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Research article

Introducing Right Turn On Red for cyclists: a before-after study in Germany

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Abstract: Right Turn On Red (RTOR) for cyclists is a low-cost and easy-to-implement improvement for cycling that is practised in several European countries and has been discussed for implementation in Germany. This study investigates the effects of introducing RTOR for cyclists based on video observations at 43 sites in nine German cities including all relevant types of cycling infrastructure (mixed traffic, cycle lanes, cycle tracks). Using a before-after approach, the study compares cyclist behaviour in terms of compliance with traffic rules and conflicts with other users. Overall, the introduction of RTOR legalised behaviour that had already been practised. The share of cyclists turning right on red, which was already high at 80% before the introduction of RTOR, increased to 93% with RTOR, and cyclists were more likely to comply with traffic rules and less likely to cycle on the pavement. Conflicts were mainly observed between right-turning cyclists and other cyclists as well as pedestrians. The number of conflicts increased after the introduction of RTOR while conflict criticality decreased. Cyclists gave more space to other users and obstructed them less with RTOR in place. The only exception to this were conflicts in the approach, where more close overtaking manoeuvres and wriggling through other users were observed. RTOR should therefore only be recommended if sufficient space is available or cyclists mainly turn right at an intersection. Based on the results of this study, recommendations for RTOR for cyclists have been introduced in the German Highway Code.

Keywords: bicycle-bicycle interaction, traffic regulation, pilot study, behavioural observation, traffic conflicts

1 Introduction

Promoting cycling is high on the agenda on national and local levels worldwide. Strategies to promote cycling range from ‘hard’ infrastructure measures such as the installation of bicycle lanes or the construction of bicycle bridges to ‘soft’ campaign measures such as the installation of bicycle counters or personalised travel planning tools for cyclists. All these measures aim to influence travel behaviour, to increase the share of bicycle mobility and traffic on the individual and local level. The effectiveness of cycling promotion has been proven in several studies (Pucher et al., 2010; Larsen et al., 2024). This increase has various positive effects, including improvements in transport efficiency, health and the environment (Gerike et al., 2021) but could also cause safety issues and hamper progress towards political goals such as vision zero (Wegman

& Schepers, 2024; Buehler & Pucher, 2021).

At the microscopic level, previous studies have found changes in on-site cyclist behaviour as a result of changes in the design and operation of cycle facilities. These changes in behaviour are analysed in before-after studies in terms of usage (Madsen et al., 2022) and conflicts (Fyhri et al., 2021). Long-term effects can also be analysed using accident data (Ling et al., 2020).

This study investigates the introduction of Right Turn On Red (RTOR) for cyclists at traffic lights in Germany. RTOR is a low-cost and easy-to-implement improvement in bicycle provision which reduces cyclists' waiting time, potentially improving comfort as well as compliance with cycle provisions. At the same time, RTOR for cyclists can lead to safety problems, e.g., with pedestrians crossing the carriageway or cyclists overtaking others while approaching the intersection.

Table 1 gives an overview of the European countries that have introduced RTOR for cyclists so far. The Netherlands was the first country introducing RTOR in 1990, followed by France, Belgium, Denmark, Switzerland and Austria. All countries allow RTOR for cyclists at specific intersections using a dedicated traffic sign (Figure 1). In all countries except Austria, cyclists may turn on red without stopping. They simply have to give way to vehicles and pedestrians who have the right of way. In some countries, RTOR for cyclists is complemented by specific regulations. In Denmark, for example, RTOR is only allowed at traffic lights on intersections with cycle tracks in the approaching and exiting legs that have separate lanes for cyclists turning right and going straight. Belgium and Austria allow RTOR for cyclists without dedicated cycling facilities but only for speed limits lower than 50 km/h.

Some countries have related regulations, such as the RTOR for motorised two-wheelers (the Netherlands) or cycling straight over a red light for cyclists (Austria, Belgium and France). Regulations for general RTOR exist in all of the countries in Table 1 except Switzerland allowing all users on the carriageway (including cyclists) to turn right on red. However, these regulations are not the focus of this study.

The above overview shows that RTOR for cyclists exists in several countries, but no scientific and internationally published studies evaluating its effects on cyclists' behaviour could be identified. Pilot studies have been conducted in the field prior to the general introduction of RTOR in four out of the six countries presented in Table 1: France, Belgium, Denmark and Switzerland. They report more cyclists turning right with RTOR being in place but provide little detail on safety mechanisms and effects mainly due to low numbers of conflicts and/or crashes.

To address these research gaps, the following three aims are formulated for this study: our first aim is to identify changes in cyclists' compliance with traffic rules before and after the introduction of RTOR. Our second aim is to determine changes in the number and criticality of interactions due to RTOR. Based on the findings from these analyses, our third aim is to develop recommendations for of the implementation of RTOR for cyclists in Germany.

The empirical analysis in this study is based on before-and-after video analysis at 43 study sites in nine German cities. A tailored conflict analysis method is developed which first categorises interactions between cyclists and other road users according to the type of mutual reactions. The criticality of interactions is assessed in a second step using Post Encroachment Time (PET) as a Surrogate Measure of Safety (SMoS), see e.g., Zheng et al. (2021). No crash analysis is conducted due to the short study period of twelve months.

The paper is organised as follows: section 2 provides an overview of the state of the art including the pilot study results and also reviews the literature on the determinants and effects of cyclist compliance with road design and operation. Section 3 presents the legal framework of RTOR for Germany. Methods are explained in section 4, followed by results in section 5 which are organised according to compliance and interactions. Results are discussed in section 6 and finally, section 7 presents recommendations and main conclusions, limitations and perspectives for further research.

2 Literature review on cyclist behaviour at traffic lights

2.1 Pilot studies evaluating RTOR for cyclists in European countries

The main characteristics and results of the studies are summarised in Table 2. All studies except Störr et al. (2017) were designed as before-and-after studies, two of them with reference sites for comparison (Egeler

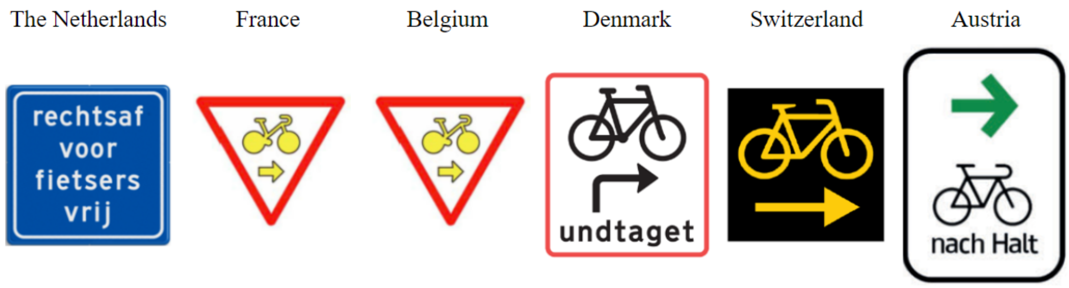


Figure 1 RTOR traffic signs in Europe

Table 1 Overview of RTOR traffic regulations for cyclists in Europe

Country	the Netherlands	France	Belgium	Denmark	Switzerland	Austria
Year of introduction	1990	2012	2012	2018	2021	2022
Obligation to stop	no	no	no	no	no	yes

et al., 2015; Eriksson, 2016). All studies collected video data to examine changes in cyclist behaviour and conflicts, except Egeler et al. (2015) who did manual on-site observations. In addition, accident data were analysed (Egeler et al., 2015) for three months to two years, which is generally too short, particularly for analysing accidents involving only one user group (cyclists) and direction of movement (right turn). Furthermore, most of the studies did not specify which accidents they considered to be related to the RTOR regulation.

