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Traffic rule violations by cyclists in the western world: a scoping review

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Abstract
Traffic rule violations by cyclists are fervently discussed in the research community as well as in the general population. Their relevance with regard to traffic safety and conflicts between road users and the situational context in which cyclists commit them remains not fully understood. This review aims to descriptively synthesize the research focusing on specific and spontaneous traffic rule violations by individual cyclists in road traffic. 59 studies were assessed for their methodologies, investigated traffic rules, and violations rates. Surveys relying on cyclists' self-reported frequency of violations as well as observations based on video-recordings are the most used methodologies. Red-light violations are investigated in about 2/3 of all studies in the scope of this review. Reported violation rates are heterogeneous between methodologies and types of rule violations. Tentative comparisons across studies suggest that the frequencies of some violations reported in observational studies are not necessarily well-aligned with the proportion of cycling-related crashes resulting from these violations types in other studies. Research gaps identified are (1) an evaluation of which traffic rule violations are relevant to study in order to increase cyclists' safety as well as to reduce conflicts with other road users, (2) a greater focus on integrating different methodologies, and (3) a lack of theoretical frameworks accounting for dispositional, situational, and motivational factors underlying cyclists' traffic rule violations.

Keywords Bicycling, Rule violations, Traffic legislation, Illegal behavior, Traffic offenses

1 Introduction

Cycling is an emission-free alternative to driving a car for urban commuting. Bicycles also consume less of the limited urban space than cars. Next to the advantages for the urban traffic system, cycling has been associated with benefits for both physical (e.g. Rojas-Rueda et al., [64], Woodcock, [83] and mental (e.g. Cavill et al., [13] health of the individual citizen. Throughout most European countries, increasing the proportion of cyclists is thus considered one of the cornerstones in the strive toward a sustainable and climate-friendly mobility transition ("European Declaration on Cycling," [18]; Reichel, [62]). Despite a rise of governmental and municipal programs aimed at increasing the popularity of cycling (in Germany, for example, [10]; PTV GROUP et al., [59]), there are several barriers impairing a further development of cycling as a widely accepted and adopted mode of transportation, such as conflicts and negative attitudes between cyclists and other road user groups.

For instance, a growing body of research underlines the fact that almost all cyclists commit traffic rule violations on a regular basis, such as running red lights (e.g. Fraboni et al., [22], Johnson, [32], riding on the sidewalk

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(e.g. Lavetti & McComb, [42]; Lind et al., [45], or riding in contraflow direction (e.g. Kummeneje & Rundmo, [37,], Langford, [40]. Although cyclists' rule knowledge can be incomplete [31, 34], many cyclists are fully aware of their infringements [2]. These violations are assumed to contribute to dangerous situations and conflicts between cyclists and other road user groups, as can be derived from the noticeable proportion of crashes involving rule violations by cyclists [41, 58], as well as to contra-cycling attitudes.

At the same time, it is important to acknowledge that despite recent developments, decent and continuous cycling infrastructure is still frequently lacking outside of the most bicycle-friendly communities, and cyclists operate within a mobility (and corresponding legal) system designed primarily for the flow of motor vehicles. For example, the energy loss that a cyclist experiences when stopping at a red light is fundamentally different from that of a motorist. Cyclists' aversion to braking for a traffic sign perceived as pointless may thus be a strong motivator for rule infringing behavior. Cyclists are also frequently affected by rule violations of other road users (and drivers in particular), as is evident from the fact the drivers of motor vehicles remain the primary culpable crash partner of cyclists as well as source of severe injuries and fatalities in road traffic. From the cyclists' perspective, violating a traffic rule thus appears to be a rationale choice in situations perceived as dangerous or uncomfortable (e.g. Marshall et al., [47], Stülpnagel, [80].

Taken together, rule violating behaviors by cyclists are fervently discussed in the research community as well as in the general population. The investigation of cyclists' traffic rule violations is frequently represented as a highly relevant issue regarding their own and other road users' safety. However, it appears that the prevalence of cyclists' rule violating behavior is often treated as a relevant outcome in itself, as if the presence of a rule violation by cyclists is the determining factor in the occurrence of or culpability for a crash. Investigations are also often limited to specific traffic rules and specific traffic situations. These isolated approaches may lead to an impaired understanding of cyclists' rule violating behavior within the larger context of mostly vehicle-centered environments where cyclists are subject to traffic risks and rule violations of other road users.

Before these issues can be tackled, it appears prudent to understand what is actually known about the rule-violating behavior of cyclists. A comprehensive overview about the scientific knowledge on this matter is missing. Thus, this review summarizes the literature on traffic rule violations committed by cyclists, with the objective of providing a descriptive overview about the used methodologies, the investigated types of traffic rule violations, and the reported violation rates. It is not aimed at comparing the implications and responsibilities of cyclists' rule violating behavior to that of other road user groups. The identified literature is synthesized with regard to potential differences emerging from the comparison of different methodologies. It is also scanned for the application of theoretical models and explanations for rule-violating behavior as well as for potential countermeasures. This will provide a greater perspective about the relative relevance of specific rule violations for traffic safety, the situational contexts in which they occur, as well as potential research gaps.

2 Methodology

2.1 Protocol

The Preferred Reporting Items for Systematic Reviews and Meta-analysis Protocols extension for Scoping Review (PRISMA-ScR; [72]), a widely-used standard for conducting literature reviews, was used to enable replication of the review.

2.2 Eligibility criteria

We defined the eligibility criteria outlined below. Studies not meeting these criteria were not considered in the literature review.

We included journal articles with peer review and conference proceedings papers published before 2025. Aggregated or summarized evidence (i.e. meta studies, reviews etc.) was excluded. To ensure the accessibility of the reviewed literature, this review was limited to research published in English. Studies had to be focused on adult cyclists (according to the respective country's legislation), because legal requirements for minors frequently differ from those for adult road users. Additionally, the physiological and psychological development of minors affects their (rule-infringing) behavior in traffic. Concerning bicycle types, all bicycle that are subject to cycling-specific legislation are within the review's scope, such as standard bicycles, pedelecs (i.e. bicycles with motor-assisted pedaling, sometimes referred to as e-bikes, regulated to a max speed of 25 km/h in almost all countries), and cargo bikes. Bicycles that are subject to other legislation were excluded (e.g. motor-assisted pedelecs with a top speed of 45 km/ in Germany are prohibited to use bicycle infrastructures).

We assume that the frequency and perceived legitimacy of traffic rule violations on a global scale are highly dependent on cultural background [75] and prevalent transportation characteristics. Thus, we limited the review to studies taking place in countries of the "western world" (i.e. Europe, North America, Australia, and New Zealand). Despite national differences (e.g. cycling on the sidewalk is generally legal in Norway), many aspects of traffic systems and traffic legislation can be considered homogeneous across these countries. At the same time, they can be expected to cover a sufficient body of research. Multinational studies were included if data for eligible countries was presented separately.

Finally, we defined circumstantial criteria of the rule-violating behavior, by limiting this review to specific and spontaneous instances of traffic rule violations committable by individual cyclists in road traffic situations. "Specific" excludes research on rule violating behavior in general (e.g. items assessing a person's overall compliance with traffic rules). "Spontaneous" excludes research rule violations resulting from decisions made prior to the actual bike ride (e.g. riding without lighting during the night or under the influence of alcohol). "Individual cyclists" excludes research investigating the behavior of groups of cyclists (e.g. race bike packs). "Road traffic" excludes studies investigating, for example, rule adherence of mountain bikers in national parks.

