Safety enhancing features of cycling infrastructure

Review of evidence from Dutch and international literature

R-2021-20

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Prevent crashes
Reduce injuries
Save lives

Report documentation

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Summary

Cycling is widely promoted as a healthy and sustainable means of transport. At the same time, traffic safety concerns are growing, both in the Netherlands and elsewhere, because of increasing numbers of cyclists involved in crashes (fatal and serious injury). Scientific evidence could help identify infrastructural factors affecting these crashes, which requires research results on different aspects of this issue to be reviewed.

In this review, we focus on different aspects of cycling infrastructure and their contribution to the risk of bicycle crashes. Dutch and international studies are reviewed that address a bicycle crash risk indicator as an outcome measure, thereby controlling for differences in cyclist flow. Controlling for cyclist flow is crucial for valid interpretation of the safety levels of infrastructure elements or designs. This requirement limits the number of relevant studies, because in many studies cycling flow is unknown and only crash frequency (not crash risk) is reported.

A distinction is made between findings from Dutch studies and international studies (not conducted in the Netherlands). This was considered necessary because of the ‘advanced’ cycling culture and infrastructure facilities for cyclists in the Netherlands. In some instances, it appears that this distinction results in different outcomes. These are mentioned in the report.

First of all, the conclusions of the review focus on the safety enhancing features of the cycling infrastructure that are to some extent evidence-based, followed by the features about which we still have no evidence.

The evidence for infrastructure features that affect safety is generally based on a limited number of studies, conducted on specific locations in different geographical settings. This implies that the results may not be interpreted as valid for every specific location, because local circumstances may differ from those included in the studies. As the number of studies increases, providing consistent evidence on different locations, the generalisability of the outcomes will be stronger.

For each of the different infrastructural elements, the main findings are listed below:

Urban versus rural areas
In urban areas, the number of crashes involving cyclists is higher than in rural areas. Dutch figures show that over 60% of fatalities and about 81% of serious injuries (involving motorised traffic) among cyclists are due to crashes in urban areas. Figures from other countries support this general conclusion with sometimes different proportions.

Network route choice
Dutch cyclists prefer routes with bicycle facilities, low speed limits, low motorised traffic volume, good surface quality and short travel time. International studies found comparable results and point to additional preference factors, i.e. light conditions.

Route
There is growing evidence for improved safety as a result of implementing bicycle tracks compared to bicycle lanes, or no facilities for cyclists. Recent Dutch studies do not show safety effects of bicycle lanes compared to no bicycle facility. However, some relatively recent international studies show that bicycle lanes do improve safety compared to no bicycle facility.

If we consider intersection safety, two-way bicycle tracks are found to be less safe than one-way bicycle tracks.

Road section
Because this perspective addresses quite specific features, only few studies focus on them, and evidence is still based on a very limited number of studies. We found indications for the following features affecting safety:

1. Wider bicycle tracks improve safety.
2. On-street parking decreases bicycle safety.
3. Tram tracks on the road decrease bicycle safety.
4. Presence of obstacles such as poles, trees, and signs within two meters of the bicycle facility decreases cycling safety
5. Presence of road lighting increases cycling safety

Intersections
A general finding is that, for cyclists, intersections are more dangerous than road sections. Concerning intersection safety we found that:

1. Intersections with lower speed limits are safer.
2. Bicycle crash risk is reduced when the bicycle crossing at the intersection is deflected further away.

Roundabouts
Relating to the safety of roundabouts, Dutch and international studies have contrary results. In the Netherlands, bicycle crash risk at roundabouts is lower than at intersections. However, international studies show that roundabouts increase the risk of a bicycle crash compared to intersections. Concerning intersection safety we found that:

1. Roundabouts with bicycle tracks are safer than roundabouts with bicycle lanes or roundabouts without any bicycle facility.
2. Two-lane roundabouts increase the risk of a bicycle crash.
3. Higher speed limits at roundabouts decrease bicycle safety.
4. Roundabouts are safer when vehicles have priority.

Other
We identified a number of relevant infrastructure features for which no cycling safety evidence was found in the literature. These are listed below.

1. Location data for seriously injured cyclists not involving motorised traffic were not found.
2. No information was found on bicycle **crash risk** in urban versus rural areas.
3. No **safety risk** indications were found for shared space with pedestrians and solitary bicycle tracks.
4. On the issues of kerbs and surface condition no studies addressing **crash risk** were found**.**
5. No **risk-based** evidence was found that bicycle boxes and dedicated green phases at intersections improve cycling safety.

The general conclusion of this review is that there is a growing body of evidence that several infrastructure features relate to cycling safety, but that the evidence is still based on a limited number of studies, that it only concerns crash frequency (not risk), and does not cover all relevant features. The need for more studies is not only prompted by the lack of knowledge as such, but more importantly by the growing concern about the increasing number of crashes involving cyclists.

Contents

1 Introduction

Active modes of transport are beneficial to health, accessibility and sustainability and are therefore encouraged by national, regional, and local policymakers. Improving cycling infrastructure is part of this policy. Engineers, urban designers, and decision makers aim to increase cycling mode share and enhance cyclist safety.

In the Netherlands, the length of cycling infrastructure increased from 9,282 km in 1978 to 18,175 km in 1992 and about 35,000 kilometres in 2019 (CBS, 2020). Also, the total number of bicycles in the Netherlands increased from 17.8 million in 2000 to 22.9 million in 2018; which is an increase of almost 30% (KiM, 2020). Among this total, the number of e-bikes has grown from 1 million in 2012 to 2.1 million in 2018. In total, more than one quarter of all trips made by Dutch residents are made by bicycle, spanning a distance of 17.6 billion bicycle kilometres in 2019 (KiM, 2020).

