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Assessing the safety of international examples of bicycle streets to identify important design elements—an expert judgement

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Abstract: The two most common types of cycling infrastructure are separated bicycle tracks and bicycle lanes. Several studies have been carried out to examine their impact on cycling safety. A relatively new type of cycling infrastructure, which is increasingly being implemented, is the bicycle street, defined as a street where bicycle traffic is prioritised and where motorised vehicles are limited in terms of volume and speed. Since bicycle streets are developed recently, the literature about their safety is scarce. Therefore, in order to provide directions for further research to the safety of bicycle streets, the present study aims to identify which design elements of bicycle streets are important to assess their safety, based on expert judgement. The expert judgement data were collected from 49 cycling safety professionals, divided over ten groups, during a workshop about the safety of bicycle streets during the 11th International Cycling Safety Conference 2023 in the Hague. The groups of cycling safety professionals categorised nine international examples of bicycle streets over three piles: 'Safest', 'In between', and 'Least safe'. They also provided arguments about why they put a bicycle street on a specific pile. These arguments are used to identify important design elements that impact the safety of bicycle streets and are compared to existing literature. The results showed that expert judgements are considerably similar across the example bicycle streets and their design elements. The most important design elements to assess the safety are: width of the street, design to prioritise cyclists, road markings and parking. The literature shows that for some elements, general road safety knowledge exists, but that for most design elements no studies exist that examine their relation to the safety of bicycle streets in particular.

Keywords: bicycle streets, cycling safety, cycling infrastructure, expert judgement

1 Introduction

In many cities around the world, cycling levels are increasing due to promotion of cycling as a healthy and sustainable mode of transport as well as due to investments in cycling infrastructure. While implementing cycling infrastructure may attract more people to use a bicycle (Pucher & Buehler, 2008), it also helps to provide a safer road environment for cyclists (DiGioia et al., 2017). Common types of cycling infrastructure are separated bicycle tracks and bicycle lanes, of which the former proved to be more beneficial for cycling safety compared to bicycle lanes and mixed traffic conditions (van Petegem et al., 2021). A type of cycling infrastructure that becomes more popular is the bicycle street. It is a special type of street with mixed traffic conditions, often designed in a way that it can be recognised as a street where cyclists have priority over cars and where speed and volume of cars are low (Bruno, 2020). Although bicycle streets are relatively new, there are more concepts that restrict volumes and speeds of motorised traffic to prioritise cycling and/or walking. Examples are 30 km/h-zones and woonerven in the Netherlands (SWOV, 2018), the American Garden City Planning (And & Ahn, 2003), area-wide traffic calming (Bunn et al., 2003), and home zones in the United Kingdom (Clayden et al., 2006). In contrast with other types of cycling infrastructure and these concepts, the number of studies investigating the safety of bicycle streets is limited. Therefore, in order to provide directions for further research to the safety of bicycle streets, the present study aims to identify which design elements of bicycle streets are important to assess their safety, based on expert judgement. Accordingly, the following research question is examined: 'How is the safety of bicycle streets assessed by international cycling safety professionals and how does this relate to existing literature?'.

Existing studies of the safety of bicycle streets can be divided in studies of subjective safety and of objective safety. Studies of the latter investigate the actual aspects of road safety, such as crash frequency or observed behaviour. Studies of subjective safety examine the perceptions and experiences of road users related to the safety of traffic. Subjective safety can be used as an addition to objective safety. Most of the subjective safety related studies identified specific behaviours of other road users that affect the perception of safety of cyclists on bicycle streets, such as speeding or taking over too closely (Baert et al., 2021; CROW-Fietsberaad, 2021; von Stülpnagel et al., 2022a), or compared subjective safety between multiple types of cycling infrastructure (Berghoefer & Vollrath, 2022; von Stülpnagel et al., 2022b). The impact of specific design elements of bicycle streets on subjective safety were investigated in only two studies from Sweden (Jörgensen, 2020; Rivera Olsson & Elldér, 2023).

As for subjective safety studies, the number of objective safety studies that examine the safety impact of specific design elements at bicycle streets is limited. Most of these studies investigated the impact of width, often in relation with speed of motorised vehicles (CROW-Fietsberaad, 2021; Delbressine, 2013). Other studies of objective safety mainly compared different types of cycling infrastructure (Minikel, 2012; von Stülpnagel et al., 2022b), where only one study also included the design of different types of streets (Teschke et al., 2012). However, this study only used the design elements to distinct between the different types of streets.

Several gaps exist in these studies. In general, most of these studies excluded specific design elements, which means that the number of studies that investigate the impact of design elements on either subjective or objective safety is scarce. Moreover, subjective safety studies that included design elements are limited to one country only. Therefore, it is difficult to generalise and transfer the results to other regions, because the design of cycling infrastructure may vary per country, per region, or even per bicycle street. Furthermore, the objective safety studies that included design elements mostly look to width in relation to safety, while other design elements are excluded. The present study tries to fill these gaps by assessing the safety of several international examples of bicycle streets to establish a list of design elements that should be further explored in future studies that evaluate the safety of bicycle streets in more detail.

2 Literature review

2.1 Approach of the literature review

A quick scan of the available literature was carried out in order to identify search terms. The list of search terms increased during the search for literature and includes the following 32 terms (including several translations of bicycle streets in other languages), see Table 1.

