# Intuitively usable Cycling Infrastructure – a systematic Literature Review

David Friel[a]

[a]*Integrated Transport Planning, Technische Universität Berlin, Berlin, Germany*

David Friel

Sekr. SG 4, Salzufer 17-19

10587 Berlin, Germany

Tel: +49 (0)30 314-78772

Mail: david.friel@tu-berlin.de

ORCID: 0009-0004-8231-3031

# Intuitively usable Cycling Infrastructure – a systematic Literature Review

While infrastructure planning guidelines frequently emphasise the need of comprehensible, easy to use or unambiguously understandable infrastructure, they lack information on how to design such intuitively usable cycling infrastructure. Furthermore, while cyclists already criticise the current traffic system not to be intuitively usable, this issue will be even more relevant as cycling usage may increase in the next years. Thus, this paper presents a systematic literature review to identify studies that already investigated the intuitiveness of cycling infrastructure. Furthermore, this study aims to identify major research gaps. Searching three databases with a predefined set of keywords resulted in more than 1300 titles. Applying inclusion and exclusion criteria, eleven titles remained in the last review step and were analysed in detail. Results show that these studies use a variety of methods and terms to describe and investigate intuitiveness of various cycling infrastructure designs. Conclusions from these studies range from very specific infrastructure design recommendations over highly general design advices to recommendations that do not refer to infrastructure design at all. Three main research gaps were identified. Firstly, there are various infrastructure types that have not been covered by the studies. Furthermore, there is a need for basic research on how to apply principles of intuitive design to cycling infrastructure design in general. Lastly, a large amount of research investigated behavioural responses to infrastructural changes but was not designed to specifically assess intuitiveness. Thus, there are large research gaps to be filled by upcoming studies to design intuitively usable cycling infrastructure.

Keywords: intuitive design, cycling infrastructure, comprehensibility, self-explaining roads, systematic literature review

## Introduction

Using bicycle infrastructure in a dense urban traffic system can be a challenging task. Paying attention to other road users may be hard enough in many situations. But as recent findings show as well, cyclists regularly feel confused due to a lack of cycling infrastructure’s comprehensibility. Moreover, comprehensibility acts as a key factor for assessing infrastructure’s cycling friendliness and affects cyclists’ perception of both safety and comfort (Friel et al., in press).

Infrastructure planning guidelines already address this issue by stating that cycling infrastructure must be comprehensible, easy to understand or easy to use. For example, the German cycling infrastructure guideline “Empfehlungen für Radverkehrsanlagen” states that cycling infrastructure at intersections must be unambiguously understandable for all road users (FGSV, 2010, p. 37) while, the Scottish brochure “Cycling by Design” states that “cycling infrastructure should be intuitive for all who use it or interact with it” (Transport Scotland, 2021, p. 9). In turn, the City of Vancouver recommends that “intersections should be intuitive and provide directional messaging when needed.” (City of Vancouver, 2017, p. 6) However, these guidelines lack information on how to implement such an intuitively usable bicycle infrastructure. Moreover, there seems to be little to no research concerning this issue.

In contrast, there is a concept for intuitively usable car infrastructure called self-explaining roads (SER). This concept has been pronounced by Theeuwes and Godthelp (1995). In their paper, they describe how car drivers categorise roads subjectively and behave according to their subjective categorisation. They state: "Roads are self-explaining when they are in line with expectations of the road users." (Theeuwes & Godthelp, 1995, p. 222)

In a more recent paper, Theeuwes (2021) further describes SER:

> The underlying idea is that the design and layout of the road environment elicits automatically the behavior that is appropriate for that type of road. In other words, the road nudges the right behavior without the need for much enforcement or education. (Theeuwes, 2021, p. 1)

In the last decades, this concept has spread from its origin in The Netherlands: It has been adopted and used for the development of road designs in several countries, e.g. USA (Mackie et al., 2013), Germany (Becher et al., 2006), and Czech Republic (Ambros et al., 2017). This human centred approach has also been used by the World Road Association (Birth et al., 2016).

Thus, the design of car infrastructure is increasingly linked to findings on the field of behavioural research, making human perceptions part of the design process as proposed in the concept of human centred or user centred design (e.g. Law et al., 2009).

However, there are relatively few efforts to integrate human perceptions in cycling infrastructure design in such a way. As Barrero and Rodriguez-Valencia (2022) describe it:

> As part of the literature review, we revised 48 bicycle related policy manuals and/or bicycle infrastructure design guidelines […]. We found that only two guides include the user's opinions or preferences in the bicycle infrastructure design process. […] Despite these two exceptions, in other guides, user involvement is limited to research surveys on overall satisfaction/dissatisfaction, commute preferences, and origins and destinations. (Barrero & Rodriguez-Valencia, 2022, p. 247)

Thus, users' needs and especially the need of intuitively comprehensible infrastructure are hardly present in today's cycling infrastructure planning processes. And while cyclists already criticise the lack of comprehensibility in the current traffic system, this issue will be even more relevant as cycling usage may increase in the next years.

To further investigate the topic of intuitively usable cycling infrastructure, I conducted a systematic literature review. As described by van Wee and Banister (2016), this systematic literature review aims to provide "a comprehensive overview of (or a selection of) the literature in a specific area, bringing together the material in a clearly structured way, and adding value through coming to some interesting conclusions." (van Wee & Banister, 2016, p. 279)

Apart from describing the current state of research on this topic, the analysis primarily aims to add value by clearly indicating research gaps to be closed by future research. The paper presents the process and results of this systematic literature review and describes research questions that remain to be investigated by future research.

From the general impression that there is a lack of research concerning the intuitive usability of cycling infrastructure, I formulated three research question for the systematic literature review:

(1) Which studies investigated the question of how intuitively usable cycling infrastructure is?

(2) What are their main findings?

(3) Which research gaps remain?

## Method

### *Developing a Boolean Search String*

Conducting several pre-tests, I iteratively developed a Boolean search string which comprises synonyms of the three keywords "cyclist", "infrastructure", and "intuitive" in both German and English:

> ((Fahrrad* OR Rad*) AND (Infrastruktur* OR Gestaltung* OR Straße*) AND (*Verhalten* OR *Wahl OR Verständlich* OR Usability OR Intuitiv* OR *Manöver* OR *Nutz* OR Veränderung* OR Wahrnehmung* OR wahrgenommen* OR empfunden* OR selbsterklärend* OR Nudge)) OR ((cycl* OR bicycl* OR bike* OR biking) AND (infrastructur* OR design* OR street OR road) AND (behaviour* OR behavior* OR choice OR comprehensib* OR usage

OR use OR usability OR intuitiv* OR maneuver OR manoeuvre OR chang* OR shift* OR variati* OR perceiv* OR perception* OR self-expl* OR nudge*))

Theeuwes and Godthelp (1995) is the first paper presenting the concept self-explaining roads which in turn is the first conceptual attempt to integrate behavioural research into traffic design. The paper refers to several studies that helped to frame the concept. As the earliest of these studies dates from 1988 (Riemersma, 1988), I decided to limit my research to articles published in 1988 or later.

### *Used Databases*

Starting from a list of possible databases to search, I decided to use three different databases: Transport Research Integrated Database (TRID) as a specific database for the field of transport research, and both Web of Science and Scopus as databases for peer reviewed papers of all research fields.

As the number of results would have gone beyond the scope of this review (160.000+ results at the first pre-test at Scopus), I decided against using the search string for both title and abstract. Instead, I searched titles only, resulting in about 200 titles at TRID and more than 800 articles in Web of Science in the pre-test.

Both limiting the research to three databases and limiting the initial research to titles reduced the number of potential results, resulting in a limited scope of the systematic literature review in first place. Thus, I chose to actively use snowballing to find literature that otherwise might not have been found due to the described limitations.

### *Inclusion and Exclusion Criteria*

According to Wetterich and Plänitz (2021), I defined and tested inclusion and exclusion criteria before I conducted the actual systematic literature review.