2.3 Information sources and search strategy

We relied on Web of Science and Scopus for identifying relevant research. The search strategy was developed to capture synonyms of (A) bicycles and (B) traffic rule violations in a study's topics (i.e. within title, abstract, and keywords). It was informed by an initial inspection of central research items and refined through discussion of authors and collaborators. The query format was structured as follows:

("bicycl*" OR "bik*" OR "cyclist*")

AND

("deliberate" OR "violat*" OR "complian*" OR "infringe*" OR "illegal")[1]

2.4 Selection of sources of evidence

After importing all studies identified in the queries described above into the Covidence software[2] and the removal of duplicates, the selection process consisted of three stages: (1) Title and abstract screening, (2) Full text screening, and (3) Extraction.

In Stage 1, two separate raters independently evaluated titles and abstracts of all studies for eligibility. To standardize the eligibility criteria, research published in 2024 was first rated individually and then discussed collectively. Conflicting evaluations were resolved through discussion with the first author.

In Stage 2, studies not meeting the eligibility criteria after a full text screening by one of the two raters were excluded. Uncertainties were resolved through collective discussion.

In Stage 3, information from each paper was extracted by one rater, respectively, and confirmed by the first author.

[1] Full queries are provided in the Appendix.

[2] Covidence.org.

2.5 Data items

From all studies fulfilling the eligibility criteria, all information listed in Table 1 was extracted. Please note that the items listed under "Investigated traffic rule" were not defined a priori by the authors (other than the eligibility criteria detailed in Sect. 2.2), but reflect what was investigated in the studies.

We extracted a *violation indicator*, that is, a numerical value describing each studied violation, whenever possible. This is represented as (i) the mean of a Likert-scale item across all participants for surveys based on self-reports, behavior estimates, and judgement of others, (ii) a proportional value of the number of violations relative to the overall number of observations for observations and naturalistic cycling studies, or (iii) a proportional value of the number of crashes resulting from the respective violation relative to the total number of crashes.

3 Results

3.1 Selection of sources of evidence

Figure 1 provides a flow diagram illustrating the selection process. Two studies [22, 23] reported about the identical dataset. We thus excluded the latter publication. We identified two additional studies [43, 58] fulfilling all eligibility criteria despite missing the outlined keywords, resulting in a final set of 59 studies.

3.2 Characteristics of sources of evidence

Early studies relied mostly on observational data (see Fig. 2). Since 2013, rule violations by cyclists have attracted continuous scientific interest, and were investigated with a wider range of methodologies.

Geographically, most research on cyclists' rule violations was conducted in the US, followed by Germany and Australia (see Fig. 3).

3.3 Results of individual sources of evidence

Information about each study's main aim, geographical focus, methodology, and sample characteristics is provided in the Appendix and Supplementary Material 1.

3.4 Synthesis of results

We look at the five most frequently researched rule violations in greater detail, before summarizing the findings on less investigated rule violations.

3.4.1 Red light violations

Red light violations were investigated in 41 of the 59 studies, making it the by far most frequently analyzed traffic rule violation. Observation and self-reported behavior are the most prevalent methodologies. Table 2 groups the respective studies by methodology and in ascending order of the violation indicator.

Table 1 Data items extracted from eligible sources

Data item	Sub-category	Definition/Example
Publication outlet and year		
Geographical focus		The country in which the data was collected or observed.
Main aim of the study		
Applied Methodology	Crash data	Analysis of crashes involving cyclists obtained from police or hospital records.
	Observation	Rule violations counted by in-situ observers or based on video-recordings.
	Naturalistic study	Longitudinal video recordings from a device installed on a bike used by an individual cyclist over an extended period of time.
	Self-reported behavior	Surveys asking participants to estimate the frequency they commit specific rule violations.
	Behavior estimate	Surveys asking participants to estimate the likelihood they would commit rule violations in hypothetical or presented situation.
	Judgement of others	Surveys assessing participants' estimates or opinions about the rule violating behavior of other cyclists.
Investigated traffic rule	Illegal riding on vehicle lane	Riding on a vehicle lane despite legally mandatory use of, for example, a bike track.
	Illegal riding on sidewalk	Riding on a sidewalk reserved for pedestrians, despite legally mandatory use of, for example, a bike track.
	Riding against the direction of traffic	Illegally riding in contraflow direction, either on the vehicle lane or on a bike lane/track.
	Red light violation	
	Failure to obey traffic signs	e.g. not coming to a complete stop at stop signs or zebra crossings
	Failure to indicate turn via hand signal	
	Failure to yield	e.g. to pedestrians traveling straight when turning right at an intersection
	Taking an illegal turn	e.g. turning left when a left turn is prohibited
	Illegal crossing of railway crossing	
	Close overtaking/cutting of another road user	
	Speeding	Estimates of inadequate or unsafe travelling speed (rather than riding in excess of official speed limits).
	Phone use	e.g. receiving or making a phone call, sending text messages, or checking for information

The reported prevalence of red-light violations differs drastically between and within studies and methodologies. In observation studies, the lower end of the violation rates stands at about 3% (e.g. Detzer et al., [16], Kassim, [35], Lange, [39]. On the other end of the spectrum, studies report violation rates of over 40% to up to 98% (e.g. Fabbri & Hoeppner, [19,], Fraboni, [23,], Goodno, [24,], Lange, [38]. The three papers featuring naturalistic cycling studies show a similar spectrum with low (3%, [52]), medium (16.3%, [67]), and high (> 70%, [40]) violation rates. In sum, red light violations appear to be a frequently committed rule violation by cyclists in the best cases, and the de-facto norm in the worst cases.

The observed violation rates stand in stark contrast to assessments of self-reported behavior. The mean values of many studies using Likert scales indicate that participants report to commit red-light violations "never" to "hardly ever" (e.g. Bishop et al., [8], McIlroy, [48] or "sometimes" [54, 56, 60]. In other words, the (often high) observed frequency of red-light violations is poorly aligned with the (low) self-reported violation frequency. However, two studies assessing participants' judgement of other cyclists rather than their own behavior converge on the assumption that other cyclists violate red lights more frequently than oneself [63, 76].

Concerning crash statistics, three studies show converging proportions with 3.3–3.9% of all crashes between cyclists and a motorized vehicle resulting from a red light violation of the cyclist [27, 41, 58][3]. A fourth study reports a higher proportion of 5.5% for cyclists wearing helmets, which raises to 12.6% for cyclists not wearing helmets ([81]; with a corresponding trend reported by [41]). Additional, indirect evidence for safety-related relevance comes from observational studies: Despite a noticeable proportion of red-light infringements in their naturalistic cycling study, Schleinitz et al., [67] state that they did not observe a single conflict. Brezina and Hildebrandt, [11] identified a single conflict in 1,124 observed red light violations (equaling 0.1%).

[3] The proportions reported in Prati et al., [58] and Haworth and Debnath [27] encompass crashes resulting from cyclists running red lights and disobeying stop signs. Thus, the true proportion of crashes resulting from red light violation is lower than the reported value.

