

Research Article

Analysis of interactions between crossing cyclists at intersections based on trajectory data[☆]

Claudia Leschik^{*}, Kay Gimm

Institute of Transportation Systems, German Aerospace Center (DLR e. V.), Lilienthalplatz 7, 38108 Braunschweig, Germany



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ABSTRACT

Cyclists have the option of crossing at various streets and intersections, with or without traffic lights, and with or without a bicycle path. Frequently, the traffic regulations pertaining to cross on vehicle lanes are clearly stipulated for cyclists as well. However, in Germany, the situation regarding bicycle paths is often more complex. In Germany, a total of 32% ($n = 1565$) of all bicycle-bicycle accidents in 2023 ($n = 4867$) were accidents involving injuries when cyclists crossed paths, resulting in 3 deaths [7]. Due to the paucity of research on intersection behaviour, it is imperative to ascertain how cyclists behave when crossing on a daily basis and whether critical interactions frequently occur. This publication presents the research methodology and descriptive results of two traffic observations and a related survey. One observation was conducted at a signalised urban intersection with separated bicycle and footpaths, and the other one at a non-signalised intersection without a separated bicycle path. Both locations are in Braunschweig, Germany. At these intersections, the trajectories of road users were recorded by using camera systems and subsequently analysed with the aim of identifying interactions between crossing cyclists. It appeared that there was direct crossing of the path or a merging of the two bicycle paths. At the main measurement location, a total of 171 h of video data were analysed. Of these, 120 interactions were recorded at a PET ranging from -3 to 3 s. A low PET is often considered a safety critical indicator of an interaction. 2.2% of interactions occurred at a PET between -1 and 1 s, suggesting an elevated possibility for conflict. The results indicate that, irrespective of the presence of traffic lights on the bicycle path or the absence thereof, approximately only 50% of cyclists yield to other cyclists, which have the right-of-way. A survey conducted as part of this study revealed that many cyclists are unaware of the rules that govern their use of bicycle paths. A second measurement location without a bicycle path also shows that around 50% of cyclists give way. Due to the width of the road, distances and PET values are greater, but speeds are also higher. The study highlights the serious potential for cyclist conflicts at intersections and the need to develop mitigating measures like education.

1. Introduction

Cycling is becoming increasingly popular, as recent sales of bicycles have indicated [1]. Cycling also helps saving carbon dioxide emissions, reduces air and noise pollution and is healthier than driving a car [2]. However, an increase in the number of cyclists can lead to an increased number of interactions and resulting conflicts on the bicycle path. At intersections, cyclists travelling in different directions cross each other's paths.

The aim of this study is to analyse how cyclists cross each other and to investigate the adherence to the priority to the right rule in Germany.

The study will provide a general understanding of the crossing behaviour between cyclists. This enables the implementation of measures to enhance infrastructure and develop realistic traffic behaviour models for cyclists in simulations. The structure of the remainder of this paper is as follows: firstly, the current state of related work is proposed in Section 1. Then, in Section 2, the relevant methods are introduced, which are applied in Section 3 to present the results of two different measurement locations and a survey. The obtained results are interpreted and discussed in Section 4. Finally, in Section 5, the paper is summarised and prospects on future work are presented.

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^{*} Corresponding author.

E-mail addresses: Claudia.Leschik@dlr.de (C. Leschik), kay.gimm@dlr.de (K. Gimm).

1.1. Legal situation

If a traffic light system for cyclists is installed, the legal situation is clearly regulated in Germany. Cyclists are obliged to stop at the bicycle traffic light when it shows red.

In the absence of an explicit bicycle traffic light, attention must be paid to the design of the intersection. There are no traffic signs that clearly regulate the right-of-way; however, there are signs that indicate when one is allowed to ride and when one should stop. The following evidence suggests that a cyclist is not obligated to stop at traffic lights for vehicles on the bicycle path. However, should one of the points from a-d not apply, it is possible that the cyclist may be obliged to stop. The definition of this is not clear. [3]:

- a. The traffic lights for motor vehicles end in front of the bicycle path and do not include it.
- b. There is a waiting area between the road and the bicycle path for crossing pedestrians and cyclists to stop.
- c. The bicycle path does not have a stop line (often not present even when stopping is required).
- d. The bicycle path is not interrupted by a footpath or other path.

Often, even local residents are unaware of the legal situation. The same rules apply for bicycles at intersections without bicycle infrastructure and without traffic lights, whether these are priority roads, priority to the right streets or streets with equal rights (§ 8 (1) sentence 1 StVO (German Highway Code)).

In this study, an intersection is examined where points a-d apply: collated path and the crossing cyclist must give way (Fig. 1A). This has been confirmed by the local police. Furthermore, a case study of an intersection without a designated bicycle path, situated within a 30 km/h zone and governed by priority to the right rule, is presented (Fig. 1B).

1.2. Literature review

The present study examines the behaviour of cyclists crossing each other on bicycle paths. There are already numerous studies that deal with bicycle accidents at junctions, but these mostly concern conflicts between bicycles and motorised vehicles [4,5]. In [6] it was found evidence that cyclists were more likely than car drivers to violate the right-of-way at the intersection in a 30 km/h zone.

The Unfallatlas (Accident Atlas) is a compilation of data on road accidents, collated by the Federal and State Statistical Office of Germany. The data is derived from police reports and presented in an online map format, which allows users to interact with the information. Alternatively, the data can be downloaded as Open Data. The statistics do not include accidents where the police was not called. Before publication, the reported accident data is subject to a plausibility check, which may lead to the exclusion of individual accidents. On average, 90% of the accidents reported for each federal state are finally mapped

and made usable. [7] In 2023, there were 4867 reported incidents of bicycle-bicycle accidents in Germany, with 32% of these classified as crossing accidents and 36% as accidents involving oncoming bicycle traffic. The remaining incidents were divided between overtaking and cycling in a convoy.

A study of 148 bicycle-to-bicycle crashes in the Netherlands [8] found that approximately 12% of all crashes occurred while crossing. However, no additional details were provided concerning the manifold characteristics and causes of crossing. To date, the behavioural patterns exhibited by cyclists during such interactions have received scant attention from researchers.

In a study of cyclists' behaviour in a bicycle simulator, [9] examined the behaviour of cyclists at various sections of the route. At the unsignalised intersection, it was found that some of the cyclists disregarded the right-of-way. However, it is not clear whether this would also apply in reality.