Several resources were used to find studies: Science Direct, Google Scholar, SWOV library, CROW-Fietsberaad publications, Google, and reference lists of found studies. Note that the literature review was part of a more extensive literature review presented in a report published by SWOV (Dutch Institute for Road Safety Research) (Nabavi Niaki et al., 2023), which also includes a discussion of local design manuals and guidelines. In this study, however, we focus solely on the safety-related studies. In total, the search terms led to almost one million hits. For each search term, and only for the relevant hits (generally the first 30 to 50 hits), the titles and abstracts were scanned. This scan led to a list of 90 most relevant studies, chapters,

Table 1 Literature search terms

• Fietsstraat veiligheid	• Rue de cyclables sécurité
• Fietsstraten veiligheid	• Fahrradzone
• Bike boulevard safety	• Zone de cyclables
• Bicycle boulevard safety	• Bicycle priority street
• Neighbourhood greenway	• Quiet street
• Neighbourhood greenway safety	• Neighbourhood connectors
• Bicycle street safety	• Neighbourhood byways
• Bike street safety	• Bicycle friendly streets
• Cycle street	• Bicycle friendly corridors
• Cycle street safety	• Bicycle parkways
• Fietszone	• Neighbourhood parkways
• Bicycle zone	• Local bicycle streets
• Bike zone	• Ciclocalles
• Cycle zone	• Sykkelgater
• Fahrradstraβe	• Velostrassen
• Vélorue sécurité	• Cykelgade

reports, and websites of which the abstracts were read more thoroughly. Based on the review of the abstracts, 67 hits were indicated as most relevant related to the topic of design and safety of bicycle streets. Since the number of safety studies related to bicycle streets is limited, grey literature is used in addition to scientific papers.

2.2 Subjective safety studies

In general, subjective safety of bicycle streets can be investigated relative to the subjective safety on other cycling infrastructure types. For example, the study by von Stülpnagel et al. (2022b) in Munich, Germany, compared different types of cycling infrastructure based on both objective and subjective safety. To examine the subjective safety, cyclists were asked to add crashes, near-crashes, and conflicts on a map. These data were compared with official reported crash data, bicycle volumes, and road characteristics (type of cycling infrastructure and speed limit). Compared to other types of cycling infrastructure, bicycle streets have a lower subjective and objective risk (corrected for bicycle volume), especially compared to roads without cycling infrastructure.

Focussed on the safety of children in particular, the results in the study by VanZerr (2010) are contradictory. A survey was carried out among residents living close to a bicycle street in Portland, Oregon (USA). The questionnaire contained one safety-related question, about the observed safety for children. Results were contradictory: 37% believed that bicycle streets have a positive impact on the safety of children, 22% believed there is a negative impact, and 41% indicated no impact on the safety of children. However, one must be careful in drawing conclusion based on this study, since it is difficult to rely on the results from one survey question only.

2.2.1 Design of the bicycle street

In the Netherlands, a handful of studies investigated the experiences of road users on bicycle streets by the use of questionnaires. Although there are some concerns about interactions between cyclists and cars, in general, most respondents are positive about the design of bicycle streets (Ligtermoet, 2006; Vriens, 2018; Waagmeester, 2005). In addition, Belgian and German studies also show that the recognisable design of bicycle streets increases the subjective safety of cyclists (Baert et al., 2021; von Stülpnagel et al., 2022a). This design is especially recognised when the bicycle street has a red carriageway, ‘Cars are guests’ signage, and corresponding road marking, as shown in Swedish studies (Jörgensen, 2020; Rivera Olsson & Elldér, 2023) and recommended by the Dutch design manual that includes bicycle streets (CROW, 2021).

2.2.2 Impact of motorised vehicles

A factor that has a strong impact on the subjective safety of cyclists on bicycle streets is the presence, speed, and overtaking behaviour of (drivers of) motorised vehicles. First, in terms of presence, Dutch and Belgian reports about design recommendations found that high volumes of motorised vehicles negatively impact the comfort and subjective safety of cyclists (Andriesse, 2016; Andriesse & van Boggelen, 2016; Baert et al., 2021; van Boggelen & Hulshof, 2019). More specifically, CROW-Fietsberaad (2021) found a non-linear relationship between cyclists' opinion about traffic volume and the actual observed traffic volume. With low traffic volumes, this opinion is neutral, while with increasing volume the opinion becomes disproportionally more negative. Particularly, when there are 100 cars per hour, cyclists fully agree with the statement ‘there are too many cars in the street’. A low motorised vehicle volume, on the other hand, positively impacts the perception of safety (Rivera Olsson & Elldér, 2023).

Second, in terms of speed, a higher speed leads to a lower score for bicycle streets in Belgium, as was found in a survey that investigated the experiences of cyclists and non-cyclists at 17 bicycle streets in 13 Flemish cities (Baert et al., 2021). Similarly, in the Netherlands, CROW-Fietsberaad (2021) found a relationship between the experienced speed of motorised vehicles and carriageway width. At wider carriageways, regardless of being a bicycle street or control street, cyclists are more negative about the speed of motorised vehicles. Furthermore, according to a survey among traffic engineers and experienced cyclists from Gothenburg, Sweden, the width of the road and the surface type are most important to decrease the speed of motorised vehicles (Jörgensen, 2020).

Last, overtaking behaviour by drivers of motorised vehicles impacts subjective safety in several ways. In terms over overtaking frequency, cyclists in the Netherlands give a lower grade when they are more often overtaken by cars or when they stay behind the cyclists in an annoying or dangerous manner (i.e. tailgating) (CROW-Fietsberaad, 2021). In Belgium, on the other hand, overtaking cyclists is restricted by law for drivers of motorised vehicles. Bicycle streets where this restriction is ignored receive a lower grade from cyclists, as well as bicycle streets with through traffic, parking movements, and loading or unloading on the carriageway (Baert et al., 2021). Also the overtaking distance affects the perceived safety of cyclists. A German survey about the expected passing distance of cars at several cycling infrastructure types showed that cyclists expect that cars overtake more dangerously (closer than the legal 1.5 metres) on bicycle streets (von Stülpnagel et al., 2022a).

2.2.3 Comfort

Berghoefer & Vollrath (2022) carried out structured interviews (Repertory Grid method) (Wright, 2004) under frequent German cyclists to evaluate different types of cycling infrastructure. The evaluations can be summarised with five indicators: mental comfort, interaction, environment, ease of use, and physical comfort. Bicycle streets received similar scores as bicycle lanes, but with a higher score on mental comfort. Moreover, bicycle streets received a higher score than residential roads. More in general, cycling infrastructure types where cyclists are physically separated from other road users were best graded. However, when physical separation is impossible, cyclists may prefer bicycle streets over other cycling infrastructure types due to its specific attention for bicycle traffic. Two studies of route choice of cyclists in Portland, Oregon (USA) found that bicycle streets increase comfort for cyclists (Blanc & Figliozzi, 2016) and that cyclists are willing to take a detour to cycle on bicycle streets (Broach et al., 2012).