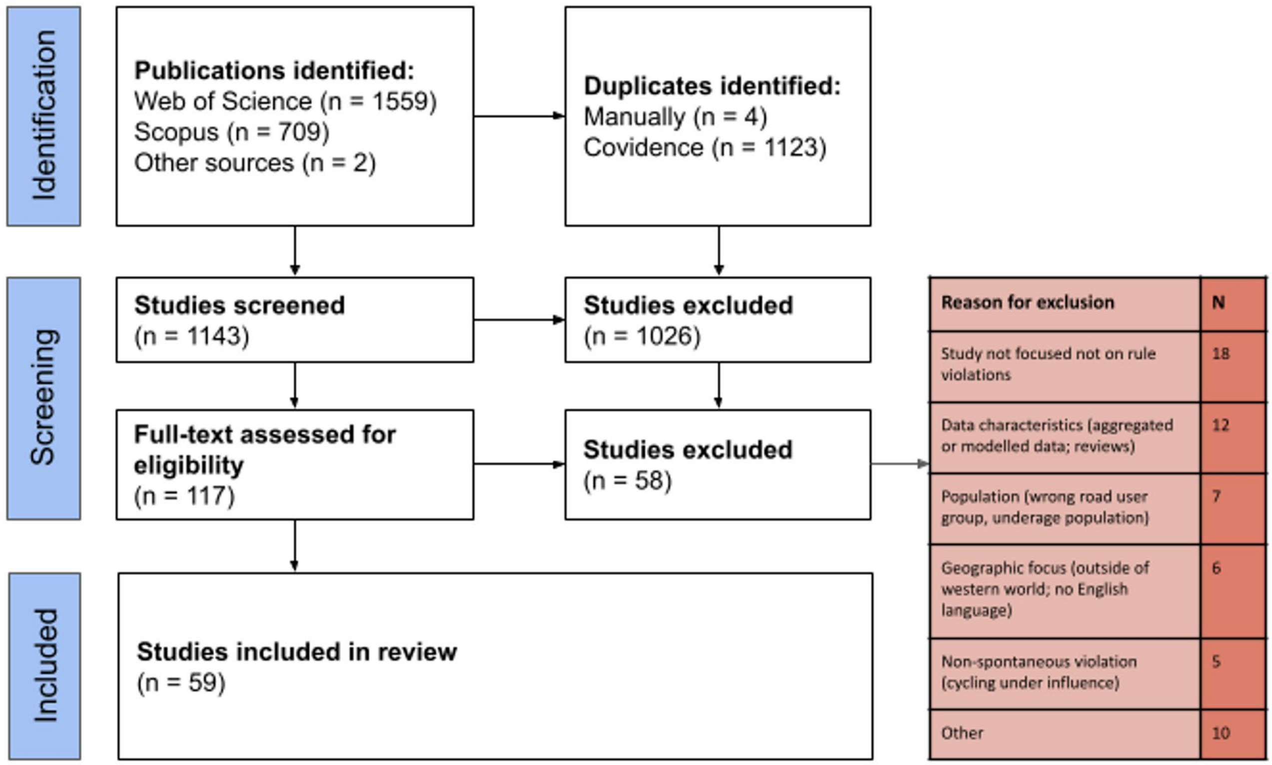

Fig. 1 Prisma Flow diagram illustrating the selection process

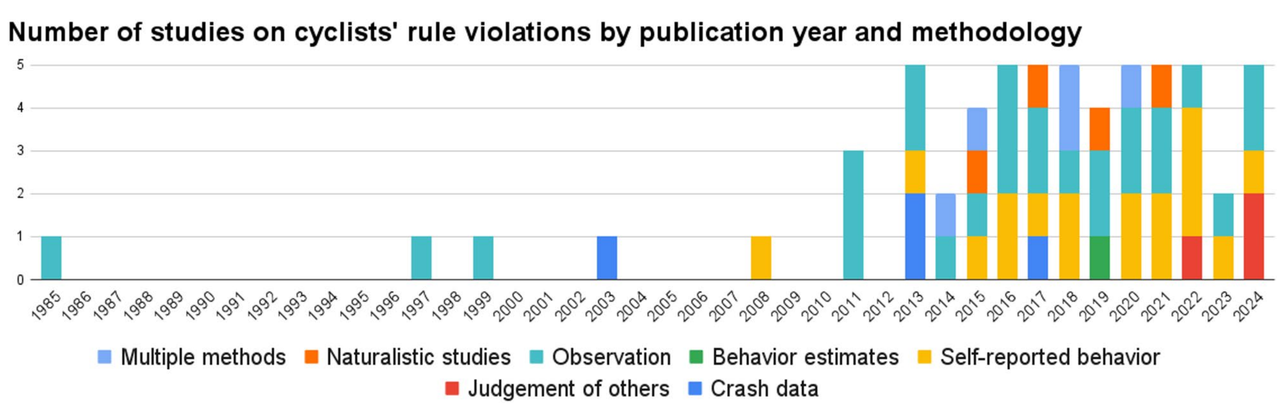

Fig. 2 Number of studies by publication year and methodology

The closer inspection of the studies revealed several topics that appear to affect the proportion of red-light violations. These are presented below.

3.4.1.1 Red-light violations and evasions of cyclists turning right Several studies report that cyclists are much more likely to run red lights when turning right (in right-hand traffic), attributing this to the reduced number of potential points of conflict ([32, 33]; Lind et al., [45]; [67, 68]). Two studies observed that cyclist circumvented red traffic lights by evasion on the sidewalk in about 5% of the cases (Lind et al., [45]; [67])[4]. Schröter et al., [68] found a significantly higher evasion rate to the sidewalk (32%) for cyclists making a right turn.

Some countries have introduced traffic legislation allowing cyclist to turn right on red. Schleinitz et al., [67] distinguished between standard traffic lights and those featuring an additional green arrow, which allows cyclists in Germany to turn right at red, but only after coming to a complete stop. Schleinitz et al., [67] find that 81% of the observed cases, cyclists failed to stop completely.

[4] As an immediate response to a red traffic light, and not an instance of sidewalk cycling in itself, which is addressed further below.

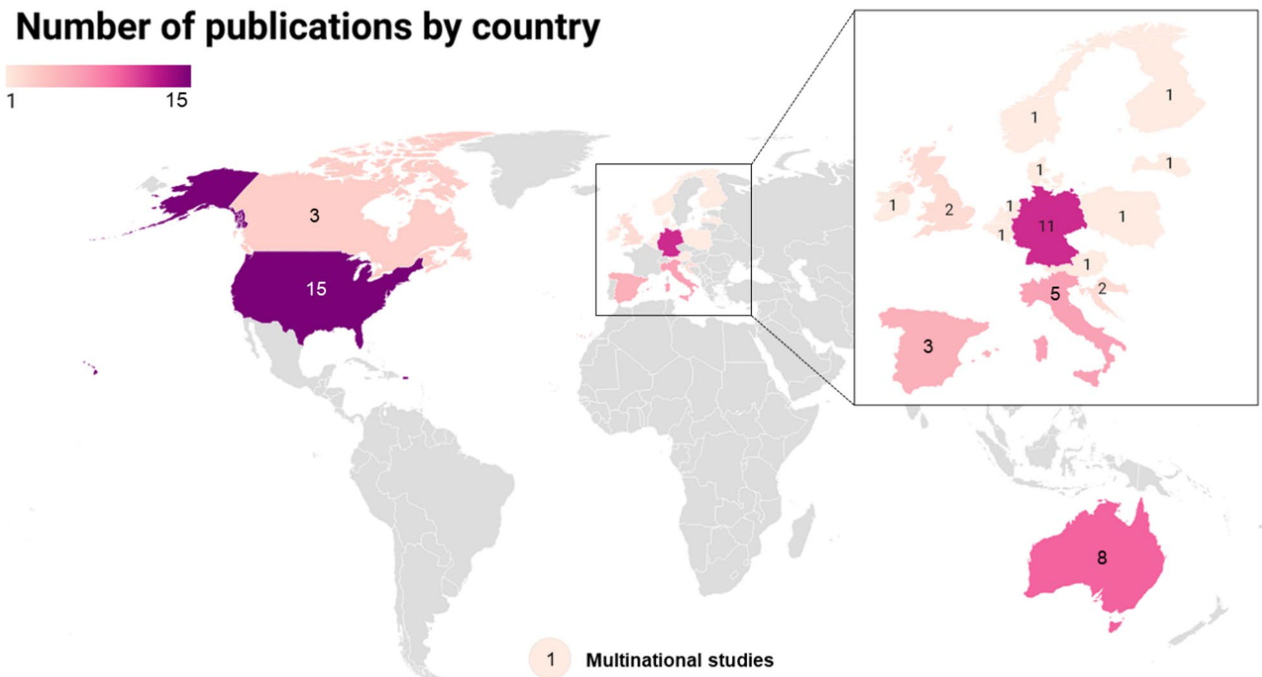

Fig. 3 Overview about the geographical distribution of studies

Schröter et al., [68] found that few cyclists observed the legal requirement to come to a complete stop in these situations, but that overall, pedestrians appear to benefit from this regulation.

