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(E-)Cyclists running the red light – The influence of bicycle type and infrastructure characteristics on red light violations

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ABSTRACT

Red light running is one of the most common traffic violations among cyclists. From different surveys, we know that about 40 % of all cyclists run a red light at least occasionally. However, specific data on red light running of e-bike riders (pedelec and S-pedelec riders), a population of cyclists that has been growing steadily in the past few years in Germany and elsewhere, is largely missing. Similarly unclear is the role of the used infrastructure (e.g., carriageway or bike path) or the intersection type on the riders' propensity to run the red light. The goal of this study was to investigate the red light running behaviour of three different bicycle types (bicycle, pedelec, S-pedelec) in Germany, with specific focus on various infrastructure characteristics. We reanalysed data obtained in a naturalistic cycling study, in which we observed 90 participants riding their own bicycles (conventional bicycles, pedelecs, S-pedelecs) on their daily trips over four weeks each. The video material of these trips was annotated and analysed with regard to red light running. Overall, our participants experienced nearly 8,000 red light situations. In 16.3% of these situations, they ran the red light, with nearly identical rates for cyclists, pedelec and S-pedelec riders. Red light running rates were lowest when cyclists rode on the carriageway, while the complexity of the intersection appeared to play a role as well. In general, red light running was more common when riders were about to turn right instead of turning left or riding straight through the intersection. Interestingly, we also observed a considerable number of cases in which the riders changed their used infrastructure (e.g., from the carriageway onto the pavement) to avoid a red light.

Keywords: traffic violations, pedelec, electric assisted bicycle

1 INTRODUCTION

Red light running is one of the most common traffic violations among cyclists. In a Brazilian survey of cyclists, 38% acknowledged running a red light at least occasionally (Bacchieri, Barros, Dos Santos, & Gigante, 2010). In Germany, 45% of the cyclists admit violating a red light every once in a while (Alrutz et al., 2009). However, the proportions obtained from observational studies of red light running vary a lot. In Australia, over 4,000 cyclists were observed at ten intersections. In 7% of the cases in which the traffic light showed red, the cyclist rode past it (Johnson, Newstead, Charlton, & Oxley, 2011). In the Netherlands, stationary observations recorded a red light running rate of about 28% (van der Meel, 2013). A study from the US reported a rate of red light violations as high as 56% (Cole et al., 2011), which was only surpassed by Italian riders, who were observed to run the red light in more than 60% of the cases (Fraboni, Marín Puchades, De Angelis, Prati, & Pietrantoni, 2016). While the clear differences in these findings suggest that there might be a variety of factors - such as the traffic culture in the respective nation, or simply the type of intersection - that play a role for the probability of running a red light, the results overall also show that red light running is a very common phenomenon.

Unfortunately, red light running has the potential to contribute to conflicts and crashes at intersections. This is problematic as cyclists already are - even without running a red light - at a high risk of being involved in crashes at intersections and subsequently suffer severe or fatal injuries (OECD/International Transport Forum, 2012; Walker, 2011). Crash analyses in Florida indicate that about 15% of cyclist crashes were caused by right-of-way violations of the cyclist, which included cases of red light running (Osland et al., 2012). Analyses of Canadian crashes found that disobeying a stop sign or a red light was the cause in 11% of the cyclists' crashes (Thom & Clayton, 1992). In Berlin, nearly 6% of all crashes caused by cyclists could be ascribed to red light violations (Stab des Polizeipräsidenten, 2016).

A number of factors that have an influence on the frequency of red light running incidents, such as age or gender of the cyclist, have already been identified in previous studies, with younger cyclists and men being the more frequent violators (De Ceunynck et al., 2016; Johnson, Charlton, Oxley, & Newstead, 2013; Johnson et al., 2011; Wu, Yao, & Zhang, 2012). The type of the bicycle has been suspected to play a role as well, although Johnson and colleagues (2011) did not find a significant relationship to red light running rates when looking into different types of conventional bicycles (categorised as "road bike" and "mountain bike / flat bar"). Field observations at intersections in Beijing, however, showed that e-bike riders violated a red light more often than conventional cyclists (Wu et al., 2012; Yang, Abdel-Aty, Huan, Jia, & Peng, 2016; Yang, Huan, Si, Gao, & Guo, 2012). In other cases, e-bike riders were found to run the red light at nearly twice the rate as riders of conventional bicycles (Zhang & Wu, 2013). As an explanation, it has been suggested that, because of their motor assistance, it takes e-bike riders less time to cross an intersection, which might tempt them to run the red light. However, it has to be acknowledged that the definition of e-bikes in China differs considerably from the Western one, and, therefore, the described findings are not necessarily applicable elsewhere. Indeed, data for the Western hemisphere, and especially data on red light running of different groups of e-bike riders (pedelec and S-pedelec riders[2]) is largely missing. This is somewhat problematic, as this group of cyclists has been growing steadily in the past few years in Germany and elsewhere (COLIBI & COLIPED, 2014), and could, therefore, change the situation at intersections considerably.