The small number of study sites as well as cyclists and conflicts per site makes it difficult to draw reliable conclusions from these analyses, but the studies do give some indication of the determinants and effects of RTOR, which can be summarised as follows: The proportion of cyclists turning right on red tends to increase with the introduction of RTOR, but was already high at the study sites previously. With RTOR, more cyclists stay on the carriageway rather than cutting across the pavement to avoid the red light. Cyclists wriggling through others when approaching the intersection on the carriageway and conflicts between cyclists and pedestrians on the crossings might be negative effects, while less cyclists and conflicts on the pavement might be a positive effect of RTOR. No spill-over effects were found, the introduction of RTOR does not seem to have significant effects on cyclists going straight at RTOR intersections or on cyclists' right turn behaviour at other intersections.

2.2 Red light running and further relevant behaviour and safety issues for cyclists

In addition to the few identified applied pilot studies that focus specifically on RTOR for cyclists, the literature on cyclist compliance with the design and operation of signalised intersections and related implications on cyclist safety is relevant to this study. While red light running is of main interest for compliance in terms of operation, behaviour of cyclists approaching or exiting the intersection (including changing from the carriageway to the pavement or vice versa) is of main interest for compliance with the design. The pilot studies indicate an increase in conflicts in the approach, in the exit and at the crossings, and a decrease in conflicts on the pavement. No scientific studies were identified that investigate conflicts between cyclists and other users approaching or exiting the intersection, or crossing the approach or exit legs of the intersection. Few studies were found that investigate conflicts between pedestrians and cyclists.

Cyclist red light running rates from observations at specific intersections range from 7% (Johnson et al., 2011) to 60% (Fraboni et al., 2018; Richardson & Caulfield, 2015; Wu et al., 2012). Red light running rates for right-turning cyclists are consistently higher than for cyclists turning left or going straight (Alrutz et al., 2009; Johnson et al., 2011; Twaddle & Busch, 2019). This is particularly the case for cyclists turning right on a cycle track off the carriageway compared to cycle lanes in the carriageway or mixed traffic provisions (Schleinitz et al., 2019).

Table 2 Overview of RTOR pilot studies in Europe

Country	France	Belgium	Denmark	Switzerland	
Period	2008–2010	2012	2014–2016	2013	2015–2016
Study sites	unknown number of RTOR signs in several cities	8 RTOR signs in one city	33 RTOR signs in several cities	3 RTOR signs in one city	12 RTOR signs in one city
Study design	before-after study	before-after study	before-after study	before-after study	after study
Data	not stated	● 4-hour video observation at 8 sites each before and after	● 2 days · 9-hour video observation at 4 sites (2 trial sites, 2 reference sites) each before and after	● 1.75-hour manual on-site observation at 4 sites (3 trial sites, 1 reference site) each before and after	● 8 days · 6-hour video observation at 11 sites; 4 days · 6-hour video observation at 1 site
Considered effects	● compliance of right turning cyclists ● accidents (no period stated)	● compliance of right turning cyclists ● right of way/conflicts ● accidents (period: three month)	● compliance of right turning cyclists ● conflicts ● accidents (period: two years)	● compliance of right turning cyclists ● compliance of cyclists going straight -conflicts	● compliance of right turning cyclists ● conflicts ● accidents (period: one year)
Results: compliance	● no negative impact on traffic light compliance for other movements or at other junctions;	● low number of cyclists (<10) at 5 sites does not allow comparisons ● 39%–94% of cyclists turned right on red light before and 60%–81% after RTOR Introduction	● 30% increase of cyclists turning right on red (before-after; trial sites) ● increase of cyclists turning right on red from 63%–78% to 90% (before-after; reference sites)	● 33%–100% of cyclists turned right on red light before and 68%–100% after RTOR introduction ● decrease of cyclists turning right on red from 35% to 24% (before-after; reference site) ● no increase of red light running for straight riding cyclists (before-after; trial sites)	● 64%–93% (mean = 78%) of cyclists turned right on red light after RTOR introduction
Results: behaviour	● better channelling of previously erratic cycling practices; ● cyclists stay on the road and no longer cut across the pavement to avoid the red light	-	● low number of cyclists observed on the pavement (before and after)	● where cyclists are guided in mixed traffic in the entry, they tend to wriggle through standing cars	● 4% of right-turning cyclists wriggle through standing cyclists/cars ● 2% of right-turning cyclists ride on the pavement ● 2% of right tuning cyclists stop before turning
Results: conflicts	-	● 18 potential conflicts with pedestrians in the before period; ● none in the after period	● zero to one conflict per intersection, no increase after introduction of RTOR	● 9 conflicts with cyclists/motorists in the before period, 6 in the after period	● 31 conflicts mainly with pedestrians; most of them on crossing 2 (exit of the right turn)
Results: accidents	● no accidents related to RTOR	● no accidents	● no bicycle- accidents related to RTOR	–	● no bicycle-accidents related to RTOR
Reference	Certu (2012)	BIVV (2012)	Eriksson (2016)	Egeler et al. (2015)	Störr et al. (2017)

Red light running rates are lower at more complex intersections (Schleinitz et al., 2019) and higher at lower carriageway widths (Twaddle & Busch, 2019; Van der Meel, 2013). In terms of signalling, red light running is consistently higher with longer red light phases and waiting times (Lv et al., 2022; Pai & Jou, 2014; Van der Meel, 2013). Red light running rates are highest at the beginning and at the end of red light phases (Bai & Sze, 2020; Twaddle & Busch, 2019; Wu et al., 2012). De Ceunynck et al. (2016), as one of the very few studies on RTOR for cyclists, found a spillover effect in their online-survey. Respondents with a high awareness of RTOR for cyclists reported that they are more likely to turn right on red at intersections without RTOR.