3.4.1.2 Bicycle signals Baumanis et al., [5] report that participants expect that cyclists are less likely to run red lights if a dedicated bicycle signal is present, and also claim to observe fewer cyclists running red lights at intersections with (as compared to intersections without) dedicated bicycle signals (with observational evidence by [12], supporting this assumption). An active feedback device at intersection featuring a bicycle signal was not found to affect the red light violation rate [9]. Brezina and Hildebrandt, [11] found that the probability of red-light violations at traffic lights featuring push buttons for cyclists was six times higher than at a normal traffic light. They also conclude that red light phases exceeding 60 s lead to a 2.7 times higher probability of a violation as compared to shorter red-light phases.

Two studies by Lange [38, 39] indicate that at intersections featuring consecutive traffic signals (e.g. one traffic light for a right-turn lane and a second traffic light for the other lanes), red light violations increase significantly during inconsistent phases. In other words, if the first traffic signal shows green, cyclists are much more likely to violate a consecutive red light.

3.4.1.3 Intersection design and cycling infrastructure Lind et al., [45] concludes that violation rates are more probable at more complex intersections (also see [67]). However, not every dedicated cycling infrastructure was found to reduce red light violations. The presence of a bike box (i.e. an area allowing cyclists to position themselves immediately in front of the traffic lights and in front of the cars) led to an increase of red light violations from 7% to 20%, possibly due to the better view of crossing traffic [46]. In contrast, Casello et al., [12] report that a bike box increased the proportion of cyclists remaining on the road for a left turn (rather than to illegally use the pedestrian crossing), but only if a dedicated bicycle signal was present as well. Richardson and Caulfield, [63] found that the violation rate on a bicycle lane with a regular signal was significantly lower (19%) as compared to that on a cycling track with a bicycle signal (97%, and see [68], for similar numbers for cyclists turning right on bicycle tracks). Schleinitz et al., [67] report higher violation rates for cyclists riding on bicycle infrastructures as compared to when riding on the carriageway.

3.4.1.4 Social influence The presence of other cyclists and children in particular has been found to lead to a significant reduction of red light violations (see for example [19]: from 68% in the absence of others to 30% and below 8% in the presence of adults and adults and children, respectively; [23]: from 72% in the absence of other cyclists to 27% in the presence of one or more cyclists; and [32, 33], for further evidence).

Table 2 Studies concerned with red light violations, grouped by methodology and in ascending order of the violation indicator

#	Study	Violation indicator
Observation		
1.	Lange et al., [39]	2.6–83.6%
2.	Detzer et al., [16]	3%
3.	Kassim et al., [35]	3%
4.	Loskorn et al., [46]	5–20%
5.	Johnson et al., [33]	6.9%
6.	Szczuraszek & Klusek, [71]	7%
7.	Boudart et al., [9]	7.5%
8.	Lange et al., [38]	7.6–98%
9.	(Lind et al., [45])	11.6%
10.	Schröter et al., [68]	12–48%
11.	Micucci & Sangermano, [50]	19–28%
12.	Twaddle & Busch, [74]	19.8%
13.	Trinkaus, [73]	31%
14.	Brezina & Hildebrandt, [11]	35.8%
15.	Goodno et al., [24]	> 40%
16.	Fraboni et al., [23]	> 60%
Self-reported behavior		
17.	Bishop et al., [8]	0–4 scale: M = 0.49 (SD = 0.70)
18.	McIlroy et al., [48]	0–4 scale: M = 0.67 (SD = 0.92)
19.	Li et al., [44]	0–4 scale: M = 0.84 (SD = 1.04)
20.	Useche et al., [77]	0–4 scale: M = 1.09 (SD = 0.81)
21.	Volgemute et al., [79]	0–4 scale: M = 1.34 (SD = 1.22)
22.	O'Hern et al., [56]	0–4 scale: M = 1.83 (SD = 1.18)
23.	O'Hern et al., [54]	0–4 scale: M = 1.88 (SD = 0.83)
24.	Angelis et al., [15]	1–5 scale: M = 1.35 (SD = 0.61)
25.	Puchades et al., [60]	1–5 scale: M = 2.37 (SD = 1.14)
26.	O'Hern et al., [55]	1–6 scale: M = 1.93 (SD = 1.18)
27.	Kummeneje & Rundmo, [37]	1–5 scale own behavior: 22% (occasionally-often) 1–5 scale: acceptable behavior: 41%
28.	Bernhoft & Carstensen, [7]	Not "Never": 30%
29.	Johnson et al., [32]	37.3%
30.	Shaw et al., [69]	38% (Left turn: 2.9%; pedestrian crossing 4.6%)
Crash data		
31.	Lardelli-Claret et al., [41]	3.3% of all crashes
32.	Prati et al., [58]	3.3% of all crashes, including disobeyed stop signs
33.	Haworth & Debnath, [27]	3.9% of all crashes, including disobeyed stop signs
34.	Webman et al., [81]	5.5/12.6% (with/without helmets)
Naturalistic studies		
35.	Nygårdhs, [52]	3%
36.	Schleinitz et al., [67]	16.3%
37.	Langford et al., [40]	> 75%
Judgement of others		
38.	Useche et al., [76]	0–4 scale: M = 2.20 (SD = 1.12)
39.	Baumanis et al., [5]	-
Multiple methodologies		
40.	Fabbri & Hoeppner, [19]	Self-reported behavior estimate (nobody present): 68%; Observation: 68%
41.	Richardson & Caulfield, [63]	Observation: 19–97% Self-reported behavior: 52% occasionally/frequently/always Judgement of others: 85% occasionally/frequently/always

3.4.2 Riding against the direction of travel

Twenty-seven studies investigating cyclists riding against the direction of travel, with about half of them making use of self-reported behavior (see Table 3).

According to mean values reported in these studies, participants report to ride against the direction of travel "never" or "hardly ever" (e.g. Bishop et al., [8], Li, [44], McIlroy, [48]. However, the majority or even all participants admit that they violated this rule at some point in their lives [7, 29], and a high proportion reports to do so at least sometimes [37, 60].

Table 3 Studies concerned with travelling against the direction of travel, grouped by methodology and in ascending order of the violation indicator

#	Study	Violation indicator
Self-reported behavior		
1.	McIlroy et al., [48]	0–4 scale: M = 0.24 (SD = 0.52)
2.	Bishop et al., [8]	0–4 scale: M = 0.49 (SD = 0.66)
3.	Li et al., [44]	0–4 scale: M = 0.53 (SD = 0.91)
4.	O'Hern et al., [56]	0–4 scale: M = 0.56 (SD = 0.78)
5.	Useche et al., [77]	0–4 scale: M = 1.02 (SD = 0.86)
6.	Volgemute et al., [79]	0–4 scale: M = 1.03 (SD = 1.11)
7.	O'Hern et al., [54]	0–4 scale: M = 1.43 (SD = 0.70)
8.	Puchades et al., [60]	1–5 scale: M = 2.82 (SD = 1.00)
9.	Kummeneje & Rundmo, [37]	1–5 scale: own behavior: 32% (occasionally-often)
10.	O'Hern et al., [55]	1–6 scale: M = 1.92 (SD = 1.22)
11.	Shaw et al., [69]	Wrong way on one-way street: 6.9%; against direction: 1.7%
12.	Bernhoft & Carstensen, [7]	Not "Never": 40%
13.	Huemer, [29]	100% (did commit violation in their life)
Observation		
14.	Twaddle & Busch, [74]	1.3%
15.	Micucci & Sangermano, [50]	4–11%
16.	Huemer et al., [30]	4.4%
17.	Detzer et al., [16]	6%
18.	Leschik et al., [43]	12% (0% crashes during observation)
Crash data		
19.	Webman et al., [81]	2.8/12.3% (with/without helmets)
20.	Lardelli-Claret et al., [41]	3.33% of all crashes
21.	Prati et al., [58]	7.3% of all crashes
Naturalistic studies		
22.	Hamann & Peek-Asa, [26]	0%
23.	Langford et al., [40]	> 40%
Judgement of others		
24.	Anke et al., [3]	1–6 scale: M dispositional/situational = 4.2/2.1 (SD = 1.3/1.4)
25.	Useche et al., [76]	0–4 scale: M = 1.92 (SD = 0.99)
Behavior estimate		
26.	Chaloux & El-Geneidy, [14]	9–16%
Multiple methodologies		
27.	(Lavetti & McComb, [42])	Observation: 100%; Self-reported behavior: 25%; 0% collisions; 4% near misses with motorized vehicles

