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Research article

Interactions among cyclists riding the wrong way on the bicycle path

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Abstract: Cycling in the opposite direction can lead to many critical interaction situations and sometimes to severe crashes among cyclists. Unfortunately, no official statistics are kept of such situations in Germany. Since the number of cyclists increases in many locations in Germany faster than the cycling infrastructure improves, we can expect more of such dangerous situations in the near future. To reduce their number and severity and to develop realistic simulation models, it is essentially important to understand, how cyclists interact with each other in this particular scenario of wrong-way cycling and what consequences result for safety and cycling behaviour. This paper presents methodology and descriptive results of a traffic observation study at a signalled urban intersection in Braunschweig, Germany, with separated bicycle and footpaths. At this instrumented intersection, road user trajectories were recorded and analysed with regard to identify interactions between normal and wrong-way cyclists, and to find behavioural patterns. It appeared that several different behavioural patterns, for instance switching from bicycle path to footpath, occurred, speeds of wrong-way cyclists were slower. The distances before switching appeared to be different in some of the patterns while in others they appeared to be similar.

Keywords: bicycle-bicycle interaction, traffic safety, trajectory data, wrong-way cycling

1 Introduction

Analyses in large cities in Germany show that more than 40% of car journeys are less than 5 km. According to the study, the bicycle is the fastest means of transport over this distance. Additionally, cycling is not only fast, but also healthy due to the physical exercise and, compared to motorised traffic, it is also environmentally friendly and cheap (Umweltbundesamt, 2022). In 2020, the retail trade in bicycles was +32.4% and 2021 still +28.1% increase compared to 2019 before the Corona Pandemic (Destatis, 2022). An increase of bicycle traffic may lead to an overcrowded bicycle infrastructure. Furthermore, the proportions of e-scooter and electric cargo bikes, which also adopt the cycling infrastructure, also increase. Due to this, we have to expect an increase of potential conflicts. According to the ADAC (German Automobile Club), every third bicycle path in Germany's state capitals is already too narrow and does not meet the legally required minimum width of 1.60 m (Kruse, 2020). It can therefore be expected that not only the number of conflicts on the cycling infrastructure increases, but also on lanes or even footpaths, if there is no cycling infrastructure available, if it is too narrow or if the road is perceived as too dangerous. In 2020, 92 273 crashes involving cyclists, including 426 fatal accidents, were reported. Even though the number of cycling fatalities decreased by 4.3% compared to

2019, the number of cyclists increased by 5.6%. With 71.9%, car drivers are still the most common opponent of cyclists. In 11.3% of cyclists' crashes a cyclist was the opponent of the accident, and this trend is increasing (2017: 8.7%) (Destatis, 2018, 2021). We have to expect an increasing number of bicycles and thus, an increase of overloaded cycling infrastructure. Therefore, it is important to understand, how cyclists interact with each other and what the consequences are. This includes to understand, how cyclists interact with wrong-way cyclists. With a sample of this scenario, the behaviour of cyclists can be analysed descriptively and afterwards modelled. This allows the implementation of measures to improve infrastructure and validated traffic behaviour models of cyclists for simulations. The information can also be used for scenario-based testing of automated driving functions.

The aim of this article is to quantify, describe and depict the traffic behaviour of cyclists interacting with wrong-way cyclists. Different types of cyclists will be identified and described within the scenarios. The remainder of this paper is structured as follows: in section 2 the current state of related work is proposed. Then, in section 3 the relevant methods are introduced, which are applied in section 4 to present the results. The obtained results are interpreted and discussed in section 5. In section 6 the paper is summarised and prospects on our future work are presented.

2 Literature review

Cyclists who ride the bicycle path in the wrong direction are encountered on many bicycle paths. Yet the topic of interactions between them and legal riding cyclists has rarely been investigated and only a few statistics are available. We will give insights in the legal situation in Germany in section 2.1. If a cyclist riding in the legal direction of travel (we will call him/her normal cyclist—NC) and a wrong-way cyclist (WWC) collide, this can lead to severe injuries or even fatalities. As a matter of this an insight into accident statistics is given in section 2.2 as well as empirical studies, which are another way to get an insight into WWC and NC accidents based on online news and investigative research. Several measures and campaigns to prevent WWC from cycling were identified. One of them that includes recommendations for actions, countermeasures and a limitation is presented in section 2.3.

2.1 Legal situation

In Figure 1 the German traffic signs for bicycle use with or without pedestrian use are shown. When a German traffic infrastructure is marked with signs 237 (bicycle path), 240 (joint foot- and bicycle path) or 241 (separated foot- and bicycle path), the cyclist has to adopt the bicycle infrastructure and must not use the roadway. Exceptions only apply, if the bicycle infrastructure is unusable (e.g. due to snow or ice layers) and if children are under eight years old. Furthermore, bicycle paths may only be used in the correspondingly signposted direction, which is usually located at the right side of the roadway. If not exceptionally signalled, riding in the opposite direction on the bicycle path is a traffic offence (§2 para. 4 StVO) in Germany, regardless of hindering or endangering other cyclists and pedestrians. WWC disregard their duty of care and in the event of an accident they are legally at least partly to blame or even fully to blame. In contrast to WWC, cyclists who obey rule §2 StVO (2013) are called 'normal cyclists' (NC) in the following. WWC endanger themselves and car drivers, for example, at junctions or when turning, since the car driver does not expect cyclists against the direction of travel.