At the same time, cyclists are vulnerable because cyclists are not physically protected in the event of a crash. They have higher speeds compared to pedestrians, and can perform swift unexpected manoeuvres. As a result, in response to their presence, drivers need to react faster and be more alert. In the Netherlands, cyclists account for 38% of road deaths, while fatal crashes among car occupants account for 32%, indicating the dangers of cycling (SWOV, 2021a). In 2020 in the Netherlands, 229 cyclist fatalities were recorded due to crashes (CBS, 2021). Between 2009 and 2019, the average annual number of cyclist fatalities increased by 2% (Aarts et al., 2020).

To highlight the safety of cycling in the Netherlands, it is important to look not only at the frequency of crashes, deaths and injuries, but also at the traffic volume (as an exposure measure). *Figure 1.1* shows the fatality risk of cycling in the Netherlands to be higher than the risk of driving a car or walking.

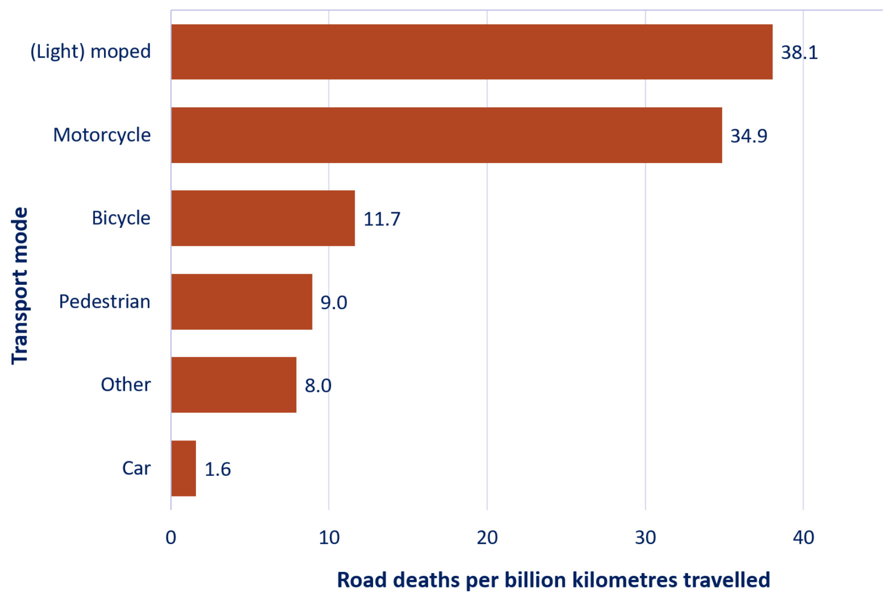


Figure 1.1. Fatality risk by mode of transport averaged over 2018 and 2019 (Statistics Netherlands, edited by SWOV).

In addition to cycling fatalities, serious cycling injuries also occur. From 2010 to 2020, the proportion of cyclists who were seriously injured increased (SWOV, 2020), and the prognosis is that it will further increase in the coming years (Wijlhuizen, et al. 2021). In 2019, most of the serious road injuries involving cyclists were due to crashes not involving motor vehicles (82%). In many of these crashes, elements of the road infrastructure were involved; Schepers (2008) estimated that this was the case in more than half of these crashes.

While policies aimed at improving cycling safety have already been implemented, there are still many cyclist fatalities and injuries. In order to improve cycling safety, knowledge about determinants and preventive measures is a necessary condition for effective road safety policy at local, regional and national level.

Safe infrastructure is an important pillar in this respect (Reurings et al., 2012; Dai et. al., 2021). Developing knowledge about determinants and prevention strategies aimed at infrastructure contributes to the development of effective measures and evidence for the safety requirements of cycling infrastructure (SPV, 2020). SWOV has addressed these issues in several reports which will be described throughout this document (Schepers et al., 2020; Aarts & Dijkstra, 2018; Dijkstra, 2005; Duivenvoorden, 2021; Nabavi Niaki et al., 2020; SWOV, 2017; 2020; 2021a; 2021b; Van der Kooi & Dijkstra, 2003; Van Minnen, 1995; Van Minnen, 1998; Van der Leeden, 2012; Beek, 2019; Grijpstra 2017; Delbressine 2013). These studies are the basis and motivation for conducting this literature study to identify infrastructural elements affecting cycling safety in the Netherlands and elsewhere.

1.1 Objective

In this report, results are compiled from a review of Dutch and international literature to consolidate the past efforts made in identifying infrastructural elements that contribute to an increase or decrease in cycling safety. This will provide a basis for further research into the existence of certain infrastructural elements in the network that should be eliminated or implemented to improve cycling safety.

1.2 Report structure

Chapter 2 provides the methodology used to carry out the literature review. *Chapter 3* summarises the results from the literature on bicycle accidents and infrastructure. *Chapter 4* concludes the research results and presents future studies and relevant policy topics.

2 Method

In this review, we focus on cycling infrastructure and its contribution to the risk of bicycle crashes. Dutch and international studies are reviewed that address a bicycle crash risk indicator as an outcome measure, thereby controlling for differences in cyclist flow. Controlling for cyclist flow is crucial for valid interpretation of the safety levels of infrastructure elements or designs. This requirement limits the number of relevant studies because in many studies cycling flow is unknown, and only crash frequency (not crash risk) is reported.

In our literature search we addressed the following perspectives related to cycling infrastructure:

1. *Urban versus rural:* this perspective is relevant because the combination of road infrastructure designs differs between urban and rural environments. In addition, the maximum speed of motorised traffic is significantly higher in rural environments. This implies that cyclists on rural roads and crossing these roads are exposed to potentially high impacts and more often sustain serious or fatal injuries compared to urban environments.