Also lacking is information on the role that variations in infrastructure and infrastructure use play for red light violations. As most available studies were conducted as stationary observations at selected intersections, they cover only one specific infrastructure scenario. As a consequence, there is hardly any knowledge on the role that, e.g., the type of intersection (T-intersection vs. four arms, etc.) might play for a rider's willingness to run a red light. Likewise, information on the potential relationship between the infrastructure which is used by the cyclists, e.g., the carriageway or bicycle infrastructure, and their propensity to violate the red light is rare - the exception being an investigation by Cole and colleagues (2011), which found twice as many red light violations when the cyclists used bicycle infrastructure compared to when they used the carriageway.

The goal of the study presented in this paper was to address this shortage, and to characterise the red light running behaviour of cyclists in Germany, with specific focus on the potential effect of the bicycle type (bicycle, pedelec, S-pedelec) on red light running frequency, as well as infrastructure characteristics at the site of the violation.

[2] In Germany, we distinguish between so-called "pedelecs", which support pedalling up to 25 km/h (250W), are legally treated as conventional bicycles and constitute 99% of e-bikes sold (Zweirad-Industrie-Verband, 2017) and the faster S-pedelecs, which support up to 45 km/h (500W), and are legally categorised as powered two wheelers, i.e. the rider needs to be in possession of a moped driving licence, and is required to wear a helmet (Lawinger & Bastian, 2013). Similar categorisations (often with consequences for licensing, insurance, etc.) exist in most European countries (Jellinek, Hildebrandt, Pfaffenbichler, & Lemmerer, 2013).

2 METHOD

To address the research questions, a reanalysis of a naturalistic cycling dataset collected in a previous study (Schleinitz et al., 2014) was conducted. Only details of the methodology that are relevant for the analysis presented in this paper are described in this section. For a more detailed description of the whole study, see Schleinitz et al.,(2014) and Schleinitz, Petzoldt, Franke-Bartholdt, Krems and Gehlert (2015).

2.1 Participants

Ninety participants took part in the naturalistic cycling study (NCS). However, for the analysis of red light running, only the data of 88 participants (32 female, 56 male) were used, as for the two remaining participants, no encounter of a red light was recorded during the data collection period. Thirty-one of the participants rode a conventional bicycle (12 female, 19 male), 47 a pedelec (20 female, 27 male) and 10 an S-pedelec (10 male). The conventional cyclists were on average 51.5 years old (*SD* = 17.2), the pedelec riders were slightly older (54.4 years, *SD* = 16.7), whereas the S-pedelec riders were younger (41.7 years, *SD* = 17.5). All riders received a monetary compensation of 100 € for their participation.

2.2 Material and procedure

The data was collected for four weeks of cycling in and around Chemnitz (Germany). Technicians equipped the bicycles of our participants with a data acquisition system (DAS) which consisted of two cameras, a speed sensor (2 Hz) and a battery. The cameras were placed in a small box, which was fitted at the handlebar of the bicycle. One camera recorded the forward scenery, so that, e.g., traffic signals or the infrastructure the rider was using were clearly visible. The other camera was directed at the upper body of our participant. The participants were instructed to record each single trip and to use their bicycle during the period of data acquisition as they normally would do. Data privacy was ensured in accordance with relevant institutional and national guidelines and regulations. In addition to the data collected with the help of the DAS, participants filled in a number of questionnaires before and after data acquisition.

2.3 Data analysis

In a first step, all situations in which the participants encountered an intersection regulated by traffic lights were identified. More than 4,300 video clips with more than 1,000 hours of cycling were reviewed. At the same time, a coding scheme was developed to assess the frequency of red light violations, their circumstances and potentially influencing factors.

All coders received extensive training on the coding scheme. During the coding process, the scheme was revised in order to reflect initial feedback by the coders. Some red light running situations were difficult to identify, e.g., because of the camera angle. These scenes were reviewed and discussed within the group of coders and a senior researcher before a decision was made to include or not include them in the final set of red light running situations.

The coded red light situations cover all situations in which a cyclist violated a traffic light according to the definition of the German road traffic act (Bundesministerium der Justiz und für Verbraucherschutz, 2013). This includes situations in which the traffic light shows red, but also situations in which the traffic light changes from yellow to red or shows yellow for more than three seconds. Traffic lights at railway crossings are covered as well. Special cases are situations in which a traffic light shows red, but also has the so called green arrow sign ("Grünpfeil") installed next to it. In this case, road users (including cyclists) are allowed to turn right on red, but only after they have come to a complete stop (Bundesministerium der Justiz und für Verbraucherschutz, 2013). This is comparable to the "right on red" rule in some states of the USA and in Canada, which allows a driver to turn right on red after coming to a complete stop (Maier, Hantschel, Ortlepp, & Butterwegge, 2015). If a participant did not stop, this situation was also coded as a red light violation. In this paper, for simplification, the term "red light running" was used for all these types of violations. In the vast majority of cases (90%), the traffic light showed plain red.