In a thesis of [10], an empirical investigation was conducted on two intersecting bicycle paths, one was designated with priority markings and the other without. The study revealed that, in the absence of priority markings at the intersection, cyclists from the right were accorded precedence, and of the 158 conflicts observed, 61% of cyclists yielded to those with higher priority. The authors concluded that the implementation of priority markings has a positive influence on the priority behaviour of cyclists.

The current literature on the topic is limited, with only a small number of studies addressing the potential for conflict in the context of bicycle-to-bicycle accidents during crossing manoeuvres. The subsequent section will provide a detailed overview of the relevance of the scenario and the relevance of the study.

2. Methods

The collection of cycling data can be achieved through a variety of methods. These include the use of traffic censuses, induction loops or GPS devices (smartphones or additional devices). Additionally, traffic observation with camera systems can be employed to receive naturalistic bicycle traffic data, which is especially helpful for analysing traffic behaviour on a microscopic level. In order to analyse interactions between cyclists at intersections, trajectory data from traffic observations in Braunschweig, Germany was used. The trajectory data included route, speed and distance. Video annotation was also used for verification.

2.1. Traffic observation

Two traffic observations were conducted. A local Research Intersection was selected for the study of the crossing behaviour of cyclists. At this location a survey was conducted to explain the observed riding behaviour. As a comparison, a 30 km/h zone was examined with mobile traffic measuring technology in the absence of a bicycle path and without traffic lights.

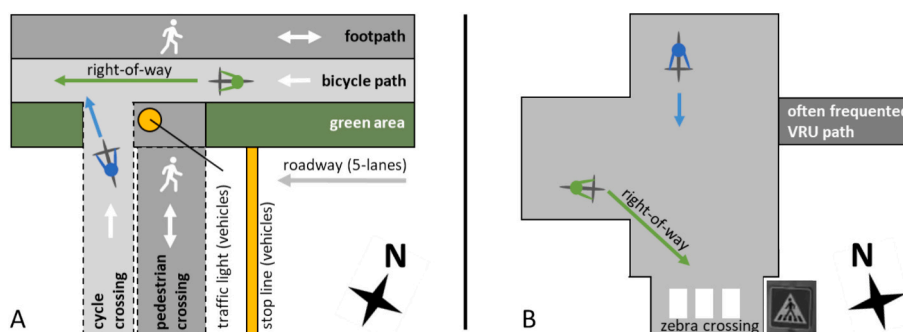


Fig. 1. Schematic illustration of A: The Research Intersection, where cyclists have the priority to the right on the bicycle path; B: The intersection in a 30 km/h zone without bicycle path and without traffic lights.

2.1.1. Research intersection

The main study took place at the Application Platform for Intelligent Mobility (AIM) Research Intersection in Braunschweig, Germany. It is a traffic light-controlled intersection with bicycle path and footpath (Fig. 2A). This large-scale research facility is an instrumented intersection that records trajectory data at 20 fps based on 14 stereo camera-systems. The north-eastern area was chosen for investigation because of the better field of view of the detection system (Fig. 2B).

The north-eastern crossing location is highlighted in yellow in Fig. 2C and shown in detail in Fig. 3 (right). The red markings in Fig. 2A and Fig. 3 (right) show the location of the camera-system and coverage area that were used for this study.

Fig. 3 (left) shows the measurement location as a sketch (green for cycle traffic, purple for pedestrian traffic, traffic lights for vehicles (C) and pedestrians (P) are illustrated; traffic lights for cycle traffic do not exist in this section). It shows that the traffic light for motor vehicles terminates before the bicycle path and does not encompass the bicycle path. Therefore, cycle traffic approaching from the east is not required to observe the motor vehicle traffic light.

2.1.2. Intersection in a 30 km/h zone

For reference data without bicycle infrastructure, data from the @city project is reused [11]. There are publications on interactions between vehicles or cyclists and other vehicles [6,12]. The study area is located at the street Büldenweg in Braunschweig, Germany. One camera was positioned to capture the northern area of Büldenweg (Fig. 4B), while a second camera was placed to cover the southern section (Fig. 4C). The collection of data was facilitated by two mobile structures (Fig. 4A). These devices are equipped with the same hardware and software as the Research Intersection [13]. However, a salient feature of these devices is their portability. The mast is equipped with two stereo cameras and an IR flash for illumination at night.

The location is subject to a 30 km/h speed limit, and priority to the right rule applies. The area in question is situated between Spielmannstraße and Büldenweg in Braunschweig, Germany. Cyclists travelling from the west to the north/south can cross with bicycle traffic coming from the north or south at this point. In the east, there is a small road that is not a classified road. There is a zebra crossing in the south.

2.1.3. Data processing

The data processing is the same for both measuring sites. Data includes GNSS-based timestamp, location, speed, acceleration, user type (e.g. pedestrian, bicycle or car) and size of each detected user [13].

Stereo video signal processing is used to capture the objects. This is based on spatial correlation, which calculates distances in the image using the Hamming distance (disparity). Temporal correlation is also employed, which links identical pixels in successive images (optical flow). The linking of disparity measurements in consecutive images allows the speed of pixels to be measured directly. This means that the position and speed of the traffic participants can be derived. [14,15] The accuracy is expected to be better than 25 cm of deviation on average per

trajectory. In tests with vehicles equipped with high-precision positioning systems at the Research Intersection, the lateral deviation was found to be better with a deviation in average of one digit in cm.

The trajectories of the detected traffic participants and video material with augmentation of the bounding box were stored in a database. In the initial level of processing (pose processing), infrastructural data is processed for the purpose of measuring individual objects. DLR's own open source tool, TASI (TrAffic Situation analysis and Interpretation), can be used to load, visualise and analyse data from the database or live from the ring buffer. TASI is a kind of collaborative toolbox that is constantly being expanded. [16]

2.2. Traffic analysis

At the Research Intersection a total of 171h of video material, recorded between 8 and 9 February 2022 (37h), 18–28 October 2022 (108h) and 26–27 April 2023 (26h) was analysed, with interactions most frequently occurring between 6 a.m. and 6 p.m. The time periods were selected because data were recorded for specific measurement campaigns.

The analysis of the intersection in the 30 km/h zone was based on data from the @city campaign (18 September 2019 to 28 September 2019). Interactions were only detected between 7 a.m. and 6 p.m., with the most frequent interactions occurring at 5 p.m.

It was checked when a trajectory intersected the area of interest and whether another trajectory also intersected it within 3 s using polygons. The polygon has been generously sized to accommodate many encounters. This pair of interactions was used for further analysis. In the calculation of intersections, the centres of the objects were used. In addition, it must be considered half the width of the steering wheel or half the length of the bike. Common length and width dimensions are 1.90 m and 0.70 m [17].