As my initial search string is limited to articles' titles, I developed a scheme that starts with highly general and easy-to-apply criteria for articles' titles, continues with more precise criteria for abstracts and ends with specific and precise criteria for the full texts. Thus, in the first step, only obviously irrelevant articles are rejected while a large number of potentially relevant articles remain in the research body. As abstracts and full texts are included in the following steps, inclusion and exclusion criteria become more precise to determine which articles are relevant for the research questions. In general, if it remains unclear if inclusion or exclusion criteria apply to an article, the article remains part of the review and will be revised in the next evaluation step.

After a pre-test with the first 50 search results from TRID I applied some minor modifications to the criteria. The final criteria have been operationalised as described in Table 1.

Table 1: Inclusion and Exclusion Criteria for the evaluation of titles, abstracts and full texts

| | **Inclusion criteria** | **Exclusion criteria** |
|---|---|---|
| **Titles should** | be research results (including grey literature) or reviews concerning<br>• either cyclists or cycling infrastructure<br>• and behaviour, perception, evaluation, choice, safety etc. | not be Websites, guidelines, position papers, project descriptions etc. or<br><br>research results concerning completely different topics (e.g. „design of polyaromatic ethers using cyclopentadienyliron complexes") |

| | | |
|---|---|---|
| **Abstracts should** | describe the relation between cycling infrastructure and comprehensibility or<br><br>the effect of either<br>• infrastructure on cyclists' riding behaviour, comprehensibility, intuitiveness, infrastructure use etc. or<br>• cycling infrastructure on other road users' behaviour, comprehensibility, intuitiveness, infrastructure use etc. | be not concerning infrastructure or<br><br>concerning safety perception or alike without any link to comprehensibility or<br><br>relating to both, infrastructure and behaviour etc. but not relating these topics |
| **Full texts should** | investigate the relation between cycling infrastructure and comprehensibility<br><br>Or the effect of either<br>• infrastructure on cyclists' riding behaviour, perception or infrastructure use as an effect of comprehensibility | not investigate perception, usage, riding behaviour without any link to comprehensibility |

| | |
|---|---|
| | or alike or<br>• cycling infrastructure on other road users' behaviour, perception or infrastructure use as an effect of comprehensibility or alike |

***Procedure***

On June 16th 2023 I applied the search string and date range to all three databases and retrieved 1643 titles. 414 titles were removed as they were duplicates retrieved from multiple databases. Thus, I started the analysis with 1229 titles being imported into the reference application Citavi (Swiss Academic Software GmbH, 2023).

After applying all inclusion and exclusion criteria as described above, I had seven titles selected, which I analysed in detail. Furthermore, from previous research and hints from other researchers, I received another eleven titles. Applying inclusion and exclusion criteria for abstracts and full-texts, three titles remained in the list after full-text analysis.

Afterwards, snowballing was conducted for these ten titles and then iteratively for each document being added to the list. Backward snowballing, e.g. finding titles cited by the respective papers, resulted in another 29 titles, from which four were included after applying inclusion and exclusion criteria for abstracts and full texts. In turn, forward snowballing, e.g. finding citations to the papers, was conducted using the respective feature in Scopus and Web of Science. This process resulted in another 44 titles, of which two titles were included after full-text analysis.

In sum, this process resulted in 16 titles. Analysing these titles in detail, I excluded another five titles: Although these titles used the terms comprehensibility or intuitive design either in the introduction or in the discussion, they did not actually investigate how intuitive usable the infrastructure was. As this step in the process is found to be a relevant finding, this issue is described in the discussion section in more detail.

Figure 1 depicts the whole process, while Table 2 gives an overview on the number of titles that were included after each evaluation step.

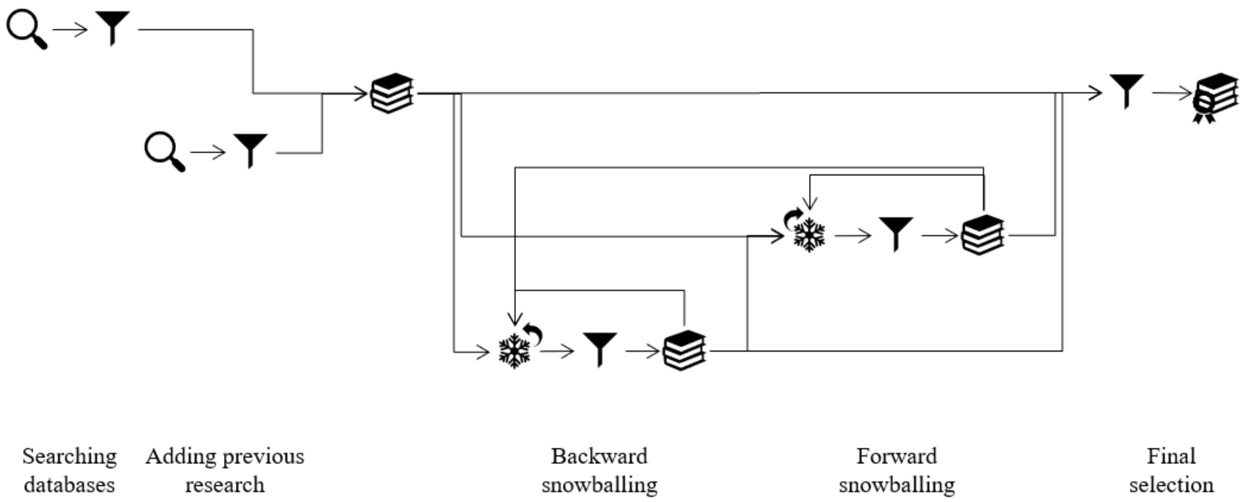


Figure 1: Systematic literature review process

Table 2: number of titles at each process step throughout the whole systematic literature review

| **Data source** | **# of titles included after…** | | | | |
|---|---|---|---|---|---|
| | **removing duplicates** | **analysing titles** | **analysing abstracts** | **analysing full texts** | **final analysis** |
| **Web of Science** | 948 | 149 | 34 | 5 | 3 |
| **TRID** | 141 | 77 | 27 | 1 | 1 |

| | | | | | |
|---|---|---|---|---|---|
| **Scopus** | 140 | 29 | 6 | 1 | 0 |
| **previous research** | 11 | * | 8 | 3 | 3 |
| **backward snowballing** | 29 | * | 18 | 4 | 3 |
| **forward snowballing** | 44 | 31 | 9 | 2 | 1 |
| **Sum** | **1315** | **286** | **102** | **16** | **11** |

*) Inclusion and exclusion criteria for titles deriving from previous research and backward snowballing were applied only on abstracts and full texts.

**Results**

In sum, the research process resulted in eleven titles being included in the final literature review (see Table 3 for an overview). Five titles were peer reviewed papers, another four titles were research project reports. The two remaining titles were a diploma thesis and a paper defined as grey literature. The titles date from 1996 to 2022. While the majority of titles have been published within the last ten years, only two titles were published earlier (1996 and 2009). In the following sections, topics, findings as well as methods and terminology used in the titles will be described.

