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The Dutch road to a high level of cycling safety

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Abstract

Many governments attempt to improve cycling safety to reduce the number of bicycle crashes and encourage cycling. The Netherlands is a world leader in bicycle use and safety. This paper explores how the Netherlands achieved an 80% reduction in the number of cyclists killed (predominantly bicycle-motor vehicle crashes) per billion bicycle kilometres over a thirty year period. Factors found to contribute to this improvement include the establishment of a road hierarchy with large traffic-calmed areas where through traffic is kept out. A heavily used freeway network shifts motor vehicles from streets with high cycling levels. This reduces exposure to high-speed motor vehicles. Separated bicycle paths and intersection treatments decrease the likelihood of bicycle-motor vehicle crashes. The high amount of bicycle use increases safety as a higher bicycle modal share corresponds with a lower share of driving and greater awareness of cyclists among drivers. Low cycling speed was also found to contribute to the high level of cycling safety in the Netherlands.

Keywords: bicycle, road safety, cycling safety, infrastructure, safety in numbers, conceptual model, road hierarchy.

1. Introduction

Many governments are attempting to improve cycling safety to reduce the significant health burden resulting from bicycle crashes (European Commission, 2010) and to encourage people to take up cycling since a perceived lack of safety is a deterrent to cycling (Horton et al., 2007, Fishman et al., 2012). The latter is important because regular daily physical exercise through cycling has great health benefits, e.g. Dutch people have half-a-year-longer life expectancy due to cycling (Fishman et al., 2015). It is therefore important to understand how cycling safety can be improved. This study is focused on the Netherlands which, together with Denmark, has achieved the lowest fatality rate amongst cyclists (Pucher and Buehler, 2008a). The paper sets out to explain the high level of cycling safety in the Netherlands.

Conditions in the Netherlands are conducive to cycling, with a flat terrain, mild climate, high quality bicycle infrastructure, abundant bicycle parking facilities, and short travel distances within cities resulting from high densities and mixed land use (Ministry of Infrastructure and the Environment, 2009, Heinen et al., 2010). The Dutch national bicycle modal share amounts to 26% which is higher than any other country (Pucher and Buehler, 2008a, Ministry of Infrastructure and the Environment, 2009). It has been at a high level for almost a century (De la Bruhèze and Veraart, 1999, Ebert, 2012), and it was only at the beginning of the sixties that the number of kilometres travelled by motor vehicles exceeded the number of bicycle kilometres (during which time bicycle use started to decline). Since 1975 there has been a gradual increase in the distance travelled by bicycle of some 40%. This corresponds to a 20% increase in per capita usage; the other 20% is due to population increase (Blokpoel and Harris, 1989, Statistics Netherlands, 2011).

Previous studies have sought to explain the high cycling participation rate in the Netherlands by comparing the circumstances for cycling to those in other countries (Pucher and Buehler, 2008b, a). A small number of studies with a comparable study approach have focused specifically on the factors explaining the high level of cycling safety. These suggested that the following policies are critical to the high level of cycling safety in the Netherlands: safe infrastructure (in particular separated cycle paths), traffic calming and intersection treatments, comprehensive traffic education and training of both cyclists and motorists, and traffic regulations that favour cyclist and pedestrians, particularly strict liability (i.e. drivers are almost always liable when they crash into a cyclist or pedestrian) (Pucher and Dijkstra, 2003, Pucher and Buehler, 2008b, Jacobsen and Rutter, 2012). The high incidence of cycling and behavioural adaptation of motorists in the presence of cyclists has also been suggested as an important contributing factor (Jacobsen, 2003). This has been called the "Safety in Numbers" (SiN) phenomenon.

The aforementioned studies are very important in showing how circumstances for cycling in the Netherlands differ from those in other countries and this paper builds on their outcomes. However, as the results have not yet been sufficiently tested against empirical road safety research and theories, this study analyses the evidence for factors present in the Netherlands and measures taken to improve bicycle safety levels, in comparison with the absence of these factors and measures in other countries. In that context it considers the effects of policy interventions and their consequences from the 1950's onwards. The paper is focused on serious and fatal bicycle-motor vehicle (BMV) crashes because the research for crashes without motor vehicles is more limited (Schepers et al. , 2015).

1.1 Cycling safety in the Netherlands

Notwithstanding the high level of cycling safety in the Netherlands from an international perspective, the share of cyclist fatalities in the total number of road crash fatalities amounts to 25% and for serious road injuries, the share is as high as 60% (SWOV, 2014). This makes road safety a key issue for the Ministry of Infrastructure and the Environment (2008). Crashes involving cars account for 60% of cyclist deaths, and those involving goods vehicles and public transport account for 20%, see Table 1 for crash types since 1987 for which statistics are available. Distributor roads and busy arterial roads have the highest share of fatal BMV crashes (Danish Road Directorate, 2000, Teschke et al., 2012, Schepers et al., 2013) and most crashes occur at intersections (Reurings et al., 2012). Note that this paper does not address the impact on single bicycle crashes which are rarely fatal. Although these crashes frequently result in serious injuries, data records and studies are extremely rare and not suited for international comparisons or evaluations (Schepers et al., 2015).