2. *Network:* this perspective is relevant because it addresses the issue of how cyclists (intend to) use the network infrastructure for reaching their destination. This knowledge has potential safety implications because it gives indications where interactions and conflicts of cyclists with motorised traffic can be expected. Also, the connectivity of an attractive and safe cycling infrastructure network might encourage the use of bicycles along this infrastructure.

3. *Routes:* this perspective addresses the safety-related characteristics of different types of cycling infrastructure that might be present in a network for cyclists while getting from A to B. A broad range of route-related infrastructure characteristics are distinguished with different grades of exposure to motorised traffic or pedestrians, including the number of intersections per kilometre, and the density of intersections.

4. *Road sections:* this perspective addresses the design aspects of cycling infrastructure of road sections like width, obstacles, alignment, and quality of the pavement.

5. *Intersections/roundabouts*: this perspective focuses on the design characteristics that are intended to guide cyclists as safely as possible along intersections and roundabouts where motorised traffic is merging with, or crossing the path of cyclists.

Another question that was taken into account in the literature search was if the research was based on studies on the safety of Dutch cycling infrastructure or on studies in other countries. This distinction was made because of the specific characteristics of the Dutch cycling infrastructure, for instance, the many separate bicycle tracks.

In order to scan relevant literature, a list of keywords was assembled, listed in *Appendix A*. The keywords were used for the literature review in SafetyLit, ScienceDirect, BMJ journals, Google Scholar and Springer. After reviewing the publication title and abstract, relevant papers were selected for further study. Related papers were also searched for in the Reference lists of the previously mentioned publications. Although studies evaluating cycling safety related to infrastructural elements have been carried out since the early 60s, we focused on recent publications. The search criteria specified studies after 2000, however earlier key studies found through the reference lists were also considered.

A collection of Dutch road safety studies is available in the SWOV 'library portal' (https://library.swov.nl/). Dutch publications for this study were therefore selected from the SWOV library portal. In most cases, these publications had already been referred to in 'bicycle reports' published by SWOV.

From the review of articles found by means of the mentioned search engines, over 500 hits were checked by their title. If the title appeared relevant, the abstracts were reviewed, and if the abstracts were relevant, those articles were selected for detailed reading. Over 80 articles were selected and summarised in this review.

3 Literature results

The following sections in this chapter provide a categorised summary of the literature. Each paragraph will start with a list of the main findings, and the findings will be presented in each section. First the findings from the Dutch literature will be given followed by those from the international literature.

3.1 Urban versus rural

The literature on urban and rural cycling safety is covered separately, given the difference in their infrastructural nature. Urban areas are densely populated and built-up, compared to rural areas which are outside towns and cities, less densely populated with no built-up area. Speeds are higher on rural roads, whereas intersection density is higher in urban areas. The high population and road density in urban areas means more bicycle trips due to shorter distances, resulting in a high number of urban kilometres travelled. Urban cyclists are also more exposed to other road users like fellow cyclists, pedestrians and motorised traffic. This higher exposure compared to rural cyclists has an effect on safety. The number of occasions that urban cyclists interact or have traffic conflicts with other road users is much higher than it is for rural cyclists.
These general infrastructural differences have an effect on cycling safety as summarised in the table and paragraphs below.

Table 3.1. Summary of evidence from literature: urban vs. rural

Summary of findings
1. Over 60% of fatalities among cyclists are due to crashes in urban areas
2. About 81% of serious injuries among cyclists involving a motorised vehicle happen in urban areas
3. Location data for seriously injured cyclists *not involving* motorised traffic were not found
4. No information was found on bicycle crash **risk** in urban versus rural areas.

From the Dutch perspective, over 60% of road deaths among cyclists are due to crashes in urban areas and 40% are outside the urban area (SWOV, 2017; Schepers et al., 2020).
In 2000-2009, 81% of cyclists who were seriously injured in a crash involving a motorised vehicle were urban cyclists (Reurings et al., 2012). No location data are available for bicycle crashes without the involvement of a motor vehicle (crashes with pedestrians or other cyclists and single-bicycle crashes). International studies also agree that most fatal crashes happen in urban areas (around 70%) (Coleman & Mizenko, 2018; Chen et al., 2018; Ding, et al. 2020). The European InDeV project found that in the seven countries studied (Belgium, Germany, Denmark, Spain, the Netherlands, Poland and Sweden), out of the 974 self-reported non-fatal crashes, 78% occurred in built-up areas (Møller et al., 2018).

Both Dutch and international data show that a majority of fatal crashes, from 60% up to around 70%, occur in urban areas. For crashes resulting in serious injury among bicyclists it seems that this percentage is even higher in urban areas; around 80% for crashes involving motorized vehicles. For single-bicycle crashes we do not have safety evidence about urban proportion.

No studies or data were found to compare bicycle crash risk between urban and rural areas. This is mainly due to a lack of data about cycling kilometres travelled for both areas separately. We do not have accurate location data for single-bicycle crashes either.

3.2 Network

In general, it is relevant to know how the available road and street network is used by cyclists: which routes do they choose? How safe are the routes? Is a frequently chosen route sufficiently safe? If not, can the route be improved or is there a better alternative route? At network level, relevant features are the road composition such as number of lanes, presence of median, lane width, intersection density and intersection types as well as physical barriers (waterways, railways, natural boundaries). Important facilities at this level are bridges, tunnels, bicycle tracks and the degree of mixing with motorised traffic. The table and paragraphs below summarise the network-related bicycle safety studies.