Table 3: Titles included in the final literature review.

| **Authors (Year)** | **Title** | **Document type** | **Data Source** |
|---|---|---|---|
| Alrutz et al. (2009) | Unfallrisiko und Regelakzeptanz von Fahrradfahrern | project report | Backward snowballing |

| | | | |
|---|---|---|---|
| Angenendt and Wilken (1996) | Gehwege mit Benutzungsmöglichkeiten für Radfahrer | project report | Backward snowballing |
| Baumgartner et al. (2020) | Die Wirkung des Mobilitätsdesigns auf die Nutzung und Wahrnehmung von Fahrradstraßen: Untersuchungen anhand eines Fallbeispiels in Offenbach am Main | gray literature | Previous research |
| Bergh Alvergren et al. (2019) | Specification of nudges | project report | Previous research |
| Berghöfer and Vollrath (2022) | Cyclists' perception of cycling infrastructure – A Repertory Grid approach | peer reviewed paper | Web of Science |
| Huemer et al. (2018) | Influences on anger in German urban cyclists | Peer reviewed paper | Foreward snowballing |
| Kaplan and Prato (2016) | "Them or Us": Perceptions, cognitions, emotions, and overt behavior associated with cyclists and motorists sharing the road | peer reviewed paper | Web of Science |

| | | | |
|---|---|---|---|
| Monsere et al. (2015) | User Behavior and Perceptions at Intersections with Turning and Mixing Zones on Protected Bike Lanes | peer reviewed paper | Backward snowballing |
| Muggenburg et al. (2022) | What is a good design for a cycle street? - User perceptions of safety and attractiveness of different street layouts | peer reviewed paper | Web of Science |
| Polaček (2014) | Vorsicht Vorrang! Die Problematik der Vorrangregelung sowie rechtliche und bauliche Möglichkeiten für eine verständliche und sichere Gestaltung des Vorrangs zwischen Fahrrädern und Kraftfahrzeugen im österreichischen Straßenverkehr | diploma thesis | TRID |
| Schäfer et al. (2021) | Duale Radlösungen 2.0 | project report | Previous research |

***Topics and findings***

To get an overview, the following section will describe the main topics and findings of all eleven studies being included in the literature review. However, most of the studies investigated more than intuitively usable cycling infrastructure. For example, Bergh Alvergren et al. (2019) describe three separate studies of which only one meets the inclusion criteria for the systematic literature research. Thus, only the topic and findings of this study is part of the presented literature research. Following this example, the following sections will focus on topics and findings concerning intuitively usable cycling infrastructure.

*(Un)clear regulations*

The main topic covered by most titles were existing regulations or different infrastructural implementations and their effects on behaviour and comprehensibility.

*Usage of non-mandatory cycling infrastructure*: Three titles investigated different aspects of cycling on sidewalks with non-mandatory cycle lanes in Germany. These cycle lanes are very common in Germany, as many cycle paths became non-mandatory due to changes in the respective law. Thus, these cycle paths still exist and cyclists are allowed to choose between these cycle paths and cycling on street level. Another common setup in Germany is the sign “Radverkehr frei” that allows cyclists to use the sidewalk (for a brief overview on different German regulations concerning (non-)mandatory use of cycle paths in different settings, see ADFC, 2020).

Angenendt and Wilken (1996) used observations, on-site-surveys and accident data to investigate under which circumstances this latter regulation – sidewalk with permitted usage for cyclists – should be installed. Among other findings they observed that some cyclists used these sidewalks as they expected them to be mandatory for them (Angenendt & Wilken, 1996, p. 76). Moreover, in the survey only 23 % could correctly tell which rules apply for cycling on a sidewalk with the sign “Radverkehr frei”. Consequently, the authors recommend information campaigns to increase the knowledge of the rules.

Alrutz et al. (2009), in turn, investigated cyclists’ knowledge of rules, behaviour, and safety on different cycling infrastructure designs for straight road segments using observations, on-site-surveys, telephone-interviews, and accident data. These infrastructure designs included mandatory and non-mandatory cycle paths on sidewalks, the latter indicated by the respective sign (for the results on other infrastructure designs, see the respective section below). On some of the mandatory cycle paths, more than 80 % of the cyclists were convinced that they had to use them (Alrutz et al., 2009, p. 92). In line with Angenendt and Wilken (1996), Alrutz et al. (2009) recommend to provide more information and instruction for road users to increase the knowledge of the rules for this particular case.

Schäfer et al. (2021) used online-surveys, on-site-interviews and a focus group to study cyclists behaviour and its influencing factors at so-called dual cycling infrastructure. In the study, dual cycling infrastructure is defined as infrastructure with two parallel cycling facilities at different levels, e.g. a cycle path on the sidewalk and an advisory cycle lane on street level (Schäfer et al., 2021, p. 7). The authors found that many participants in the online-survey were not aware of the possibility to choose between the two cycling facilities. They expected existing cycle paths to be mandatory and therefore stated to use these. Accordingly, participants in the focus group highlighted this issue by stating that not all road users intuitively understand dual cycling infrastructure. They therefore wished for clear and unambiguous markings to indicate for both cyclists and motorists where cyclists are to be expected (Schäfer et al., 2021, 40). The authors conclude that consistent and clearly recognisable markings should be implemented. Furthermore, to increase the knowledge of the rules concerning mandatory cycle paths, this issue should be highlighted in road safety education (Schäfer et al., 2021, p. 42).

Concerning non-mandatory cycling infrastructure on sidewalks, all three studies conclude that many respondents are not aware of the existing rules allowing them to choose between cycling on the sidewalk or on street level. While all three studies recommend to provide more information on the topic for both cyclists and motorists, only Schäfer et al. (2021) give additional recommendations on how to improve the infrastructure design to make it more intuitively usable.

*Cycle streets:* Two studies from the same university investigated the effects of different designs for a specific cycle street in Offenbach, Germany. On the one hand, Baumgartner et al. (2020) conducted two focus groups to investigate how participants both perceive the redesign into a cycle street and how they assess several design concepts. On the other hand, Muggenburg et al. (2022) used an online survey to further investigate three specific cycling street designs that have derived from the design concepts presented by Baumgartner et al. (2020). Both studies deal with the current paper's topic of intuitive usable cycling infrastructure, although they use a different wording. While Baumgartner et al. (2020) focus more on the designs' capability to indicate which rules apply at this street, Muggenburg et al. (2022) investigated the clarity of designs.

In the study by Baumgartner et al. (2020), participants emphasise the importance of good infrastructure design to indicate how the cycle street is intended to be used. From their experiences with the recently redesigned street, participants conclude that the markings are inconsistent, incomplete and even wrong, or more generally spoken not well done as it still remains unclear for many road users which rules apply in the cycle street (Baumgartner et al., 2020, pp. 19f.). Concerning the various design concepts, participants wish for a design that fosters thoughtfulness regarding other road users. This can be achieved by infrastructural measures that break routines and draw attention to the newly applied rules, for example a blue coloured surface or a curved pathway (Baumgartner et al., 2020, pp. 26f.).

Muggenburg et al. (2022) investigated three design concepts for the cycle street in detail: A conventional design, consisting of a straight roadway with blue and white markings, car parking areas and sidewalks on both sides, a so-called flow design, consisting of a curved roadway, larger sidewalks, less parking space and more greenery, and a shared space design without separation of travel modes or markings, coloured paving as well as benches, trees, and water elements. Participants evaluated these three designs in terms of safety, clarity, attractiveness, and fun. Results show that both conventional and flow design score significantly higher on clarity than shared space. Besides, the authors found a correlation between clarity and safety. However, as shared space scores lowest on clarity and highest for safety at the same time, they emphasise that clarity cannot be used as a sole explanation for safety. The authors conclude that the lack of cars and the presence of trees and people in the street in the shared space design "[seem] to evoke a higher sense of safety than the strict separation of pedestrians seen in the *conventional* street design." (Muggenburg et al., 2022, p. 1383). Finally, they recommend flow design as the design best suitable for cycle streets as it provides clarity, safety and attractiveness at once (Muggenburg et al., 2022, p. 1385).

Hence, both studies conclude that the conventional design is not the most suitable design for a cycle street. But while Muggenburg et al. (2022) found the design to provide a high level of clarity, Baumgartner et al. (2020) conclude that the design does not indicate clearly which rules apply on the cycle street. Thus, although they both refer to the same design, the results concerning intuitively usable infrastructure seem to contradict each other.

*Other (un)clear regulations:* A few other studies investigated various regulations apart from sidewalks and cycle streets.