Corresponding to these self-reports, the observed violation rate is frequently reported to be below 6% [16, 30, 74], and mostly below 12% [43, 50]. A single study reports a very high violation rate of 100% (Lavetti & McComb, [42]). Two naturalistic cycling studies show highly diverging trends with 0% violations [26] and a > 40% violation rate, respectively [40]. Two observation studies did not observe any collisions (Lavetti & McComb, [42]; [43]), but near misses with both pedestrians and motorized vehicles (Lavetti & McComb, [42]).

Concerning more detailed investigations, Leschik et al., [43] reports that cyclists riding against the direction of travel on a bicycle track avoided conflicts with cyclists travelling in the intended direction by evading to the pedestrian lane in 14% of the cases (but were much more likely to ride on the pedestrian lane in any case).

Three studies investigate crashes resulting from cyclists riding against the direction of travel: Lardelli-Claret et al., [41] report 3.3% of crashes involving this violation, Webman et al., [81] report 2.8% and 12.3% for cyclists with and without helmet, respectively, and Prati et al., [58] report 7.3% of crashes involving riding against the direction of travel.

Taken together, the violation rates for riding against the direction of travel (both for observational and self-report studies) appear to be lower as compared to red light violation rates. At the same time, the proportion of crashes resulting from cyclists riding against the direction of travel are similar to those resulting from red light violations in two studies [41, 81], and noticeably higher in the third study [58]. Although such a comparison across studies must remain highly tentative, this may be a hint that riding against the direction of travel poses a crash risk for cyclists which is relatively larger as compared to running a red light.

3.4.3 Failure to obey a traffic sign

Of the nineteen studies investigating cyclists' failure to obey traffic signs (mostly stop signs, but also zebra crossings), 53% assessed self-reported behavior (see Table 4).

Most self-report studies report that cyclists report to "never" or "hardly ever" fail to obey traffic signs (e.g. McIlroy et al., [48], O'Hern, [56]. The mean values for self-reported disobeying stop signs are consistently lower as compared to disobeying right-of-way at zebra crossings. However, Piatkowski et al., [57] report that many cyclists indicate to fail observing traffic signs occasionally or even frequently, and according to Chaloux and El-Geneidy [14], they estimate that they would so in a high proportion of cases. The latter findings are more in line with observational studies: All three studies using

Table 4 Studies concerned with failures to obey a traffic sign, grouped by methodology and in ascending order of the violation indicator

#	Study	Violation indicator
Self-reported behavior		
1.	McIlroy et al., [48]	Stop sign: 0–4 scale: M = 0.12 (SD = 0.34) Zebra crossing; 0–4 scale: M = 0.33 (SD = 0.57)
2.	O'Hern et al., [56]	Stop sign; 0–4 scale: M = 0.13 (SD = 0.44) Zebra crossing; 0–4 scale: M = 0.56 (SD = 0.67)
3.	Bishop et al., [8]	Stop sign; 0–4 scale: M = 0.26 (SD = 0.46)
4.	Li et al., [44]	Stop sign: 0–4 scale: M = 0.32 (SD = 0.73) Zebra crossing; 0–4 scale: M = 0.50 (SD = 0.85)
5.	Useche et al., [77]	Stop sign; 0–4 scale: M = 0.35 (SD = 0.55) Zebra crossing; 0–4 scale: M = 1.00 (SD = 0.57)
6.	O'Hern et al., [54]	Stop sign; 0–4 scale: M = 1.30 (SD = 0.58) Zebra crossing; 0–4 scale: M = 1.33 (SD = 0.57)
7.	O'Hern et al., [55]	Zebra crossing; 1–6 scale: M = 1.48 (SD = 0.92)
8.	Shaw et al., [69]	Stop sign: 4.6%
9.	Piatkowski et al., [57]	Stop sign: "Occasionally": 40%; "Most of the time" to "All the time": 36.4%
Observation		
10.	Farris et al., [20]	Stop sign: 86%
11.	DeVeauuse et al., [17]	Zebra crossing: 100%; Stop sign: 98.2%
Crash data		
12.	Prati et al., [58]	3.3% of all crashes, including disobeyed traffic lights
13.	Haworth & Debnath, [27]	3.9% of all crashes, including disobeyed traffic lights
14.	Lardelli-Claret et al., [41]	Stop sign: 4.1% of all crashes Yield sign: 2.1% of all crashes Other signs or police instruction: 0.4% 0.6% of all crashes Zebra crossing: 0.6% of all crashes
Naturalistic studies		
15.	Hamann & Peek-Asa, [26]	Stop sign:19.4 per 100 miles
16.	Langford et al., [40]	Stop sign; low speed: 80% Stop sign; high speed: >20%
Judgement of others		
17.	Useche et al., [76]	Stop sign; 0–4 scale: M = 2.07 (SD = 1.14) Zebra crossing; 0–4 scale: M = 1.68 (SD = 1.03)
Behavior estimate		
18.	Chaloux & El-Geneidy, [14]	Stop sign: 84–99%
Multiple methodologies		
19.	(Lavetti & McComb, [42])	Self-reported behavior: 50%: Observation: 96%; 0% collisions; 4% near misses with motorized vehicles

observational data converge on violation rates of 86% or higher ([17, 20]; Lavetti & McComb, [42]), with corresponding findings from naturalistic cycling studies [26, 40].

Finally, the proportion of crashes resulting from cyclists disobeying stop signs are between 3.3% and 4.1% (with the percentages reported by [27, 58], including red-light violations; and 0.6% being additionally associated with zebra crossings by [41]). Tentatively comparing studies, cyclists' failures to obey a traffic sign thus seem to be present in a similar proportion of crashes as other rule violations.

Although many cyclists are observed to fail to come to a complete stop at stop signs, a high proportion is found to reduce their speed significantly [17, 26, 40]. Thus, cyclists may appear to mitigate potential risks resulting from their infringement by adapting their riding behavior.

The mismatch between self-reported and observed frequencies might be interpreted as cyclists either not to realizing or not to admitting that they disobey stop signs as frequently as is frequently observed elsewhere. Comparing cyclists' high frequency of violations in observational studies and the reported risk-mitigating riding behavior on the one hand, and the average proportion of crashes linked to this behavior on the other hand, it could be suspected that failures to obey a traffic sign are not necessarily increasing cyclists' crash risk.

3.4.4 Failure to yield

Seventeen studies investigate cyclists' failure to yield to either pedestrians or motor vehicles (see Table 5).