Table 1. Police reported cyclist fatalities per year in the Netherlands in 1987-2013 according to crash type (SWOV, 2014)

Deaths per year	*1987-1995*	*1996-2004*	*2005-2013*
Cars and vans	171	117	86
Lorries and busses	59	42	27
Other traffic modes, e.g. motor cycles	25	21	12
Without motor vehicles	17	16	18
Total	272	196	144
Share			
Cars and vans	63%	60%	60%
Lorries and busses	22%	21%	19%
Other traffic modes, e.g. motor cycles	9%	11%	8%
Without motor vehicles	6%	8%	13%
Total	100%	100%	100%

1.2. The development of cycling safety

To illustrate the historical development of cycling safety in the Netherlands since 1950, the upper part of Figure 1 shows the number of police-recorded cyclist fatalities per billion bicycle kilometres for those years. The graph at the bottom depicts the numbers of kilometres travelled by bicycle and by motor vehicles in the same period. The number of cyclist fatalities per billion bicycle kilometres amounted to almost 25 in the 1950s and doubled to almost 50 during the 1970s. However, from the 1970s onwards there has been a strong (five-fold) and continuous reduction to the current level of approximately 10 fatalities per billion bicycle kilometres. This is an impressive reduction because the representation of cyclists over 75 years in the population has doubled (Statistics Netherlands, 2011). Cyclists in this age group are ten times more likely to be killed per billion bicycle kilometres than cyclists in other age groups (Twisk et al., 2013b).

It has been suggested that the improvement the Netherlands has achieved results from increased amounts of cycling, i.e. more cyclists on the road leads to behaviour modification by motorists (the SiN phenomenon) (Jacobsen, 2003). The distance travelled by bicycle per capita increased only by some 20% during the period of the 80% reduction in bicycle fatalities. According to Jacobsen (2003) a 20% increase of the number or people cycling corresponds to a risk decrease of some 10% (application of his prediction model yields $1 – 1^{(0.4-1)} = 0.1$). Other factors like road safety measures were apparently more important than an increase in the amount of bicycle use. Note that the number of people cycling also increased by some 20% due to a population increase but this relates to an expansion of the traffic system and mobility and not to a change of road safety risks. There will be more drivers, more cyclists and new roads, but per driver and per location the number of encounters with cyclists remains roughly the same as before the change (assuming all system characteristics like road length, intersection density, and design quality remain the same per inhabitant during the expansion). SiN as described by Jacobsen (2003) assumes an increase of encounters with cyclists.

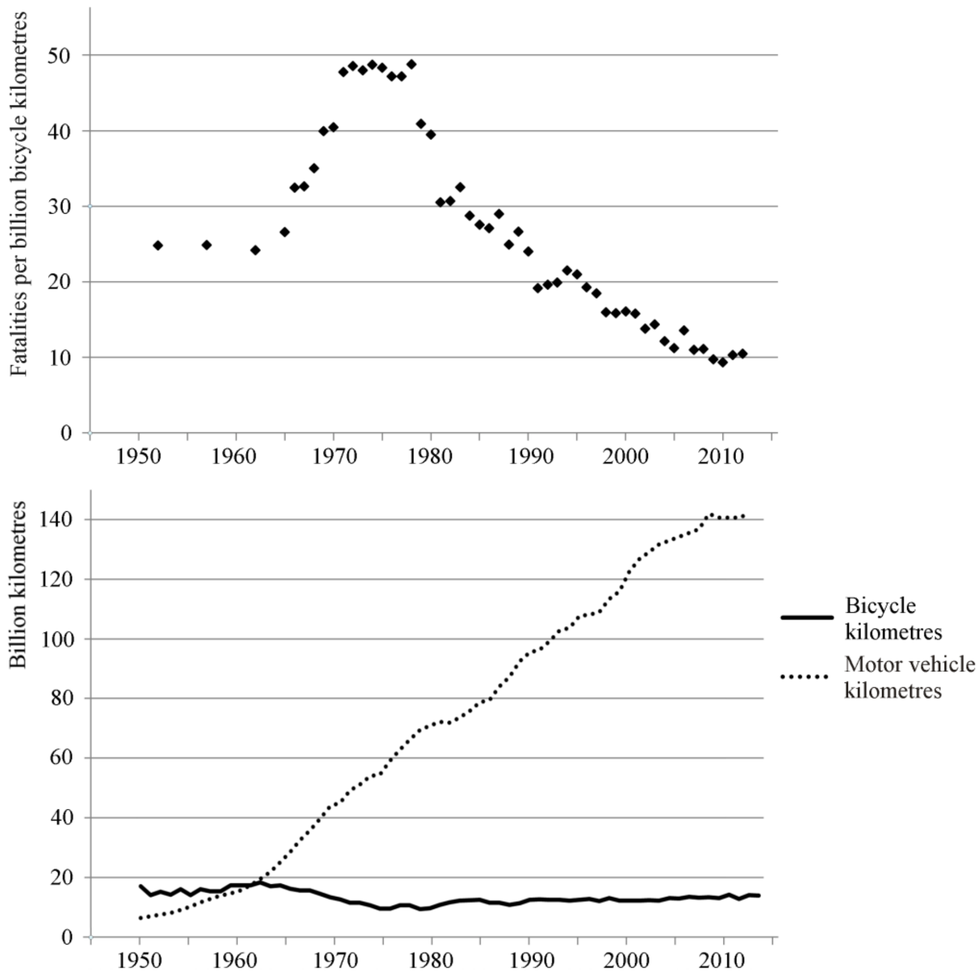

Figure 1. Number of recorded cyclist fatalities per billion bicycle kilometres (figures up to the first half of the 1970s are 5-year averages as the estimates for the amount of bicycle kilometres were not yet based on the National Travel Survey) (Statistics Netherlands 2011, Blokpoel and Harris 1989)

1.3. Cycling safety and road safety compared to other countries

Another indication of a potential link between road safety policies and levels of cycling safety is provided by Figure 2 which depicts the level of road safety in general (road fatalities per 100,000 population) and cycling safety (cyclist fatalities per billion bicycle kilometres) in European countries. It shows a correlation between cycling safety and road safety in general. For instance, Sweden, a world leader in road safety, has one of the lowest number of cyclist fatalities per billion bicycle kilometres. This is indicative of a strong relationship between road safety in general and cycling safety.