Monsere et al. (2015) conducted video analyses to evaluate cyclists behaviour at five different intersection designs in the USA. Furthermore, using on-site and resident surveys they asked participants to name the correct lane for through cyclists to investigate the comprehensibility of each design. Both self-reported comprehensibility and observed usage differed widely between the different designs and between road users. While for example at a design with a mixing zone for cyclists and turning cars, 93 % of turning cars used the correct lane, only 63 % of cyclists used the intended lane when a car was also present in the turning lane. Furthermore, when asked to name the correct lane for through cyclists, 55 % incorrectly chose the buffer space next to the turning lane (Monsere et al., 2015, p. 118). In contrast, 94 % named the correct lane for through cyclists at a design with a dedicated through bike lane and a bike box and 91 % of through cyclists used the correct lane at a design with a dedicated through bike lane without a bike box. The authors conclude that dedicated through bike lanes “help position cyclists and reduce confusion compared with sharrows in mixing zones.” (Monsere et al., 2015, p. 121).

In turn, Polaček's (2014) diploma thesis investigates Austria’s right of way rules between cyclists and car drivers in various infrastructural circumstances using an online-survey. The author found that while participants could state well who had right of way at situations concerning straight road segments, they had larger problems at situations concerning intersections with error rates up to 91 % (Polaček, 2014, pp. 75, 83). Including the results of several expert interviews, the author proposes various modifications for the existing Austrian right of way laws (Polaček, 2014, pp. 96ff.).

A further study deals with cyclists using motorways in Israel (Kaplan & Prato, 2016). The authors analysed user comments on online news items concerning cyclist accidents on shared roads to investigate “the chain of stimuli, cognition, emotion, and behavior associated with the roadsharing experience.” (Kaplan & Prato, 2016, p. 193) Concerning comprehensibility, on the one hand, results show that subjective road categories did not necessarily correspond to the legal road categorisation.

> Consequently, rural and urban highways as well as other interurban roads were largely perceived as motorways. The definitions were often disputed, with ensuing discussions about the dichotomy between the legal and the perceived definition of motorways on which cycling is prohibited. (Kaplan & Prato, 2016, p. 196)

On the other hand, it was largely discussed if cycling on the road shoulders was legal or not and if the presence of shoulders would even determine if cycling was prohibited or not. Subsequently, the authors recommend to emphasise on policy accountability through transparency and public participation (Kaplan & Prato, 2016, p. 199).

Finally, the previously mentioned study conducted by Alrutz et al. (2009) also deals with comprehensibility of other infrastructural elements apart from cycling on sidewalks. Compared to mandatory and non-mandatory cycle lanes on sidewalks and advisory lanes (indicated by a dashed line), cycle lanes (indicated by a solid line) were found to be significantly more unambiguous and clear (Alrutz et al., 2009, p. 92). Furthermore, participants complain about nonsensical routing for cyclists and rules that are hard to follow due to the infrastructure (Alrutz et al., 2009, p. 94). However, no specific recommendations result from these findings. Instead, the authors give the general recommendation to design cycling infrastructure in a clear and consistent way and to enhance road safety education (Alrutz et al., 2009, pp. 117ff.).

Summarising, the studies presented in this section deal with various regulations and infrastructure designs that differ in terms of comprehensibility. While Monsere et al. (2015) give a specific recommendation on how to alter infrastructure design to enhance infrastructure’s intuitiveness, the other three studies recommend either changes to the legal framework or to enhance road users’ compliance to road traffic rules.

*Other studies*

Apart from the described studies investigating existing regulations, three studies address intuitively usable cycling infrastructure on different levels.

On a more general level, Berghöfer and Vollrath (2022) investigated cyclists’ perception of factors affecting cycle route choice using a repertory grid approach. Presenting photos of different infrastructure types, the authors asked participants to sort the stimuli according to their subjective preferences and to explain their decision. Analysing the qualitative statements and the quantitative ratings, Berghöfer and Vollrath (2022) found that clarity and foreseeability, summarised as ease of use, were relevant attributes for the assessment of cycling infrastructure. They used the term ease of use to establish a link to usability research which, as they conclude, has not been investigated in previous studies concerning cycling infrastructure design (Berghöfer & Vollrath, 2022, pp. 256–257).

As well on a very general level, Huemer et al. (2018) conducted focus groups and diary studies to find anger provoking events for cyclists. First of all, they found infrastructure in general to be one of the main clusters for anger provoking events. In detail, unclear traffic situations were one of the 20 most mentioned topics. Additionally, in the diary studies, confusing intersections were mentioned to provoke anger.

The third study investigates intuitively usable cycling infrastructure in a very specific way: Bergh Alvergren et al. (2019) developed and evaluated several visual nudges for cyclists to slow down. They defined a nudge as "any aspect [...] of road infrastructure that will mindlessly influence an individual's choosing a certain behaviour." (Bergh Alvergren et al., 2019, p. 11) Using GPS data and interviews, they investigated the nudges on a test route in Gothenburg, Sweden, and found that all nudges worked as intended as cyclists slowed down at all places with nudges being installed. However, the nudges varied both in the way how much cyclists slowed down and in how cyclists were aware of the nudges. While a digital sign displaying the current speed reduced cyclists' speed the most, it only worked if the cyclists actively recognised the sign. In contrast, the other nudges consisting of markings on the cycle path affected cyclists' speed regardless of whether they actively recognised it or not (Bergh Alvergren et al., 2019, p. 67). Moreover, more apparent nudges reduced cyclists' speed more effective than less apparent nudges. Participants stated also that they preferred the more apparent nudges. Thus, the authors conclude that these highly apparent nudges based on markings on the cycle lane work well as subconsciously noticed nudges.

*Summary on topics, findings, and recommendations*

The presented studies deal with a broad range of topics that all refer to intuitively usable cycling infrastructure (see Table 4 for a brief overview). On the one hand, Berghöfer and Vollrath (2022) and Huemer et al. (2018) deal with intuitively usable cycling infrastructure on a general level. While the former emphasise the relevance of cycling infrastructure's ease of use as a factor to assess cyclists' route choice in general, the latter found that unintuitive cycling infrastructure can provoke anger. On the other hand, all other studies investigated cyclists' behaviour and perception based on specific infrastructural or regulatory circumstances. Three studies investigating mandatory cycling infrastructure on sidewalks found that many cyclists use these cycle paths as they misinterpret them to be obligatory. Two studies investigating a German cycle street design conclude that the design does not sufficiently suit road users' needs. Some studies investigate road users' perceptions concerning rules and behaviour on various other infrastructure types. Lastly and most specifically, Bergh Alvergren et al. (2019) investigated the effect of different visual nudges on cyclists' speed.

Furthermore, the presented studies vary regarding recommendations arising from the findings on intuitively usable infrastructure. Alrutz et al. (2009), Angenendt and Wilken (1996), Huemer et al. (2018), and Kaplan and Prato (2016) do not or provide hardly any recommendations on how to adjust infrastructure design to road users' needs. Instead, they emphasise on road safety training or other ways to increase road users' knowledge and acceptability for rules. Other studies (Baumgartner et al., 2020; Berghöfer & Vollrath, 2022; Polaček, 2014; Schäfer et al., 2021) give some general recommendations for infrastructure design adjustments, for example, by stating that the cycle street design should foster thoughtfulness regarding other road users (see for example Baumgartner et al., 2020). In contrast, Muggenburg et al. (2022), Bergh Alvergren et al. (2019), and Monsere et al. (2015) give a specific recommendation for one or two of the tested designs each.

