach, but will need to be somewhat different from those in recent decades. We recommend to develop several scenarios on how to improve cycling safety. Scenarios should cover all three crash types (crashes with motor vehicles, single-bicycle crashes and crashes with other vulnerable road users) and are only meaningful when they use good quality road safety data and reliable ex-ante evaluation results.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

We used publicly avialbale data available datadata

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