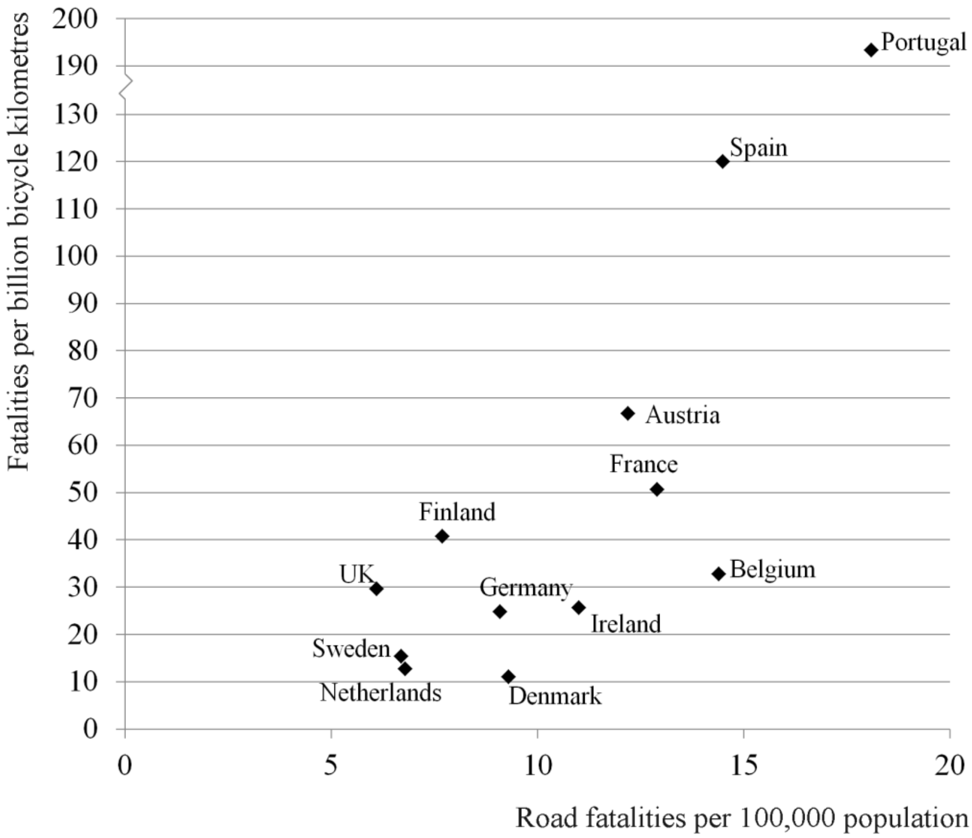

Figure 2. Fatalities per billion kilometres travelled by bicycle in 2002 against total road fatalities per 100,000 population in European countries (the vertical axis is broken to accommodate Portugal) (OECD, 2012; Van Hout, 2007)

2. Study approach and data use

2.1 Conceptual framework

To visualise the factors and their causal relationships, and to structure the findings accordingly, the study applied a recently published conceptual framework for road safety (Schepers et al., 2014b; see Figure 3) which has been adapted to explain the risk of serious and fatal BMV crashes. In this form, the model closely resembles a conceptual framework by Elvik et al. (2009). The model has two main blocks that are also used to structure the results in Section 3, i.e. travel behaviour and exposure to risk (motor vehicles, especially those at higher speed) in Section 3.1 and risk (the likelihood of a collision and injury consequences if a crash occurs) in Section 3.2.

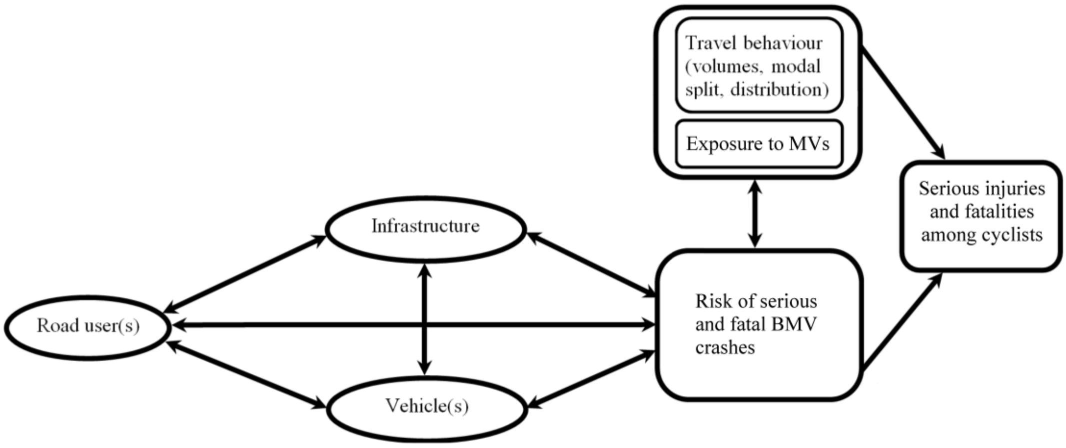

Figure 3. Conceptual framework on factors affecting road safety (adapted from (Schepers *et al.* 2014b))

The modal split and distribution of traffic over space – two aspects of travel behaviour – determine the numbers of motor vehicles encountered by cyclists and thereby their exposure to risk. Volumes are important because it has been found, at different levels such as intersections, road sections and jurisdictions, that the amount of bicycle and motor vehicle traffic affect the likelihood of BMV crashes (an arrow from exposure to risk) (Jacobsen, 2003; Elvik, 2009). This also works in reverse because perceived risk affects decisions to cycle (an arrow from risk to exposure) (Heinen et al., 2010). Crash risk results from interaction between three elements, sometimes called the three traffic safety pillars: road user(s), vehicle(s), and infrastructure (e.g. Othman et al., 2009).