In terms of compliance with design, various types of changes in behaviour have been identified when cyclists do not feel safe or comfortable on their provision. These include switching to the pavement (Schleinitz et al., 2019) as well as changes of speed and trajectories (Kazemzadeh et al., 2023; Zhang et al., 2023). Ihlström et al. (2021) examined the practice and underlying motives of cycling on the pavement. They identified three main reasons for this practice: avoiding close proximity to cars, increasing smoothness of the ride and unclear infrastructure design.

Studies investigating conflicts between pedestrians and cyclists usually combine behavioural-based conflict measures such as speed, lateral overtaking distances or evasive actions with the typical SMoS that are also used for conflicts involving motorised vehicles (Beitel et al., 2018; Hosford et al., 2020; Zhang et al., 2023). For example, Liang et al. (2021) found a positive relationship between the volumes of cyclists and pedestrians and the number of conflicts (measured as combination of TTC and PET) in shared spaces, with swerving being the most common evasive action.

Overall, the applied pilot studies show tendencies for the specific effects of RTOR on cyclists, and the general literature on cyclists' compliance with operation and design provides background knowledge on behavioural mechanisms with relevance for RTOR. At the same time, the literature review highlights the need for more comprehensive empirical evidence on the effects of RTOR on cyclist behaviour and its implications for tailor-made study designs.

3 Legal framework and requirements for RTOR in Germany

To understand the legal framework on RTOR for cyclists in Germany, the general RTOR regulation was considered first, as an initial requirement for this study was that the future regulation on RTOR for cyclists in Germany should be based on and be consistent with the existing general RTOR regulation which had been in place since 1992. The general RTOR allows motorists and all other users on the carriageway to turn right on red after having stopped. Since the RTOR for cyclists is supposed to be in line with the general RTOR regulation, cyclists in Germany are required to stop before turning when RTOR for cyclists is in place. This is an important difference from other countries.

Regarding the context of application, the general RTOR regulation is only allowed in Germany if the person turning right can see the oncoming pedestrian and vehicle traffic in the permitted direction of traffic sufficiently well. RTOR is according to VwV-StVo (2021) specifically not allowed when:

- oncoming traffic is signalled with a (semi-) protected left turn,
- right turning vehicles have a protected/separate phase,
- (tram) tracks must be crossed or passed when turning right,
- the cycle track to be crossed is a two-way facility or there is a substantial volume of bicycle traffic riding in the opposite direction,
- several right-turn lanes are marked,
- the traffic light serves primarily to safeguard a school route, or
- intersections are frequently used by physically or visually impaired persons.

These exclusion criteria were used in the selection of the study sites. For the new regulation on RTOR for cyclists, the above criteria could be amended but not changed.

4 Methods

4.1 Study sites

Cycle provisions at signalised intersections differ greatly and might be different in the approach and the exit leg of an intersection. The literature review shows that cyclist compliance varies depending on the type of cycle provision, so a detailed approach was required that distinguished between the different possible types of cycle provisions and between potential conflict points.Table 3 shows the final typification, distinguishing between nine types of study sites.

In the first step, participating cities were selected based on their willingness to cooperate as well as population size, spatial distribution in Germany, modal share of cycling and topography. The sample of nine cities (Bamberg, Darmstadt, Düsseldorf, Cologne, Leipzig, Munich, Münster, Reutlingen and Stuttgart) ranges from major cities (> 500 000 inhabitants) to large cities (> 100 000 inhabitants). No medium-sized or small cities could be convinced to participate.

In the next step, the nine city partners made suggestions for potential study sites based on pre-defined criteria which included the legal exclusion criteria for the general RTOR as introduced in section 3 and, in addition, high crash numbers, recent or planned reconstruction, shared facilities for pedestrians and cyclists on the pavement, missing stop line for right-turning cyclists and waiting pockets for two-step left-turning cyclists in the right turn path. Cyclist volumes should be significant to generate sufficient numbers of observations for on-site video recording. All potential sites were initially assessed and suitable sites were visited on-site to confirm their suitability in terms of the quality of the surface and width of facilities, sight lines, potential bicycle traffic volumes and the possibility of mounting cameras. Based on these considerations, the final set of study sites was selected.

The nine city administrations proposed a total of 112 sites to be considered for the study resulting in a sample of 48 study sites that were, based on the assessment, finally selected for the before video recordings. After the before video recordings had been completed, the signposting took place. At five of the 48 sites, the RTOR sign was not mounted (due to space or time constraints) resulting in a reduced final sample of 43 sites with the complete before and after data collection. The total of 43 study sites were classified as shown in Table 3. One site in this study is defined as one corner of an intersection, which means that 43 corners were investigated. 27 of these sites are single sites where only one corner of the intersection is regulated with RTOR, six intersections have two corners with RTOR and one intersection is fully equipped with RTOR at four corners.

4.2 Field work

The before-video recordings took place in September and October 2018. Video data was recorded at each site for at least one day with two cameras, one filming the approach and one filming the exit of the right-turn relation to make sure that the status of the traffic lights as well as interactions and compliance could be observed reliably.

The RTOR traffic sign was subsequently mounted at the sites in early 2019 based on a special legal approval for the pilot study by the local road traffic authorities. The signposting was accompanied by press releases in local and national media. There was no additional awareness campaign on the streets.

The after-video recordings followed from May to August 2019 so that a period of familiarisation with the new RTOR regulation of at least three months was guaranteed at all sites. Video data was recorded similarly to the before observation with the same camera positions and duration of recording. All videos were recorded on working days excluding local holidays.

4.3 Analysis

Video data was analysed for three hours in the afternoon (including PM peak hour) for each site in both the before and after periods. Data was analysed manually by instructed surveyors with the same methodology for before and after observations. Direction of travel and arrival at green or red light was coded for all cyclists approaching the intersection. For arrivals at red light, information was added on whether cyclists turned on red without stopping, on red with stopping or waited for green. This data was used to analyse cyclists' compliance with traffic rules. In addition, the facilities used by cyclists approaching and exiting the intersection were coded, including changing from the carriageway to the pavement and situations where cyclists dismounted and pushed their bicycle.

Volumes of right-turning cyclists and conflicting traffic were counted for the before and after periods and included as exposure in the analysis.

Interactions of cyclists with other users were determined for six pre-defined conflict points as shown in Figure 2. Cyclists' behaviour and their interactions were analysed along the entire right turning movement from approaching to exiting the intersection, resulting

Table 3 Typification of study sites and sample size

Type	MT–MT	MT–CL	MT–CT	CL–MT	CT–MT	CL–CL	CL–CT	CT–CL	CT–CT
Entry	Mixed Traffic	Mixed Traffic	Mixed Traffic	Cycle Lane	Cycle Track	Cycle Lane	Cycle Lane	Cycle Track	Cycle Track
Exit	Mixed Traffic	Cycle Lane	Cycle Track	Mixed Traffic	Mixed Traffic	Cycle Lane	Cycle Track	Cycle Lane	Cycle Track
Sites	4	7	7	8	4	5	3	2	3

MT = Mixed Traffic; CL = Cycle Lane; CT = Cycle Track

in no or several interactions of one or more types per cyclist.