The complete data process is illustrated in Fig. 5 for the Research Intersection, which encompasses all the requisite processing steps from data recording, direction of travel detection to interaction analysis.

A five-stage methodology was applied: raw traffic information (video and trajectories) was recorded; trajectories were filtered by route classifications (East/West, West/East, West/South, and South/West); temporal and spatial relationships between filtered routes were identified to extract interaction scenarios; pattern recognition analysis was performed on these scenarios; and meaningful behavioural insights were derived from the identified traffic patterns. Subsequently, key parameters were calculated and the results were verified in the videos. The process for the intersection in the 30 km/h zone is similar.

The proximity of cyclists while crossing will be assessed. This will be done by calculating the post-encroachment time (PET) and predicted PET (pPET) and by calculating the minimum distances between cyclists as members of the so-called surrogate measures of safety (SMoS). For each crossing scenario, the PET is calculated as a measure to evaluate the situation in terms of traffic safety [18]. The PET measures the time interval between two vehicles when their paths cross. The first vehicle



Fig. 2. Application Platform for Intelligent Mobility (AIM) Research Intersection in Braunschweig, Germany. A: Aerial image of AIM Research Intersection (yellow: area of interest for this analysis; red: camera systems used in this analysis, with example in Fig. 2B); B: Stereo camera system; C: Perspective view of the crossing scenario.

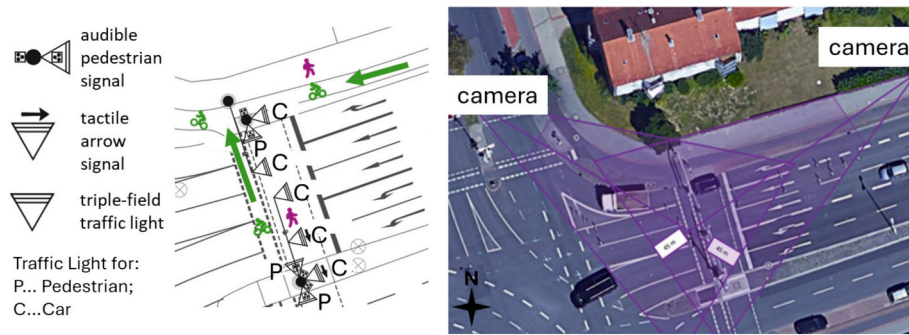


Fig. 3. Measurement location overview. (a) Site sketch showing cycle traffic (green), pedestrian traffic (purple), and traffic lights for vehicles (C) and pedestrians (P) (no cycle traffic lights present in this section). (b) Camera Position and coverage area used for this study.



Fig. 4. Place of measurement campaign at Bültengeweg, Germany. A: Mobile structure 1 (camera position shown in C); B: View facing north from the mobile structure; C: View facing south from the mobile structure.

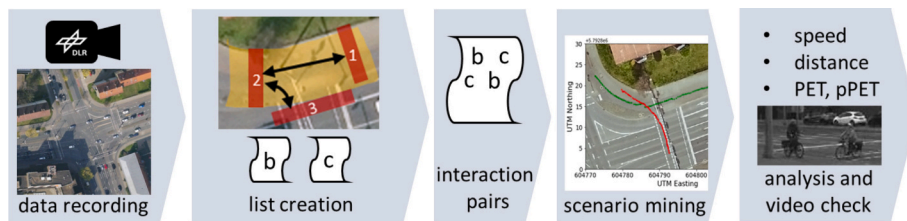


Fig. 5. Outline of the analysis procedure from data recording (left) to analysis (right) for the example of the Research Intersection.

exits the intersection at time t_0 , whilst the second vehicle enters at time t_1 . This temporal difference is used to calculate the PET value: PET value: $PET = t_0 - t_1$. Higher PET values indicate less critical interactions, as they suggest greater safety margins between road users. This occurs either because the vehicles naturally pass each other with sufficient clearance, or because one or both drivers have created additional space through braking or steering manoeuvres. PET values can be positive or negative, depending on which road user has priority. For example, a PET of +3 s or -3 s not only indicates the interaction's criticality but also reveals which road user crossed the conflict zone first (determined by the mathematical sign). In this study, a negative PET means that the cyclist with right-of-way passes through first, whilst a positive PET indicates that the cyclist without right-of-way passes through first. If the trajectories did not actually cross, for instance because of swerving, no PET was calculated. Instead, assuming both crossing cyclists maintain constant headings and velocities, the predicted PET (pPET) can be calculated for each time step based on their extrapolated paths. This calculation involves normalising distance vectors and projecting velocity to determine the velocity component directed towards the intersection point. For each object, the Time To Arrival (TTA) is calculated by dividing the distance to the intersection by this projected velocity. The pPET is then determined as the difference between the two TTA values.

For all proximity measurements, the Euclidean distances between the object centres of the interacting couples were computed. The identified interactions were checked manually in the video. Interaction pairs

were excluded where one or both of the trajectories were too short or too fractured. The dataset analysed did not differentiate between individual interactions or groups of cyclists.

The objective of the analysis is to ascertain the manner in which cyclists interact with other cyclists, the frequency with which the right-of-way is assumed or relinquished, and the near misses that occur between cyclists. Additionally, the analysis will examine whether there are any differences between an intersection in a 30 km/h zone without a bicycle lane and a bicycle lane at the Research Intersection.

2.3. Survey

Aim of the survey is to gather subjective data in addition to the objective data in the traffic observation to understand reasons for identified behaviour patterns for example not respecting the right-of-way. A total of 124 questionnaires were received, although not all were completed in full. Following a thorough examination, 104 questionnaires were deemed to be complete and were thus utilised in the subsequent analysis.

The online questionnaire was realised using SoSci Survey [19] and made available to participants at www.socisurvey.de.

The questionnaire consisted of nine pages, of which respondents had to complete eight, depending on the answer to the question about cycling in the wrong direction. The following pages of questions had to be answered:

- Data protection declaration of consent and information about the processing of the data
- General driving behaviour
- Query about previous wrong-way driving behaviour
- If the respondent had driven the wrong way at least once, they received the WWC questionnaire. In the event that the respondent asserted that they had never ridden the wrong way, they received the NC questionnaire.
- Query about crossing behaviour
- Demographic information
- A page for information on receipt of the questionnaire and a free text field for comments
- Last „thank you“ site

The survey period commenced on 23rd October 2024 and concluded on 31st December 2024. The final valid questionnaire was recorded on 3rd December 2024.

The wrong-way cycling part is not included in this study as it is part of another study.

3. Results

The results of the analysis at the Research Intersection with the associated survey are presented below, along with the comparative results for the intersection in a 30 km/h zone.