2.2 Methods and data

A literature review was conducted to bring the results of key publications in two lines of research together. The first line comprises international comparisons (e.g. Pucher and Buehler, 2008a, Jacobsen and Rutter, 2012) that describe how circumstances in the Netherlands differ from those in other countries. The second line concerns general cycling safety research. Within this stream there are general review studies about cycling safety (e.g. by Wegman et al., 2012), reviews about measures to improve cycling safety (e.g. Twisk et al., 2013b), and reviews focused on specific areas like the link between the amount of cycling and risk of BMV crashes (Elvik, 2009), and bicycle infrstructure safety (e.g. Thomas and DeRobertis, 2013). We also used evaluation research available from Dutch institutes like SWOV (2014) and Fietsberaad (2014) because of their validity for Dutch circumstances. Only in the few cases where there were gaps within these publications did we undertake further search via search systems like Scopus and Google Scholar. The study took in data on road safety in the Netherlands which are publicly available at the website of SWOV Institute for Road Safety Research (SWOV, 2014).

3. Relevant factors

This section explores explanations for the high level of Dutch cycling safety. Factors are structured according to the conceptual framework depicted in Section 2. Section 3.1 followed on travel behaviour and exposure to risk (the upper part of the conceptual model), while section 3.2 is related to risk (the lower part of the model).

3.1 Travel behaviour and exposure to risk

This section is about travel behaviour and exposure to risk, i.e. the risk posed by motor vehicles due to differences in mass and speed compared to cyclists. The travel behaviour aspects of distribution of traffic, modal split and volumes are described separately for reasons of readability. However, although this has to our best knowledge not been addressed integrally in empirical research, exposure to risk should be understood as resulting from the interaction between these three characteristics of travel behaviour. For instance, many cyclists and motor vehicles at the same location results in higher exposure to the risk of motor vehicles than the same volumes on separated locations.

3.1.1 Distribution of traffic over the road network

Important to cyclists' exposure to motor vehicles is the distribution of cycle and motor traffic over the road network, which is strongly affected by the Dutch 'street hierarchy'. This hierarchical structure is based on the two key principles of *Homogeneity* and *Functionality*. Homogeneity implies that differences in speed, direction and mass should not be too large, e.g. a safe speed for mixing cyclists with motorised traffic is no higher than 30 km/h (Tingvall and Haworth, 1999). A 30 km/h speed is the standard in traffic-calmed areas. On distributor roads where the limit is 50 to 70 km/h, the ambition is that cyclists are separated from motorised traffic on road sections by bicycle paths, while motor vehicle speed is to be reduced at intersections. Functionality refers to classification of roads in a hierarchical road network. The function of higher order through roads (mostly freeways) is traffic flow, whereas lower order access roads provide access to origins and destinations. Distributor roads distribute traffic from through roads to access roads. Table 2 lists the speed limits and the location of cyclists for the three road classes.

Table 2. Road classification and speed limits in the Netherlands

	Speed limit in urban areas	Location of cyclist
Access roads	30 km/h	Mixed with other traffic
Distributor roads	50 or 70 km/h	Separated from motorised traffic by bicycle paths or lanes*
Through roads	100 or 120 km/h	Cycling not allowed

* Paths are physically separated from the carriageway, whereas lanes provide a visibly delineated space on roads

The street hierarchy has a long tradition starting with experiments in the 1960s with so-called ‘Woonerfs’ (literally translating to “home zones”) to enable children to play safely in residential streets. Woonerfs, an example of which is given in Figure 4, were legally recognised in the 1970s with a 15 km/h speed limit (Hass-Klau, 1990). Subsequently, the 30 km/h zone was legally recognised in 1984 to achieve traffic calming in larger areas, up to 2 km^2 and in new towns, even larger (SWOV, 2010). Agreement on implementation of the street hierarchy on a national scale (along with a number of other road safety measures) was reached in 1998. By 2008, the speed limit on 85% of the roads in built-up areas classified as access roads had been reduced to 30 km/h (Weijermars and Wegman, 2011).

Figure 4. Example of a woonerf (home zone)

The Dutch 'street hierarchy' strongly reduces cyclists' exposure to motorised traffic by shifting vehicles away from where there is a lot of cycling. The Netherlands has the densest motorway network in Europe at 57 km per $1000km^2$, where about half of all motor vehicle kilometres are travelled (KiM, 2012). This network shifts away motor vehicles from where cycling levels are high. For comparison, less than one-third of all vehicle miles in the US (interstate and other freeways) and around a quarter in Europe are travelled on motorways (De Hartog et al., 2010, FHWA, 2013). Access roads are designed for low speeds and use speed-reducing measures and street closures to deter through motor traffic. These areas are still relatively permeable to cyclists ('filtered permeability', see Melia, 2012) as a result of authorization of contraflow cycling in one-way streets (see Figure 5, left), short cuts for cyclists where roads are closed to motor vehicles (see Figure 5, right), and standalone bicycle paths that offer additional route options to cyclists, etc. (Weijermars and Wegman, 2011). In terms of road use, it is estimated that almost 60% of bicycle kilometres in urban areas are travelled in traffic-calmed areas (Gommers and Bovy, 1987, Schepers et al., 2013).