Table 4: topics, methods, and findings of the investigated studies

| **Authors** | **Topic** | **Methods** | **Findings concerning intuitive usable cycling infrastructure** |
|---|---|---|---|
| Alrutz et al. (2009) | Knowledge of rules, behaviour, and accidents at different cycling infrastructure designs on straight road segments | observations, on-site-surveys, telephone-interviews, accident data | cycle lanes are clearest and most unambiguous compared to the other designs; mandatory cycle paths are misinterpreted as obligatory |

| | | | |
|---|---|---|---|
| Angenendt and Wilken (1996) | Applicability for sidewalk with permitted usage for cyclists | observations, on-site-surveys, accident data | mandatory cycle paths are misinterpreted as obligatory; only 23 % could correctly name the rules that apply for the sign |
| Baumgartner et al. (2020) | Perception of a cycle street and assessment of several design concepts | focus groups | existing markings are inconsistent, incomplete and not well done as it still remains unclear which rules apply; design should foster thoughtfulness and lead to correct behaviour |
| Bergh Alvergren et al. (2019) | Effect and perception of visual nudges on cycle paths to reduce cyclists' speed | GPS-Data, interviews, surveys | all nudges reduced cyclists' speed; markings on the cycle path affected cyclists' speed whether or not they recognised them actively; speed reduction was higher for more apparently designed nudges |

| | | | |
|---|---|---|---|
| Berghöfer and Vollrath (2022) | Cyclists' perception of factors affecting cycle route choice | Repertory Grid Approach | clarity and foreseeability, summarised as ease of use, are relevant attributes for the assessment of cycling infrastructure |
| Huemer et al. (2018) | Anger provoking events for cyclists | Focus groups, diary study | infrastructure is one of the main reasons for anger provoking events; unclear traffic situations as one of the 20 most mentioned topics, confusing intersections as additional topic in diaries |
| Kaplan and Prato (2016) | Perception and contextualisation of cyclists using large motorways | content analysis of online comments | subjective and objective road categorisation do not necessarily match; unclear, if cycling on road shoulders is legal or illegal |
| Monsere et al. (2015) | Behaviour and comprehensibility at five different intersection | video analysis, on-site survey, resident survey | varying levels of comprehensibility and correct use; dedicated |

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| | designs | | through bike lanes work better than mixing zones |
| Muggenburg et al. (2022). | Assessment of three different cycle street designs in terms of safety, clarity, attractiveness, and fun | online-survey, regression model | conventional and flow design score best on clarity; shared space has best values for safety, attractiveness, and fun; clarity and safety correlate |
| Polaček (2014) | Comprehensibility and behaviour at right of way rules between cyclists and car drivers at straight road segments and intersections | online-survey | right of way is rather clear for straight road segments; high error rates (up to 91 %) at intersections |
| Schäfer et al. (2021) | Cyclists' behaviour and its influencing factors at dual cycling infrastructure | online-survey, on-site-interviews, focus group | mandatory use is not clear; wish for clear, unambiguous, and consistent markings |

***Terminology and methods used***

Most studies use several terms to describe how intuitively usable infrastructure is. For example, Berghöfer and Vollrath (2022) refer to *clarity, foreseeability*, and *ease of use*, while Baumgartner et al. (2020) use the terms *unambiguous*, *incomplete*, and *inconsistent* to describe the respective attributions to infrastructure design. Only Polaček (2014) uses *knowledge of rules* as solely term.

Besides, some terms are used by various studies. To start with, the term *clarity* or *(un)clear* respectively is used by five studies: While in Berghöfer and Vollrath (2022), Huemer et al. (2018), and Schäfer et al. (2021) the term derived from qualitative data, e.g. open-ended questions, Muggenburg et al. (2022) used the term clarity as one of four factors to be evaluated on a Likert scale. Furthermore, the term *unambiguous* was used in two studies (Alrutz et al., 2009; Schäfer et al., 2021). Other studies referred to *knowledge of rules*: Polaček (2014) asked the respondents if they knew who had right of way, Alrutz et al. (2009) asked where respondents thought they were allowed to ride. Angenendt and Wilken (1996) asked respondents in a qualitive way to state reasons for their behaviour. These three studies used the term *knowledge of rules* to discuss their findings. The terms *understanding* (Bergh Alvergren et al., 2019; Monsere et al., 2015), *unambiguous* (Alrutz et al., 2009; Schäfer et al., 2021), and confusion (Huemer et al., 2018; Schäfer et al., 2021) were used by two studies each. Other terms used in the studies include *foreseeability*, *ease of use* (Berghöfer & Vollrath, 2022), *irritation by routing* (Alrutz et al., 2009), or *comprehension* (Monsere et al., 2015).

Furthermore, the studies use various methodological approaches to investigate intuitively usable infrastructure. Applied by five studies, the most often used method is on-site surveys or interviews conducted with either preselected participants or with road users that agreed to participate at the investigated location (Alrutz et al., 2009; Angenendt & Wilken, 1996; Bergh Alvergren et al., 2019; Monsere et al., 2015; Schäfer et al., 2021). Online surveys (Muggenburg et al., 2022; Polaček, 2014; Schäfer et al., 2021) or paper based resident surveys (Monsere et al., 2015) were used by four studies. Three studies conducted video observations (Monsere et al., 2015) or on-site observations (Alrutz et al., 2009; Angenendt & Wilken, 1996). Another three studies conducted focus groups (Baumgartner et al., 2020; Huemer et al., 2018; Schäfer et al., 2021). GPS data (Bergh Alvergren et al., 2019), Repertory Grid Analysis (Berghöfer & Vollrath, 2022), diary studies (Huemer et al., 2018), and content analysis (Kaplan & Prato, 2016) were used by one study each. Apparently, seven studies use multiple methods for data acquisition, while Berghöfer and Vollrath (2022), Kaplan and Prato (2016), Muggenburg et al. (2022), and Polaček (2014) used one method to gather the required data.

Summarising, the studies use a broad range of terms and methods to investigate cycling infrastructure's intuitiveness. Moreover, most studies use multiple methods to gather data and multiple terms to describe the findings.

## Discussion

In the introduction, three research questions were posed to be answered by this systematic literature review:

(1) Which studies investigated the question of how intuitively usable cycling infrastructure is?
(2) What are their main findings?
(3) Which research gaps remain?

While the results section described the main findings of all investigated studies and thus already answered the second research question, the following sections will discuss the two other research questions. In the next section, the term *intuitive design* will be further discussed and implications on the investigated studies will be made. Following this, a brief overview is given on topics that have not been covered by the investigated studies. Furthermore, I will discuss the fact that a large number of studies had to be excluded from the research even though they seemed to investigate cycling infrastructures’ intuitiveness. Lastly, the section describes limitations of the methodological approach of this paper.

### *Intuitively usable (cycling infrastructure) design*

In the introduction, I presented intuitively usable cycling infrastructure based on Friel et al.'s (in press) finding that comprehensibility acts as a key factor to assess cycling infrastructure. Subsequently, I cited various cycling infrastructure guidelines that recommend infrastructure to be unambiguously understandable and self-explaining, concluding that there seems to be a lack of information on how to design intuitively usable cycling infrastructure. Hence, in the introduction I already used four terms synonymously to describe one vague concept. As described above, the investigated studies used a wide variety of terms to refer to intuitively usable infrastructure as well, adding terms like clarity, ease of use or knowledge of rules to the list. Hence, the literature review even broadens the scope of what intuitively usable infrastructure may refer to. Thus, it remains an open question what intuitively usable cycling infrastructure really is and if it corresponds to the concept I introduced in the first section.

To answer this question, a brief excurse is made to understand intuitive design in general. Concerning this, Naumann et al. (2007) developed a definition for intuitive design:

> “A technical system is, in the context of a certain task, intuitively usable while the particular user is able to interact effectively, not-consciously using previous knowledge.” (Naumann et al., 2007, p. 129)

They further emphasise that not the system itself can be labelled as intuitive but only the human information process in a certain context with the system (see Naumann et al., 2007, p. 129).

However, this definition refers to technical systems and human-interface interactions. Hence, we need to draw a connection between cycling infrastructure and technical systems. Assuming that cycling infrastructure can be seen as a technical system and that all recognisable elements such as markings, traffic lights, and curb stones can be defined as an interface, it is possible to apply the definition of intuitive design to cycling infrastructure design.