3.1. Research intersection

In the analysis, cyclists travelling from east mainly crossed with

those travelling from the south. These are the two main directions when cyclists ride in the correct direction of travel. Interactions with wrong-way cyclists were rarely observed and were not analysed in the following. The correlation between the total number of cyclists at the Research Intersection and the number of encounters in the intersection scenario is $R = 0.83$ ($p < 0.05$). This indicates that a higher number of cyclists results in an increased number of encounters, interactions and potential conflicts. In total, 282 encounters have been identified, within a 3 s time interval between crossing of two trajectory paths on a polygon area.

In the following, an encounter is to be understood as two cyclists being visible in the area of interest, but so far apart from each other that they do not influence one another and would presumably behave as they would have done if they had been travelling alone. An interaction involves an adaptation to the cycling behaviour; speed is gradually reduced, there is a switch from the bicycle path to the footpath to make room. Interactions are defined in this study as occurring between a (p)PET +3 s and -3 s. A conflict is rather more drastic than an interaction. Here, there is sharp braking, short-term evasive action, and the (p)PET is between -1.5 s and +1.5 s. These threshold values align with comparable ranges used in bicycle-vehicle interaction studies, where interactions are typically defined with PET values between ±1.5 and ±3.0 s and serious conflicts with PET values between -1.5 s and +1.5 s [20–22]. The boundaries between these categories are fluid, reflecting the continuous nature of traffic safety criticality.

3.1.1. Interactions

The PET and pPET values were calculated for the 282 trajectory pairs, and the values between -3 and 3 s were further analysed.

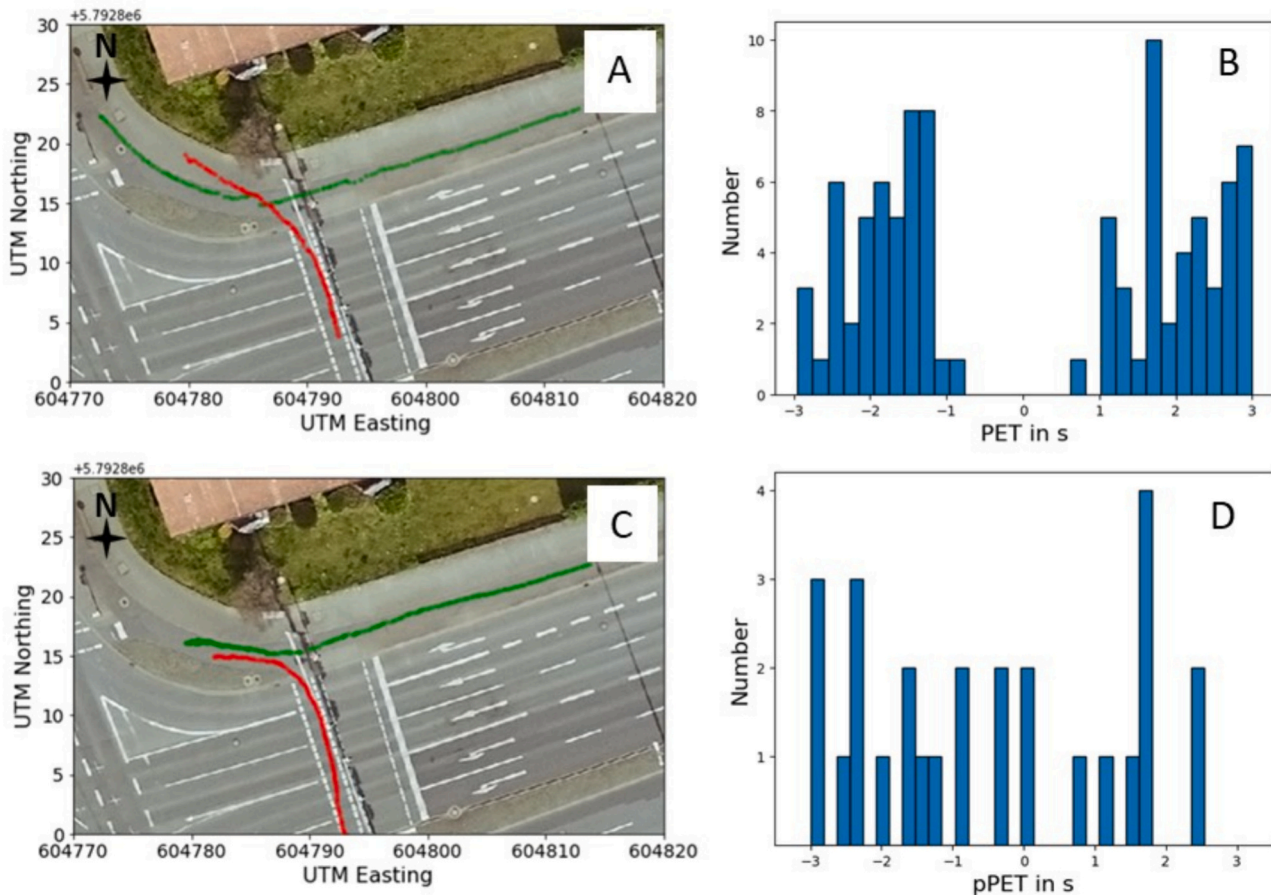


Fig. 6. Traffic interactions: (A) with (spatial) crossing, (B) corresponding PET calculation at intersection point, (C) without (spatial) crossing, (D) corresponding pPET calculation without intersection point. For the p(PET) calculation, ego is the cyclist from the east and the second user is the cyclist from the south.

93 of the 282 encounters have a PET within 3 s, as their trajectories intersect in the area of interest. Fig. 6a shows an example of a trajectory for two cyclists crossing each other, where the cyclist coming from the south crosses the bicycle path and continues north on the footpath.

For further 27 pairs, no PET could be calculated because the trajectories did not cross directly, but it was determined where they had headed, their distances between them and their speeds. Fig. 5c shows trajectories that do not intersect, although the cyclist from the south merges onto the bicycle path.

In the following discussion, the 120 cases with a crossing point ($n = 93$) and in which merging was observed ($n = 27$) will be examined in greater detail. In 69 out of 120 cases where PET or pPET was within 3 s, it was possible without annotation to ascertain the direction in which the cyclists continued after the interaction. Of the cyclists travelling from a southerly direction, 38 continued in a northerly direction and 31 continued in a westerly direction. With the exception of one case, all cyclists riding from a southerly to a westerly direction were using the designated bicycle path, while 90% of those riding from a southerly to a northerly direction used the footpath (Fig. 6a). So, most of the cyclists from the south cut a corner not following the bicycle path. Of the cyclists coming from the east, 8 continued north, 4 of whom switched to the footpath before the interaction. Of those travelling from east to west ($n = 59$), 96% used the bicycle path. In the other two cases, the cyclist switched from the bicycle path to the footpath.