2.3 Objective safety studies

2.3.1 Crash or injury based studies

In terms of objective safety, bicycle streets are compared to other cycling infrastructure types, like some subjective safety studies also did. An exploratory crash study from the Netherlands found that, on average, the crash density on bicycle streets is lower compared to other types of cycling infrastructure (Odijk, 2023). However, when correcting for bicycle volume and using crash cost rate as outcome variable, results show that the crash cost rate is higher on bicycle streets than on separated bicycle tracks and roads with mixed traffic conditions. Note that, due to the low sample size of bicycle streets, synthetic data was generated (with adaptive synthetic sampling approach for imbalanced learning) which might affect the results. In Munich, Germany, however, contradictory results were found, since in absolute figures, a significantly higher number of crashes occurs on bicycle streets compared to roads without cycling infrastructure. Conversely, when correcting for bicycle volume, the risk of having a crash is lower on bicycle streets compared to roads without cycling infrastructure (von Stülpnagel et al., 2022b).

Two studies from North America examined crash severity and injury risk at bicycle boulevards (the North American name for bicycle streets). In Berkley, California (USA), Minikel (2012) compared the safety of bicycle boulevards with the safety of parallel located arterials. Crash data and data about bicycle volumes are used to compare crash frequency and crash severity between the two road types. In terms of crash frequency, two to eight times less crashes occur on bicycle streets compared to parallel arterials. However, no significant difference was found between crash severity on the two road types. The study from Canada found similar results, since local roads that are designed similar to bicycle streets elsewhere (i.e. local roads designed as bicycle routes with traffic calming measures) have no significantly higher or lower injury risk compared to the reference route (i.e. a main road with parked cars and without cycling infrastructure) (Teschke et al., 2012).

2.3.2 Conflicts and observed behaviour

Like for subjective safety, motorised vehicles affect the objective safety of cyclists in terms of conflicts and as a result of their drivers' behaviour. For example, it seems that standing vehicles on the carriageway (e.g. to load and unload), are a problem for cyclists (Delbressine, 2013). However, other studies found increased safety due to drivers of motorised vehicles who adapt their behaviour on bicycle streets. Based on camera observations, Goldenbeld & van Schagen (1997) found that car drivers and cyclists adapt to the newly implemented bicycle street; car users decrease their speed, keep distance when driving behind cyclists and avoid overtaking of cyclists. Cyclists use their right to cycle in front of cars and to cycle side-by-side. Moreover, it is shown that on two-way bicycle streets in the Netherlands, higher bicycle volumes go along with lower driven speeds of motorised vehicles (Delbressine, 2013). Similarly, a study from Portland, Oregon (USA), used a before-after study design to investigate driven speed reduction after a decrease in speed limit of 5 mi/h (±8 km/h) (Schaefer et al., 2022). The study distinguished regular roads and roads with high levels of bicycle traffic (comparable to bicycle streets). The most important result was that the driven speed decreased more on bicycle streets due to a speed limit reduction than on regular roads. Presumably, traffic calming measures play a role here, as well as road markings indicating that the road is shared with cyclists. Another result is that on bicycle streets with higher bicycle volumes, the driven speeds are considerably lower.

In contrast to these studies, other studies found that there is no difference in the speed of motorised vehicles after implementing a bicycle street, like in Norway (Fyhri et al., 2020). This study only found a decrease in motorised vehicle volume, while the driven speed of cyclists, bicycle volumes and the number of conflicts remained the same. Moreover, in the Netherlands, the study by Delbressine (2013) shows that a large share of motorised vehicles violates the 30 km/h speed limit (between 32% and 51% on seven bicycle streets and 82% on one bicycle street). Speeding was also found for (light) mopeds. In addition, this study also found a relationship between a wide carriageway and a higher speed of motorised vehicles, except for (light) mopeds.

Besides speed, overtaking behaviour, including avoiding to overtake, of drivers of motorised vehicles affects the objective safety of cyclists on bicycle streets. For example, camera observations in the Netherlands showed that most observed conflicts occur when cars overtake cyclists in cases when there is also oncoming bicycle traffic and conflicts where cars stay behind the cyclists (Odijk, 2023). Conversely, the study by CROW-Fietsberaad (2021) shows that, for several types of encounters where the car overtakes cyclists or stays behind cyclists, nearly no severe conflicts are observed. This study also found that the number of annoying or unsafe encounters can be estimated based on traffic volume and carriageway width. However, one should be aware of the fact that volume and width highly correlate, which makes it difficult to distinguish their separate effect. Therefore, this approach may be less accurate for bicycle streets that deviate too much from the observed bicycle streets in terms of traffic volume and carriageway width. It is also shown that the width of the rumble strips affects the number of annoying or unsafe encounters. On bicycle streets with wider than 40 cm rumble strips, more annoying or unsafe encounters occur than expected based on traffic volume and carriageway width. This implies that wide rumble strips negatively impact the effective carriageway width, resulting in more annoying or unsafe encounters, in particular with high motorised vehicle volumes (CROW-Fietsberaad, 2021).

The passing distance is also an important factor when motorised vehicles overtake cyclists. A study from Freiburg, Germany, investigated this passing distance, measured on bicycle streets and other types of cycling infrastructure (von Stülpnagel et al., 2022a). At bicycle streets, the passing distance is smaller compared to 30 km/h roads without cycling infrastructure. However, the number of passing manoeuvres on bicycle streets is relatively low. This low number of passing manoeuvres may be an intended consequence of a bicycle street, but the passing manoeuvres that do take place occur on a smaller distance.

2.4 Summary of the literature review

Table 2 shows a summary of the most important factors that affectboth subjective and/or objective safety of cyclists on bicycle streets. The table illustrates that the most important factor is the presence of motorised vehicles. On the one hand, the design of bicycle streets or bicycle volume on those streets minimise the negative impact of motorised vehicles, since some studies found a lower volume and/or speed. On the other hand, other studies found that the motorised vehicle volume and speed are still (too) high on some streets. Additionally, the overtaking behaviour by drivers of motorised vehicles is often found as a negative factor since they overtake cyclists too frequently and closely. Conversely, other drivers avoid to take over and drive to closely behind the cyclists, which is experienced as tailgating. On top of that, motorised vehicles standing on the carriageway (e.g. to load or unload) negatively affect both the objective and subjective safety. On top of that, it is noteworthy that the impact of bicycle streets on cycling safety may be context-specific, since part of the differences in the results addressed in this literature review may be explained by the fact that various study areas are considered. For example, the cycling and driving culture and the infrastructural design in North American cities may strongly differ from European cities, and, for example, specifically from the Dutch context.