Table 3.2. Summary of evidence from literature: network

Summary of findings:
1. Dutch cyclists prefer routes with bicycle facilities, low speed limits, low motorised traffic volume, good surface quality and short travel time.
2. International studies found comparable results and also additional influencing factors; for instance, light conditions.

3.2.1 Route selection

Two Dutch studies (Joolink, 2016 and Van Overdijk, 2016) found that cyclists, including users of e-bikes, prefer to ride on bicycle facilities (specifically bicycle tracks), along lower speed limit roads with low motorised traffic volume and with good surface quality. Also, short travel time is preferred.

There is a large number of international studies addressing the issue of cyclists' route choice. We refer to a review that covers many recent publications and summarizes their main findings: Shin (2016) points to the issue that route choice for cyclists is a multicriteria phenomenon and that many studies lack coverage of the required relevant factors. They often include only a limited number of factors. This implies that future studies aiming at explaining or predicting cyclists' route choice need to include multiple relevant factors in order to reach a higher level of accuracy. For instance, Shin found that gender and light conditions also affect route selection, in addition to infrastructure features of bicycle routes.

Schepers et al. (2013) carried out a crash analysis study with data from 192 municipalities. The analysis involved comparing two types of routing (called 'bundling' by Schepers): cyclist routes along distributor roads, and cyclist routes through residential areas (no bundling). The analysis shows that in municipalities with a lower degree of bundling (not on main roads), there were fewer casualties (fatalities, serious injuries) among cyclists.

3.3 Route

In this section we discuss the evidence of the safety of different cycling infrastructure, irrespective of how this infrastructure was designed. This design aspect – relating to for instance width or obstacles - is addressed in the following paragraphs.

Table 3.3. Summary of evidence from literature: route

Summary of findings
1. Bicycle tracks have about two to eight times lower crash risk than other facilities for cyclists.
2. One-way bicycle tracks have more than two times lower crash risk than compared to two-way bicycle tracks.
3. Dutch studies found evidence that bicycle crashes are more frequent on bicycle lanes than on bicycle tracks.
4. Relatively recent international studies show that bicycle lanes reduce crash frequency compared to roads without any bicycle facility.
5. No studies with safety risk indications are found for shared space with pedestrians and bicycle tracks.

3.3.1 Bicycle track

Several studies found that bicycle tracks are safer than other infrastructure for cyclists. This applies to the combination of road sections and intersections in the Netherlands (Welleman & Dijkstra, 1988). A recent Dutch study, carried out in Amsterdam, showed a positive effect (two times lower crash risk) of bicycle tracks on cycling safety compared to marked cycle lanes (Van Petegem et al., 2021). In his master's thesis, Beek found that regardless of type, the presence of any bicycle facility reduces risk by a factor of 4.3 (Beek, 2019).

International studies have found that dedicated bicycle tracks along busy streets reduce crash risk and risk of injury by roughly 49% to 90% (Thomas & DeRobertis, 2013; Ling et al., 2019; Kullgren et al., 2019; Teschke et al., 2012). A study by Minikel (2012) in the U.S. showed that collision risks are two to eight times lower along dedicated bicycle tracks compared to parallel adjacent routes. Lusk et al. (2011) found the risk to be 3.5 times lower along dedicated bicycle tracks compared to parallel roads without a bicycle facility.

As a result of both Dutch and international studies, there is growing evidence that bicycle tracks improve cyclist safety (reduction between about two to eight times in crash risk).

3.3.2 Comparing one- and two-way bicycle tracks

Schepers et al. (2010; 2013) and SWOV (2020) provide figures on Dutch crash risk for cyclists, showing that, at intersections, crash risk on two-way bicycle tracks is 3.8 times higher compared to one-way bicycle tracks. Also according to Fietsberaad (2017), in the Netherlands, two-way bicycle tracks are less safe because of the increased complexity of the driving task, since drivers have to look at two-way traffic on both the carriageway and the bicycle track. The complexity is further increased at a roundabout when there are several legs or when the legs are not perpendicular to each other.

A review study by Thomas & DeRobertis (2013) in the U.S. also showed that, at intersections, one-way dedicated bicycle tracks are safer than two-way bicycle tracks. Studies have confirmed this risk value to be half that of two-way bicycle tracks (Vandenbulcke, 2014; Pedler & Davies, 2000). Compared to cyclists in mixed traffic, two-way bicycle tracks may even create more conflicts with motor vehicles.

There is growing evidence that, at Dutch and international intersections, one-way bicycle tracks are more than twice as safe as two-way bicycle tracks.

3.3.3 Bicycle lane

As mentioned in 3.3.1, Welleman & Dijkstra (1988) concluded that, in the Netherlands, bicycle lanes are less safe than bicycle tracks and even less safe than a road without bicycle facilities. A possible explanation is that drivers drive slightly faster on a road with bicycle lanes (Goudappel, 1984 and 1993, Van der Kooi & Dijkstra, 2003) and that drivers (outside built-up areas on access roads) drive slightly closer to the lane (Van der Kooi & Dijkstra, 2003). Furthermore, the lane does not provide any physical protection to cyclists. A more recent study, by Van Petegem et al. (2021), however, found no difference between the safety of bicycle lanes compared to roads without bicycle facilities.

A look at international studies yields different results. Improvements in safety have been found after implementing bicycle lanes on roads with no previous bicycle facility (Lott & Lott, 1976; Smith et al., 2019; Pedroso et al., 2016), and one risk analysis study by Hamann & Peek-Asa (2013) found a 60% reduction in crash rate on roads with a bicycle lane compared to roads without any bicycle facility. An international review study from Cochrane by Mulvaney et al. (2015) concluded that there are mixed results relating to the safety effects of bicycle lanes.