In these 120 cases, the priority to the right rule was determined in 50% and ignored in 50%.

Fig. 6b shows the PET distribution. The distribution is similar for both sites, except for a peak towards higher values in negative PET. These interactions happen when cyclists who have the right-of-way go first. It is unclear whether these cyclists are enforcing their right, which is why PET is closer to zero. There are also cases of unexplained clusters of values around 1.8 s. As illustrated in Fig. 6d, the pPET distribution exhibits a predominance of negative values relative to positive values. However, a notable accumulation of values around 1.8 s remains unaccounted for, warranting further investigation. Minimal and medium PET and pPET values for various crossing scenarios are shown in Table 1. Overall, about 56% of the crossing interactions ($n = 93$) had a PET between -2 and 2 s, with a further 2.2% between -1 and 1 s. Among the cyclists who merged during the interaction ($n = 27$), the proportion of pPET between -2 and 2 s was about 67%, while the proportion of pPET between -1 and 1 s was about 26%.

Fig. 7b shows an example interaction with a negative PET of -1.25 s, i.e. the cyclist from the east, who has the right-of-way, also rides first. Fig. 7c shows a positive PET of 1.45 s. Here, the cyclist coming from the south takes the right-of-way from the cyclist coming from the west.

For intersecting trajectories, a distribution plot of the intersection points is shown in Figure 7a_pos and Figure 7a_neg. Here a_pos represents the intersection points with positive (blue dots) and a_neg represents the negative (yellow dots) PET values. The figures show that the distribution of the location of the intersection points – whether a_pos or a_neg – is very similar.

3.1.2. Distance, velocity and PET

For further analysis, the minimum distance during the interaction and the average speed were determined. C_{EW} is the cyclist travelling on

the bicycle path from east to west, while C_{SN} is the cyclist crossing the intersection (south to north). The analysis also considered whether C_{EW} and C_{SN} were on the bicycle- or footpath.

Combinations with fewer than five cases are not included in Table 1. Table 1 distinguishes between scenarios “with crossing” (where trajectories have a spatial intersection point and PET is calculated) and scenarios “without crossing” (where trajectories do not spatially intersect and pPET is calculated instead). The minimum and mean values for PET and pPET are given in Table 1.

As seen in the PET distribution, the mean PET is closer to zero for negative PET values. This results in a lower average minimum distance for these cases. The cyclist coming from the east is either slower or travelling at the same speed as the cyclist coming from the south. The lowest values (pPET) and distances were found when merging onto the bicycle path, where the incidence was also lower than when crossing the footpath. The minimum distances are measured when both cyclists meet on the bicycle path and neither of them uses the footpath. Consequently, when merging onto the bicycle path, lower (p)PET values are also measured. However, the question arises as to whether the cyclists saw each other early on and adapted to each other and whether it was a controlled crossing. For a deeper investigation the behaviour was checked in a video annotation. Due to the low resolution of the videos, it is not always possible to discern the direction in which the cyclist is looking in the annotation. Only a distinct head movement is recognisable. However, since the area is clearly visible from both sides, a head movement is not absolutely necessary to see an approaching cyclist. In one case where the right-of-way was taken, a clear hand signal and head movement from C_{SN} was visible in the videos. It is also not possible to determine from the video annotation or trajectory analysis whether the cyclist is stopping to counteract an interaction or because of the infrastructure. Cyclists coming from the south have to make a curve except if they continue on the footpath to the north. This is the group with the highest speed, which shows that they have the opportunity to continue unhindered, even if not legally. However, it is also the group with the greatest distances, which does not initially suggest that this is the most conflictual interaction. Cyclists coming from the east also have to bend if they want to go north. For cyclists coming from the south and east, there is a traffic light in the west. Here, too, cyclists can reduce their speed early because the light is in sight, so they do not have to stop or wait long. In the end, it is not clear whether a response was due to interaction, infrastructure or a combination of both.

3.2. Survey

The majority of respondents (87%) are between the ages of 30 and 59. Furthermore, over 80% of respondents are male. None of the respondents identified as gender diverse.

The following are some of the potential causes of misconduct. In addition to conscious misbehaviour, distraction can also result in misconduct or highlight conflicts. The question ‘I don't think about anything’ shows that no one chose ‘always’ and only 11% chose ‘often’. Respondents indicated that they think about something while cycling, with a total of 91.1% of respondents stating that they are always or often very focused on traffic.

However, 55.5% of respondents also stated that they think about

Table 1
Interacting crossing cyclist pairs with speed: $|v|$, mean of minimum distance: $d_{min,mean}$ and (p) PET.

Scenario	C_{EW}	C_{SN}	(p)PET _{min} in s	(p)PET _{mean} in s	$d_{min, mean}$ in m	$C_{EW} v $ in m/s	$C_{SN} v $ in m/s
with crossing	Bicycle path	Foot-path	0.80 ($n = 27$)	2.03 ± 0.74	5.71 ± 2.35	2.41 ± 1.07	4.22 ± 0.83
		Bicycle path	-0.95 ($n = 27$)	-1.80 ± 0.50	4.06 ± 1.62	2.85 ± 1.16	3.37 ± 0.99
		Bicycle path	1.15 ($n = 17$)	2.36 ± 0.75	3.77 ± 2.38	2.28 ± 0.92	2.41 ± 1.34
without crossing	Bicycle path	Bicycle path	-1.25 ($n = 18$)	-1.90 ± 0.54	3.75 ± 1.67	3.17 ± 1.19	2.42 ± 1.03
		Bicycle path	0.00 ($n = 7$)	1.48 ± 0.98	3.54 ± 2.24	2.04 ± 0.52	2.61 ± 0.88
		Bicycle path	-0.40 ($n = 10$)	-1.97 ± 1.34	3.42 ± 1.90	2.71 ± 1.46	2.34 ± 0.72
	Foot-path		-0.25 ($n = 5$)	-1.73 ± 1.00	4.06 ± 2.08	3.59 ± 0.98	1.94 ± 0.65