For each of these conflict points, interactions were counted and their criticality was assessed in a two-step approach: In the first step, four levels of interaction were determined by assessing cyclist compliance with traffic rules using the decision tree shown in Figure 3. This assessment scheme has been used before in Maier et al. (2015). Interactions of level 0 (full control) describe the interaction of two users whose routes cross each other, but whose compliance with traffic regulations creates a clear traffic situation. Interactions of level 1 (unobstructed) and level 2 (obstructed) require a reaction, and, thanks to this reaction, do not lead to a collision. In interactions of level 3 (collision), there is no or an insufficient reaction, leading to a collision. Level 2 and level 3 interactions can be considered as critical interactions because users who have right of way are affected by users who do not comply with the traffic rules.

A reaction was defined as braking, stopping, accelerating, swerving or other visible changes in behaviour. The definition of priority differs between the conflict points in Figure 2: at *Crossing 1*, *Crossing from the left* and *Crossing 2*, right-turning cyclists must give way to crossing users. At the *Approach*, users standing and waiting are considered as having priority. A cyclist overtaking a cyclist on the left or a motorised vehicle on the right-hand side at a distance of at least one metre is not violating traffic rules. For *Turning from the opposite*, right-turning cyclists have priority over the user turning left. Pedestrians on the *Pavement* always have priority over cyclists riding on the *Pavement*.

Interaction rates were computed to allow comparisons between the study sites and periods with different traffic volumes. They were calculated as the multiplied ratio of right-turning cyclists and the conflicting flow for each conflict point and user group with the following basic equation:

$$IR = \frac{no.\ of\ interactions}{10^{-3} \cdot V_{RTC} \cdot V_{CF}} \tag{1}$$

where:

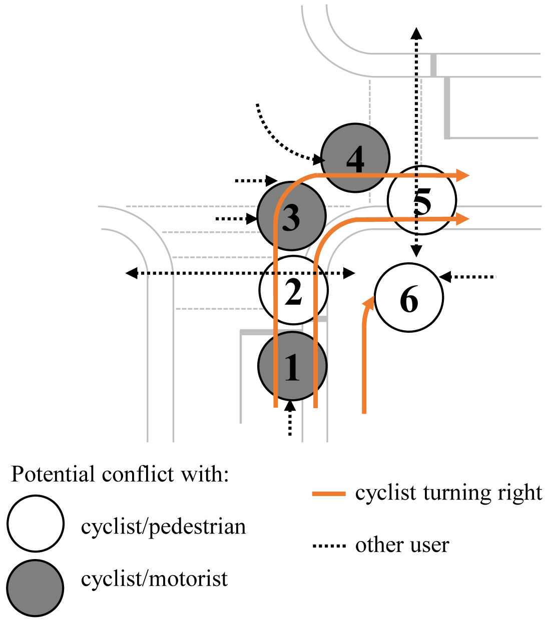
IR = interaction rate;
V_{RTC} = volume of right-turning cyclists;
V_{CF} = volume of conflicting flow.

The *Pavement* is the only conflict point for which the volume of the conflicting flow was not determined because the potential conflicting users are so diverse in behaviour (standing, playing, chatting on the pavement) and positioning (very close or very far to the traffic light) that no definition for the basic population of these users could be found and therefore they were not quantified.

In the second step, the Post-Encroachment-Time (PET) was computed to assess the criticality of the interactions in terms of the time elapsed between a user leaving a conflict point and the arrival of the conflict partner at that point (Zheng et al., 2021). PET is typically used in conflict studies on vulnerable road users (Liang et al., 2021) and was chosen here because it can be determined even if the conflict parties are not on a collision course. Time to Collision (TTC) was therefore not considered.

PET can only be recorded for interactions with crossing trajectories and was therefore only measured for the conflict points *Crossing 1*, *Crossing from the left* and *Crossing 2*. The PET values are interpreted as the cumulated frequencies, because an interpretation based on thresholds was not considered appropriate. PET values for interactions of levels 0 (full control) to 2 (obstructed) according to Figure 2 were included in the analysis because full control interactions might also have a small PET value. PET values larger than five seconds were not considered because higher values were assessed to be regular and non-critical

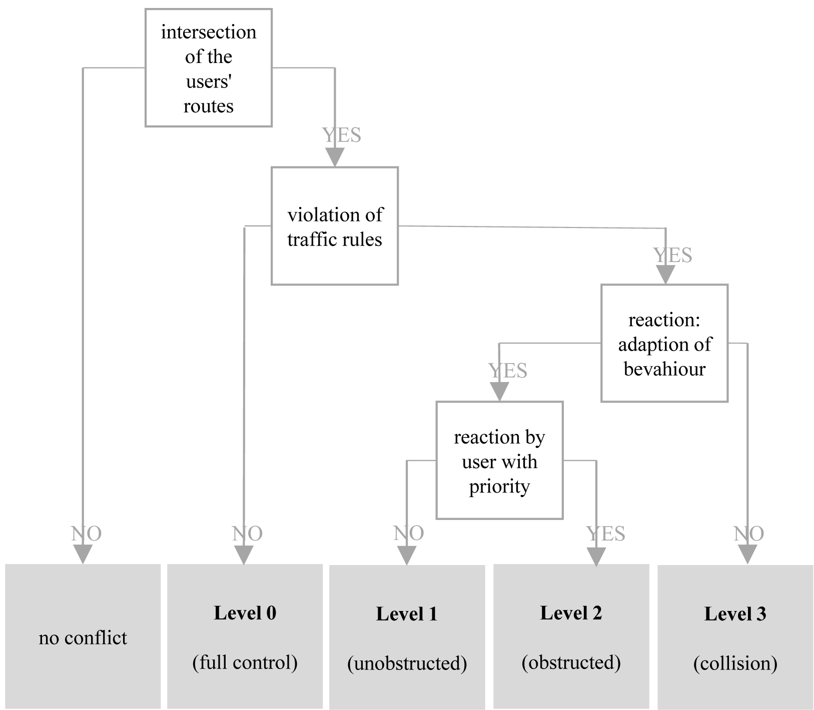
Illustration



Definition (interaction between a cyclist turning right and …)
① Approach: cyclists or motor vehicles stopping in the access road
② Crossing 1: cyclists or pedestrians crossing the approaching leg
③ Crossing from the left: cyclists crossing on cycle lanes or cyclists or motor vehicles travelling straight ahead on the carriageway from the left
④ Turning from the opposite: oncoming left-turning cyclists or motor vehicles
⑤ Crossing 2: cyclists or pedestrians crossing the exiting leg in parallel
⑥ Pavement: cyclists or pedestrians on the pavement in longitudinal traffic

Figure 2 Pre-defined conflict points

Illustration (decision tree on level of interaction)



Definition
Level 0 (full control): All users behave in compliance with the rules and react in a controlled manner.
Level 1 (unobstructed): At least one of the users involved does not comply with the rules, but there is still enough space and time available so the road users with priority do not have to adapt their behaviour.
Level 2 (obstructed): At least one of the users involved does not comply with the rules and the road users with priority must adapt their behaviour to avoid a collision.
Level 3 (collision): At least one of the users involved does not behave according to the rules and the users touch each other.