In addition, the circumstances under which the red light running occurred were coded. The coding scheme included the following variables:

- direction of cycling:
    - passing straight
    - turning right
    - turning left
- type of infrastructure used shortly before the traffic light was reached (i.e., the traffic light is within sight of the cyclist), and when the cyclist was about to pass the traffic light (i.e., the rider is about one to two meters from the traffic light pole):
    - carriageway

    - bicycle infrastructure
    - pavement (In Germany, it is mostly illegal to ride on the pavement for adults. There are only few exceptions, which were marked by a specific sign)
- intersection type:
    - five arms or more
    - four arms
    - T-intersection (approaching on the road that ends)
    - T-intersection (approaching on the through road)
    - railway crossing
    - road without junction (e.g., pedestrian traffic light, usually operated by a push-button)
    - bicycle infrastructure crosses a carriageway
    - pavement crosses a carriageway

For the analysis of the red light violations, a red light running rate was calculated. Based on the usual definition of red light running (continue trajectory and pass the traffic light), situations in which the red light was circumvented by a change of the infrastructure were not included in this calculation, since they do neither represent a genuine red light violation, nor can they be considered as rule - compliant behaviour. Cases in which the green arrow sign was present and relevant (i.e., the rider turned right) were excluded as well. As a consequence, to calculate the red light running rate, the number of genuine red light violations was divided by the total number of red light situations (excluding circumventions and red light with green arrow sign relevant).

To investigate red light running on the carriageway in more detail, a generalised estimating equation model was used (Liang & Zeger, 1986; Zeger & Liang, 1986). The generalised estimating equation model is comparable to a binary logistic regression analysis, but also considers correlations between outcome measures across cases for repeated measurement designs. The outcome measure of red light running was binary (yes / no). Variables included in the model (gender, bicycle type, direction of cycling, intersection type) were treated as categorical variables, with the exception of the rider's age, which was a continuous variable. Since all variables were included simultaneously, each was automatically adjusted for confounding effects of the predictor variables included in the model. An independent correlation matrix, which is recommended when there is no prior knowledge about the structure of dependencies in the data (as was the case here; Baltes-Götz (2016)) was used. When compared to other correlation matrices, the fit for the independent correlation matrix was one of the best, with QIC = 1,938.8 and adjusted QICC = 1,892.8. This analysis was limited to the carriageway, since this type of infrastructure was the only one for which a sufficient level of standardisation as well as variation with regard to the different intersection scenarios could be assumed. What we simply labelled "bicycle infrastructure" was actually a complex mixture of different types of cycle paths and lanes, routed adjacent to the carriageway or not, with implications for what types of intersection can be encountered, etc. There were too many interdependencies in the different aspects of the ensuing intersection scenarios to arrive at meaningful results. On the other hand, for the use of the pavement, there is basically only one intersection scenario possible – crossing the carriageway straight at a pedestrian signal – so there would be no variation in two central variables of the model. (In addition, the carriageway is the only type of infrastructure on which all three of the investigated bicycle types are legal to be operated.)

For the separate investigation of circumventions (infrastructure changes to avoid a red light), the infrastructure used before the traffic light was reached and the infrastructure type while passing the position of the traffic light were compared. In a final analysis step, all red light violations and circumventions were compared on a descriptive level, i.e., we used the total number of all red light encounters (including circumventions and red light with green arrow sign relevant) as reference.