It is also important to stress that the literature that examines the impact of specific design elements on safety is limited. The most important design element identified in the literature is the width of the carriageway, since width has a strong impact on the speed and overtaking behaviour of drivers of motorised vehicles. A wider carriageway may invite for speeding, while a too narrow carriageway may lead to dangerous overtaking manoeuvres. The effective width of the carriageway is decreased by implementing too wide rumble strips. Other design elements that affect the safety of cyclists, mainly discussed in the subjective safety literature, are a red coloured carriageway, 'Cars are guests' signage, and corresponding road markings. Studies that discuss the design of bicycle streets in relation to objective safety are even more limited and if they do, often only the traffic calmed character of bicycle streets is mentioned.

3 Data and methods

3.1 Data collection

The data collection took place at the 11^{th} International Cycling Safety Conference 2023 (ICSC 2023) in the Hague, the Netherlands, during a workshop from 09:00 to 12:30 about the safety of bicycle streets. This workshop started with an introduction, followed by presentations by CROW (Dutch knowledge platform that develops practical guidelines for infrastructure and transport) and University of Freiburg about safety of and design guidelines for bicycle streets in the Netherlands and Germany. Afterwards, the 49 participating experts were randomly divided over ten groups of about five persons. Table 3 shows there is a slight overrepresentation of male participants (57%) and that most participants are from institutes in Europe (82%), in particular from Germany (24%) and the Netherlands (18%). Furthermore, most of the participant are from a university (67%), followed by research institute (14%).

Table 3 Characteristics of the participants of the workshop

Characteristic / categories	n	%
Sex		
Male	28	57.1
Female	21	42.9
Origin of institute		
Europe (excl. DE and NL*)	19	38.8
Germany	12	24.5
Netherlands	9	18.4
Asia	6	12.2
USA	2	4.1
Australia	1	2.0
Type of institute		
University	33	67.3
Research institute	7	14.3
Government	5	10.2
University of applied sciences	2	4.1
Software developer	1	2.0
Unknown	1	2.0

*DE = Germany; NL = the Netherlands

The assessment to fulfil by the groups was to categorise nine international examples of bicycle streets in three piles: 'Safest', 'In between', and 'Least safe'. Each pile must consist of three bicycle streets, which are entered in *LimeSurvey* by the groups. Per group, experts were also asked to provide a maximum of two arguments per bicycle street about the reason of putting this bicycle street in a specific pile. These arguments were written down on a form that was handed out together with the printed images of the bicycle streets. The printed images included a text box with information about the city and country of the bicycle street on the image.

Table 2 Most important factors impacting subjective and/or objective safety of bicycle streets

	Factor	Effect	Location	References
Subjective	Recognisable design of bicycle streets (priority for cyclists)	+	the Netherlands, Belgium, Germany, Sweden	Baert et al. (2021); Jörgensen (2020); Ligtermoet (2006); Rivera Olsson & Elldér (2023); von Stülpnagel et al. (2022a); Vriens (2018); Waagmeester (2005)
	Low motorised vehicle volume	+	Sweden	Rivera Olsson & Elldér (2023)
	Low speed of motorised vehicles (affected by width and surface type)	+	Sweden	Jörgensen (2020)
	High motorised vehicle volume	−	the Netherlands, Belgium	Andriesse (2016); Andriesse & van Boggelen (2016); Baert et al. (2021); CROW-Fietsberaad (2021); van Boggelen & Hulshof (2019)
	High speed of motorised vehicles (in particular at wider carriageways)	−	the Netherlands, Belgium	Baert et al. (2021); CROW-Fietsberaad (2021)
	Dangerous (too close) overtaking by motorised vehicles	−	Germany	von Stülpnagel et al. (2022a)
	Frequently being overtaken by motorised vehicles	−	the Netherlands	CROW-Fietsberaad (2021)
	Ignoring overtaking restrictions		Belgium	Baert et al. (2021)
	Tailgating by motorised vehicles	−	the Netherlands	CROW-Fietsberaad (2021)
Objective	Drivers and cyclists adapt behaviour after implementing bicycle street	+	the Netherlands, USA	Goldenbeld & van Schagen (1997); Schaefer et al. (2022)
	Lower speed of motorised traffic (partly due to high bicycle volume)	+	the Netherlands, USA	Delbressine (2013); Schaefer et al. (2022)
	Lower motorised vehicle volume	+	Norway	Fyhri et al. (2020)
	Traffic calming measures	×	USA, Canada	Schaefer et al. (2022); Teschke et al. (2012)
	Unsafe overtaking/ encounters at narrow bicycle streets	−	the Netherlands, Germany	CROW-Fietsberaad (2021); von Stülpnagel et al. (2022a)
	Speeding of motorised vehicles at wider bicycle streets	−	the Netherlands	Delbressine (2013)

Impact: positive (+), negative (−), no impact (×)

The nine examples of bicycle streets come from Odense (Denmark), Palo Alto (USA), Luxembourg (Luxembourg), Dresden (Germany), Zurich (Switzerland), Jyväskylä (Finland), Utrecht (the Netherlands), Berlin (Germany), and Kalmthout (Belgium). The images of these examples are presented in Section 4.1.2 and originated from online news articles and official documents about bicycle streets (e.g. design manuals from local governments) that were looked up on Google Street View. Note that in the instruction for the experts, the bicycle and motorised vehicle volumes are fixed across the examples, all with a fictive peak hour flow of 120 cyclists per hour and 60 cars per hour. The reasoning behind this fixed volume is that volumes may vary substantially across the international examples and to prevent that participants are too distracted by the volume on the images. Moreover, it is assumed that, since bicycle streets are specifically designed to prioritise cyclists, all of the nine examples have a considerable amount of cyclists relative to the standards of the city or country of origin and that, at least during the peak hours, the cycling volumes are higher than the car volumes. For the exact volumes, it was argued that they should not be unreasonably high (like Dutch or Danish standards) or unreasonably low (like in countries with very low cycling rates). At the beginning of the group work during the workshop it was once more stressed that participants should not be distracted by the volume on the image and to keep in mind the fixed volume. All other characteristics to assess are left open in order to provide that participants are free to decide for themselves how they assess the safety of bicycle streets.