Figure 3 Level of interaction definition

interactions (Beitel et al., 2018; Liang et al., 2021). Interactions measured with PET were differentiated according to whether the right-turning cyclist is the first or the second to leave the conflict area.

The final set of criteria for the analysis includes the compliance with traffic rules, interaction numbers and rates, levels of interaction in terms of compliance with the traffic rules and PET as a SMoS measuring the criticality of an interaction. Each indicator is analysed and interpreted individually to create a detailed understanding of cyclists' changes in behaviour and their implications resulting from the introduction of RTOR for cyclists at the 43 study sites. The results are presented as average effects across all study sites, weighted by the number of sites per type of cycle provision as introduced in Table 3. Differences between the individual types are described in the text, if these are found to be significant.

5 Results

The presentation of the results is organised along the research aims for this study as introduced above. Changes in cyclists' compliance with traffic rules are described in section 5.1, followed by the findings on changes in the numbers and rates of interactions due to RTOR in section 5.2 and the assessment of their criticality in terms of yielding behaviour in section 5.3. Finally, the criticality of interactions measured as PET is presented in section 5.4.

5.1 Compliance

Table 4 gives an overview of cyclists' compliance with traffic regulation in the before and after observations. 51% of the observed right-turning cyclists arrive at green in the before and 46% in the after observation and are therefore not affected by the RTOR regulation. Of the cyclists arriving at red light, 80% turn right on red before and 92% after the introduction of RTOR which corresponds to an increase of 15%. Five percent of the cyclists turning right on red in the before period and six percent in the after period stop before turning. For cyclists turning right on red, the share of cyclists using the pavement instead of the cycle provision (mixed traffic, cycle lane or cycle track) decreases from 40% to 30% with the introduction of RTOR.

Looking in at the changes in compliance for the different cycle provisions in more detail, the share of cyclists turning right on red is highest at 97% at sites with a cycle track in the approach and any cycle facility (either track or lane; CT–CL and CT–CT in Table 3) in the exit with hardly any change in the after period (99%). The largest change in the proportion of cyclists running red lights, from 49% in the before to 86% in the after period, is observed at sites with mixed traffic provision in the approach and the exit (MT–MT in Table 3). No differences for the share of cyclists who stop before turning right on red are identified for the different types of cycle provisions, these shares are consistently low at all sites and in both periods.

For cyclists turning right on red, the proportion of cyclists using the pavement is highest at around 80% (both before and after) for sites with a cycle track in the approach and any type of cycle facility in the exit (CT–CL, CT–CT in Table 3), when cyclists are already at pavement level and do not have to climb a kerb to access the pavement. The share of cyclists riding on the pavement in the before period is lowest for mixed traffic provisions in the approach at 29% (MT–MT, MT–CL, MT–CP in Table 3). The largest change in behaviour was found for sites with mixed traffic both in the approach and exit (MT–MT in Table 3) where the share of cyclists on the pavement decreased from 27% in the before to eight percent in the after observation.

In addition to the cyclists as listed in Table 4, we observed persons that reach the traffic light at red as a cyclist, dismount before the stop line, step onto the pavement and push their bicycle to continue cycling after having left the intersection. This behaviour occurred 26 times in the before and 10 times in the after period which are low numbers but still a substantial decrease. The impact of this specific user behaviour on interactions is assumed to be low due to the small numbers. However, the comfort might improve for cyclists when they stop changing to the pavement with the new RTOR regulation and instead complete their right-turn manoeuvre as cyclists on the carriageway. Persons dismounting and pushing their bicycle are not considered in further analysis.

About 90% of cyclists arriving on red light and cycling straight ride on green light with no significant change between the before and after periods. Differences between the different types of cycle provisions are generally low for this group and are therefore not interpreted.

Table 4 Observed cyclists and compliance with traffic rules in the before and after observations

Observation		Before		After	
		abs.	rel.[%]	abs.	rel.[%]
Cyclists turning right	arrival at red light	681	100	952	100
	and wait for green	138	20	71	7
	ride on red after stop	25	4	50	5
	ride on red without stop	518	76	831	87
	ride on red (with or without stop)	543	100	881	100
	and cycle on the cycle provision	328	60	613	70
	cycle on the pavement	215	40	268	30
	arrival at green light	707	-	800	-
Cyclists riding straight	arrival at red light	3 555	100	4 520	100
	and wait for green	3 116	88	4 045	90
	ride on red	439	12	475	10
	arrival at green light	4 739	-	5 792	-

5.2 Interaction numbers and rates

Concerning interactions involving cyclists turning right on red, the total number of observed interactions is generally low. For 543 cyclists turning right on red before introduction of RTOR, 411 interactions are recorded. For 881 cyclists turning right on red with RTOR, 811 interactions are identified. This is on average less than one interaction per cyclist (0.75 interactions per cyclist before; 0.92 interactions per cyclist after) and less than 20 interactions per site across all 43 study sites.

Table 5 shows the total numbers of interactions by conflict points and levels. In both periods, interactions in the *Approach* have the highest share followed by interactions with users on *Crossing 1* and *Crossing from the left*. Interactions on *Crossing 2* and on the *Pavement* are relatively rare. The observation of interactions with users *Turning from the opposite* is with 6 (before) resp. 12 (after) so low in numbers, that they do not allow comparisons of behaviour in the before and after observations. Interactions at this conflict point are therefore not considered further.

The total number of interactions is divided by the volumes of the different conflicting flows to calculate the interaction rates which are shown in Figure 4 by conflict point and user group. Unlike the interaction numbers, the interaction rates are approximately in the same magnitude for all conflict points, showing the high relevance of the exposure for interaction numbers.

The interaction rates increase between the before and after observations for each conflict point except the *Pavement* where only the volumes of right-turning cyclists are considered.

In the *Approach*, the majority of interactions occur with other cyclists in both periods and, there is also a substantial increase in cyclist-cyclist interaction rates from before to after observations. A qualitative investigation of selected single sites with particularly high or increased interaction rates with the introduction of RTOR shows that the interactions increase most at sites with mixed traffic provision for cyclists, bike boxes and when traffic volumes increase between before and after periods. Interaction rates with users *Crossing from the left* look similar in magnitudes and involved user groups to interaction rates in the *Approach*. They are also observed mainly with other cyclists and also increase from the before to the after period. Interaction rates cyclist-motorist hardly change at both conflict points (*Approach, Crossing from the left*). The qualitative investigation of selected sites shows the high relevance of sufficiently long sight lines and traffic volumes particularly for interactions with users *Crossing from the left*.