3 RESULTS

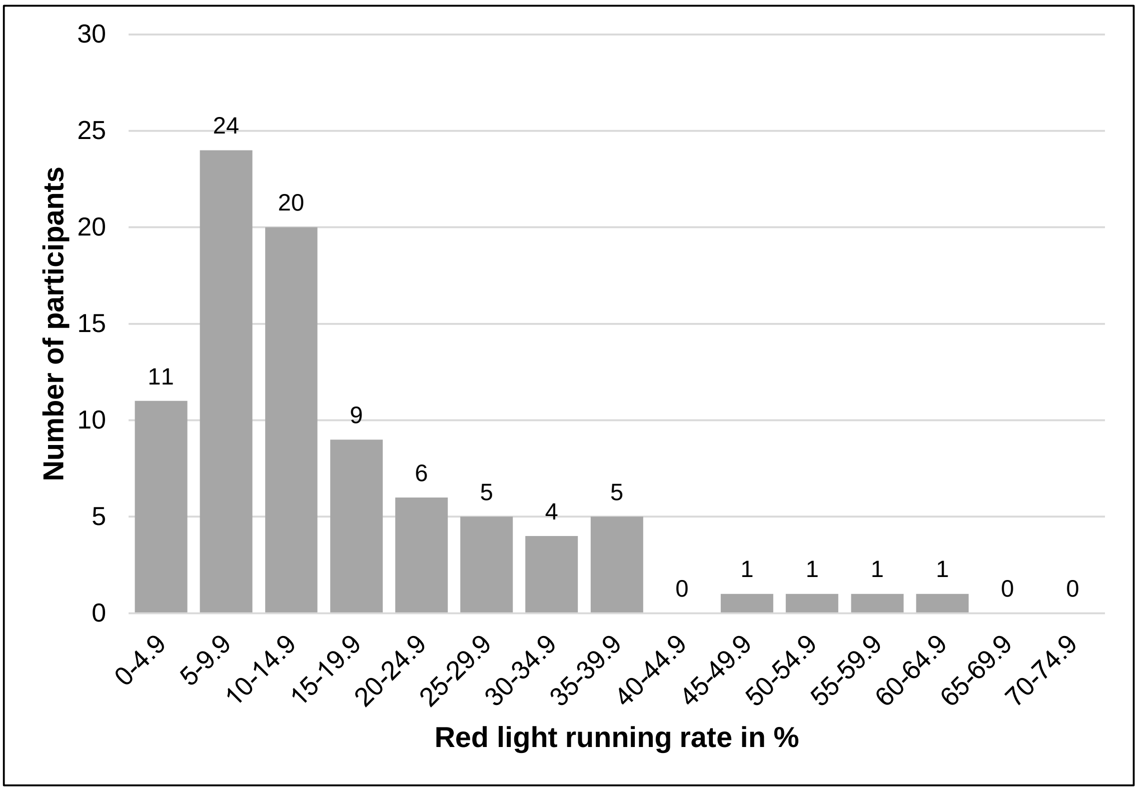
3.1 Frequency of red light running

The video review revealed a total of 7,969 situations in which the participants approached a traffic signal showing red (or yellow for more than 3s). Among these red light encounters, there were 155 cases (2.0%) in which the traffic signal had an additional green arrow, i.e., a right turn on red was allowed, but only after coming to a complete stop. Among these cases, we found 125 violations, i.e., participants turned right on red without stopping. This translates into a red light running rate of more than 80% (although it should be noted that the sample size is rather small). These cases were not included in the further analysis of the circumstances of red light running, as this specific scenario (running the red light "allowed" if certain conditions are met) is a typical. We also observed 391 cases (4.9%) in which the riders changed their used infrastructure (e.g., from the carriageway onto the pavement) to circumvent the red light. These cases were analysed separately.

In 6,213 of the remaining 7,423 red light encounters (83.7%), participants complied with the road rules, i.e., they stopped at the red light, and continued only when the traffic light switched to green. In 1,210 situations (16.3%), the participants ran the red light. None of these situations resulted in a safety critical event.

Figure 1 shows the distribution of red light running rates by participants. As can be seen, half of our participants exhibited red light running rates of 5% to 15%. For eleven participants, we found infringement rates of only 0 to 5%. Five of these riders did not show a single red light violation. On the other end of the spectrum, one participant violated the red light in 64% of all red light situations. Men infringed a red light in 17.2% and women in 14.9% of all encounters, while older riders (65 years and older) showed a reduced violation rate (12.8%) compared to other age groups (17.8%). On average, conventional cyclists violated a red light in 15.8% of all encounters. Pedelec riders ran red lights at a rate of 16.8%, and riders of S-pedelecs in 16.1% of all cases.

Figure 1: Histogram of red light running rates (*N* = 88).



3.2 Circumstances of red light running

One central aspect for the riders' willingness to run a red light was the direction of cycling (see Table 1), or, more precisely, the required manoeuvre. When participants turned right, they ran a red light in more than 40% of all cases. This tendency was particularly strong in conventional cyclists, but still highly prevalent also in riders of pedelecs and S-pedelecs. When passing straight through the intersection or turning left, the proportion of cases in which participants ignored the red light was much smaller, and rates were comparable between the bicycle types.

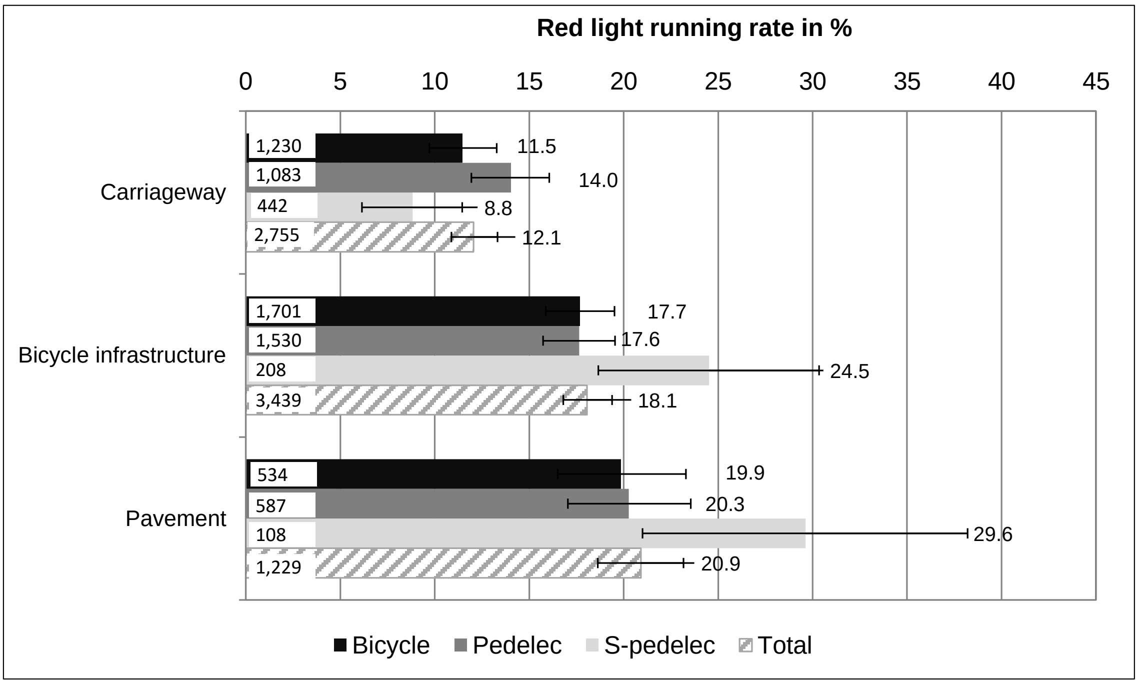
Table 1: Red light running rate (in %) with 95% CI dependent on direction of cycling separate for the three bicycle types (N = 7,423).