Figure 5. Example of a street closure (left) and one-way street with allowance of contraflow cycling, indicated by the traffic sign (right)

The importance of this form of 'network level separation' (also called 'unbundling') to cycling safety is indicated by a lower likelihood of fatal and serious crashes in Dutch municipalities with a higher share of bicycle kilometres in traffic-calmed areas. More bicycle kilometres through traffic-calmed areas, along with the installation of grade separated intersections (bicycle bridges or tunnels) to cross distributor roads was found to be related to strong reductions in the fatality crash rate. One standard deviation (SD representing 34% of the study population) on a score that was developed to measure network level separation for Dutch municipalities corresponded to a 24% decrease in the likelihood of fatal bicycle crashes. The score combines the share of bicycle kilometres through traffic-calmed areas and the number of bicycle tunnels and bridges to cross distributor roads per bicycle kilometre (both related to a decreased exposure to high speed motor vehicles). More specifically, a 12% higher share of bicycle kilometres through traffic-calmed areas and 1 additional grade-separated intersection to cross distributor roads per 10 kilometres travelled by bicycle corresponds with a 24% lower number of cyclist fatalities in BMV crashes per bicycle kilometre (Schepers et al., 2013). These outcomes show the importance of network level separation in explaining the variation in fatality risk between municipalities.

3.1.2 Other effects of travel behaviour and exposure

A second aspect of travel behaviour affecting exposure to risk is the modal split. The Netherlands has high individual levels of cycling (on average 2.4 km per person per day), with cycling having a high modal share (35% of all trips up to 7.5 km) and driving having a correspondingly lower modal share (also 35% of all trips up to 7.5 km) (KiM, 2011). The latter is important to cycling safety as it reduces cyclists' exposure to motor vehicles, especially for the vast number of short utilitarian bicycle trips travelled within urban areas (Stipdonk and Reurings, 2012). In contrast, the majority of bicycling in countries with lower volumes of cycling like the US is for recreation rather than transportation (Xing, et al., 2010) which does not reduce the need to travel by car and accordingly the exposure to motor vehicles remains constant.

A third aspect of travel behaviour concerns the SiN phenomenon, which states that higher volumes of cyclists on the road reduce the risk of BMV crashes when the number of motor vehicles on the road is kept constant (Jacobsen, 2003), an explanation consistent with expectancy theory (see e.g. Houtenbos, 2008). Others have suggested that improvements in road infrastructure may provide an explanation (e.g. Brüde and Larsson, 1993). When more road users take up cycling, there will be a greater push for developments towards safer cycling infrastructure (Wegman et al., 2012). Note though that the phenomenon is also found in studies (including one Dutch study by Schepers et al. (2011)) that statistically control infrastructure factors such as the presence of bicycle infrastructure (Elvik, 2009, Schepers et al., 2011), thereby giving some support for the SiN explanation.

A study comparing Dutch municipalities provides an indication of the relevance of these last two factors (Schepers and Heinen, 2013). Using the results of this study it can be estimated that, all other things being equal, a modal shift resulting in a 7% higher bicycle modal share (corresponding to one Standard Deviation for Dutch municipalities and some 25% more bicycle kilometres per capita) would reduce the number of fatalities per billion bicycle kilometres by 10%.

To summarise, we compared how the variation among Dutch municipalities related to network level separation and bicycle modal share, expressed in Standard Deviations (SD’s), is related to cycling safety. While one SD of the network level separation score by Schepers et al. (2013) was related to a 24% lower fatal BMV crash risk, one SD of bicycle modal share reduced the fatal BMV crash risk by only 10% (Schepers and Heinen, 2013). Both factors reduce the exposure to motorised vehicles. However, the former explains more of the variation in fatality rate amongst Dutch municipalities than the latter (Schepers and Heinen, 2013, Schepers et al., 2013).

3.2 Risk factors related to road user behaviour, infrastructure and vehicle design

This section on risk factors is structured according to the three pillars of road safety. Section 3.2.1 is about road users with subsections for cycling speed, experience as a cyclist, education and training, legal liability, and safety measures to reduce risky behaviour). Section 3.2.2 focuses on road infrastructure and includes subsections for bicycle paths and intersection treatments. Section 3.2.3 focuses on motor vehicles and bicycles that can be involved in BMV crashes.

3.2.1 Road users

Crash risk is also influenced by the behaviour of road users. Here we discuss the following aspects: speed choice, experience, training and assessment, legal liability, and safety measures to reduce risky behaviour. We compare these practices in the Netherlands with those in other countries, its main purpose being the identification of practices that might have contributed to greater cycle safety in the Netherlands.

Cycling speed

Concerning speed choice, Fyhri et al. (2012) distinguished two groups of cyclists with different risk profiles and riding speeds, i.e. a speed-happy group with lots of cycle equipment, including helmets, and a group of cyclists travelling slowly in regular clothes without helmets. With operational speeds (excluding stops) between 16 and 18 km/h (Allen et al., 1998, Twisk et al., 2013a, Van Oijen et al., 2013), the Dutch cycle more slowly than cyclists in most other countries. The speed of electric bicycles is slightly higher at 19 km/h (Van Oijen et al., 2013). Higher average operational speeds of between 18 and 26 km/h have been reported in the UK, US, and Canada where bicycle modal shares are much lower (Parkin and Rotheram, 2010). Higher cycling speeds have been found to be related to injury severity (Schepers et al., 2014a). Low cycling speeds have been suggested as an explanation for lower injury rates among users of bicycle-sharing systems compared to private bicycle users (Woodcock et al., 2014). Low cycling speeds allow car drivers more time to respond to cyclists at intersections (Summala et al., 1996). Another aspect not mentioned in the literature may be that a lower cycling speed offers greater reaction time for cyclists to take action to avoid collisions. Although there is empirical support for the role of cycling speed, the available data and research do not allow for quantitative assessment of the effect of this behavioural factor.