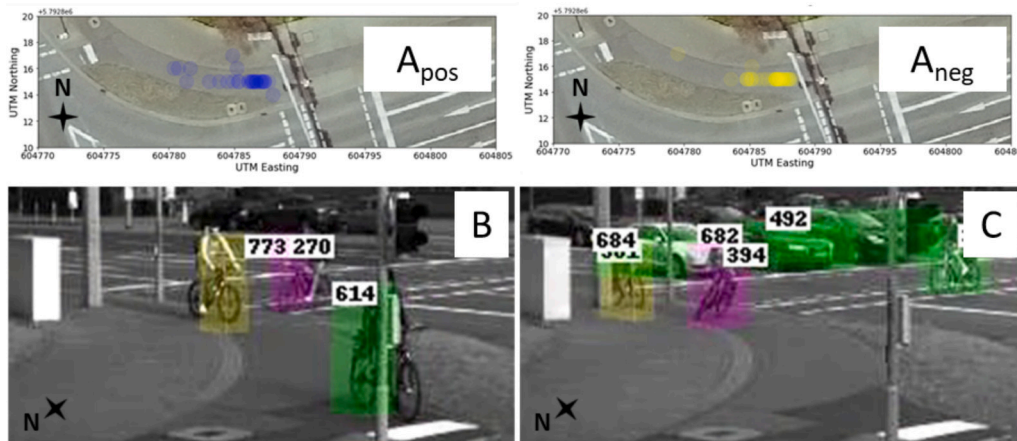


Fig. 7. left: Distribution of the intersection points of two trajectories (positive PET blue (a_pos) and negative PET yellow (a_neg)). b: Negative PET with video image of a_neg = -1.25 s; c: Positive PET with video image of a_pos = 1.45 s. Crossing cyclists are shown in yellow (from east) and purple (from south). Other road users are shown in green.

various things while cycling. Approximately 37% of respondents acknowledged occasional distractions, while only around 12% reported consistent or frequent use of music during cycling. Furthermore, less than half of respondents always wear a helmet while cycling. The distribution of responses to each question is illustrated in Fig. 8.

The respondents were presented with an illustration and an animation depicting a cyclist crossing an intersection. At the intersection's end, a cyclist approached from the right, and the respondents were tasked with determining whether they would proceed or wait.

As illustrated in Fig. 9, an aerial view of the intersection is shown on the left. The question under consideration is whether the yellow cyclist has the right-of-way, or if the cyclist (yellow) must grant right-of-way to the cyclists (blue). On the right side of Fig. 9, a screenshot from an animation is shown, showing the scene from the point of view of the yellow cyclist.

The respondents were invited to state whether they were aware of which bicycle had the right-of-way and therefore elected to wait or to proceed; whether they were unaware but nevertheless elected to wait or to proceed; or whether they had reached an agreement with the other cyclist.

It was revealed by over half of the respondents (54%) that they would yield to the other cyclist and wait for them to pass, while 41% of respondents indicated that they would take the right-of-way. The remaining respondents expressed a desire to attempt to reach an agreement with the other cyclist (Fig. 10).

3.3. Intersection in a 30 km/h zone

During the observation period, 57 encounters were detected at the intersection in a 30 km/h zone. Of these, 35 had a PET due to the unambiguous crossing situation. Table 2 shows the route combinations that occurred during the 10-day observation period. Direction a denotes the initial direction of travel, specifically east or west, while direction b indicates the starting direction of travel, which is north or south, as illustrated in Fig. 4B. The most common case observed was a cyclist travelling from north to south. This cyclist should have given way. The second cyclist was either travelling from west to north or from west to south. In both cases, right-of-way was not given in 43% and 53% of cases respectively. The direction of travel that must yield the right-of-way has been indicated by the † symbol in Table 2.

In most cases the PET is around ±3 s and therefore not in the critical interaction range. Only in the case of a3/b1 is the PET below 2 s, although the number of cases observed is not meaningful.

In the majority of cases, the cyclist who must yield the right-of-way is typically travelling at a higher velocity. This principle applies to instances where the right-of-way has been formally granted, as well as to situations where the right-of-way has been taken. Only in case a3/b1 does this not apply. This case also differs from the others because there is no official road in the east, but a secret route. Nevertheless, the number of observed cases involving this particular direction of travel is not significant.

Fig. 11 shows example situations for different interactions. In

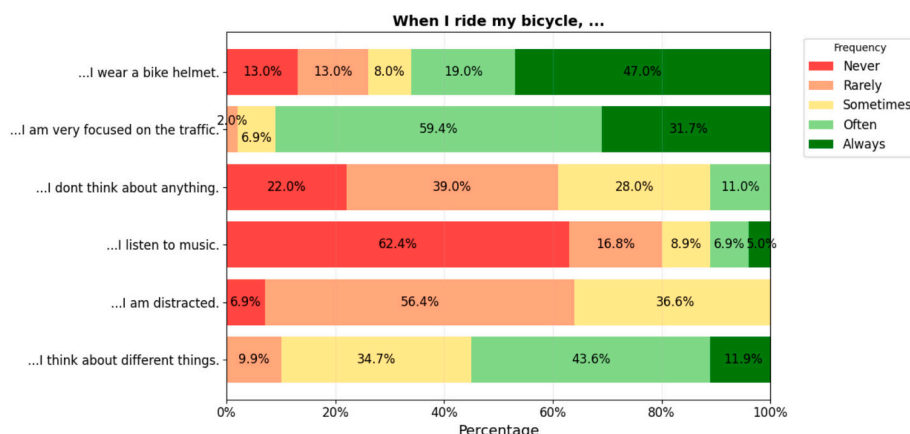


Fig. 8. Survey results on attention issues when cycling and about using a helmet.



Fig. 9. Orthophoto of the Research Intersection in Braunschweig, Germany. Left: Crossing scenario between two cyclists (blue and yellow); Right: Screenshot of an animation of the crossing scenario of Fig. 9, left; viewed from the perspective of the yellow cyclist.

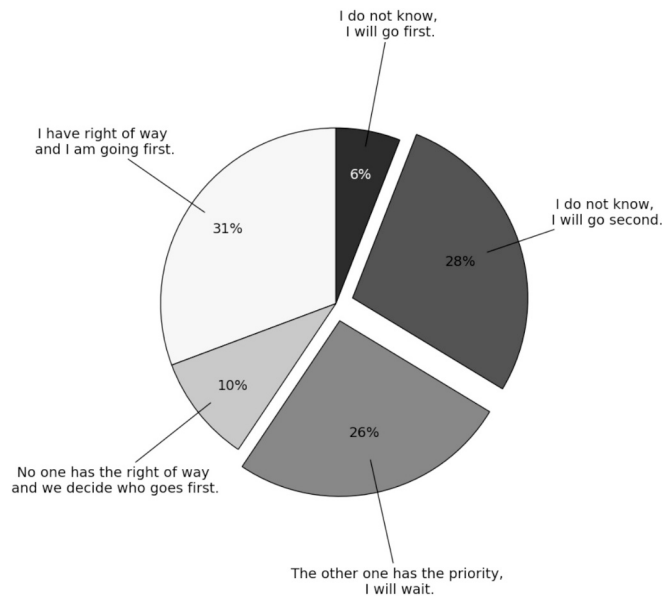


Fig. 10. Results for the question of how to act when you are the cyclist in yellow and another cyclist (blue) crosses your path.