	Red light situations*	Bicycle type			
	N	Bicycle *n* = 31	Pedelec *n* = 47	S-Pedelec *n* = 10	Total
Passing straight	6,479	14.5 [13.3; 15.8]	16.1 [14.8; 17.4]	15.1 [12.2; 18.0]	15.3 [14.4; 16.2]
Turning right	296	50.0 [40.8; 59.3]	45.8 [36.9; 54.7]	29.7 [18.5; 40.9]	43.9 [38.3; 49.5]
Turning left	648	16.1 [11.9; 19.9]	11.5 [7.3; 15.8]	13.7 [7.5; 19.9]	14.1 [11.4; 16.8]

* excluding circumventions and signals with green arrow sign

Figure *2* shows the red light running rates for different infrastructure types separated for the three bicycle types. For all bicycle types, we found relatively high rates when they were travelling on the pavement (however, it should be acknowledged that the low number of cases of S-pedelecs on the pavement limits the interpretation). When the participants used a carriageway, the red light running rate was considerably lower than when riding on cycling infrastructure or the pavement.

Figure 2: Red light running rate (in %) with 95% CI dependent on infrastructure type separate for the three bicycle types (N = 7,423, number of red light situations* (100%) presented inside the bars).



* excluding circumventions and signals with green arrow sign

When looking into different intersection types, we found the highest red light running rate at T-intersections when the participant approached on the road that ended (see Table 2). Pedelec riders and conventional cyclists ignored the red light in about one third of these situations. Likewise, we found relatively high rates of violations at traffic lights on roads without junctions (e.g., pedestrian traffic lights) especially for conventional cyclists. At intersections with four arms, the red light running rates were comparatively low. For railway crossings and intersections with five arms and more, sample sizes were too small for an interpretation of the data.

Table 2: Red light running rate (in %) with 95% CI dependent on intersection type separate for the three bicycle types (*N* = 7,423).

	Red light situa-tions*	Bicycle type			
	N	Bicycle *n* = 31	Pedelec *n* = 47	S-Pedelec *n* = 10	Total
Five arms or more	7	16.7 [-13.2; 46.6]	0.0	0.0	14.3 [-11.6; 40.2]
Four arms	2,104	8.8 [7.0; 10.6]	13.1 [10.8; 15.4]	12.1 [8.5; 15.7]	10.9 [9.7; 12.3]
T-intersection (approaching on the road that ended)	274	29.0 [18.3; 39.7]	33.6 [25.6; 41.6]	14.1 [6.0; 22.2]	27.4 [21.9; 32.5]
T-intersection (approaching on the through road)	449	16.2 [10.7; 21.7]	13.4 [8.8; 18.0]	13.4 [5.3; 21.6]	14.5 [11.3; 17.8]
Railway crossing	40	22.6 [7.9; 37.3]	40.0 [-2.9; 82.9]	0.0	22.5 [9.6; 35.4]
Roads without junctions	210	36.9 [27.6; 46.2]	19.0 [10.6; 27.4]	4.3 [-4.0; 12.6]	26.2 [20.3; 32.1]
Bicycle infrastructure crosses a carriageway	3,131	16.6 [14.8; 18.4]	16.5 [14.5; 18.7]	24.7 [18.4; 31.0]	17.0 [15.7; 18.3]
Pavement crosses a carriageway (pedestrian crossings)	1,208	20.3 [16.9; 23.8]	19.9 [16.7; 23.1]	20.4 [12.4; 28.4]	20.1 [17.9; 22.4]

* excluding circumventions and signals with green arrow sign

Generalised estimating equation model for red light violations on the carriageway

The model of red light running on carriageways included the variables age, gender, bicycle type, direction of cycling and intersection type as predictors, and (non-)compliance as outcome variable. There was no significant effect of bicycle type, age or gender (see Table 3). For turning right, the odds of non-compliance was nearly three times higher compared to passing straight, whereas turning left seemed to have the opposite effect, with an OR of 0.179. We also found significant effects on red light running for roads without junctions. The odds were 2.7 times higher than for intersections with four arms. Descriptive data on red light violations when riding on the carriageway is presented in Table 7 in the appendix (analogous to Table 6).