Beck et al. (2016) found that 67% of on-road crashes in the state of Victoria, Australia, occurred on a bicycle lane. On the other hand, Poulos et al. (2015) found that in the state of New South Wales, Australia, cyclists who cycle on bicycle tracks have 40% more crashes than cyclists who cycle in bicycle lanes. They mention that these results may (in part) be due to a lack of information on cyclist characteristics, and they do not provide information on bicycle facility lengths (e.g. more bicycle tracks compared to bicycle lanes).

A study on cycling in the opposite direction along one-way street lanes in Sweden showed that opposite-direction cycling on bicycle lanes is safer than opposite-direction cycling without a bicycle facility, since the cyclists are provided with a lane to travel in without directly interacting with pedestrians or motor vehicles. However, it becomes less safe when the bicycle lane is blocked by for example parked cars or containers (Bjørnskau, Fyhri & Sørensen, 2012).

There is mixed evidence about the safety of bicycle lanes. Dutch studies show bicycle lanes are unsafe compared to bicycle tracks and roads without any bicycle facility. However recent international studies show that bicycle lanes do improve safety compared to roads without any bicycle facility.

In an Australian study, Beck et al. (2016) found an 83% higher crash risk for cyclists using shared-pedestrian paths than for cyclists using dedicated bicycle tracks. Another Australian study considering average weekly traffic counts showed that for shared-pedestrian paths crash rate was twice as high as for bicycle lanes (De Rome et al., 2014).

3.3.4 Off-road/solitary cycle paths

The safety levels of off-road cycle paths are unknown. It is not very clear what a solitary cycle path should be compared to. A comparison with a parallel route made up of a different kind of infrastructure (roads with or without cycle paths) is obvious, but these routes are sometimes absent (outside built-up areas) or of a completely different nature.

3.4 Road Section

Table 3.4. Summary of evidence from literature: road section

Summary of findings
1. Wider bicycle tracks reduce crash frequency.
2. On-street parking increases bicycle crash frequency.
3. Tram tracks on the road increase bicycle crash risk.
4. Presence of obstacles such as poles, trees, signs, within two meters of the bicycle facility decreases cycling safety (frequency and risk).
5. Presence of road lighting decreases bicycle crash risk.
6. The evidence for findings 1. to 5. is mainly based on a very limited number of studies (not more than two studies).
7. On the issues of kerbs and surface condition no studies were found addressing crash risk.

3.4.1 Bicycle track width

A study by Van Weelderen (2020) showed that, in Amsterdam, wider bicycle tracks resulted in fewer bicycle crashes.

We did not find any additional Dutch or international bicycle crash risk studies on this issue.

3.4.2 Kerb of the bicycle facility

Schepers (2008) conducted a study on cyclists taken to the emergency room after a bicycle crash and found that 12% of the single-bicycle crashes are related to kerb impact collisions. In the Netherlands, kerbs are higher than the road surface or bicycle track, which can cause the cyclist to fall.

We did not find any additional Dutch or international bicycle crash risk studies on this issue.

3.4.3 Design of parking

Past Dutch and international studies established that, in various situations, on-street parking leads to bicycle crashes (Adviesbureau Van Roon, 1986; Teschke et al., 2014; Schimek, 2018; Delbressine, 2013). These studies only present frequencies or proportions of crashes involving parking and not crash risk indicators. Schimek (2018) found that “dooring” due to on street parking next to bicycle lanes accounts for 12% to 27% of urban bicycle crashes. Teschke et al. (2014) found there to be a 35% lower crash frequency on roads without on-street parking compared to those with on-street parking. Van Petegem et al. (2021) found a twofold higher crash risk for cyclists on 50 km/h roads where cars were parked on the street (kerbside parking).

No additional Dutch or international studies were found addressing crash risk of kerbside parking.

3.4.4 Surface condition

Poor quality of the road surface (potholes, trenches, manhole covers, embankments by tree roots and the like) is often the reason for a single-bicycle crash (Ormel et al., 2009; Schepers, 2008). For example, potholes and bumps play a role in 6% of single-bicycle crashes, and nearly a third of single-bicycle crashes among racing cyclists occur on slippery road surfaces and at longitudinal grooves (Schepers, 2008).

We did not find any additional Dutch or international crash risk studies on this issue.

3.4.5 Tram rails

Results from a Dutch study by Van Petegem et al. (2021) showed that streets with tram rails increased crash risk for cyclists by a factor of 1.7. Canadian studies by Teschke et al. (2012; 2016) found the risk of bicycle crashes involving injury on roads with tram rails to be three times higher compared to otherwise comparable roads without tram rails. The majority of these crashes are due to bicycle wheels getting stuck in the rails.

We did not find any additional Dutch or international studies addressing bicycle crash risk of roads with tram rails .

3.4.6 Presence of obstacles on or surrounding the bicycle track

A Dutch study found that obstacles such as poles in the middle of a bicycle track lead to crashes (Schepers, 2008), but no indicator for risk was reported. Van Weelderen (2020) found that a higher density of obstacles within two meters of the bicycle track pavement increased crash risk for cyclists.

We did not find any Dutch or international crash risk studies on this issue.

3.4.7 Road lighting

A study by Wanvik (2009) showed the presence of road lighting to decrease both bicycle crash risk and injury severity on urban and rural roads. The study found that, in the Netherlands, cycling injury and fatality risk is reduced by more than a factor of 0.6 after implementing road lighting. The improvement in cycling safety is more significant if road lighting is introduced to rural areas.

We did not find any Dutch or international crash risk studies on this issue.