With this assumption, nearly all investigated studies in this literature review refer to intuitive design as defined by Naumann et al. (2007). For example, all three studies investigating non-mandatory cycle paths on sidewalks found that cyclists misinterpreted them to be mandatory. Naumann et al.'s (2007) definition of intuitive design includes the term *effective*. They further describe that "an interaction [is] *intuitive* if it leads the user to adequate, exact and complete interaction results." (Naumann et al., 2007, pp. 133–134) Hence, for cyclists who would have preferred riding on street level but used the non-mandatory cycle lane instead as they misinterpreted it as mandatory, the design was unintuitive as it led users to an inadequate result. Furthermore, respondents stated that it is rather difficult for cyclists to ride according to the rules and that in some cases it seems ridiculous to use the designated cyclists routes (see Alrutz et al., 2009, p. 94) and wished for clear and unambiguous routes (see Schäfer et al., 2021, p. 38). Using Naumann et al.'s (2007) terminology, these statements also imply a lack of effectiveness in the design making it less intuitively usable.

The most accurate match to Naumann et al.'s (2007) definition of intuitive design is made by Bergh Alvergren et al. (2019) as they define nudges as "any aspect [...] of road infrastructure that will mindlessly influence an individual's choosing a certain behaviour." (Bergh Alvergren et al., 2019, p. 11). This definition includes the notion that the design influences the users’ behaviour on a subconscious level.

The only study that did not investigate intuitive design in terms of Naumann et al.'s (2007) definition is the one conducted by Muggenburg et al. (2022). While in the examples above, the term clarity was used in the context of clear routes for cyclists or clear indications of the applied rules, Muggenburg et al. (2022) used the survey item “the situation is clearly structured” (Muggenburg et al., 2022, p. 1380) to assess the designs’ clarity. Even though a clearly structured situation may help to understand a situation more effectively, the situation may remain unclear in terms of which rules apply. Thus, Muggenburg et al. (2022) investigated the clarity of various street designs but it seems as if they did not investigate cycle street designs’ intuitiveness according to Naumann et al.'s (2007) definition.

Summarising, it seems that even though the investigated studies used a variety of terms, nearly all studies investigated cycling infrastructures’ intuitiveness or the lack of. However, it remains to be investigated if the definition of intuitive design provided by Naumann et al. (2007) can be applied to infrastructure design as it refers the term technical system.

Adding to this, the research group providing Naumann et al.'s (2007) definition on intuitive design defined several criteria for intuitive interactions (Mohs et al., 2006). For example, the authors name compatibility, consistency, and ease of use as relevant criteria (see Mohs et al., 2006, p. 220). Assuming the applicability of the definition of intuitive design, the criteria for intuitive interactions would be applicable to infrastructure design as well. Further research could use these criteria as a basis for the design of highly intuitively usable cycling infrastructure.

### *Topics not covered*

Although the investigated studies covered a variety of topics, there remain various topics to be investigated in terms of intuitiveness. Furthermore, most findings reveal new research questions that remain to be investigated by further research.

To start with, the three studies investigating non-mandatory cycle paths on sidewalks found that they were misinterpreted as mandatory. Schäfer et al.'s (2021) study on dual cycling infrastructure even described that many cyclists wish for a clear design to indicate where they are allowed to cycle. However, as this was not in the studies’ scope, there are no further information on how to design mandatory cycle paths on sidewalk to clearly indicate that they are mandatory. Further research is required to determine design solutions to solve the problem.

The two studies investigating cycle street designs referred to one location. Furthermore, although they investigated several design concepts, there may be many other designs that could be suitable for cycle streets. Hence, further research could focus on intuitively usable cycle street designs in other locations, e.g. streets with differing widths and surroundings, and other possible designs for cycle streets. Even more, other street types like pedestrian zones or recreational cycling paths with rules differing from typical urban street rules could be investigated in terms of intuitiveness.

The other studies investigating existing regulations evaluated the intuitiveness of motorways (Kaplan & Prato, 2016), large intersections (Monsere et al., 2015), right-of-way rules on straight road segments and smaller intersections (Polaček, 2014), and some aspects of intuitiveness on different cycling facilities on straight road segments (Alrutz et al., 2009). Apart from Kaplan and Prato (2016), all studies found designs that were more intuitively usable than other designs. However, all studies also found designs that are less intuitively usable and thus should be further investigated to find appropriate design solutions. Moreover, there remains a variety of topics to be covered by further research. For example, Polaček's (2014) work focused on Austrian right-of-way rules; other countries' right-of-way rules in various infrastructural conditions may have similar challenges regarding intuitiveness and might be relevant to be investigated. As another example, Monsere et al.'s (2015) study investigated several different designs for larger intersections. However, many other designs under several other regulatory circumstances remain to be researched. Besides, smaller intersections and even roundabouts may be relevant to be investigated in terms of intuitiveness.

Regarding Bergh Alvergren et al.'s (2019) study on visual nudges to slow down cyclists, nudges for various other purposes could be investigated, as for example nudges to increase cyclists' distance to parking cars to avoid dooring accidents.

Summarising, the investigated studies covered various aspects of intuitively usable cycling infrastructure. However, due to the limited number of studies, there remain various research gaps to be closed by further research. Moreover, even though most studies were able to identify more and less intuitively usable designs, they did not actively modify the designs to increase the intuitiveness. Thus, a research gap remains in specifically investigating how to increase infrastructure designs' intuitiveness.

### *Studies not designed to investigate intuitiveness*

As mentioned in the methods section, five titles were excluded in the last analysis step as they referred to intuitive design but did not actually investigate infrastructures' intuitive usability.

Two of these titles investigated overtaking manoeuvres for different urban infrastructure settings. Kassim et al. (2019) analysed video data before and after the implementation of advisory bike lanes. They found larger overtaking distances between cars and cyclists, decreased car speeds and a larger distance between cyclists and parked cars after the installation. Duthie et al. (2010) built regression models based on a set of video observations from 48 sites. Their findings suggest that bike lanes increase overtaking distances between cars and cyclists. Moreover, bike lanes and dooring buffer zones increase the distance between cyclists and parked cars.

Another two titles investigated cyclists' trajectories at several intersections. While Lind et al. (2021) analysed cyclists' behaviour at six intersections in Barcelona, Spain, Wexler and El-Geneidy (2017) analysed two intersections in the City of Montreal, Canada. Both studies found that bidirectional cycle lanes lead to more complex designs which in turn lead to a higher number of trajectories not corresponding to the behaviour intended by the intersection design.

The last title investigated 15 different cycling infrastructure types, ranging from bicycle streets over bicycle lanes at intersections to advanced stop lines (Cieśla et al., 2018). Using video data, they observed higher rates of irregular behaviour at advanced stop lines, pedestrian crossings and other interrupted cycling facilities.

These five titles established a link between infrastructure and intuitive usability, describing infrastructure elements as "complicated" (Cieśla et al., 2018, p. 7), introducing measures as "intuitive design" (Kassim et al., 2019, p. 234), concluding "that cyclists find some turns more intuitive than others" (Lind et al., 2021, p. 734), criticising "a lack of clarity in the street design" (Wexler & El-Geneidy, 2017, p. 110) or emphasising that the infrastructure "clearly shows bicyclists and motorists where to position themselves on the roadway" (Duthie et al., 2010, p. 41). Although this wording allowed these titles to be included in the presented systematic literature review after the first full-text analysis, and even though it seems to be reasonable that the observed behaviour might be affected by the intuitiveness of the design, the studies did not actively investigate intuitiveness. They rather observed behavioural responses to existing infrastructure that might be explained by varying levels of intuitiveness. However, there might be other explanations like varying perceived safety or comfort that could have affected cyclists' behaviour. Without specifically investigating the reasons for the observed behaviour, a direct influence of infrastructure design's intuitiveness on cyclists' behavioural response cannot be shown.

The same applies to several studies that I excluded earlier in the full-text analysis. Apart from a larger number of studies that did not assess intuitiveness in any way as it was not in the scope of the respective studies, many titles did try to find reasons for cyclists' behaviour in relation to infrastructural conditions. However, due to the methods used to analyse cyclists' behaviour – observations, GPS-data, specialised bike sensor data etc. – these studies were not designed to find any relation to intuitive design even though in many cases it seems to be reasonable that the observed behaviour is at least to some extent a result of a varying degree of intuitiveness. Moreover, in contrast to the mentioned studies above, these studies did not use a wording that allowed them to be included in the last analysing step.