Interaction rates of cyclists with pedestrians at the crossings (*Crossing 1* and *Crossing 2*) are approximately the same in the before and after periods, but cyclist-cyclist interaction rates increase substantially in the after period. Interaction rates are higher at *Crossing 1* than on *Crossing 2* which is

Table 5 Observed total numbers of interactions for cyclists turning right on red in the before and after observations by conflict points and levels of interaction

Observation		Before		After	
		abs.	rel. [%]	abs.	rel. [%]
Conflict points	TOTAL	411	100	811	100
	① Approach	126	31	360	44
	② Crossing 1	95	23	140	17
	③ Crossing from the left	99	24	209	26
	④ Turning from the opposite	6	1	12	1
	⑤ Crossing 2	30	7	55	7
	⑥ Pavement	55	13	35	4
Level of interaction	TOTAL (④ excluded)	405	100	799	100
	Level 0 (full control)	80	20	180	23
	Level 1 (unobstructed)	289	71	561	70
	Level 2 (obstructed)	36	9	58	7
	Level 3 (collision)	0	0	0	0

plausible seeing that crossing road users at *Crossing 2* usually have a red light when cyclists turning right on red arrive at *Crossing 2*. Interactions at this conflict point can only occur when users cross at red or in the time when one phase changes to the next.

Interactions on the *Pavement* occur less frequently after the introduction of RTOR because fewer cyclists ride on the pavement.

5.3 Criticality of interactions assessed as cyclist behaviour towards users with priority

The shares of levels of interaction in Table 5 only change marginally between the before and after observations. Interactions of level 1 (unobstructed) have the highest shares at around 70%, followed by interactions of level 0 (full control) at around 20% in before and after periods. Interactions of level 0 (full control) are not possible for cyclists turning on red light in the before period at all crossing interactions because cyclists who ride on red automatically violate traffic rules. The share of level 2 (obstructed) interactions is low in the before and after periods and no interactions of level 3 (collision) are identified.

Figure 5 presents the shares of the level of interactions for each conflict point. In the *Approach*, the share of level 0 (full control) interactions is at 65% in the before period and therefore by far the highest compared to all other conflict points. This is because passing other users that wait at the traffic light is the only possible movement without violating traffic rules before the introduction of RTOR because users at that stage (in the *Approach*) did not run a red light. Additionally, cyclists seem to pass other users waiting at the traffic light mainly without violating traffic rules (e.g., overtaking on the wrong side and/or with insufficient distance). The share of level 0 (full control) interactions decreases substantially to 27% in the after period. This reduction shifts to a share of 61% of level 1 (unobstructed) interactions in the after period. The share of level 2 (obstructed) interactions is generally highest in the *Approach* and increases slightly from the before to the after period.

The proportion of levels are similar in magnitudes at *Crossing 1* and *Crossing from the left* in both the before and after period with increasing proportions of interactions at level 0 (full control) from before to after observations. There are higher interaction rates in the after period at these conflict points but a higher share of those interactions happen in a controlled way (level 0). The increasing shares of level 2 (obstructed) interactions at *Crossing 1* point to a different direction and show more critical interactions in the after period but the overall shares of level 2 (obstructed) interactions at this conflict point are generally low with seven (before) and nine (after) percent.

The major share of interactions is at level 1 (unobstructed) on *Crossing 2* and on the *Pavement*.

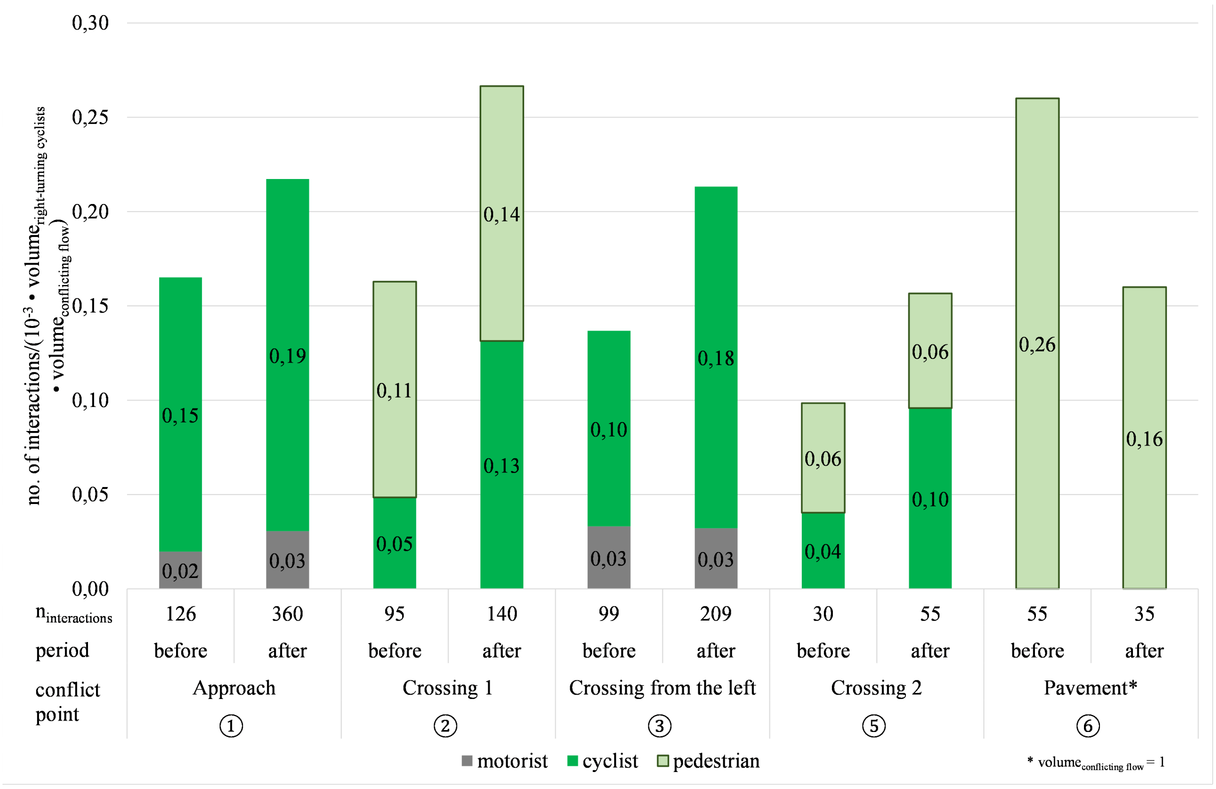


Figure 4 Interaction rates of cyclists turning right on red in the before and after observations broken down by conflict points and users