3.5 Intersections

Table 3.5. Summary of evidence from literature: intersections

Summary of findings
1. For cyclists, intersections are more dangerous than road sections (higher crash risk and frequency)
2. Intersections with lower speed limits reduce crash risk
3. Bicycle crash risk is reduced when the bicycle crossing at the intersection is deflected further away
4. No risk-based evidence was found that bicycle boxes and dedicated green phases at intersections improve cycling safety

For cyclists, intersections have been found to be more dangerous than road sections (Kullgren et al., 2019; Chen et al., 2018). Within the Dutch urban area, 65% of cyclist fatalities occur at an intersection, 54% of rural cyclist fatalities occur at intersections, and 61% of seriously injured cyclists in crashes involving a motorised vehicle were injured in crashes at intersections (Reurings, 2012; SWOV, 2021b; Schepers et al., 2020).

In an Australian study, Meuleners et al. (2020) found a nearly 50% higher number of cyclist crashes at intersections than on road sections. However, Asgarzadeh et al. (2017) and Høye (2011) found that crashes on road sections involve a higher risk of severe injury or death compared to crashes at intersections. This could be due to the fact that traffic flow is generally slower at intersections than on road sections.

In the Netherlands and elsewhere, it has been found that intersections with speeds lower than 30 km/h reduce the risk of a bicycle crash, and an intersection between two local streets are up to

80% safer than an intersection of two major roads (Duivenvoorden, 2021; Harris et al., 2013; Fortuijn et al. 2005).

3.5.1 Deflection of bicycle crossing & vehicle stop line

Moving the bicycle crossing further away from the intersection reduces the risk of a bicycle crash by a factor of 0.9 to 0.6 (Nabavi Niaki et al., 2020; Schepers et al., 2011; Cantisani et al., 2019).

3.5.2 Bicycle box

Theoretically, bicycle boxes are a good facility because cyclists are clearly visible to motorists. No Dutch studies have been found on the safety effect of bicycle boxes. A Canadian study shows the improvement in bicycle safety after implementing bicycle boxes (Zangenehpour et al., 2013). A study by Loskorn et al. (2010) in the U.S. also shows an improvement in safety for cyclists after implementing bicycle boxes.

Figure 3.1.
Example of bicycle box
(Photo by Paul Schepers)

3.6 Digital countdown timers

Several studies show that red light violations by cyclists increased after implementation of digital countdown timers (DCT) (Gao et al., 2018; Bai & Sze, 2020; Gao et al., 2020; Kaths et al., 2019). One descriptive study was found where DCTs reduced the frequency of red light running (Yu et al., 2019).

Grijpstra (2017) found that implementing a digital countdown timer increased red light negation between 5% and 6%. They saw an increase in cyclists starting to cross before the light turns green (early starts). This is understandable, since cyclists seeing a few seconds left on the red light count down, and no cars near the crossing, will start crossing before their light turns green. Grijpstra also attributes this increase in red light violations to the lower traffic volume in the after-DCT implementation scenario which could bias the results.

In these studies, no cycling safety analysis was performed. However, DCTs are interesting infrastructural elements that can be further studied for their effects on safety.

3.7 Roundabouts

Table 3.6. Summary of evidence from literature: roundabouts

Summary of findings
1. In the Netherlands, roundabouts have a lower bicycle crash risk than intersections.
2. International studies show that roundabouts increase the risk of a bicycle crash compared to intersections
3. Roundabouts with bicycle tracks are safer than roundabouts with bicycle lanes or without any bicycle facility
4. Two-lane roundabouts increase the risk of a bicycle crash
5. Higher speed limits at roundabouts decrease bicycle crash frequency
6. Roundabouts are safer when vehicles have priority

In the Netherlands, replacement of an ordinary intersection by a roundabout leads to a 60% decrease in cycling risk (Dijkstra, 2005). Two studies from Belgium and Denmark conversely found that for cyclists, in general, intersections are safer than roundabouts. However, the comparison with the Dutch situation is not reliable given the difference in cyclist volume and roundabout speeds in these two countries (Jensen, 2013; Daniels et al., 2009).

A recent study by Meuleners et al. (2019) shows that, in Australia, roundabouts increase the risk of a bicycle crash. Harris et al. (2013) also found that, in Canada, traffic circles (small roundabouts) on local streets increased the risk of these otherwise safe intersections.

A study by Van Minnen (1995) evaluated the presence of bicycle tracks, bicycle lanes and absence of a bicycle facility along roundabouts, correcting for differences in bicycle and car volumes in the Netherlands, and found that roundabouts with bicycle tracks have a considerably lower number of casualties than roundabouts with bicycle lanes. Roundabouts with a bicycle lane had the same number of casualties compared to roundabouts without any bicycle facility. This confirms previous results comparing road sections with bicycle lanes and road sections without any bicycle facility (section 4.3.2, section 4.3.4).

Three other studies confirmed this result. Jensen (2017), Daniels et al. (2009) and Schoon & Van Minnen (1994) showed an injury reduction of around 100% at roundabouts with a bicycle track compared to roundabout without a bicycle track.

A study of roundabouts with two lanes for motor vehicles showed the number of observed crashes and injuries to be twice as high as expected, whereas at single-lane roundabouts there was no difference between expected and observed crashes (Brüde & Larsson 2000). Furthermore, Akgün et al. (2018) showed a 500% increase in the probability of a serious injury for each additional number of lanes on a roundabout approach and a 4% increase with each additional entry path radius.

Studies on speeds showed that higher vehicle speed limits increase bicycle crash frequency at roundabouts (Akgün et al., 2018; Jensen 2013; Meuleners et al., 2019).