3.2 Methods

To come to a final safety score per bicycle street, every time a bicycle street is put in the ‘Safest’ pile it got 3 points, for the ‘In between’ pile it got 2 points, and for the ‘Least safe’ pile it got 1 point. These scores were summed to get a final score per bicycle street. Additionally, all written arguments were collected in one document and it was assessed whether an argument is positive, neutral, or negative. This was aggregated per bicycle street, which shows if a bicycle street receives primarily positive, neutral, or negative arguments or whether the arguments are more mixed. Moreover, the arguments are compared per bicycle street to find out whether these mention similar design elements to put a bicycle street in a specific pile. Lastly, to examine which design elements are important to cycling safety professionals for assessing the safety of bicycle streets, all arguments were categorised. In order to illustrate which design elements are most important, the categories were aggregated to get a frequency per category. These safety related design elements were compared to existing literature in order to provided future research directions.

4 Results

4.1 Ranking the bicycle streets

4.1.1 The final scores

Figure 1 shows the final scores of the nine bicycle streets, assessed by the cycling safety professionals. Images of the nine assessed streets can be found in Section 4.1.2. The results show that all groups agree on that the bicycle street in Utrecht, the Netherlands is the safest. Utrecht is followed by Kalmthout, Belgium and Jyväskylä, Finland, completing the ‘Safest’ pile. Nearly all groups put these bicycle streets on the ‘Safest’ pile. The ’In between’ pile consists of two German bicycle streets and the bicycle street from Luxembourg. Lastly, the ‘Least safe’ group consists of bicycle streets from Odense, Denmark, from Palo Alto, USA, and from Zurich, Switzerland. Note that the final scores inside all groups are relatively close to each other.

4.1.2 Arguments to assess the safety per bicycle street

The arguments to assess the safety per bicycle street are, first of all, categorised to specify whether an argument is positive, neutral, or negative (Table 4). The categorisation reflect the results of the ranking of the bicycle streets, i.e. bicycle streets with a higher final score receive more positive arguments and vice versa. Note that the total number of arguments varies among the bicycle streets and this total indicates that some groups gave more or less than the requested maximum of two arguments per bicycle street. The remainder of this section discusses the arguments per bicycle street in more detail.

Most arguments about the bicycle street in Utrecht (Figure 2) are positive. The cycling safety professionals are positive about the wide design, in particular because, despite its width, it is unattractive for motorised vehicles to exceed the speed limit due to

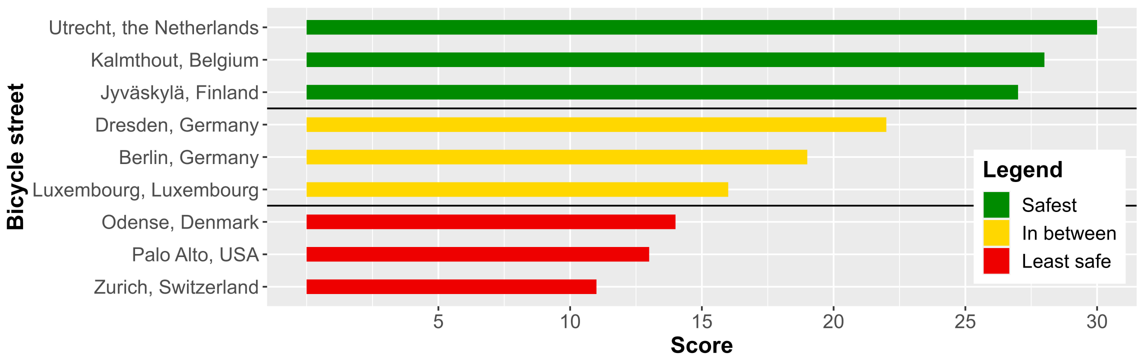

Figure 1 The final safety scores of the bicycle streets per pile

Table 4 The distribution of positive, neutral, and negative arguments per bicycle street

Bicycle street	Positive		Neutral		Negative		Total	
	Freq.	%	Freq.	%	Freq.	%	Freq.	%
Utrecht, the Netherlands	21	80.8	1	3.8	4	15.4	26	100.0
Kalmthout, Belgium	19	86.4	0	0.0	3	13.6	22	100.0
Jyväskylä, Finland	21	77.8	3	11.1	3	11.1	27	100.0
Dresden, Germany	14	58.3	2	8.3	8	33.3	24	100.0
Berlin, Germany	10	43.5	0	0.0	13	56.5	23	100.0
Luxembourg, Luxembourg	6	24.0	1	4.0	18	72.0	25	100.0
Odense, Denmark	3	15.8	1	5.3	15	78.9	19	100.0
Palo Alto, USA	3	10.7	2	7.1	23	82.1	28	100.0
Zurich, Switzerland	3	12.0	0	0.0	22	88.0	25	100.0

the implemented middle strip. This middle strip also allows safe overtaking and clearly separates the two directions. The separate lanes are judged as wide enough. In addition, the red-coloured, smooth asphalt is also mentioned as a positive element. However, there are some concerns about the absence of rumble strips on the edges; currently, there is no space between parked cars and passing cyclists to avoid dooring.

Figure 2 Example from Utrecht, the Netherlands (van 't Woud, 2018).

Most cycling safety professionals are positive about the clear marking and signage of the bicycle street in Kalmthout (Figure 3); although, some professional indicate the marking as unclear or confusing since the marking looks like marking for bicycle lanes or sharrows. On the other hand, the marking helps to position cyclists more in the middle of the street and to prevent dooring. Other arguments are about how the parking is managed. Positive about the parking is that it is partly parallel, negative is the high number of parked cars.