Fig. 11a, the cyclist coming from the east violates the right-of-way (PET = -1.96). In Fig. 11b, the cyclist coming from the west gives way. The

cyclist coming from the north slows down and swerves to avoid having to stop. The PET in this case was -1.4 s. In the example in Fig. 11c, the cyclist coming from the north continues in the middle of the lane to give way to the cyclist coming from the west without having to stop (PET = 2.4 s). Overall, about 20% of the crossing interactions (n = 35) had a PET between -2 and 2 s. No events were detected with a PET between -1 and 1 s.

4. Discussion

This study examines the crossing interaction between cyclists at a signalled intersection where the priority to the right rule applies. The interactions were evaluated in terms of safety by applying SMOs and calculating other kinematic related parameters. For the purpose of this study, 171 h of real trajectory data were recorded and analysed with regard to crossing interaction between bicycle and bicycle at an urban intersection. During the period of recording, 120 encounters have been identified with 93 of them having a PET within 3 s, as their trajectories intersect in the area of interest and are used for detailed analysis. At the intersection in the 30 km/h zone, 10 days were analysed and 35 interactions out of 57 encounters could be studied. The authors [12] also demonstrated that, at this measuring location, cyclists more frequently take the right-of-way to vehicles than vehicles to each other.

56% of interactions at the Research Intersection (n = 93) had a PET of -2 to 2 s, 2.2% of which were between -1 and 1 s. In 27 cases where cyclists merged, the PETs were mostly between -2 and 2 s (67%), with only 26% between -1 and 1 s. At the intersection in the 30 km/h zone

Table 2

Crossing situations, as well as information on right-of-way and PET_{mean} in s and |v| in m/s with ± for standard deviation. Direction a starts in the east or west, direction b starts in the north or south and nr is the number of cases that were found. For PET calculation: ego = cyclist from north, second user = cyclist from east or west.

direction a	direction b	nr	priority taken	PET _{mean} in s	v in m/s	priority given	PET _{mean} in s	v in m/s
a1 (WN)	b1 (NS)	14	6	3.03 ± 0.73	a: 4.14 ± 1.00 b: 6.76 ± 2.11 [†]	8	-3.07 ± 1.04	a: 4.39 ± 1.11 b: 4.76 ± 1.44 [†]
	b2 (SN)	2	0	-	-	2	-2.46 ± 0.26	a: 6.50 ± 0.92 [†] b: 4.00 ± 1.67
a2 (WS)	b1 (NS)	17	9	-3.51 ± 1.23	a: 4.13 ± 1.05 b: 6.05 ± 1.83 [†]	8	3.03 ± 1.35	a: 4.94 ± 1.15 b: 5.60 ± 1.53 [†]
a3 (OW)	b1 (NS)	2	1	-1.96	a: 4.38 [†] b: 6.72	1	1.08	a: 4.33 [†] b: 2.62



Fig. 11. Examples of cyclist interactions for cases A: a3/b1, B: 1/b1, and C: a2/b1. Arrows indicate right-of-way. Yellow: Cyclist has right-of-way; Red: Cyclist must give way. Ego: Cyclist from north; Second user: Cyclist from east or west.

($n = 35$), 20% of PET were between -2 and 2 s, with no events at -1 and 1 s. PET values are higher in the 30 km/h zone than on the bicycle path. This may be because there is more space to swerve on the road. However, speeds are also higher here. Cyclists at the Research Intersection coming from the south must make a turn unless they continue north on the footpath. This is the group with the highest speed, which shows that they have the opportunity to continue unhindered, even if not legally (give 4.22 ± 0.83 m/s or take 3.37 ± 0.99 m/s the right-of-way). At the Intersection in the 30 km/h zone, speeds are higher, probably due to the design of the intersection; there is more space. The highest speeds were reached by cyclists, who must give way whether they have given way or not, with speeds of up to 6.76 ± 2.11 m/s. In both cases, the other cyclist can be seen early on. At the Research Intersection, however, there is also the added pressure of having to get through the green light.

The observations revealed that 50% of cyclists disregard the priority to the right rule. A small-scale survey was conducted to ascertain whether the rule is recognised and continues to be disregarded, or whether it is entirely unfamiliar. 31% of respondents ($n = 104$) think they have the right-of-way and go first. 26% of respondents know the other cyclist has the right-of-way and wait. The data indicates that almost 60% of respondents ($n = 59$) who believe themselves to be familiar with the rule erroneously assume that they have the right-of-way. Among the remaining respondents who are not acquainted with the rule but must decide, 28% would wait for the cyclist to pass from the right. The survey findings indicate that cyclists often experience uncertainty regarding the rules of crossing, particularly at this Research Intersection, leading to potential safety concerns. Furthermore, the survey results indicated a certain degree of inattention while cycling, which can also contribute to conflicts.

The present analysis is based on the prevailing traffic regulations regarding right-of-way. Methodologically, it would be entirely feasible to employ alternative priority rules (such as 'first arrival determines priority') to examine their influence on conflict frequency and severity. Such sensitivity analyses could yield valuable insights into the effectiveness of different rule systems. However, it should be emphasised that there is little prospect of changing legislation. This could represent an intriguing new analysis.

Trajectory analysis is a valuable tool for the analysis of interactions, yet its capacity to depict particular forms of cooperative behaviour (e.g. eye contact, stopping of pedalling) is limited. The application of video annotation can enhance the analysis to a certain extent, but this approach is more time-consuming. The transferability of measurement locations to other environments is constrained due to the intersection design and prevailing regulations, necessitating the examination of numerous other locations. The method of video observation can also be applied on a global scale to observe the behaviour of cyclists when crossing. However, it is important to verify the results for other types of intersections and, in particular, different right-of-way rules. It should be noted that the results may vary for left-hand traffic compared to right-hand traffic.

The survey's modest sample size necessitates further investigation, particularly with respect to individual intersection characteristics and the resulting behaviour. The study's predominantly male participant base is a salient point of consideration, as it introduces a potential bias, but it does provide a first indication of the extent to which rules are understood and adhered to, which is a contributing factor to riders failing to yield the right-of-way on bicycle paths. Further studies should examine whether the understanding of the rules is unclear on bicycle paths everywhere or only for a specific intersection design, and whether there are intersections with the same design where the rules are better accepted.