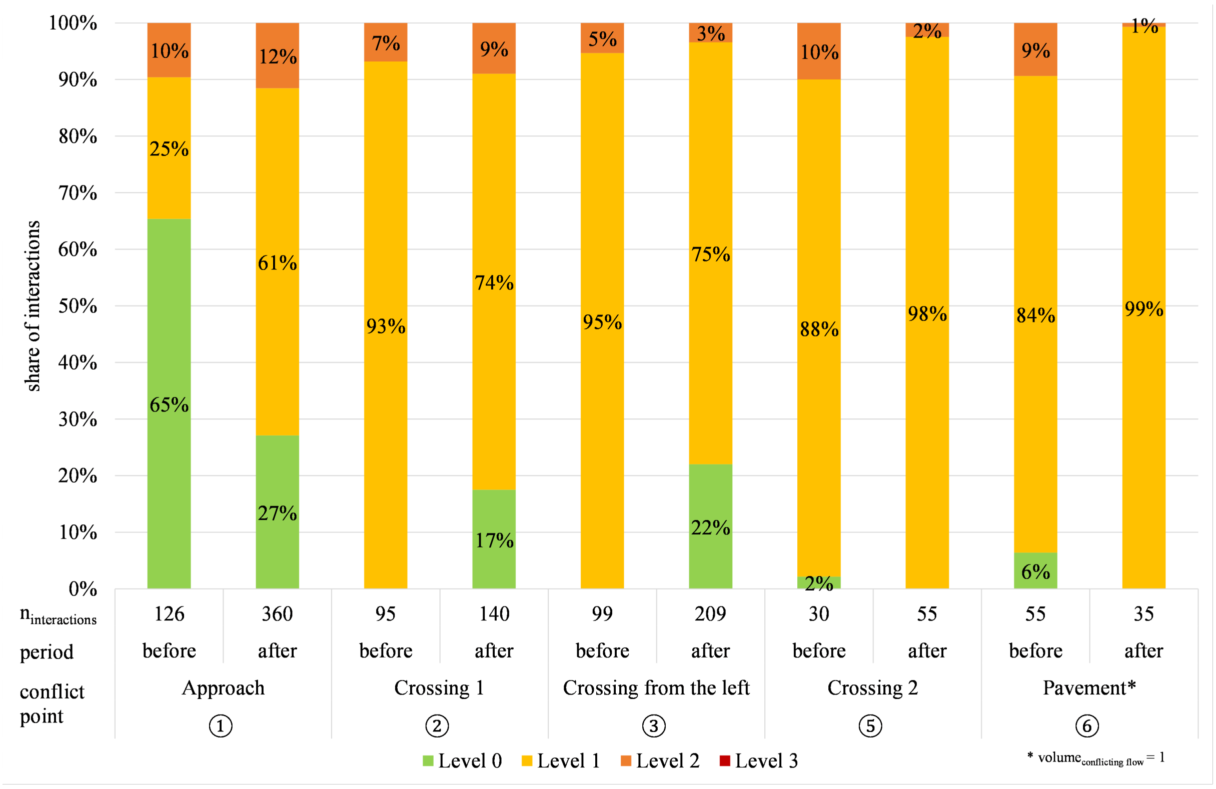


Figure 5 Levels of interaction of cyclists turning right on red in the before and after observations broken down by conflict points

Level 2 (obstructed) interactions decrease at both these conflict points from the before to the after periods so that overall, RTOR seems to lead to an improvement concerning levels of interaction at these points.

5.4 Criticality of interactions measured as PET

The presentation of the cumulative frequencies of the PET values in Figure 6 shows the total number of observations, which is 200 in the before period and 329 in the after period. The number of PET values is smaller than the total number of interactions, because only PET values of less than five seconds are considered and because PET could not be recorded for all interactions (e.g. due to obstructed vision).

The overall variance of PET values is higher and differences between the before and after observations are more distinct in the left panel of Figure 6. Variance is mainly skewed to the left. This means that PET values without RTOR are significantly lower than with RTOR when right-turning cyclists are the first to leave the conflict area. This holds particularly for smaller PET values below two seconds and for the conflict point *Crossing from the left*. For *Crossing 2*, the low number of cases needs to be considered and only allows cautious interpretation. One possible reason for the higher PET values with RTOR might be that cyclists feel more comfortable and confident and therefore complete their manoeuvre to turn right on red in a less risky way. The low PET values at conflict point *Crossing from the left* are plausible as the speed of users *Crossing from the left* (motorists and cyclists) can be assumed to be higher than on *Crossing 1* and *Crossing 2* (only pedestrians and cyclists).

6 Discussion

The aim of this study was to analyse changes in cyclists' compliance with traffic rules before and after the introduction of RTOR and related changes in interactions. The results of this study confirm the tendencies found in the pilot studies as introduced in Section 2.1, and, for the first time, add detailed insights on the number, type and criticality of interactions before and after the introduction of RTOR.

In terms of compliance as the first research aim for this study, the identified high and increasing red-light running rates for right-turning cyclists before and after the introduction of RTOR are in line with the pilot studies (BIVV, 2012; Egeler et al., 2015; Störr et al., 2017) and with previous studies investigating red light running (Richardson & Caulfield, 2015). Red-light running rates are highest on cycle tracks when cyclists are already at the pavement level which is also in line with the literature (Schleinitz et al., 2019).

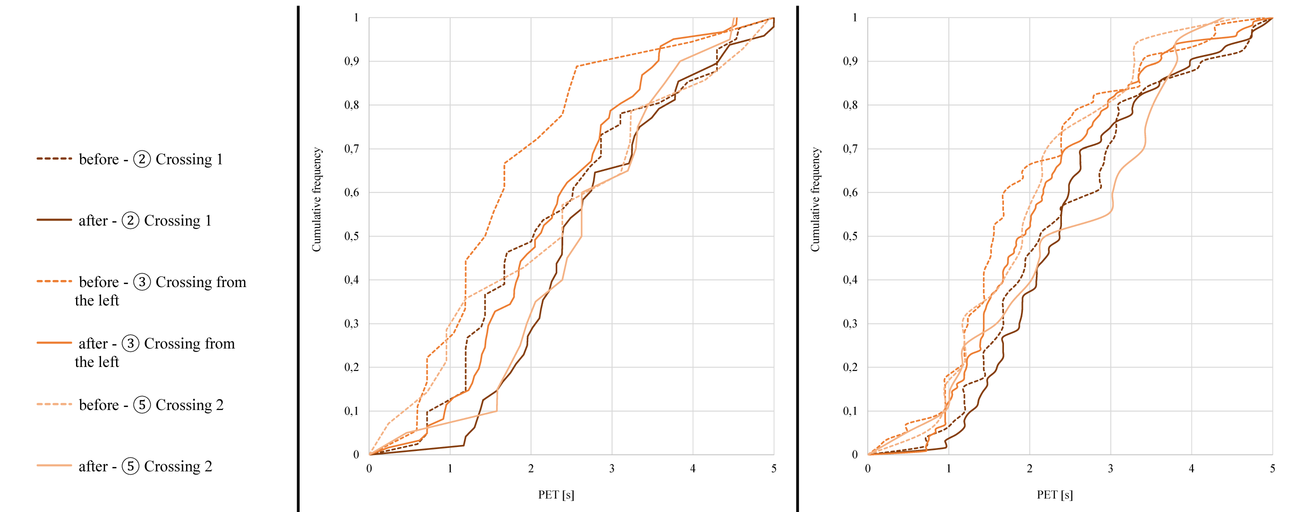
For the conflict analysis, the absolute interaction numbers are highest in the *Approach*, followed by *Crossing 1* and *Crossing from the left,* they are low on *Crossing 2* and on the *Pavement*. In addition, the increase of the absolute interaction numbers is most substantial in the *Approach* when RTOR is introduced. Interaction rates are in the same magnitude at all conflict points, they decrease on the *Pavement* and increase at all other conflict points from the before to the after period. Interaction criticality in terms of levels remains stable and PET values increase with the introduction of RTOR.