Experience as a cyclist

The Dutch are experienced cyclists. Having learned to cycle at a young age, by the time they cycle independently, usually at around 12 years of age (Reurings et al., 2012), they have developed the skills and capabilities to anticipate hazards fairly well. Furthermore, those who continue to cycle frequently throughout their lives will maintain their cycling skills. In addition, the experience of being a cyclist may help drivers anticipate cyclists. A study by Maas (2011) indicated that, after statistically controlling for motor vehicle kilometres and age, motorists who cycle frequently are less likely to collide with cyclists. However, because of the small sample size these relationships were not statistically significant. We are not aware of any larger studies on this issue, but as it is often suggested that experience plays a role in drivers' hazard perception and anticipation (Vlakveld, 2011), it is conceivable that this factor plays a role.

Education and training

A road safety education programme targeting Dutch primary school children has been in place since 1932, and became obligatory in 1959 (Veilig Verkeer Nederland, 2014). Schools can take part in a theoretical examination that focuses on traffic rules, and in a practical test of children's cycling skills on public roads. Currently, about half of the schools participate in the practical examination (Weijermars and Van Schagen, 2009). However, of the traffic education programmes that have been evaluated, the results show only minor positive effects (Reurings et al., 2012). Motorist training and examination is rather intensive in the Netherlands (Pucher and Buehler, 2008b). However, international reviews of evaluation studies suggest that formal basic driver training and examination is not related to drivers' crash rate after licensing (Senserrick and Haworth, 2005, Vlakveld, 2011). From this we are unable to conclude that education and training offer a valid explanation for the high level of cycling safety.

Legal liability

In the Netherlands, the legal liability of motorists involved in collisions with cyclists differs from that of many other countries (Pucher and Dijkstra, 2003). Under a Dutch law introduced 1 January 1994, a motorist is held responsible for any collisions in which a child, a cyclist, or a pedestrian is injured. According to article 185, the driver is still liable for at least 50% of the damage if an adult non-motorised road user was at fault (Ministry of Infrastructure and the Environment, 1994). Already before 1994, jurisprudence was moving towards more protection of vulnerable road users (Bouman and Van Wassenaer van Catwijck, 1993). However, the law gained a lot of media attention and was presented as development towards almost certain 100% liability of drivers in case of BMV crashes [1].

The suggestion that liability laws decrease the risk of BMV crashes is based on the hypothesis that drivers adapt their behaviour towards vulnerable road users to avoid financial damage (Pucher and Buehler, 2008a). There is to our best knowledge no empirical research supporting this hypothesis. According to Summala (1998), driving becomes habitual and largely automatized with experience resulting in drivers being

[1] The following film on YouTube contains an item from the national news and sketch of well-known comedians in the 1990s: https://www.youtube.com/watch?v=ivY06w83fKU

unable to take traffic risks into account to a degree that would be rational from their own point of view and that of society. The hypothesis that drivers adapt their behaviour to the risk of liability in the event of a crash is not in line with Summala's theory of driving behaviour.

Because of the lack of empirical research we fitted a linear regression line on the number of fatalities in BMV crashes per billion bicycle kilometres in 1984-2003, 10 years before and after the 1994 law:

$$Risk_{BMV} = c + b*year + d_{1994},$$

where c is a constant, b is the annual risk reduction, and d_{1994} is a dummy variable (equalling 0 between 1984 and 1993 and 1 between 1994 and 2003). As a restriction of cyclist fatalities per crash type is only available since 1987, we assumed the same BMV crash percentage of the total number of fatal cyclist crashes in 1984-1986 as in 1987-1989. The results of the analysis indicate a significant annual risk decrease (see b in Table 3) and an insignificant risk increase in 1994 (see d_{1994} in Table 3). A positive instead of negative parameter for d_{1994} suggests the new law was unrelated to cycling safety. Notwithstanding the good reasons for liability laws related to vulnerability of cyclist and pedestrians and fairness, there is, as yet, no empirical and theoretical support for a link with cycling safety.

Table 3. Results of linear regression on the risk of fatal BMV crashes per billion bicycle kilometres

Parameter	B	SE	*P*
c (constant)	1963.4	210.2	<0.001
b (annual risk decrease)	-1.0	0.1	<0.001
D_{1994} (dummy)	2.1	1.2	0.11
R^2	93%		

Safety measures to reduce risky behaviour

Safety measures to combat deliberate risky behaviour, such as deterring alcohol use among cyclists or promoting the use of helmets, may play a role in greater cycling safety. Bicycle helmets seem to provide a small protective effect when the risk of injury to head, face or neck is viewed as a whole (Elvik, 2011). However, this does not explain the high level of cycling safety as Dutch cyclists are not obliged to wear helmets and rarely do so (SWOV, 2012). Alcohol use has a negative effect on both cyclists and drivers and increases the likelihood of crashes (Kuypers et al., 2012, Martínez-Ruiza et al., 2013). Although the legal limit for the blood alcohol concentration while driving and cycling is 0.05%, the Netherlands do not enforce alcohol use by cyclists (Twisk and Reurings, 2013). Policies focused on driver behaviour such as campaigns and enforcement to reduce car driving under the influence of alcohol and drugs are important. However, these measures do not differ much from those in other countries and do not explain differences between cycling safety in the Netherlands and other developed countries.

3.2.2 Road infrastructure

Bicycle paths

Over 80% of all police-reported fatal and severe BMV crashes in built-up areas occur on distributor roads where exposure to high-speed motor vehicles is greatest (Schepers et al., 2013). The *Homogeneity* principle, already mentioned in Section 4.1.1, suggests that cyclists should be separated from motorised traffic along distributor roads because speeds exceed 30 km/h. SWOV mentioned the *Homogeneity* principle as an explanation for the desirability of separated bicycle paths as early as the 1960s (SWOV, 1965). By 1965 the country had approximately 66,000km of paved roads and 6,000 km of bicycle paths (SWOV, 1965, Lesisz, 2004). Since the 1960s the kilometres of roadway has doubled, however bicycle paths have increased six-fold, to 35,000 km in 2013 (Fietsersbond, 2014). In Figure 6, the right-hand picture shows a physically separated bicycle path, the preferred option along distributor roads, while the left-hand picture shows bicycle lanes, the option that can be applied if space for a bicycle path is lacking (CROW, 2007). Distributor roads without bicycle infrastructure are rare in the Netherlands.