Table 5 Studies concerned with failures to yield, grouped by methodology and in ascending order of the violation indicator

#	Study	Violation indicator
Self-reported behavior		
1.	O'Hern et al., [56]	0–4 scale; to pedestrians: M = 0.27 (SD = 0.61); to vehicles: M = 0.20 (SD = 0.52)
2.	McIlroy et al., [48]	0–4 scale; to pedestrians: M = 0.29 (SD = 0.51); to vehicles: M = 0.21 (SD = 0.50)
3.	Li et al., [44]	0–4 scale; to pedestrians: M = 0.39 (SD = 0.77); to vehicles: M = 0.39 (SD = 0.79)
4.	Useche et al., [77]	0–4 scale; to pedestrians: M = 0.58 (SD = 0.58); to vehicles: M = 0.34 (SD = 0.52)
5.	Bishop et al., [8]	0–4 scale; to pedestrians: M = 0.59 (SD = 0.71)
6.	Volgemute et al., [79]	0–4 scale; to vehicles: M = 0.83 (SD = 0.88)
7.	O'Hern et al., [54]	0–4 scale; to pedestrians: M = 1.37 (SD = 0.56); to vehicles: M = 1.25 (SD = 0.50)
8.	Angelis et al., [15]	1–5 scale; to pedestrians: M = 1.53 (SD = 0.73)
9.	Puchades et al., [60]	1–5 scale; to pedestrians: M = 2.02 (SD = 1.02)
Crash data		
10.	Lardelli-Claret et al., [41]	3.9% of all crashes
11.	Prati et al., [58]	4.3% of all crashes
12.	Haworth & Debnath, [27]	5.8% of all crashes
Observation		
13.	Detzer et al., [16]	1%
14.	(Lavetti & McComb, [42])	Observation: 100%; 0% collisions; 4% near misses with motorized vehicles
Judgement of others		
15.	Useche et al., [76]	0–4 scale; to pedestrians: M = 1.83 (SD = 1.09); to vehicles: M = 1.68 (SD = 1.08)
16.	Anke et al., [3]	1–6 scale: M dispositional/situational = 4.2/1.7 (SD = 1.4/0.9)
Naturalistic studies		
17.	Hamann & Peek-Asa, [26]	10 per 100 miles

About half of the studies assessed self-reported behavior with the CBQ. They converge on mean values indicating that cyclists report to "never" or "hardly ever" fail to yield to other road user groups (e.g. McIlroy et al., [48,], O'Hern, [56]. The CBQ assesses failures to yield to pedestrians and motor vehicles with two separate items. All but one study find descriptively larger values for failures to yield to pedestrians as compared to failures to yield to motor vehicles ([48, 54, 56, 77]; with [44], reporting equivalent mean values). This discrepancy might be interpreted as caused by the greater anticipated personal harm of colliding with a motor vehicle rather than a pedestrian. One study assessing the judgement of other cyclists' behavior with the CBQ [76] reports noticeably higher values as compared to those assessing cyclists' self-reported failures to yield.

Table 6 Studies concerned with speeding, grouped by methodology and in ascending order of the violation indicator

#	Study	Violation indicator
Self-reported behavior		
1.	McIlroy et al., [48]	0–4 scale: M = 0.77 (SD = 0.83)
2.	O'Hern et al., [56]	0–4 scale: M = 0.82 (SD = 0.93)
3.	Li et al., [44]	0–4 scale: M = 0.91 (SD = 0.86)
4.	Bishop et al., [8]	0–4 scale: M = 0.99 (SD = 0.77)
5.	Useche et al., [77]	0–4 scale: M = 1.09 (SD = 0.86)
6.	Volgemute et al., [79]	0–4 scale: M = 1.27 (SD = 1.22)
7.	O'Hern et al., [54]	0–4 scale: M = 2.06 (SD = 0.83)
8.	Shaw et al., [69]	0.3%
9.	(Lavetti & McComb, [42])	63%
Crash data		
10.	Haworth & Debnath, [27]	0%
11.	Lardelli-Claret et al., [41]	Only speeding: 0.5%; Speeding + other violation: 4%
12.	Prati et al., [58]	1.7% of all crashes
Judgement of others		
13.	Useche et al., [76]	0–4 scale: M = 1.98 (SD = 1.12)

In contrast to the low values from self-reports, the proportion of crashes involving cyclists' failures to yield is descriptively higher than that involving red-light infringements in all three respective studies (i.e. Haworth & Debnath, [27], Lardelli-Claret, [41], Prati, [58], and see Table 2 for comparison). This contrast derives at least two hypotheses to be tested: (1) cyclists might dramatically underreport their failures to yield, or (2) the crash risk involving his behavior is significantly higher as compared to crashes involving other types of cyclists' rule violations. Observational data would be very informative in this regard. Curiously, one of the two studies using observational methods reports almost no failures to yield ([16]: 1%), whereas the other reports the complete opposite (Lavetti & McComb, [42]: 100%).

3.4.5 Speeding

Thirteen studies reported about speeding of cyclists, mostly assessed via self-reports (see Table 6). It should be noted that speeding violations by cyclists are mostly defined by estimates of "inadequate" or "unsafe" travelling speeds (even in crash data), rather than by exceeding an objective speed limit. This may also be the reason for the complete absence of observational studies on speeding violations.

Mean values for frequencies of self-reported speeding are higher as compared to those for failures to yield or failures to obey traffic signs, but are mostly clustered at a level indicating that cyclists report to "hardly ever" speed excessively (e.g. Bishop et al., [8], Li, [44]. However, one study reports that about two-third of the participants report to be engaged in speeding (Lavetti & McComb, [42]). As with the other types of rule violations, if

Table 7 Studies concerned with other types of rule violations, grouped by methodology and in alphabetical author order

#	Study	Illegal riding on sidewalk	Illegal railway crossing	Phone use	Illegal riding on vehicle lane	No hand signal indicating turn	Close overtaking	Illegal turn
	Observation							
1.	Barić et al., [4]		22.6%					
2.	Casello et al., [12]							- [a]
3.	Farris et al., [20]					1%		
4.	Grabušić & Barić, [25]		100%					
5.	Huemer et al., [30]	2.4%		0.9% [b]	0.9%			
6.	Khattak & Luo, [36]		- [a]					
7. hu	Leschik et al., [43]	Up to 65% [g]						
8.	(Lind et al., [45])							- [a]
9.	Russo et al., [65]		3.5%/89.9% [c]					
10.	Twaddle & Busch, [74]	5.1%/3.4% [d]			1.8%			
11.	Zheng et al., [84]	32% [e]						
	Self-reported behavior							
12.	Beanland et al., [6]		4% [f]					
13.	Bernhoft & Carstensen, [7]	Not never: <50%						
14.	Angelis et al., [15], 1–5 scale			M = 1.41–1.96 (SD = 0.80–0.97) [g]				
15.	Kummeneje & Rundmo, [37]			7% [h]				
16.	(Lavetti & McComb, [42])	100%				100%	63%	71%
17.	Mulvihill et al., [51]		7%					
18.	O'Hern et al., [55], 1–6 scale	M = 3.23 (SD = 1.35)		M = 1.68 (SD = 1.08)		M = 3.01 (SD = 1.17)		
19.	Piatkowski et al., [57]			2.5% [i]				
20.	Puchades et al., [60], 1–5 scale			M = 1.93 (SD = 0.98) [j]	M = 2.32 (SD = 1.12)			
21.	Shaw et al., [69]	65%			8.1%	0.9%		1.0%
	Crash data							
22.	Lardelli-Claret et al., [41]				3.4%	0.5%	2.1%	6.0%
23.	Prati et al., [58]						2.9%	
	Judging others							
24.	Anke et al., [3], 1–6 scale						4.0/2.0[h]	
	Behavior estimate							
25.	Chaloux & El-Geneidy, [14]	< 2%		1–4%				
	Naturalistic							
26.	Schleinitz et al., [67]		21.4%					

Note. [a] Not computable due to lack of base rate; [b] Using phone on ear: 0.1%; Using phone in hand: 0.8%; [c] Before trail arrival/after train departure; [d] No bike lane/bike lane available; [e] Shared path with separator line; [f]Across drivers/motorcyclists/cyclists without significant difference; [g]Across five different items: (1) looking for information, (2) sending text message, (3) reading text message, (4) responding to a call, (5) calling someone; [h] "Occasionally" to "often"; [i] Occasionally", "Most of the time, and "all the time"; [j] "Answering a call"; [k] Dispositional/situational attribution

the behavior of other cyclists is assessed, speeding is observed "sometimes" rather than "hardly ever" [76].