The most positive element of the bicycle street in Jyväskylä (Figure 4) is that there is no parking along the street, only an off-road parking area. Another positive element is the cobblestone rumble strips. These make car drivers go slower, narrow the road, and force cyclists to ride in the middle of the street. The cobblestones also help to indicate that road users ride on a different type of street. However, negative arguments about the cobblestones are that they may be slippery when wet and they offer cyclists the

Figure 3 Example from Kalmthout, Belgium (Kalmthout, 2019)

opportunity to move away from dangerous situations while they should cycle in the middle of the street. The sight conditions are also argued as being positive, both in general and at the intersection. Another positive element at the intersection is the raised crossing for pedestrians, which is related to the intersection having a speed bump to slow down cars. Moreover, the road surface is in favour of the bicycle street, since it is argued that it is red, smooth asphalt.

Figure 4 Example from Jyväskylä, Finland (JYPS, 2022)

According to most groups of cycling safety professionals, the bicycle street in Dresden (Figure 5) is clearly marked, in particular at the intersection, which is marked fully red to highlight the intersection. The marking at the road section indicates the dooring zone. However, some groups argue that the marking of the lanes at the road section is unclear and that most of the marking stops after the intersection. Moreover, some groups are concerned about the confusing marking at the intersection since it is not clear what the priority rules are and the arrows pointing in both directions at both edges of the lane are also found confusing. The parking, on the other hand, is well-regulated, also because there is a corner island for pedestrians that prevents cars to park in the corners of the intersection.

Figure 5 Example from Dresden, Germany (ADFC Dresden, 2022)

Most groups of cycling safety professionals agree upon that the marking at the bicycle street in Berlin (Figure 6) is positive and that the green marking indicates that it is a road with a special status. The perpendicular parking is argued to be negative for the safety of the bicycle street, because there may be conflicts with parked cars leaving the parking bays. Moreover, the parked cars, as well as the vegetation and road works, lead to sight obstruction both for cyclists and for cars leaving the parking bays. On top of that, it is unclear whether the street is one- or two-way, both for cyclists and for cars.

Figure 6 Example from Berlin, Germany (Leffler, 2022)

For the bicycle street in Luxembourg (Figure 7), most groups indicate that, since the street is narrow, this leads to lower speeds as well as increased visibility of cyclists. However, some other groups are more negative about the street being narrow, since it is too narrow for cars to overtake, creating stressful situations when cars have to follow cyclists and that there is parallel parking at both sides of a narrow street. Some groups paid attention to the signage, where one group is positive about the fact that there is signage, other groups found the signage too small or confusing. The possibility of dooring is found negative by most groups, in particular because there is no marking to create space for opening doors.

Figure 7 Example from Luxembourg, Luxembourg (Google Maps, 2022; Ville de Luxembourg, 2024)

Two groups indicate that the bicycle street in Odense (Figure 8) is well-marked. The rest of the arguments is negative. The element most groups are most negative about is that the design of the road provokes for speeding: it is wide, looks similar to a higher speed road, and has no speed reducing measures. Moreover, the street is too welcoming for cars and there is no feeling of cyclists being prioritised. Lastly, although there are safety strips, the parking is found negative by some groups.

Figure 8 Example from Odense, Denmark (Hørup, 2020)

The only positive argument about the bicycle street in Palo Alto (Figure 9) is that the speed limit is enforced with speed bumps, but it is argued by only one group. The remaining comments are neutral or negative. Several negative comments are about the parking, since it is on-street, on two sides, and without separation to, for example, prevent dooring. Other negative arguments are about the width of the street, since the street is wide, it provokes for speeding and to some groups it is unclear whether the speed bumps are effective enough to prevent speeding. Moreover, the design of the street is similar to a regular street; it is unclear that this street is a specific type of cycling infrastructure, also because there is no clear marking. Lastly, some arguments are about the safety of the roundabout, since it looks unsafe for both cyclists and pedestrians and that it looks like there is a higher chance of conflicts with motorised vehicles.

Figure 9 Example from Palo Alto, USA (City of Palo Alto, 2021)

For the bicycle street in Zurich (Figure 10), two groups positively argue that the signage and road marking are clear enough to indicate a bicycle street. However, there are also several negative comments about the signage and road marking, since it feels confusing and looks unclear. The street also lacks clear road marking to prevent dooring and to clearly mark the position of cyclists on the road. Another positive argument is that the street is narrow, possibly leading to lower speeds. On the contrary, several groups argue that the street is too narrow to be a two-way street and that the on-street parking makes it even more narrow and leads to sight obstruction. In addition, the parking itself feels unsafe, since it is on-street, without space for drivers the open their door, and that it is on two sides of the street.

4.2 Most important design elements to assess the safety

Besides evaluating which arguments are given to assess the safety per bicycle street, the arguments were categorised. Such categorisation helps to examine

Figure 10 Example from Zurich, Switzerland (Sicherheitsdepartement Stadt Zürich, 2019)

which design elements are important to cycling safety professionals to assess the safety of bicycle streets. Note that for this categorisation, the direction of the arguments (positive, neutral, negative) is ignored such that the categories just show what kind of design elements cycling safety professionals look out for. This is due to the fact that the design elements itself have no 'direction', as, for example, in terms of 'width', a bicycle street can be too narrow or too wide, but the element of interest is 'width'. Table 5 shows the categorisation and frequency of the arguments.

Table 5 Frequency of mentioned design elements to assess the safety of bicycle streets

Design element	Frequency
Width	36
Cycling priority design	36
Road markings	34
Dooring	31
Parking (parallel vs. perpendicular)	26
Speeding	25
Signage	19
Intersection design	14
Parking (number of cars)	11
Other	9
Road surface (red or smoothness)	8
Attractiveness (vegetation)	3

The two most frequently mentioned design elements are the 'width' of the street, and that it should be recognised from the design that cyclists have priority over motorised vehicles (cycling priority design). Almost as often mentioned are 'road markings' and 'dooring'. Road marking relates to proper indication of a bicycle street. The possibility of dooring relates to the risk of having a crash as a result of drivers opening their door when being parked parallel to the street.