Figure 6. Example of a bicycle path (right) and bicycle lane (left)

The overall safety effect of one-way bicycle paths on busy streets is positive. Dutch research indicates the likelihood of BMV crashes at unsignalized intersections is some 45% lower with a bicycle path deflected between 2 and 5 metres away from the intersection area as compared to intersections with bicycle lanes or no facility (Schepers et al., 2013). The risk of BMV crashes is further reduced by physical separation along road sections (Welleman and Dijkstra, 1988, Thomas and DeRobertis, 2013). This is not the case for the frequently implemented two-way bicycle paths, which, compared to one-way bicycle paths, have a 75% elevated risk of BMV crashes at unsignalized intersections. (Schepers et al., 2011). This is due to, in the case of right-hand driving, drivers coming from minor roads not expecting cyclists from the right (Summala et al., 1996). Similarly, two-way bicycle paths increase the risk of BMV crashes at roundabouts (Weijermars, 2001), and of crashes with lorries (Schoon et al., 2008). However, a study by Lusk et al.

(2011), judged in the review by Thomas and DeRobertis (2013) as best meeting their quality criteria to study urban bicycle paths, still found a net safety benefit for building two-way bicycle paths as compared to road without any facilities. Moreover, as around three-quarters of all cycle tracks are one-way tracks, we can still conclude that separated bicycle paths do contribute to the high level of cycling safety in the Netherlands.

Intersection treatments

Intersections are important because the majority of BMV crashes along distributor roads are concentrated at intersections (Welleman and Dijkstra, 1988, Schepers et al., 2011). Speed reduction and a clearance between 2 and 5 m between the bicycle path and the carriageway improve cycling safety, see for example Figure 7 (Schepers et al., 2011). The latter is also important in the prevention of very severe crashes with right-turning trucks by keeping cyclists out of the blind spot on the trucks' passenger side (Niewöhner and Berg, 2005, Schoon et al., 2008). Similarly, speed reduction is associated with reduced injury severity (Kim et al., 2007). To indicate the importance of these measures, it was estimated that speed-reducing measures that have been implemented at unsignalized intersections in the Netherlands have prevented some 2.5% of the total number of cyclist fatalities (Schepers and Voorham, 2010, Schepers et al., 2013).

Figure 7. Example of an intersection treatment: a speed hump and clearance of 5m between the bicycle path and distributor road (Schepers *et al.* 2011)

Measures taken to prevent crashes at signalized intersections include advance stop lines, bike boxes and a pre-start for cycle traffic (where there are separate signals for cyclists) to make cyclists more visible (Niewöhner and Berg, 2005, Schoon et al., 2008, Dill et al., 2012), see Figure 8.

Figure 8. Example of a bike box (left) and a pre-start for cyclists, i.e. through cyclists have a green light while the light for right turning motor vehicles is still red (right)

3.2.3 Vehicles

The range of motor vehicle brands used in the Netherlands are roughly comparable to those used in other developed countries. The country does not have its own car manufacturing industry and most vehicle requirements are set at the European level. The average age of a passenger car in the Netherlands in 2011 was 8.8 years, almost equal to the EU 2011 average of 8.6 years (ACEA, 2015, Statistics Netherlands, 2015). We expect that measures such as the close proximity mirror (mandatory since the 1980s) and open side underrun protection (mandatory for new lorries since 1995) improve cycling safety (Schoon et al., 2008), but that they do not contribute to differences in cycling safety with other countries.

The basic design of bicycles has changed little over time and it is unlikely that differences between countries in this respect contribute to different fatality rates (Meijaard et al., 2007). However, more specific characteristics like conspicuity measures may have an effect on the likelihood of BMV crashes. White front lights became obligatory in 1906; red rear lights in 1927; and rear, pedal and side reflectors in the 1970s and 1980s (Van Minnen, 1982, Blokpoel, 1990, Lesisz, 2004). Use of bicycle lights is still being promoted and enforced (Ministry of Infrastructure and the Environment, 2008), but with only about three-quarters of all cyclists using front lights, usage is at about the same level as in the 1970s (Noordzij, 1973, Broeks and Boxum, 2013). Small positive effects have been found for some of these visibility measures (Van Minnen, 1982, Blokpoel, 1990), but the risk of a collision with a motor vehicle is still much higher in darkness than in daylight (Twisk and Reurings, 2013). In addition, the use does not seem very different from other countries.

To summarise, the most important risk factors contributing to the high level of cycling safety in the Netherlands are a low cycling speed, (one-way) bicycle paths and intersection treatments such as speed-reducing measures. The available data and research do not allow for quantitative assessment of these factors. The length of cycling experience may be an additional contributing factor, but this would need to be substantiated in future research.

4. Discussion and conclusions

Since the 1970s, the Netherlands has achieved an 80% reduction in cyclist's fatality rate and is now, together with Denmark, the safest country in which to ride a bicycle. This paper, structured according to a conceptual framework for road safety, explored which factors and measures explain this achievement. The following conclusions were drawn. In line with the conceptual framework, we have found both travel behaviour and exposure (the upper part of the model) and risk factors (the lower part of the model) to contribute to the low cyclist fatality rate. The most critical factor related to travel behaviour and exposure to risk (posed by high speed motor vehicles) is 'network level separation'. Large traffic-calmed areas, a rough (coarse) distributor road network for motorised traffic, and a heavily used freeway network have reduced cyclists' exposure to high-speed motor vehicles. This shifts away motor vehicles from where cycling levels are high. The high incidence of cycling is also beneficial to cycling safety as a shift from driving to cycling reduces cyclist's exposure to motor vehicles as well. Important risk reducing factors are a low cycling speed, (one-way) bicycle paths and intersection treatments that reduce speed and increase visibility.