3.7.1 Cyclist priority at roundabouts

Three studies have compared different priority schemes for cyclists at roundabouts. Van Minnen (1998) compared 17 roundabouts where cyclists have priority and 28 roundabouts where cyclists do not have priority. Weijermars (2001) then compared 30 roundabouts with cyclist priority and 36 roundabouts without priority. The third researcher, Gerts (2002) compared 22 new roundabouts with cyclist priority and 36 roundabouts without cyclist priority.

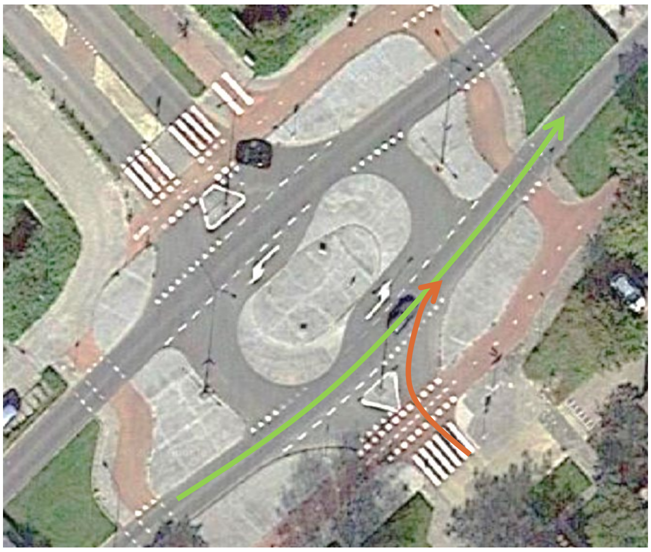
All three studies showed a higher crash frequency when cyclists have priority. Furthermore, Dijkstra (2005) showed that the scheme with cyclist priority is less safe. He lists two possible explanations. Firstly, motorists would mistakenly believe that they have priority over bicycles, perhaps confused by the lack of uniformity of the priority regulation on roundabouts in the network. Secondly, motorists on a roundabout would have to make many observations in a short time, as a result of which cyclists are noticed too late.

3.8 Bow-legged intersections

Bow-legged intersections (Dutch: pleintjes) have a centre island providing space for left turning traffic. Main traffic has right of way (green line in *Figure 3.2*). It is not held up by traffic entering or leaving the road (orange line *Figure 3.2*).

Van der Leeden (2012) carried out a study on two bow-legged intersections, two roundabouts and two priority intersections, to compare the number and severity of traffic conflicts. The results showed that bow-legged intersections are safer than roundabouts. However, the severity of a possible crash is lowest at roundabouts due to the lower speed compared to bow-legged intersections and priority intersections.

Figure 3.1. Example of a bow-legged intersection (Google maps)



4 Conclusions

Cycling is widely promoted as a healthy and sustainable means of transport. At the same time, traffic safety concerns are growing in the Netherlands and elsewhere, because of increasing numbers of cyclists involved in crashes (fatal, serious injury). Scientific evidence could help identify infrastructural factors affecting these crashes, which requires research results on different aspects of this issue to be reviewed.

In this review, we focused on different aspects of cycling infrastructure and their contribution to the risk of bicycle crashes. Wherever possible, we selected and used those studies that addressed a bicycle crash risk indicator as an outcome measure, thereby controlling for differences in cyclist flow. Controlling for cyclist flow is crucial for valid interpretation of the safety levels of infrastructure elements or designs. This requirement limits the number of relevant studies because in many studies cycling flow is unknown, and only crash frequency (not crash risk) is reported.

We also made a distinction between findings from Dutch studies and international studies (not conducted in the Netherlands). This was considered necessary because of the 'advanced' cycling culture and infrastructure facilities for cyclists in the Netherlands. In some instances, it appears that this distinction resulted in different outcomes.

The conclusions of the review first of all focus on the safety enhancing features of the cycling infrastructure that are to some extent evidence-based, followed by the features about which we still have no evidence.
The evidence for infrastructure features that affect safety is generally based on a limited number of studies, conducted on specific locations in different geographical settings. This implies that the results may not be interpreted as valid for every specific location, because local circumstances may differ from those included in the studies. As the number of studies increases, providing consistent evidence on different locations, the generalisability of the outcomes will be stronger. For each of the different infrastructural elements the main findings are listed below.

Urban versus rural areas
In urban areas, the number of crashes involving cyclists is higher than in rural areas. Dutch figures show that over 60% of fatalities and about 81% of serious injuries (involving motorised traffic) among cyclists are due to crashes in urban areas. Figures from other countries support this general conclusion with sometimes different proportions.

Network route choice
Dutch cyclists prefer routes with bicycle facilities, low speed limits, low motorised traffic volume, good surface quality and short travel time. International studies found comparable results and point to additional preference factors, i.e. light conditions.

Route
There is growing evidence for improved safety as a result of implementing bicycle tracks rather than bicycle lanes or not implementing any bicycle facilities. Recent Dutch studies do not show

safety effects of bicycle lanes compared to roads without any bicycle facility. However, some relatively recent international studies show that bicycle lanes do improve safety compared to roads without any bicycle facility.

Considering the safety of intersections, two-way bicycle tracks are found to be less safe than one-way bicycle tracks.