Table 3: Results of the generalized estimating equation model for carriageway (*n* = 2,755).

	b (SE)	Adjusted odds ratio	95% CI Odds ratio	Statistical sig.
Bicycle type				
Pedelec vs. bicycle	0.148 (0.222)	1.159	0.750 – 1.792	.506
S-Pedelec vs. bicycle	-0.534 (0.402)	0.586	0.267 – 1.290	.184
Age				
Age	-0.006 (0.006)	0.994	0.984 – 1.005	.312
Gender				
Female vs. male	-0.108 (0.223)	0.898	0.580 - 1.390	.630
Direction of cycling				
Turning right vs. passing straight	1.096 (0.396)	2.992	1.378 – 6.497	.006
Turning left vs. passing straight	-1.701 (0.540)	0.183	0.063 - 0.526	.002
Intersection type[+]				
T-intersection (approaching on the road that ended) vs. four arms	0.679 (0.434)	1.971	0.843 - 4.612	.118
T-intersection (approaching on the through road) vs. four arms	0.129 (0.227)	1.137	0.729 - 1.775	.571
Railway crossing vs. four arms	-1.186 (0.672)	0.305	0.082 - 1.140	.078
Roads without junctions vs. four arms	1.002 (0.466)	2.725	1.093 - 6.790	.031

+ The intersection types “five and more arms”, “bicycle infrastructure / pavement crosses a carriageway” were excluded from the analysis, as the sample size was too small.

3.3 Infrastructure changes to avoid a red light (circumventions)

In addition to genuine red light violations, there was a considerable number of situations in which the participants changed infrastructure type (e.g. from the carriageway onto the pavement) to avoid a red light. We observed 391 of such situations, which corresponds to a rate of nearly 5% of all red light encounters (see Table 4). The highest rate could be observed for conventional cyclists.

Table 4: Number and rate of circumventions with 95% CI separate for the three bicycle types (in %) (*N* = 7,969).

	Bicycle type			
	Bicycle *n* = 31	Pedelec *n* = 47	S-Pedelec *n* = 10	Total
Number of circumventions	205	164	22	391
Total number of red light situations (incl. circumventions and green arrow)	3,762	3,414	793	7,969
Circumvention rate (in %)	5.5 [2.4; 8.6]	4.8 [4.1; 5.5]	2.8 [1.6; 4.0]	4.9 [4.4; 5.4]

In the majority of these situations, the participants, independent of bicycle type, changed from the carriageway to the pavement (see Table 5). In a few cases, conventional cyclists avoided a red light also by changing from the carriageway to some form of bicycle infrastructure. In general, and not surprisingly, participants mostly showed this behaviour when they approached the intersection on the carriageway.

Table 5: Rate of circumventions (in %) with 95% CI separate for the three bicycle types (*N* = 391).

	Bicycle type			
	Bicycle *n* = 31	Pedelec *n* = 47	S-Pedelec *n* = 10	Total
From carriageway to pavement	84.9 [80.0; 89.8]	86.0 [80.7; 91.3]	86.4 [82.7; 90.1]	85.4 [72.1; 100.7]
From carriageway to bicycle infrastructure	9.8 [5.7; 13.8]	0.6 [-0.6; 1.8]	0.0	5.4 [-4.1; 14.9]
From carriageway to other types of infrastructure e.g., parking area	0.5 [-0.4; 1.5]	5.5 [2.0; 9.0]	4.5 [-7.8; 16.8]	2.8 [-4.1; 9.7]
From bicycle infrastructure to pavement	4.4 [1.6; 7.2]	4.3 [1.2; 7.4]	9.1 [-4.2; 22.4]	4.6 [-4.2; 13.4]
From bicycle infrastructure to carriageway	0.0	3.7 [0.8; 6.6]	0.0	1.5 [-3.6; 6.6]
From pavement to carriageway	0.5 [-0.4; 1.5]	0.0	0.0	0.3 [-2.0; 2.6]

3.4 Comparison of red light violations and circumventions

For comparison, Table 6 illustrates red light violations (including violations of red light with green arrow sign) and circumventions in relation to different situational circumstances. In total, some form of violation, either by running the red light or by circumventing it, occurred in more than 20% of all red light encounters. When participants turned right at the intersection, this rate rose to more than 60%. With regard to the infrastructure used before the violation, it is clearly visible that while red light running occurred frequently on all types of infrastructure, circumventions were found almost exclusively when the rider was approaching on the carriageway. When looking at T-intersections, it also seems noteworthy that approaches from the road that ended often resulted in red light running, whereas approaches on the through road were more often accompanied by circumvention.

Table 6: Proportions of red light running (including violations of a red light with green arrow sign) and circumvention (in %) with 95% CI for different directions of cycling, infrastructure and intersection type (*N* = 7,969).

	Red light situations	Red light running		Circumvention	
	N(n#)	*N (n#)*	*%*	*N*	*%*
Total violations	7,969 (155)	1,335 (125)	16.8	391	4.9
			[16.0; 17.6]		[4.4; 5.4]
Direction of cycling					
Passing straight	6,747 (0)	989 (0)	14.7	268	4.0
			[13.9; 15.5]		[3.5; 4.5]
Turning right	534 (155)	255 (125)	47.8	83	15.5
			[43.6; 52.0]		[12.4; 18.6]
Turning left	688 (0)	91 (0)	13.2	40	5.8
			[10.7; 15.7]		[4.1; 7.5]
Infrastructure type*					
Carriageway	2,933 (148)	452 (120)	15.4	366	12.5
			[14.1; 16.7]		[11.2; 13.6]
Bicycle infrastructure	3,467 (7)	626 (5)	18.1	24	0.7
			[16.8; 19.4]		[0.4; 1.0]
Pavement	1,569 (0)	257 (0)	16.4	1	0.1
			[14.6; 18.2]		[0.0; 0.3]
Intersection type					
Five arms or more	10 (0)	1 (0)	10.0	3	30.0
			[-8.6; 28.6]		[1.6; 58.4]
Four arms	2,380 (90)	302 (72)	12.7	189	7.9
			[11.4; 14.0]		[6.8; 9.0]
T-intersection (approaching on the road that ended)	387 (64)	127 (52)	32.8	49	12.7
			[28.1; 37.5]		[9.4; 16.0]
T-intersection (approaching on the through road)	535 (1)	66 (1)	12.3	86	16.1
			[9.5; 15.1]		[13.0; 19.2]
Railway crossing	42 (0)	9 (0)	21.4	2	4.8
			[9.0; 33.8]		[-1.7; 11.3]
Roads without junctions	263 (0)	54 (0)	20.5	54	20.5
			[15.6; 25.4]		[15.6; 25.4]
Bicycle infrastructure crosses a carriageway	3,139 (0)	533 (0)	17.0	8	0.3
			[15.7; 18.3]		[0.1; 0.5]
Pavement crosses a carriageway or each other (pedestrian crossings)	1,213 (0)	243 (0)	20.0	0	0.0
			[17.8; 22.3]		