4.1 The contribution of this study

Other studies on the high level of cycling safety in the Netherlands were based on comparing conditions for cycling to those in other countries (e.g. Pucher and Dijkstra, 2003, Pucher and Buehler, 2008a, Jacobsen and Rutter, 2012). Even though only limited attention was being given to the effectiveness of safety measures in these studies, our results confirm several of their outcomes, i.e. the importance of traffic calming, bicycle paths, and intersection treatments (Pucher and Dijkstra, 2003, Jacobsen and Rutter, 2012) as an explanation for the high level of cycling safety. However, there are also a number of factors deemed important in country comparison studies while evaluation research found no or at most a very small contribution to cycling safety, i.e. comprehensive traffic education and training of both cyclists and motorists. There is also a lack of research about the impact traffic regulations that favour cyclist and pedestrians and we did not find the introduction of strict liability in the Netherlands in 1994 to be associated with cycling safety (see also Section 4.2).

Finally, the results of our study stress the importance of measures and factors that have not yet been found in country comparison studies. These are the Dutch Sustainable Safety principles of Homogeneity and Functionality underlying Dutch practice which are important to achieve network level separation and thereby reduce exposure to the risk posed by motor vehicles. Many bicycle kilometres are travelled in traffic-calmed areas where there are few motor vehicles while many motor vehicle kilometres are travelled on freeways where cyclists are not allowed. Previous studies primarily focused on the location instead of the network level. Finally, compared to country comparison studies, a new explanatory factor that has emerged from this study is that of low cycling speeds. Future research could examine whether low cycling speeds are related to utilitarian trip purposes which dominate in countries with high volumes of cycling (Pucher and Dijkstra, 2003). Including electrically assisted bicycles is recommendable given their increasing use.

4.2 Study limitations and directions for future research

Our study draws heavily on a combination of country comparison studies on the one hand and general road safety and cycling safety research such as evaluation of measures on the other hand. The outcomes suggest that there are still research gaps that could be addressed by studies within both lines of research or a combination. For instance, we found it is conceivable the Dutch are more skilled as cyclists because they cycle a lot and learn to cycle at a young age, but empirical research about the role in BMV crashes is lacking. The EU project SARTRE4 (Social Attitudes to Road Traffic Risk in Europe), based on a common representative survey conducted in each participating member state, recently included ‘other road users’, i.e. pedestrians, cyclists and users of public transport (SARTRE, 2015). This type of research would be suitable to address the above mentioned research gap by adding questions about crash involvement and cycling and driving experience. With a sufficiently large sample or preselection to oversample crash victims and/or cyclist who are rare in countries with low bicycle modal shares (see e.g. Schepers et al., 2014a for an example of oversampling in crash research), it would be possible to examine whether drivers with cycling experience (and vice versa also cyclists with a driving license and driving experience) are less likely to be involved in BMV crashes.

Surveys are also suitable for gathering more comparable data about the compilation of the cyclist population in terms of age, gender and trip motives.

Another research gap is why researchers consistently find that increased volumes of cycling are associated with lower risks of BMV crashes (Bhatia and Wier, 2011). As a result, there is uncertainty regarding the causal mechanisms explaining higher levels of safety in countries such as the Netherlands and Denmark. Previous studies suggested this is related to more awareness and cautiousness of drivers towards cyclists when and where the encounter more cyclists (Jacobsen, 2003). This study found an additional explanation of lower cycling speeds in countries with higher volumes of cycling such as the Netherlands. There is support for the role of cycling speed in cycling safety, but research on this factor is still in its infancy. An interesting new line of research to examine these factors would be conflict observations in different countries but at similarly designed locations. Preliminary results from an observational study comparing car-cyclist interaction in matched intersections indicate that the proportion of conflicts is lower in Denmark than in Norway (De Goede et al., 2014). Even if these results are indicative of a SiN mechanism taking place, the researchers argue that several mechanisms take place at the same time when cycling levels increase (De Goede et al., 2014). Some of these, such as improved infrastructure, and “normalisation” of the cyclist population, function to amplify the SiN mechanism. More research is needed to draw firm conclusions. Combining different research designs such as the aforementioned observational studies but also questionnaire studies encompassing respondents from different countries and experimental research in driving simulators (see e.g. Duivenvoorden et al., 2015) might offer the opportunity to benefit from method triangulation (Fyhri et al., 2014).

Our study did not find support for a contribution to the low Dutch risk of BMV crashes by education of drivers and cyclists and liability laws. More evaluation research is needed to examine whether new designs for education programs might help improve their safety outcomes (Twisk et al., 2015). More studies are also needed to examine if and to what extent drivers are aware of and influenced by strict liability laws that favour vulnerable road users. Note that a lack of support for these factors does not imply we advise against their application. Especially in countries with low volumes of cycling, cycling training may be children's first experience with this healthy and environmentally friendly mode of transport. Similarly, for reasons of fairness, we recommend liability rules in favour of vulnerable road users are who sustain much more severe injuries in the case of a BMV crash than the involved motorists.

An important limitation of the study is the exclusion of single-bicycle crashes that cause almost three-quarters of all serious injuries among hospitalised cyclists (Schepers et al., 2015). Current knowledge allows for some hypotheses such as a role of sufficiently wide and even road surfaces, (winter) maintenance and the visibility of obstacles to prevent of falls and obstacle collisions (Nyberg et al., 1996). Future research could focus on the question of whether such factors explain the low risk of single-bicycle crashes in countries like the Netherlands and Denmark (Schepers et al., 2015).

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