Road section
Because this perspective addresses quite specific features, only few studies focused on them, and evidence is still based on a very limited number of studies. We found indications for the following features affecting safety:

1. Wider bicycle tracks improve safety.
2. On-street parking decreases cycling safety.
3. Tram tracks on the road increase the risk of single-bicycle crashes.
4. Presence of obstacles such as poles, trees, signs, within two meters of the bicycle facility decreases cycling safety
5. Presence of road lighting increases cycling safety

Intersections
A general finding is that, for cyclists, intersections are more dangerous than road sections. Relating to safety features of intersections we found that:

1. Intersections with lower speed limits are safer.
2. Bicycle crash risk is reduced when the bicycle crossing at the intersection is deflected further away

Roundabouts
Relating to the safety of roundabouts, Dutch and international studies have contrary results. In the Netherlands, roundabouts have lower crash risk for cyclists compared to intersections. However, international studies show that, compared to intersections, roundabouts increase the risk of a bicycle crash. Relating to safety features of intersections, we found that:

1. Roundabouts with bicycle tracks are safer than roundabouts with bicycle lanes or roundabouts without any bicycle facility.
2. Two-lane roundabouts increase the risk of a bicycle crash.
3. Higher speed limits at roundabouts decrease bicycle safety.
4. Roundabouts are safer when vehicles have priority.

Other
We identified a number of relevant infrastructure features for which no cycling safety evidence was found in the literature. These are listed below.

1. Location data for seriously injured cyclists not involving motorised traffic has not been found.
2. No information has been found about bicycle crash risk in urban versus rural areas.
3. No safety indications have been found for shared space with pedestrians and solitary bicycle paths.
4. On the issues of kerbs and surface condition no studies have been found addressing crash risk.
5. No risk-based evidence has been found that bicycle boxes and dedicated green phases at intersections improve cycling safety.

The general conclusion of this review is that the body of evidence for infrastructure features related to cycling safety is growing but is still based on a limited number of studies, and only crash frequency (not risk) is reported, while not all relevant features are covered. The need for more studies is not only prompted by the lack of knowledge as such, but more importantly by the growing concern about the increasing number of crashes involving cyclists.

Future studies & policy

This research highlights the areas in cycling safety infrastructure that have been well studied and some areas that are still lacking a risk-based study of the effect of infrastructural elements on cyclists. For example, risk analysis can be done on:

- Urban vs. rural areas.
- Bicycle track width.
- Roadside kerbs.
- Surface condition.
- Parking.
- Tram rails.
- Presence of obstacle on/surrounding bicycle tracks.
- Road lighting.
- One/two-way bicycle tracks.
- Digital countdown timers.

Policy topics are more difficult to recommend, given the lack of evidence concerning many of the infrastructural elements. The most important step is to gather more information and carry out risk-based studies with comprehensive datasets including all present infrastructural elements in order to represent the effects of such elements on cycling safety more accurately.

Based on the information gathered in this review, recommendations can be given to policymakers on the topic of implementing more one-way bicycle tracks, since their safety has been well established in the literature (Welleman & Dijkstra, 1988; Van Petegem et al., 2021; Beek, 2019; Thomas & DeRobertis 2013; Ling et al., 2019; Kullgren et al., 2019, Teschke et al., 2012; Minikel, 2012; Lusk et al., 2011; Schepers et al., 2010; 2013; SWOV, 2020; Fietsberaad, 2017; Vandenbulcke, 2014; Pedler & Davies, 2000). Bicycle lanes have also been studied and have been shown to have mixed effects and, in the Netherlands, mostly negative effects (Welleman & Dijkstra 1988, Goudappel 1984 and 1993, Van der Kooi & Dijkstra 2003, Van Petegem et al. 2021, Beck et al. 2016). Therefore, policymakers can change existing bicycle lanes to bicycle tracks or implement bicycle tracks where bicycle lanes are planned to be implemented. The reduction or removal of on-road parking will result in less bicycle crashes (Adviesbureau Van Roon, 1986; Teschke et al., 2014; Schimek, 2018; Delbressine, 2013; Van Petegem et al., 2021).

Finally, the most researched and supported topic is that relatively many bicycle crashes occur at intersections (Kullgren et al., 2019; Chen et al., 2018; Reurings, 2012; SWOV, 2021b; Meuleners et al., 2020; Duivenvoorden, 2021; Harris et al., 2013; Fortuijn et al., 2005). Policymakers should be given more data-driven information on the elements reducing safety at an intersection in order to better plan and improve the safety of intersections. Roundabouts (especially those with bicycle tracks) are safer than intersections (Dijkstra, 2005; Van Minnen, 1995; Jensen, 2017; Daniels et al., 2009; Schoon & Van Minnen, 1994). Policymakers should implement roundabouts at intersections of two distributor roads (SWOV 2021b).

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Appendix A Keywords literature review

The selection of keywords for literature review were (English/Dutch):

1. Safety/Veiligheid
2. Crash/Botsing, Ongeval
3. Bicycle, cycle, cyclist/Fiets, fietser
4. Infrastructure/Infrastructuur
5. Bicycle track/Fietspad
6. Bicycle lane/Fietsstrook
7. Shared space/Mengen
8. Shared use (different modalities)/Medegebruik (verschillende modaliteiten)
9. Bicycle Street/Fietsstraat
10. Bicycle crossing/Fietsoversteek
11. Intersections/Kruispunten
12. Roundabouts/Rotondes
13. Intersection/Kruispunt
14. Network/Netwerk
15. Route/Route
16. Street level/Straatniveau
17. Commercial areas/Winkelgebieden
18. Residential areas/Verblijfsgebieden
19. Width/Breedte
20. Berm/Berm
21. Alignment/Alignement
22. Marking/Markering
23. Obstacles in or along the cycle path/Obstakels in of langs het fietspad
24. One- or Two-way/Een- of Tweerichtings
25. Priority/Voorrang
26. Driving view or stop view/Rijzicht of stopzicht
27. Pavement quality/Kwaliteit verharding
28. Parallel roads/Parallelwegen
29. Parking of cars (dooring)/ Parkeren van auto's (openslaande portieren)

Prevent crashes
Reduce injuries
Save lives

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