It was found that the priority to the right rule was respected in only 50% of the cases in both measurement locations. This may be due to either a disregard for this rule or a lack of clarity about its applicability among cyclists in this intersection area. Ignoring or intentionally violating this rule can result in conflicts. The following measures may be

adopted in order to avoid conflict: Children need to be taught the rules of the road from an early age. Local campaigns can create more clarity for commuters. However, neither will be able to prevent the rules from continuing to be ignored. Options for regulating traffic at intersections between cycle traffic would include cycle traffic lights. These lights are exclusively for cycle traffic and often a stop line is drawn to emphasise the necessity of stopping (see Fig. 12c for an example of the Research Intersection). The advantage of this solution is that right-of-way is clearly regulated. However, installation costs additional money (electricity, switching coupled with crossing cycle traffic flows, the system itself). Traffic lights are generally more accepted than signs, although it is not clear whether a cycle traffic light would be accepted as it would require a brief interruption in the flow of traffic. Especially if no cyclist is crossing and the cycle traffic light is still red, the traffic light is likely to be disregarded more often.

Another possibility is the use of road markings with shark teeth. The lined-up triangles indicate to the relevant road user towards whom the triangles point that they must give way. At the Rijksmuseum in the Netherlands, they faced the problem that all cycle flows crossed simultaneously. What was novel was not shark teeth themselves, but applying shark teeth on bicycle paths - specifically on cycle infrastructure that previously had right-of-way because it ran alongside a priority road. A trial followed which showed that there were fewer conflicts between cyclists and that they were satisfied with this solution [23]. Some cyclists find it takes getting used to having to stop along the priority road, which also makes it legally difficult to enforce in Germany. In Germany (sign 342), these shark teeth are mainly applied on roads. However, there are also examples where cyclists are warned about other cyclists. These are primarily found on roads and road-like paths rather than on bicycle paths [24].

Cyclists crossing the intersection on green traffic light could be given their own merging lane, similar to that on the motorway for motorised vehicles (see Fig. 12b for an example of the Research Intersection). However, this would require space, which is often not available, or the infrastructure would have to be rebuilt at great expense.

A yellow flashing light may be all that is needed to signal to cyclists on the bicycle path that another cyclist is crossing (Fig. 12d). The flashing light can be linked to sensors so that it only flashes when a cyclist is actually crossing the road. But the cyclist on the bicycle path would need to pay attention and not insist on his priority to the right rule. In motorised traffic, pedestrian warning lights show mixed results - studies indicate modest improvements in driver yielding behaviour and pedestrian safety, with effectiveness varying significantly by location and design. Modern systems typically require additional control equipment and maintenance [25].

Acceptance would certainly be higher if there is a way of warning cyclists about crossing the road and not the cyclists on the bicycle path. However, none of these solutions will help if cyclists are riding the wrong way. Due to the different speeds on the bicycle path, it may also be useful to reduce the speed for cyclists at intersections. Again, cyclists must obey the rules for a positive effect.

This study focused exclusively on cyclist behaviour. However, several research opportunities emerge from these findings. Expanding future research to include pedestrian behaviour interactions would contribute to a more comprehensive understanding of vulnerable road user dynamics at this intersection.

5. Conclusions

Two camera-based traffic observations were used to study 120 intersection behaviours at the Research Intersection with bicycle path. 35 interactions were studied at the intersection in a 30 km/h zone without a bicycle path.

The study demonstrated that cyclists violate the right-of-way in 50% of cases, irrespective of whether they are on a designated bicycle path or on a road. A survey conducted on the scenario of the bicycle path also

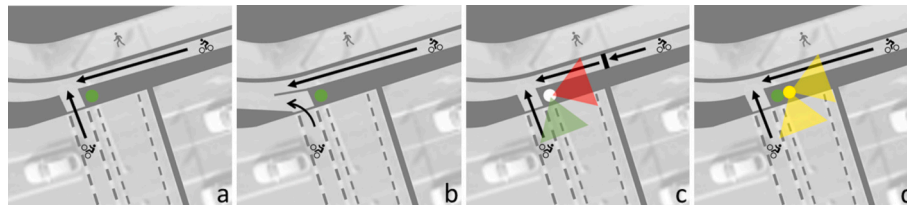


Fig. 12. Research Intersection. a. Initial situation, b. Merging lane, c. Additional cycle traffic light and stop line on bicycle path, d. Flashing light.

revealed that less than half of the respondents were aware of their right-of-way. It is hypothesised that knowledge of the rules plays a significant role. However, the data from the 30 km/h zone demonstrated a similar percentage of rule violations, which was unexpected, given the well-known priority to the right rule in Germany for 30 km/h zones.

At the Research Intersection, a PET range of -1 to 1 s was observed in only 2.2%. In the Intersection in a 30 km/h zone, no PETs were recorded in this range. Annotation of the data revealed that cyclists did stop pedalling or swerve, which was observed to defuse the situation and lead to a higher PET. While the possibility of further cooperative behaviour through eye contact cannot be discounted, this could not be observed due to the low-resolution of the camera. In conclusion, interactions between cyclists at intersections may lead to accidents, but these were not observed at the measurement locations. It was found that the right-of-way is not always respected and that conflicts are avoided by swerving or slowing down. Smaller PETs are tolerated at the Research Intersection, but speeds are also lower than in the 30 km/h zone, where people tend to swerve generously.

In the context of this work, further cases will be recorded in order to identify additional critical and rare scenarios and behavioural patterns. For example, the extent to which crossing behaviour differs between individual and group interactions will be investigated. Furthermore, outside of this publication, additional studies should examine the impact of traffic lights on determining priority to the right rule. Depending on the traffic light phase, the rule may be disregarded. At signalised intersections, an additional traffic light could be installed on the bicycle path to separate the two traffic flows of cyclists. Another option could be a flashing warning light to indicate crossing traffic. Improved education and visibility of the crossing area could help alleviate crossing conflicts. Findings can aid improving infrastructure and developing cyclist behaviour models e.g. to enhance the realism of simulations. The study underlines the serious potential of conflicts of cyclists at intersections and the need for further research in this area.

CRedit authorship contribution statement

Claudia Leschik: Visualization, Validation, Supervision, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization, Writing – review & editing, Writing – original draft.
Kay Gimm: Supervision, Writing – review & editing.

Declaration of competing interest

The authors report no competing interests.

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