For example, a study investigated car drivers' gaze and approaching behaviour in respect to different cycle lane crossing designs and other factors in a car driving simulator (Berghöfer et al., 2023). The crossing designs varied from no marking over highly visible markings to speed bumps, resulting in less critical approaches for the latter. However, due to the methods used in the study, it is not possible to determine whether this result was due to higher visibility of the markings or a higher degree of comprehensibility or any other unknown factor. The same applies to several other studies investigating for example Level of Service for different pedestrian-cyclist shared infrastructure (Nikiforiadis et al., 2023), overtaking behaviour in relation to infrastructural measures on rural roads (Chapman & Noyce, 2014; Kay et al., 2014) or urban streets (Apasnore et al., 2017; Shackel & Parkin, 2014), or cyclists' street-crossing behaviour (Bi et al., 2023).

A minimum of 20 titles were excluded for this reason: they investigated behavioural responses to infrastructure. But due to the methods used in these studies, it remains unclear if the observed behavioural changes are a result of varying intuitiveness or if they derived from other factors such as perceived safety, infrastructures' visibility, or the like.

Once again, including Naumann et al.'s (2007) definition on intuitive design described above, further research could aim to find the reasons for the observed behaviour in these studies and to specify to what extent infrastructure's intuitiveness determines behavioural changes.

### *Limitations*

As every scientific work, this systematic literature review has some limitations due to its methodological approach.

Firstly, although a systematic literature review in general provides a highly structured way to find relevant literature, it highly depends on the keywords, databases, and inclusion and exclusion criteria that were used to conduct the review. As all these decisions aim to limit the amount of titles being included in the final review process, they may have coincidentally led to gaps in the final selection of titles.

Furthermore, this systematic literature review was limited to studies in English or German. As a large number of studies in the field is funded or conducted by national or federal agencies or ministries, they are often published in the countries' language(s).

Thus, there may be a number of relevant studies from countries with official languages other than German or English that was not included in this review.

Lastly, the process of applying inclusion and exclusion criteria on the titles is to a certain extent a subjective task. Thus, and as I conducted this systematic literature review alone, personal biases may have influenced the resulting list of titles.

## Conclusion

In this systematic literature review, I analysed eleven titles in detail that investigated intuitively usable cycling infrastructure. These studies use a variety of methods and terms to describe and investigate intuitiveness of various cycling infrastructure designs. Conclusions from these studies range from very specific infrastructure design recommendations over highly general design advices to recommendations that do not refer to infrastructure design at all.

Based on these insights, I identified several research gaps. Firstly, there are various infrastructure types that have not been covered by the studies of this literature review. Furthermore, there is a need for basic research on how to apply principles of intuitive design to cycling infrastructure design. Lastly, a large amount of research investigated behavioural responses to infrastructural changes but was not designed to assess the effect of intuitiveness.

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**References**

ADFC. (2020). *Verkehrsrecht für Radfahrende*. https://www.adfc.de/fileadmin/user_upload/Im-Alltag/Recht/Downloads/Verkehrsrecht_fuer_Radfahrende_6.20.pdf

Alrutz, D., Bohle, W., Müller, H., & Prahlow, H. (2009). *Unfallrisiko und Regelakzeptanz von Fahrradfahrern: Bericht zum Forschungsprojekt FE 82.262: Unfallrisiko, Konfliktpotenzial und Akzeptanz der Verkehrsregelungen von Fahrradfahrern* (Berichte der Bundesanstalt für Straßenwesen V, Verkehrstechnik). Bremerhaven. https://bast.opus.hbz-nrw.de/opus45-bast/frontdoor/deliver/index/docId/191/file/V184.pdf

Ambros, J., Valentová, V., Gogolín, O., Andrášik, R., Kubeček, J., & Bíl, M. (2017). Improving the Self-Explaining Performance of Czech National Roads. *Transportation Research Record: Journal of the Transportation Research Board*, *2635*(1), 62–70. https://doi.org/10.3141/2635-08

Angenendt, W., & Wilken, M. (1996). *Gehwege mit Benutzungsmöglichkeiten für Radfahrer* (Forschung Straßenbau und Straßenverkehrstechnik No. 737). Bonn-Bad Godesberg.

Apasnore, P., Ismail, K., & Kassim, A. (2017). Bicycle-vehicle interactions at mid-sections of mixed traffic streets: Examining passing distance and bicycle comfort perception. *Accident Analysis & Prevention*, *106*, 141–148. https://doi.org/10.1016/j.aap.2017.05.003

Barrero, G. A., & Rodriguez-Valencia, A. (2022). Asking the user: a perceptional approach for bicycle infrastructure design. *International Journal of Sustainable Transportation*, *16*(3), 246–257. https://doi.org/10.1080/15568318.2020.1871127

Baumgartner, A., Fischer, L., & Welker, J. (2020). *Die Wirkung des Mobilitätsdesigns auf die Nutzung und Wahrnehmung von Fahrradstraßen: Untersuchungen anhand eines Fallbeispiels in Offenbach am Main* (Arbeitspapiere zur Mobilitätsforschung No. 24). Frankfurt am Main. Goethe-Universität, Institut für Humangeographie, Arbeitsgruppe Mobilitätsforschung. http://publikationen.ub.uni-frankfurt.de/frontdoor/index/index/docId/51589

Becher, T., Baier, M. M., Steinauer, B., & Krüger, H.-P. (2006). *Berücksichtigung psychologischer Aspekte beim Entwurf von Landstraßen: Bericht zum Forschungsprojekt FE 02.230/2003/AGB*. Grundlagenstudie (Berichte der Bundesanstalt für Straßenwesen V, Verkehrstechnik Heft 148). Bremerhaven. https://edocs.tib.eu/files/e01fn19/1667721488.pdf

Bergh Alvergren, V., Karlsson, M., & Wallgren, P. (2019). *Specification of nudges*. Deliverable 3.1. https://www.mebesafe.eu/wp-content/uploads/2020/01/MeBeSafe_D3.1_Specification-of-nudges.pdf

Berghöfer, F. L., Huemer, A. K., & Vollrath, M. (2023). Look right! The influence of bicycle crossing design on drivers' approaching behavior. *Transportation Research Part F: Traffic Psychology and Behaviour*, *95,* 98-111. https://doi.org/10.1016/j.trf.2023.03.017

Berghöfer, F. L., & Vollrath, M. (2022). Cyclists' perception of cycling infrastructure – A Repertory Grid approach. *Transportation Research Part F: Traffic Psychology and Behaviour*, *87,* 249–263. https://doi.org/10.1016/j.trf.2022.04.012

Bi, H., Li, A. Y., Zhu, H., & Ye, Z. R. (2023). Bicycle safety outside the crosswalks: Investigating cyclists' risky street-crossing behavior and its relationship with built environment. *JOURNAL of TRANSPORT GEOGRAPHY, 108.* https://doi.org/10.1016/j.jtrangeo.2023.103551

Birth, S., Ágústsson, L., Allan, P., Chambon, P., Elsenaar, P., Ganneau, F., Greenalgh, M., Hollo, P., Lee, S. J., Rubio, R. L., Mallejacq, P., Rouffaert, A., Vollpracth, H.-J., Westdijk, E., de Almeida Rogue, Carlos, Aubin, D., Grasse, D. de, Douglas, J., . . . Schepers, P. (2016). *Human factors guidelines for a safer man-road interface*. PIARC. https://www.piarc.org/en/order-library/6159-en-Human%20factors%20guidelines%20for%20safer%20road%20infrastructure

Chapman, J. R., & Noyce, D. A. (2014). Influence of roadway geometric elements on driver behavior when overtaking bicycles on rural roads. *Journal of Traffic and Transportation Engineering (English Edition)*, *1*(1), 28–38. https://doi.org/10.1016/S2095-7564(15)30086-6

Cieśla, K., Krukowicz, T., & Firląg, K. (2018). Analysis of cyclists' behaviour on different infrastructure elements. In *MATEC Web Conf.* (Vol. 231). https://doi.org/10.1051/matecconf/201823103001

City of Vancouver. (2017). *Transportation Design Guidelines: All Ages and Abilities Cycling Routes*. https://vancouver.ca/files/cov/design-guidelines-for-all-ages-and-abilities-cycling-routes.pdf

Duthie, J., Brady, J. F., Mills, A. F., & Machemehl, R. B. (2010). Effects of On-Street Bicycle Facility Configuration on Bicyclist and Motorist Behavior. *Transportation Research Record: Journal of the Transportation Research Board*(2190), 37–44. https://doi.org/10.3141/2190-05

FGSV. (2010). *Empfehlungen für Radverkehrsanlagen: ERA R2* (FGSV R2 - Empfehlungen). Köln. Forschungsgesellschaft für Straßen- und Verkehrswesen.