Speeding in itself also appears to be no major contributor to cycling-related crashes [27, 58], although it may be linked to other types of rule violations [41].

3.4.6 Other types of rule violations

Information about rule violations investigated in a smaller number of studies are summarized in Table 7 and the following paragraphs. Please note that interpretations are limited by the low number of studies.

3.4.6.1 Illegal riding on sidewalk Illegal riding on sidewalk is investigated in nine studies[5]. Many cyclists report to illegally ride on the sidewalk at least occasionally ([7]; Lavetti & McComb, [42, 55, 69]). This is in line with the observational data from two studies [43, 84], whereas two other studies find much lower violation rates [30, 74]. Interestingly, very few bicyclists report that they would evade to the sidewalk based on images shown to them [14]. We did not identify crash data concerning cyclists

[5] Illegal riding on the sidewalk as an attempt of evading red lights is described in Sect. 3.4.1.1.

riding on a sidewalk. We suspect that cyclists-pedestrian crashes are underrepresented in crash statistics of the police.

3.4.6.2 Illegal railway crossing Illegal railway crossing is investigated in seven studies (four of them observation studies, two self-report studies, one naturalistic study), with violation rates ranging from below 4% [6, 65] to 90% and higher [25, 65]. Investigated factors are, for example, whether the train is arriving or has departed [65] and the type of warning signals [6, 65], and waiting times [4, 6].

3.4.6.3 Phone use Phone use is investigated in seven studies. On average, people report that they use their phones rarely to occasionally when riding a bike [14, 15, 55, 60], with a low percentage reporting to do so occasionally or even often [37, 57]. This is in line with the single observational study, which also finds a low infringement rate [30]. Violation rates differ depending on how the phone is used [15, 30].

3.4.6.4 Illegal riding on a vehicle lane Illegal riding on a vehicle lane is investigated in five studies. Puchades et al., [60] report that their participants reported to ride on the vehicle lane at least occasionally (also see [69]). The two studies relying on observational data, however, report rather low violation rates of 0.9% [30] and 1.8% [74], respectively. Given the low observed rate, the proportion of crashes involving illegal riding on a vehicle lane is at a remarkably high at 3.4% [41].

3.4.6.5 No hand signal indicating turns No hand signal indicating turns is investigated in five studies. Although cyclists report to commit this violation occasionally or even frequently in two studies (Lavetti & McComb, [42]; [55]), they indicate to do so quite rarely according to another study [69]. The single study using observational data finds a very low incidence rate [20], and few crashes are linked to a violation of this rule [41].

3.4.6.6 Close overtaking Close overtaking is investigated in four studies. According to Lavetti & McComb [42], this is a violation many cyclists report to commit. It is attributed to dispositional rather than to situational factors [3]. It is linked to a comparatively low but still noticeable number of cycling-related crashes [41, 58].

3.4.6.7 Illegal turns Illegal turns are investigated in three studies. One study finds a high proportion of their participants admitting to perform illegal turns (Lavetti & McComb, [42]), whereas very few participants in another study report to do so [69]. A surprisingly high proportion of cycling-related crashes involve incorrect turns [41]. Two studies approaching this matter discuss the intersection layout as a factor for more, or less, compliant behavior ([12]; Lind et al., [45]). However, it was no possible to extract unambiguous values for infringement rates from these studies.

4 Discussion

In a scoping literature review, we identified and analyzed 59 studies concerned with traffic rule violations by cyclists. The review shows that even within one type of traffic violation and one methodology, the reported violation rates frequently diverge greatly. We identified several key issues deserving further attention.

4.1 An over-prevalence of research on red-light violations

About two third of all reviewed studies were (at least partly) concerned with red light violations. Clearly, red-light violations represent an infringement of traffic legislation, with a theoretically high conflict potential. However, several authors conclude that cyclists running red lights do so with ample consideration for the situation and the safety of their behavior [33, 52, 67]. One study even found a lower probability for red light violations near cycling crash hotspots [11]. In contrast to the often high infringement rates found in observation studies (see Sect. 3.4.1 and Table 2), there is little evidence that cyclists' red light infringements are a particularly prominent feature in crash statistics. In comparison, the respective proportions of crashes involving riding against the direction of travel or failures to yield (both addressed in a much lower number of studies) are similar or even higher than that involving red-light violations. At the same time, the observed frequency appears to be lower for riding against the direction of travel, and inconclusive for failures to yield as compared to red-light violations. With respect to crash risk, it may thus be suspected that riding against the direction of travel or failures to yield may be more relevant than red-light violations. This is not to say that cyclists should be exempted from obeying traffic lights, but based on the available data, the emphasis on this particular rule violation appears not fully justified.

4.2 A need for cross-methodological evaluation

The questions raised in the last section point towards another challenge. Understandably, almost all studies rely on a single methodology, which each coming with different strengths and limitations. Studies relying on observation provide valid data on rule violation types that are comparatively easy and unambiguously to record. They may offer insights into the proportions of cyclists violating traffic rules and circumstances affecting these violations. However, this approach provides no information about cyclists' motivation for infringing the respective rule. Naturalistic cycling studies collecting longitudinal data provide detailed insights into the behavior of individual cyclists. However, the data collection and preparation is highly time-consuming, thus limiting the sample size of the respective studies. They also do not provide robust information about violation prevalence. Surveys can assess large samples for a wide range of rule violations (with the CBQ developed by [75], being the most commonly used one) but do not give information on circumstances of violations an may be biased by individual understandings of the ratings scales for frequencies. Finally, crash data provide insights into the proportion crashes involving a specific rule violation relative to other rule violations. On the downside, this information is of limited value because the base rate of the infringing behavior is unknown.

This review points towards discrepancies between studies investigating the same traffic violation (e.g. failures to yield, illegal turns) with different methodologies. This may be interpreted as violation types where the crash risk may be underestimated by the cyclists committing them. But at the other side, it appears highly plausible that the different data sources are subject to specific biases. Self-reports about infringing behavior are prone to biases by memory failures, self-serving attribution, and optimistic estimates of the participants (which is evident from the difference between estimates of own and other's behavior reported by, for examples, [63, 76]), thus potentially underestimating the true prevalence of rule violations. Observational data are frequently limited to specifically selected locations, the selection being biased by assumed infringement potential, thus potentially overestimating the true frequency of rule violations. Finally, crash data linked to a specific rule violation are yet mostly mute to the base rate of cyclists' committing this violation, and information about minor crashes without injuries or crashes between cyclists and pedestrians are more likely to not be reported to the authorities and thus cannot appear in official crash statistics.

Clearly, linking the base rate of cyclists riding at a given location with their self-reported behavior, the actual violation rates, and the proportion of crashes involving these violations represents an immense challenge. However, the current approach of inspecting and interpreting isolated data sources limits a more complete understanding of the effects of cyclists' rule violations on traffic safety.