* The total number of red light situations and number of violations differ from previous analyses (3.2), since situations in which a circumvention and red light running (including violations of a red light with a green arrow sign) occurred were not included in the previous analysis.

Number of cases in which a green arrow sign was present and relevant

4 DISCUSSION

The main aim of the analysis conducted in this study was to gather information on red light running rates of e-bike riders as well as conventional cyclists within a German traffic context. When compared to observations from other countries, the observed red light running rates of our cyclists, pedelec and S-pedelec riders might be considered moderate (Cole et al., 2011; Fraboni et al., 2016; van der Meel, 2013; Yang et al., 2016). The total violation rate of about 20% (including circumventions and violations of a red light with green arrow sign) appears to be much lower than what has been observed (e.g., in Italy), but is, nevertheless, too high to be dismissed as isolated incidents. However, contrary to the assumption that e-bike riders might be more willing to cross an intersection on red, we found no difference in the red light running rates in general between pedelec riders, S-pedelec riders and conventional cyclists. When looking at red light encounters on the carriageway only, there was no significant difference between the bicycle types as well, which is contrary to Chinese findings (Wu et al., 2012) - again highlighting the limited applicability of Chinese data to the Western context.

In addition to cases of genuine red light running, we were able to observe a substantial number of situations in which the cyclists changed from one infrastructure type to another to avoid stopping at the red light and continue the ride unimpeded. Aside from the fact that in basically all cases, one violation (running the red light) was only exchanged for another (riding on an infrastructure - the pavement - on which it was illegal to ride), this behaviour can obviously lead to safety issues. Cycling on the pavement, where the circumvention led the riders in more than three-quarters of the cases, has been found to be risky (Aultman-Hall & Kaltenecker, 1999; Moritz, 1998; Wachtel & Lewiston, 1994), as it can result in conflicts with pedestrians (Petzoldt, Schleinitz, Heilmann, & Gehlert, 2017; Schleinitz et al., 2015; Stab des Polizeipräsidenten, 2016). More crucially, as using the pavement is illegal in Germany, drivers of motorised vehicles might not expect cyclists approaching on the pavement at intersections or driveways, potentially resulting in safety critical events and crashes (Kolrep-Rometsch et al., 2013).

When looking into specific characteristics of red light violations, what stood out was that when turning right, red light running was actually more frequent than compliance with the rules. This is in line with results of previous research (Jahangiri, Elhenawy, Rakha, & Dingus, 2016; Johnson et al., 2013). In general, right turn situations seem to be more inviting with regard to red light running, as usually no traffic lanes have to be crossed, so there are some limits to whom potential conflict partners are, and where they come from. This behaviour was especially prevalent in cases where a green arrow on the traffic signal indicated that a turn on red would be legal, although only after coming to a complete stop. Only in a small number of these situations, the riders complied with the rules and stopped. It appears that the fact that the turning manoeuvre in principle is legal (under the described circumstances) somewhat invites the violation.

At T-intersections, when approaching on the road that ended, red light running rates were highest, even when excluding the relevant green arrow cases. Different from four armed intersections, for example, turning right was one of only two behavioural options (turning left being the other). Interestingly, when riders approached T-intersections on the through road, circumventions were more likely than genuine red light violations. It appears that cyclists behave quite opportunistically, as the specifics (e.g., no traffic light on the pavement, lowered curbs close to the traffic signal to switch to the pavement) of such intersections practically encourage this form of behaviour. It should also be noted that violation rates were quite high for roads without junctions. It can be assumed that the good visibility and the low traffic encouraged the participants to run a red light. Although we found minor differences between the three bicycle types in their violation rates in relation to different infrastructure characteristics, interpretations are difficult, as sample sizes for specific factor combinations are rather small. The propensity to commit a violation in a certain scenario largely depends on context factors (e.g., if it is even possible to change the infrastructure at these intersections) or other factors such as trip purpose or route choice. So a larger event sample would be required to cover these different cases to a sufficient degree.