Slightly less frequently mentioned are the orientation of 'parking (i.e. parallel vs. perpendicular)', and 'speeding'. The orientation of parking is also related to dooring, since dooring is only possible with parallel parking. When parked perpendicular, the professionals are concerned about sight obstruction of other parked cars, street furniture, or vegetation and about backwards entering the bicycle street. Speeding is mentioned in relation with width, since wider streets may provoke speeding. The following design elements are 'signage', 'intersection design', and 'parking (i.e. number of cars)'. Signage relates to the presence of a sign that indicates that the street is a bicycle street as well as signs to indicate the speed limit, intersection design relates to how complex an intersection is for cyclists and sometimes also pedestrians, and parking to how many cars are parked along the bicycle street.

The category 'other' contains various arguments which were difficult to attach to the other categories. It includes *temporary loading zone*, *volume of cyclists*, *sight obstruction due to road works*, *facilities for pedestrians (e.g. crossing facilities)*, *perceived safety*, and that the bicycle street is complicated. Some arguments are about the 'road surface', whether it is red coloured and whether it is smooth. Only three arguments are about the attractiveness of the environment surrounding the bicycle streets, such as vegetation.

5 Discussion and conclusions

5.1 Width of the carriageway

In the eyes of the groups of cycling safety professionals, the most frequently mentioned characteristic to assess the safety of bicycle streets is the width of the carriageway. Width on the one hand can increase the safety of a bicycle street, because narrow streets help to decrease the speed of motorised vehicles, while on wide streets the opposite may occur. This is in line with existing studies, showing that width is an important factor for both the objective and the subjective safety of bicycle streets. In terms of subjective safety, cyclists experience the speed of cars more negative on wider streets and narrower streets may slow down cars (CROW-Fietsberaad, 2021; Jörgensen, 2020). Narrow streets, on the other hand, impact the experience of a bicycle street negatively for side-by-side cyclists, caused by motorised vehicles being unable to overtake (CROW-Fietsberaad, 2021). Studies of objective safety of bicycle streets also found width as an important factor, but that the impact of width is highly correlated with motorised vehicle volume. Width and volume together determine how many critical encounter occur on bicycle streets (CROW-Fietsberaad, 2021). In addition, it was found that, compared to narrower bicycle streets, wider bicycle streets more provoke for speeding (Delbressine, 2013).

5.2 Cycling priority design

Cycling priority design is related to what extent it is clear that cyclists have priority over motorised traffic. Two studies indicate that a 'cycling priority design' increases the subjective safety of cyclists (Baert et al., 2021; von Stülpnagel et al., 2022a). In terms of objective safety, Goldenbeld & van Schagen (1997) show that car drivers adapt their behaviour in favour of cyclists on newly implemented bicycle streets. Similarly, Schaefer et al. (2022) show that, after a decrease in speed limit, the driven speed is reduced more on bicycle streets than the same decrease in speed limit on regular arterial roads. Presumably, traffic calming measures on the bicycle street play a role here; however, it is unknown what these traffic calming measures are. Note that both road markings and signage also apply on 'cycling priority design', but since these are assessed separately by some of the groups of experts and in existing studies, these are discussed in separate sections (5.1.3 and 5.1.6).

5.3 Road markings

Another often mentioned characteristic is road markings. The groups of cycling safety professionals paid attention to whether the bicycle street is properly marked with marking indicating it is a bicycle street. In existing studies of subjective safety, Swedish and Belgian studies found that road markings with bicycle symbols improve the perception of safety of cyclists (Baert et al., 2021; Jörgensen, 2020; Rivera Olsson & Elldér, 2023). In terms of objective safety, Teschke et al. (2012) found a lower injury risk on local roads that are designed as bicycle routes by means of road markings that indicate the road as a bicycle route. Moreover, Schaefer et al. (2022) found a higher reduction in driven speed as a result of a decrease in speed limit on bicycle streets compared to regular arterials. This may be achieved as a consequence of both traffic calming measures and road markings to indicate that the road is shared with cyclists.

5.4 Parking

Parking is divided over three factors: dooring, the orientation of parked cars (i.e. parallel vs. perpendicular), and the number of parked cars. The chance of being hit by a opened door is found to be mentioned most by the cycling safety professionals to assess the safety of bicycle streets. Therefore, it is even more striking that no existing studies of the safety of bicycle streets found in the literature review (Section 2.3) specifically evaluates the consequences of providing too limited space at parking lots along bicycle streets for drivers to open their door. However, it is known from other studies that opening of doors by drivers increases both crash risk and injury risk of cyclists (Hagemeister & Kropp, 2019; Jänsch et al., 2015; Johnson et al., 2013; Pai, 2011; Schimek, 2018).

Most groups that mention the orientation of parked cars argue it is safer when cars are parked in parallel direction rather than perpendicular. However, none of studies referred to in the literature review (Section 2.3) evaluates the impact of the direction of parked cars. Nevertheless, one can argue that with perpendicular parking, sight of the car driver may be obstructed by other parked cars, especially when the car is leaving the parking bay in backwards direction (Cicchino, 2019). On the other hand, the abovementioned studies show that dooring is an issue with parallel parking.

Lastly, the number of parked cars seems an issue for some of the groups of cycling safety professionals. It is argued that more parked cars may lead to more conflicts. This may be related to the turnover rate: the number of cars parking or leaving a parking spot. Although not specifically related to bicycle streets, existing studies found increased crash risk with a higher number of parked cars along the road (Greibe, 2003) and the parking movement itself is also found to be risk increasing to cyclists (Vandenbulcke et al., 2014).