4.3 Motives and reasons for committing traffic rule violations

Although cyclists' rule knowledge has been found to be sketchy [31, 34], typical rule violations by cyclists are reported to be a deliberate decision [2]. Thus, one unsettled question, that could not be answered in this review, is why cyclists infringe traffic rules in the first place. Many studies are primarily concerned with assessing the frequency of rule violations, but not at all with the motives and reasons underlying these violations. Other studies (most of those relying on self-reports) appear to understand rule violations as a result of dispositional factors (e.g. Kummeneje & Rundmo, [37,], O'Hern, [55]. Although these studies identify links to both demographic and psychometric variables, it can be questioned whether this focus provides the means for a systematic reduction of infringements, or even a reduction in harm, as is stated most times as a goal for the reduction of infringements. Other authors conclude that cyclists justify their unlawful behavior with safety concerns or to save energy [14, 29, 66]. Only few studies did assess cyclists' reasons for their infringing behavior directly. Lavetti & McComb [42] summarize open responses of their participants giving reasons for violating traffic rules. Their summary implies that recklessness and attentional errors are more common reasons for violations than assumed by many authors. Marshall et al., [47] conclude that from the cyclists' perspective, violating a traffic rule is frequently a rationale choice in situations perceived as dangerous or uncomfortable. In other words, unlawful behavior by cyclists does not necessarily constitute intentionally risky behavior, but a response to situational factors. A recent study also suggests that the motives for rule violations may depend on the type of rule violation [80], with some violations showing closer links to situational factors, and others to comfort issues or attentional errors.

Taken together, one worthwhile direction for understanding cyclists' rule violations appears to be a greater focus on assessing their motives as well as the situational context in which the violations occur, including a mobility system that is primarily designed for motorized vehicles, and cyclists' role as vulnerable road users affected by rule violations of other road users.

4.4 A lack of theoretical background

Only a handful of the reviewed studies aimed at understanding cyclists' rule violations within a theoretical framework at all. The most prominent framework on this matter can be considered the Theory of Planned Behavior (TPB; [1]), which is referred to by two studies [29, 69] as well as by another not meeting the eligibility criteria [53]. Another two studies [23, 33] discussed their findings in light of the Social Control Theory [28]. Lardelli-Claret et al., [41] referred to the idea of risk compensation [82], but conclude that there is little evidence supporting this assumption.

Next to these theories, the development of a more comprehensive theoretical framework could build upon, for example, concepts from the field of safety research, where rule violations are seen as a form of human error reflecting a response that appears suitable within a current situation [61]. On a more general level, the social practice theory (Smolka, [70]) aims to determine the link between practice and context within social situations. Mobility justice [78] may provide concepts for integrating the inequalities between cyclists and other road user groups.

4.5 Countermeasures and solutions

A final question concerns possible countermeasures. Traditionally, measures thought to increase road safety are described with the "3Es" *Engineering*, *Enforcement* and *Education* (e.g. McKenna, [49]. Engineering solutions are mentioned in a good number of studies, for example by recommending shorter red-light phases [11] or unambiguous signage [24]. The effects of these solutions are not always unambiguous with regard to rule compliance (e.g. bike boxes, [12, 46], see Sect. 3.4.1.3). Other potentially beneficial engineering solutions are linked to a respective legislation, for example traffic legislation allowing cyclist to turn right on red, thus adapting the legislation to the road users' needs. Again, the effects of these measures are not straightforward (e.g. Schleinitz et al., [67,], Schröter, [68]. Education about correct behavior or about potential negative consequences as a mean of countering cyclists rule violations is proposed by some authors (e.g. Bernhoft & Carstensen, [7,], Huemer, [29], but deemed insufficient by others [43]. Several studies discuss the role of enforcement (or the lack of enforcement). In line with a German article [21], at least three studies conclude that enforcement is insufficient, unachievable, or impractical [14, 17, 36]. A high proportion of the investigated studies did not discuss any countermeasures to reduce cyclists' rule violations. In other words, the effectiveness of countermeasures for cyclists' rule violations deserves more attention.

4.6 Limitations

Several German reports by both governmental and non-governmental institutions include data about rule violating behavior of cyclists. However, it was difficult to define unambiguous criteria for in- or exclusion for these sources, and they did not appear in Web of Science or Scopus. Similarly, without a geographical limitation to the Western world, the number of eligible studies would have been beyond a manageable volume. This decision is justified by national and cultural differences in cyclists' behaviors and attitudes [75]. A restriction to European countries would have reduced the body of research further, with even greater homogeneity of the studies' general context. This would have resulted in more isolated cases of evidence for individual traffic rules and methodologies, due to the wide range of possible rule violations. However, a cross-cultural comparison would be a worthwhile endeavor.

5 Conclusions

This review shows a great heterogeneity in the studies concerning rule violations by cyclists regarding the used methodologies, the investigated traffic rule, and the reported violation rates. There is an overemphasis of research on a few types of rule violations (red-light violations in particular), which appears not fully justified considering their relevance for cyclists' safety.

Clearly, cyclists do commit rule violations on a frequent basis. A key question emerging from this review concerns the purpose for which traffic rule violations by cyclists are studied. One the one hand, rule violations are involved in a large proportion of cycling-related crashes. Thus, reducing traffic rule violations may help to increase traffic safety, but only if the respective rule violations contribute significantly to crash risk or severity. This connection seems not always to be straightforward, as seen for red-light violations. On the other hand, traffic legislation has been developed with the overall goal to reduce conflicts. Thus, reducing traffic rule violations may help to reduce conflicts with other road user groups (and thus contra-cycling attitudes), but only if the respective violations are actually the source of those conflicts.

In this light, information about the various data sources about traffic violations by cyclists (especially mismatches between crash data and prevalence data) can give important insights into research needs that consider cyclists' motives for rule violations in order to eventually find sustainable solutions. In other words: if a cyclist considers the illegal behavior to be the best available option in a given situation, even with the potential for creating conflict with other road users, the cyclist's rule-obeying options are deemed less feasible. Mitigating these types of rule violations by cyclists requires a greater emphasis on their evaluation process and the situational context, rather than the outcome alone. The research gaps outlined above (i.e. understanding cyclists' motives, developing a theoretical framework) appear essential in this regard.

6 Appendix

Search queries

The full query submitted to Web of Science was:

(TS=(bicycl*) OR TS=(bik*) OR TS=(cyclist*)) AND (TS=(deliberate) OR TS=(violat*) OR TS=(complian*) OR TS=(infringe*) OR TS=(illegal)).

The full query submitted to SCOPUS was:

(TITLE-ABS-KEY ("bicycl*") OR TITLE-ABS-KEY ("bik*") OR TITLE-ABS-KEY ("cyclist*")) AND (TITLE-ABS-KEY ("deliberate") OR TITLE-ABS-KEY ("violat*") OR TITLE-ABS-KEY ("complian*") OR TITLE-ABS-KEY ("infringe*") OR TITLE-ABS-KEY ("illegal")) AND (LIMIT-TO (SUBJAREA, "SOCI") OR LIMIT-TO (SUBJAREA, "ENGI") OR LIMIT-TO (SUBJAREA, "PSYC") OR LIMIT-TO (SUBJAREA, "ENVI")).

Sample characteristics and study aims

Table A1 in Supplementary Material provides an overview about all studies included in the review, providing information about the methodology (as described in the manuscript), sample characteristics, and study aims. In case of multinational studies, the column 'geographical focus' lists only the countries eligible for the review. 'Sample size' refers to the number of cyclists (if more than one road user group was investigated). The sample's age distribution is provided as mean (and standard deviation) if possible, and limited to the cyclists' part of the entire sample. If age was collected as a grouped variable, the number of groups and the proportion of the largest age group are provided. Each study aim reflects statements of the respective paper as close as possible. Citation marks indicate verbatim statements extracted from the study.

Supplementary Information

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Supplementary Material 1

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Author contributions

R. S. was responsible for conceptualization, data preparation, analysis, visualization, funding acquisition, and writing of the initial draft. A. H. was responsible for funding acquisition and review/editing of the initial draft. A. L. was responsible for funding acquisition and review/editing of the initial draft.

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Data availability

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Declarations

Competing interests

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