What seems clear, though, is that one motive for red light running and circumvention appears to be the reluctance to stop and accelerate again. Therefore, a conceivable measure would be to set up so-called "green waves" for cyclists at least on certain main routes. In Copenhagen, on special sections of the road traffic lights are phased in a way so that when cyclists ride at a constant speed of 20 km/h (which is the cyclists' mean speed in Copenhagen), they would be able to pass all of them on green (Fahrradportal, 2016). This measure could also be used to counteract changes from one infrastructure to another - like the evasion to the pavement - and thus prevent conflicts with pedestrians.

In addition to such potential infrastructure shortcomings, a perceived lack of enforcement with regard to red light violations might have facilitated this form of behaviour. In a representative German survey, most of the cyclists stated that it is “rather unlikely” or “very unlikely” to be caught by the police after running a red light (Kröling & Gehlert, 2016). Compared to a 2010 survey, the number of cyclists who stated that there is a high probability of being caught by the police has dropped considerably. Changing this subjective impression - either through actual policing, or through measures that merely address the perceived probability of being caught - might contribute to a reduction in red light running rates. A first attempt for better enforcement has been made in Berlin, where, since 2014, police officers are riding bike patrol. For this period of time, reduced crash rates were registered, while at the same time prosecution of traffic infringements (not only those of cyclists, but also users of motorised vehicles), e.g., - red light running, increased (Unfallforschung der Versicherer - Gesamtverband der Deutschen Versicherungswirtschaft e.V., 2017).

It should be acknowledged that, although the naturalistic cycling approach can provide new insights into cyclists' behaviour, the method is not without limitations. The camera setup used in this study did not allow for a complete coverage of the whole intersection, so there is a chance that certain red light running situations might have been overlooked. Similarly, some of the factors that were investigated in stationary observations (e.g., traffic volume, which other road users cross at the intersection or waiting time at the signal) could not be observed to a sufficient degree. This would require wider camera angles to cover all side arms of the intersection. Furthermore, the influence of trip purpose on the decision to run a red light could not be taken into account. Likewise, the riders' actual motivations for each individual violation, as well as for violations in general, remain unclear, and cannot be established through NCS. To accomplish that, corresponding interviews and questionnaires might need to be integrated into the approach.

5 CONCLUSION

The results of this study are indicative of the fact that red light running of cyclists and e-bike riders is a complex behaviour which is heavily dependent on a range of factors including infrastructure characteristics and type of manoeuvre being undertaken. An overall red light running rate is, therefore, insufficient to describe the scope of the problem, as the infrastructure the cyclist is riding on, the type of intersection, as well as, of course, the cyclist's intended direction of travel all impact on the rider's propensity to run the red light (or to circumvent it). In contrast, the bicycle type itself did not have a statistically relevant effect on the rate of violations.

It should be noted, however, that, despite the fact that we observed far more than 1,000 cases of red light running, we did not observe a single safety critical situation. While this, by no means, should be considered as evidence that this behaviour is safe, it points to a relevant gap in research. We know, for example, from police reports, that individual crashes can be blamed on cases of red light running. Also, on a theoretical level, it can be argued that road users behaving in a predictable manner (which includes, most of the time, behaviour in compliance with road rules, e.g., stopping on red) is safer than unpredictable behaviour. Nevertheless, as far as we are aware, there is has been no quantification of the crash risk in relation to cyclist red light running. While it is reasonable to assume that stopping on red is safer than not stopping, so far, there is no way of telling how serious the issue is. Also, given that our results show that red light running rates depend on a variety of factors, it would not be surprising if also the crash risk as a result of running a red light would differ considerably. But again, information is lacking.

So, while future investigations should certainly go beyond our analyses of infrastructure characteristics, and try to uncover even more factors influencing a cyclist's willingness to run a red light, what seems even more important is to try to link this type of behaviour with crash risk. As a cyclist's decision to violate the signal most likely also includes some subjective assessment of risk, asking cyclists directly about their motives and "strategies" for red light running could be a starting point to understand why and when cyclist red light running occurs. Ultimately, however, safety relevant behavioural measures will be required to justify the continued interest in that matter.

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8 APPENDIX

Table 7: Proportions of red light running (in %) on carriageways for age groups, gender, different directions of cycling, and intersection type differentiated for bicycle type (*n* = 2,755).

	Red light situations	Red light running	
	N	*N*	%
	Bicycle type		
Bicycle	1,230	141	11.5
Pedelec	1,083	152	14.0
S-Pedelec	442	39	8.8
	Age groups*		
Under 65 years	2,155	269	12.5
65 and older	600	63	10.5
	Gender		
Male	1,834	219	11.9
Female	921	113	12.3
	Direction of cycling		
Passing straight	2,056	253	12.3
Turning right	217	66	30.4
Turning left	482	13	2.7
	Intersection type		
Five arms and more	3	1	33.3
Four arms	1,913	190	10.0
T-intersection (approaching on the road that ended)	232	38	16.4
T-intersection (approaching on the through road)	390	49	12.6
Railway crossing	29	1	3.5
Roads without junction	176	43	24.4
Bicycle infrastructure crosses a carriageway	5	4	80.0
Pavement crosses a carriage-way (pedestrian crossings)	7	6	85.7

* Although age was included as continuous variable in the GEE model, in the table we present the two age groups, in order to give an impression of the effect of age on red light running on carriageways.