5.5 Speeding

In terms of speeding, it is argued by the groups of cycling safety professionals that speeding is an issue on some of the bicycle street examples. This is often related to the fact that some examples provoke speeding due to their width or the absence of a cycling friendly design. Several existing studies also pay attention to speed in relation to the safety of bicycle streets. High speeds of cars at bicycle streets are perceived as negative in terms of subjective safety, especially on wider roads (Baert et al., 2021; CROW-Fietsberaad, 2021; Jörgensen, 2020). Moreover, in objective safety studies it is also observed that speeding can be an issue on bicycle streets and that this indeed is related to the width of the carriageway (Delbressine, 2013). In Norway, the implementation of a bicycle street had no effect on the driven speed of cars (Fyhri et al., 2020). However, when comparing the speed on bicycle streets after a speed limit reduction to the same reduction on regular arterials, it is found that the driven speed decreased more on the bicycle streets (Schaefer et al., 2022). Besides speeding of cars, speeding of (light) mopeds on bicycle streets in the Netherlands is addressed in Section 2 Literature review (Delbressine, 2013). Given the increased popularity of new, electrically powered micromobility modes, speeding is a topic that should be further explored related to bicycle streets since several studies show that mixing of these micromobility modes with cyclists or pedestrians leads to increased numbers of conflicts and crashes (Porojkow & Lißner, 2024; Šucha et al., 2023).

5.6 Signage

Signage is an issue that some groups of cycling safety professionals looked at. In most cases, the presence of signage is argued as something positive, but sometimes the signs are unclear. Most signs indicate that 'Cars are guests' on a bicycle street. Accordingly, one of the studies from the literature review (Section 2.2.1) found a positive effect on subjective safety of the sign with 'Cars are guests' (Jörgensen, 2020). The respondents from that study indicated that mixing cyclists with motorised vehicles is best possible when, amongst others, there is a sign with 'Cars are guests'.

5.7 Intersection design

Intersection design is also mentioned by some groups of cycling safety professionals to assess the safety of bicycle streets. Several elements of intersections are discussed, such as complexity, road markings and corner islands. In the studies from the literature review (Section 2.3), however, intersections are discussed in only one study. That study found, compared to main roads without cycling infrastructure, a lower injury risk on local roads that are designed as bicycle routes and therefore have separate traffic lights for cyclists at intersections with main roads and road markings to indicate the road as bicycle route (Teschke et al., 2012). For this characteristic it is important to note that not all images of the bicycle streets contain intersections or are focussed on an intersection, which might affect the importance of this characteristic.

5.8 Road surface

The last characteristic to discuss is road surface, but the importance of surface to assess the safety of bicycle streets is limited in the eyes of the groups of cycling safety professionals. Road surface is mostly about the colour of the pavement or the type or smoothness of the pavement. A red, smooth road surface made from asphalt is most in favour of cyclists, since the street can be identified as a cycling friendly environment. Baert et al. (2021) argue that a red surface helps to recognise the street as bicycle street. In Jörgensen (2020), respondents argue that a red pavement can help to decrease the speed of motorised vehicles.

6 Limitations and future research

A limitation of this study is the quality of the images, which might affect the expert judgement of the cycling safety professionals. Since the images come from different sources, the size and angle differ per image. This may affect the quality in terms of pixels, but also in terms of what can be seen on the image. For example, some images clearly contain intersections, while other photos are taken from an intersection causing that only part of the intersection is captured, and some images contain only a stretch of a road section. As a result, some bicycle streets are assessed based on the intersection on the image, while others are not due to the absence of an intersection. Moreover, since the images are a snapshot, quality may also affect the expert judgement in terms of how many cyclists are captured on the image. Some groups were distracted by the fact that some bicycle streets are used by a lot of cyclists while others are empty. To minimise the effect of this limitation, fixed bicycle and motorised vehicle volumes are provided in order to let the groups focus on other elements of the bicycle streets and to provide that they are assessed on the same amount of traffic. In future studies, it may be useful to use higher quality images or to edit the images in a way that the bicycle and motorised vehicle volumes look more similar. The same goes for the number of parked cars, which varies over the day. Some of the expert groups assessed the safety based on the number of parked cars on the image while it might have been more fair to assess the available space for parking. However, to minimise the impact of this limitation, the focus in Section 4.2 is on the design elements rather than on the direction of the argument.

Second, the method is partly a drawback of this study. To some extent, it may be unfair to compare international examples of bicycle streets due to large cultural differences in terms of bicycle use. For example, the difference between the Dutch example and the Zurich example is quite large in terms of design and bicycle volume. This may influence the way the bicycle streets are assessed, as the Zurich example may have scored higher when it was compared to other examples from Switzerland. To decrease the impact of this limitation, future studies may use a wider variety of bicycle street examples as well as multiple examples from one country or region. In addition, the goal of the method was to organise a workshop at a conference rather than on collecting data for research. Nevertheless, the data is collected among a large group (N=49) of international cycling safety professionals and revealed useful insights in what kind of characteristics are important to this group in order to assess the safety of bicycle streets. On the other hand, relying solely on expert judgement might bias the results since these experts are not the actual users of the bicycle streets. Future work may repeat the present study with actual users of bicycle streets and compare the results to this study in order to find out to what extent they align.

Lastly, it was found that some of the characteristics that are important for cycling safety professionals to assess the safety of bicycle streets received limited attention in existing literature about bicycle streets. Despite some elements are investigated in a more general way related to cycling safety, it could be interesting for future studies to investigate the impact of specific characteristics on the safety of bicycle streets in particular. For example, some images (e.g. Dresden) showed specific intersection designs related to the bicycle street, but it is unknown what the effect of such designs is on safety. Although a grade-separated intersection may be the safest solution, these intersection designs are not always feasible and future studies may look into the safety other types of intersection designs specifically for bicycle streets when they cross a main road. On top of that, the literature review showed that the number of studies using crash data to examine the safety of bicycle streets is limited. It would provide more insights in the impact of the identified characteristics on the safety of bicycle streets when future studies include crash data in the analysis. This is important since the bicycle street is increasingly implemented in several countries while the knowledge about their safety is limited. Although for some characteristics it is evident from general road safety literature that they are important for the safety of cyclists, some characteristics must be investigated specifically in relation to bicycle streets. This will benefit the development of guidelines for safe implementation of bicycle streets.

CRediT contribution statement

Teun Uijtdewilligen: Conceptualization, Data curation, Investigation, Methodology, Visualization, Writing—original draft. **Gert Jan Wijlhuizen:** Conceptualization, Data curation, Investigation, Methodology, Writing—review & editing. **Matin Nabavi Niaki:** Conceptualization, Data curation, Investigation, Methodology, Writing—review & editing.

Declaration of competing interests

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