The increasing interaction rates indicate that cyclists turn right on red more frequently with RTOR, despite the presence of other road users, but they seem to do this with more confidence and less hastily so that PET values also increase. Interactions in the *Approach* are of particular relevance in the before and after period which is in line with the pilot studies that also find high and increasing numbers of cyclists wriggling through other road users (Egeler et al., 2015; Störr et al., 2017).

Interaction rates mainly increase between cyclists so that overall, pedestrians seem to benefit from RTOR. Fewer cyclists ride on the *Pavement* in the after period, interaction rates pedestrian–cyclist at *Crossing 1* or *Crossing 2* remain stable and interaction rates at the *Pavement* substantially decrease between the before and after period. The decreased share of cyclists using the pavement with RTOR is consistent with the pilot studies (Certu, 2012; Eriksson, 2016) and with Ihlström et al. (2021) who find the smoothness of the ride being one main reason for cyclists to change to the pavement.

The low percentage of cyclists complying with the obligation to stop at RTOR in this study is also in line with the identified previous studies in Germany (Maier et al., 2015; Schleinitz et al., 2019). No international studies from other countries could be found investigating this aspect because this specific requirement only applies in Germany and Austria.

No spillover effects between right-turning cyclists and cyclists going straight are identified with RTOR which supports the overall finding that benefits from RTOR outweigh negative effects. Interaction rates



	Right-turning cyclist is the first to leave the conflict area		Right-turning cyclist is the second to leave the conflict area	
Conflict Point	Before	After	Before	After
② Crossing 1	41	48	51	63
③ Crossing from the left	18	61	57	117
⑤ Crossing 2	14	20	19	20

Figure 6 Cumulative frequencies of PET values for cyclists turning right on red in the before and after observations broken down by conflict points and the position of the right-turning cyclist leaving the conflict area first (left) or second (right)

between cyclists and motorised vehicles are low with and without RTOR, the main challenges of RTOR are related to cyclists' interactions with other cyclists and pedestrians.

7 Recommendations and conclusions

To address the third research aim of this study, recommendations for operating conditions for RTOR are developed based on the empirical insights gained so far. The increased number of cyclists turning right at red leads to higher interaction rates, particularly in the *Approach*, for cycle provision in mixed traffic and with many straight-riding cyclists who wait for green and are overtaken by right-turning cyclists. RTOR for cyclists should therefore only be implemented where sufficient space for overtaking cyclists in the *Approach* is available. The Danish regulation that RTOR for cyclists can only be implemented at traffic lights with cycle tracks with separate lanes for going straight and turning right in the approach of the intersection might be appropriate to ensure that sufficient space for overtaking is available. Interactions mainly increase between cyclists with the introduction of RTOR which should therefore preferably be implemented at intersections where either crossing cyclist volumes are low or where the proportion of cyclists riding straight in the same approach is not dominant. A critical issue in the detailed investigations of all conflict points at selected sites was good sight conditions. It is essential that users can see the approaching traffic not only when stopped, but also when approaching the intersection.

The approval of RTOR for cyclists was recommended for Germany in parallel to this study and was officially introduced in the 2021 amendment of StVO (StVo, 2023). The above recommendation of low traffic volumes has been added to VwV-StVo (2021).

While this study provides novel insights, it also has limitations. These include the case numbers which are low for some analyses even though the overall sample of 43 sites is large and required substantial resources for the investigation. Speed of conflict parties, further details of signalling such as cycle and waiting times as well as cyclists' and pedestrians' perceptions of behaviour and interactions could not be considered. Interaction rates assume a linear relationship between user volumes and interactions which has not been proved in detail. More empirical evidence on person-related determinants of cyclists' behaviour and interactions with RTOR would also be beneficial and could be compared with previous studies on general red-light running (De Ceunynck et al., 2016; Johnson et al., 2011; Su et al., 2023; Van der Meel, 2013).

Future international research on the effect of RTOR for cyclists and of signalling in general for the behaviour of cyclists and other road users would help to validate the findings from this study in terms of transferability to other local contexts. The two-stage methodological approach applied in this study for conflict analysis as the combination of compliance with priority and PET values proved suitable and provides detailed insights into the behavioural mechanisms. Further applications of this approach and research on suitable indicators and thresholds for analysing conflicts between vulnerable road users would be desirable, as there is little knowledge in this area to date. A long-term accident analysis could help to better understand the impact of RTOR on safety, but it was not yet possible because most RTOR signs in this study have not been in place for a sufficiently long time (three years) to analyse changes in accidents. Additionally, the possible period of analysis (2021–2023) is affected by the COVID-19 pandemic and its aftermath which result in major changes in bicycle volumes.

Overall, this study shows that the RTOR legalises behaviour that already existed before but that is now practised by cyclists in a more confident way with higher PET values to the other road user groups. With RTOR, more cyclists use the cycle facilities provided in the carriageway; the resulting increased interaction rates particularly in the *Approach* need to be addressed with suitable design solutions. The higher share of cyclists in the carriageway with RTOR is beneficial for pedestrians so that overall, RTOR can be recommended as an easy-to-implement possibility to support cycling given that the criteria for suitable designs of cycle facilities developed in this study are respected.

CRediT contribution statement

Bettina Schröter: Data curation, Formal analysis, Investigation, Software, Visualization, Writing—original draft. **Sebastian Hantschel:** Conceptualization, Formal analysis, Funding acquisition, Investigation, Methodology, Supervision, Visualization, Writing—review & editing. **Miriam Niestegge:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Visualization. **Hagen Schüller:** Conceptualization, Funding acquisition, Methodology, Project administration, Supervision. **Regine Gerike:** Supervision, Writing—original draft, Writing—review & editing.

Declaration of competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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