Friel, D., Wachholz, S., Zimmermann, L., Werner, T., Schwedes, O., & Stark, R. (in press). Cyclists’ Perceived Safety on Intersections and Roundabouts – a Qualitative Bicycle Simulator Study. *Journal of Safety Research*.

Huemer, A. K., Oehl, M., & Brandenburg, S. (2018). Influences on anger in German urban cyclists. *Transportation Research Part F: Traffic Psychology and Behaviour*, *58*, 969–979. https://doi.org/10.1016/j.trf.2018.07.026

Kaplan, S., & Prato, C. G. (2016). "Them or Us": Perceptions, cognitions, emotions, and overt behavior associated with cyclists and motorists sharing the road. *International Journal of Sustainable Transportation*, *10*(3), 193–200. https://doi.org/10.1080/15568318.2014.885621

Kassim, A., Culley, A., & McGuire, S. (2019). Operational Evaluation of Advisory Bike Lane Treatment on Road User Behavior in Ottawa, Canada. *Transportation Research Record: Journal of the Transportation Research Board*, *2673*(11), 233–242. https://doi.org/10.1177/0361198119851450

Kay, J. J., Savolainen, P. T., Gates, T. J., & Datta, T. K. (2014). Driver behavior during bicycle passing maneuvers in response to a Share the Road sign treatment. *ACCIDENT ANALYSIS and PREVENTION*, *70*, 92–99. https://doi.org/10.1016/j.aap.2014.03.009

Law, E. L.-C., Roto, V., Hassenzahl, M., Vermeeren, A. P., & Kort, J. (2009). Understanding, scoping and defining user experience: A survey approach. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (pp. 719–728). ACM. https://doi.org/10.1145/1518701.1518813

Lind, A., Honey-Rosés, J., & Corbera, E. (2021). Rule compliance and desire lines in Barcelona’s cycling network. *Transportation Letters*, *13*(10), 728–737. https://doi.org/10.1080/19427867.2020.1803542

Mackie, H. W., Charlton, S. G., Baas, P. H., & Villasenor, P. C. (2013). Road user behaviour changes following a self-explaining roads intervention. *Accident Analysis & Prevention*, *50*, 742–750. https://doi.org/10.1016/j.aap.2012.06.026

Mohs, C., Hurtienne, J., Scholz, D., & Rotting, M. (2006). Intuitivität: definierbar, beeinflussbar, überprüfbar! In VDI & VDE-Gesellschaft Mess- und Automatisierungstechnik (Eds.), *Useware 2006* (pp. 215–224). VDI-Verlag. https://www.researchgate.net/publication/280015034_Intuitivitat_definierbar_beeinflussbar_uberprufbar

Monsere, C. M., Foster, N., Dill, J., & McNeil, N. (2015). User Behavior and Perceptions at Intersections with Turning and Mixing Zones on Protected Bike Lanes. *Transportation Research Record: Journal of the Transportation Research Board*, *2520*(1), 112–122. https://doi.org/10.3141/2520-13

Muggenburg, H., Blitz, A., & Lanzendorf, M. (2022). What is a good design for a cycle street? - User perceptions of safety and attractiveness of different street layouts. *Case Studies on Transport Policy*, *10*(2), 1375–1387. https://doi.org/10.1016/j.cstp.2022.04.021

Naumann, A., Hurtienne, J., Israel, J. H., Mohs, C., Kindsmüller, M. C., Meyer, H. A., & Hußlein, S. (2007). Intuitive Use of User Interfaces: Defining a Vague Concept. In D. Harris (Ed.), *Lecture notes in computer science Lecture notes in artificial intelligence: Vol. 4562. Engineering psychology and cognitive ergonomics: 7th international conference, EPCE 2007, held as part of HCI International 2007, Beijing, China, July 22 - 27, 2007 ; proceedings* (Vol. 4562, pp. 128–136). Springer. https://doi.org/10.1007/978-3-540-73331-7_14

Nikiforiadis, A., Chatzali, E., Ioannidis, V., Kalogiros, K., Paipai, M., & Basbas, S. (2023). Investigating factors that affect perceived quality of service on pedestrians-cyclists shared infrastructure. *TRAVEL BEHAVIOUR and SOCIETY*, *31*, 323–332. https://doi.org/10.1016/j.tbs.2023.01.006

Polaček, C. M. (2014). *Vorsicht Vorrang!: Die Problematik der Vorrangregelung sowie rechtliche und bauliche Möglichkeiten für eine verständliche und sichere Gestaltung des Vorrangs zwischen Fahrrädern und Kraftfahrzeugen im österreichischen Straßenverkehr* [Diplomarbeit]. Technische Universität Wien. https://doi.org/10.34726/hss.2014.21142

Riemersma, J. B. J. (1988). An empirical study of subjective road categorization. *Ergonomics*, *31*(4), 621–630. https://doi.org/10.1080/00140138808966704

Schäfer, P. K., Freyer, L., Bohl, M., & Winkler, Z. (2021). *Duale Radlösungen 2.0: Nutzungsverhalten der Radfahrenden bei dualer Radinfrastruktur durch Befragung*. Abschlussbericht. Frankfurt am Main. Frankfurt University of Applied Sciences. https://www.frankfurt-university.de/fileadmin/standard/Hochschule/Fachbereich_1/FFin/Neue_Mobilitaet/Veroeffentlichungen/2020/Duale_Radloesungen_Abschlussbericht.pdf

Shackel, S. C., & Parkin, J. (2014). Influence of road markings, lane widths and driver behaviour on proximity and speed of vehicles overtaking cyclists. *Accident; Analysis and Prevention*, *73*, 100–108. https://doi.org/10.1016/j.aap.2014.08.015

Swiss Academic Software GmbH. (2023). *Citavi* (Version 6.10.0.0) [Computer software]. https://www.citavi.com/de

Theeuwes, J. (2021). Self-explaining roads: What does visual cognition tell us about designing safer roads? *Cognitive Research: Principles and Implications*, *6*(1), 1–15. https://doi.org/10.1186/s41235-021-00281-6

Theeuwes, J., & Godthelp, H. (1995). Self-explaining roads. *Safety Science*, *19*(2-3), 217–225. https://doi.org/10.1016/0925-7535(94)00022-U

Transport Scotland. (2021). *Cycling by Design*. https://www.transport.gov.scot/media/50323/cycling-by-design-update-2019-final-document-15-september-2021-1.pdf

van Wee, B., & Banister, D. (2016). How to Write a Literature Review Paper? *Transport Reviews*, *36*(2), 278–288. https://doi.org/10.1080/01441647.2015.1065456

Wetterich, C., & Plänitz, E. (2021). *Systematische Literaturanalysen in den Sozialwissenschaften: Eine praxisorientierte Einführung* (1st). Verlag Barbara Budrich.

Wexler, M. S., & El-Geneidy, A. (2017). Keep ’Em Separated: Desire Lines Analysis of Bidirectional Cycle Tracks in Montreal, Canada. *TRANSPORTATION RESEARCH RECORD*, *2662*(1), 102–115. https://doi.org/10.3141/2662-12