Figure 1 Traffic signs 237 (left), 240 (middle) and 241 (right) (StVO, 2013)

2.2 Infrastructure

The total length of bicycle paths in Braunschweig is approximately 500 km, comprising 205 km of separated bicycle paths along the road and 200 km of separate bicycle paths within green spaces or parks. Additionally, there are 90 km of shared footpaths and bicycle paths, 15 km of bicycle lanes, and approximately 5 km of bicycle protective lanes. Of the 205 km of separated bicycle paths, 64 km are designated as two-way bicycle paths. These are primarily situated between residential neighbourhoods where a bicycle path is only available on one side of the road (Braunschweig, 2024).

The area under investigation in this study is traversed by a distinct footpath and bicycle path. The footpath is 2.25 m wide and could be made even narrower in accordance with the relevant regulations. The bicycle path complies with the minimum requirement of 1.50–1.60 m.

The decision as to whether bicycle and pedestrian traffic can run without visible separation (shared footpath and bicycle path) is dependent upon the number of pedestrians and cyclists per path width, in accordance with the German recommendations for pedestrian traffic facilities (EFA 2002), the German recommendations for bicycle traffic facilities (ERA 2010) or the German guidelines for the design of urban roads (RASt 06). There is no legal measure regulating pavement widths. The German Road and Transportation Research Association (FGSV) has developed the "Recommendations for pedestrian traffic facilities" (EFA), which provides guidance on the design of footpaths. The minimum recommended width for a footpath is 2.50 m, allowing for two pedestrians to walk past each other in a relaxed manner.

There is currently a lack of data on the number of separate footpaths and bicycle paths in existence, as well as the specific dimensions of these facilities in Germany. While the creation of a shared footpath and bicycle path is an option for paths measuring less than 3.50 m in width, this approach can give rise to a number of challenges. The potential for conflicts is increased by the interaction between pedestrian and NC on a shared path, while the presence of WWC can further complicate matters, particularly in situations where there is limited space for manoeuvring.

2.3 Statistics

In Germany, a total of 4 867 bicycle—bicycle accidents were recorded in 2023. The distribution of bicycle accidents by direction of travel indicates that 31.4% of accidents involving cyclists occur in the same direction of travel (i.e. riding side by side or overtaking) while 32.2% occur when crossing, and 36.4% with oncoming traffic (Unfallatlas, 2024). This indicates a 5% disparity in the occurrence of accidents with oncoming traffic compared to those with traffic travelling in the same direction. However, from these statistics, it is not possible to distinguish whether the oncoming cyclists travelled legally or illegally, but instead, other causes can be identified. The causes of head-on collisions can be attributed to a number of factors. First, sudden swaying of NC or WWC can result in a collision between the cyclists. Second, the attempt of WWC and NC to avoid each other can result in a collision when they swerve in the same direction. However, a series of events may also occur, whereby an NC overtakes another NC and subsequently collides with a WWC. In conclusion, it is not possible to state whether WWC are involved in a greater number of accidents than NC.

According to traffic accident statistics, wrong-way cycling is the second leading cause in 13% of accidents involving cyclists (Braunschweig Police, 2021). Among the causes of road accidents with injuries caused by cyclists, WWC accounts for 8% and decreased to 5% in 2022 (Braunschweig Police, 2022). According to the Braunschweig Police (2024), there were eight accidents between WWC and NC in 2022 and seven in 2023.

2.4 Empirical studies

Some of the observation studies show that the proportion of irregular use of the bicycle path in the wrong direction of travel varies widely. In case of separate bicycle paths, 20% of approximately 39 000 observed cyclists adopted the wrong way, with values scattering between 8% and 50% for each study area (Alrutz et al., 2009). This study also shows that in 5% of the cases cyclists adopted the pedestrian walkway to overtake other cyclists or to avoid oncoming WWC. In Huemer & Vollrath (2014) 16% of 2 549 observed cyclists took the wrong way due to time savings and convenience. Bjørnskau et al. (2016) studied cycling in Oslo, Norway, and found that 80% of cyclists used the bicycle path in the right direction and almost all WWC used the footpath. It turned out that the most common conflicts were near accidents caused by blocking the bicycle path. Sørensen et al. (2022) showed that WWC were mainly found at intersections, but varied greatly (up to 33%) depending on the Danish location. WWC were most frequently detected at peak times. According to their study, the risk of conflict was seven times larger for WWC than for NC.

The width of the bicycle path also plays an important role in legal oncoming traffic, as in the Netherlands. The relationship between bicycle path width and lateral distance of cyclists was investigated. For this purpose, the oncoming cyclist was represented with a parked bike. The two experimental studies showed that cyclists keep a greater distance from the verge and from oncoming cyclists when the bicycle path is wider. The authors recommend a bicycle path width of 2.50 m when considering behaviour and wheel width to ensure a safe manoeuvre (Schepers et al., 2023).

2.5 Investigative research

On July 6 2023, a search for the keyword 'Geisterradler' (cyclists cycling in the wrong and forbidden direction, synonymous: ghost cyclists) on Google News returned 111 entries. Among them were 7 posts about accidents with WWC. Including 3 with cyclists, 3 with cars and 1 with pedestrians. The injuries sustained by NC and WWC range in severity from minor injuries with property damage to serious injuries and loss of consciousness. Most importantly, the non-mandatory requirement to wear a helmet has been identified as a significant contributing factor to severe head injuries. A review of newspaper articles provides some insight in accident statistics. It is reasonable to conclude that the number of unreported accidents involving WWC is significantly higher, given that smaller accidents are not reported.

In a guideline about 'ghost cycling' causes for misuse were sought (Große & Böhmer, 2021). Ghost cycling includes both left-hand riding and riding on footpaths. In addition to safe movement, the length and duration of the route are also important for cyclists while ignorance of the rules plays a subordinate role. The infrastructure also plays an important role, especially multi-lane roads, bridges, gradients, surfaces or traffic lights. Due to the statistical method of recording accidents, the authors had to read texts, and wrong-way cyclists had to be singled out separately as part of the project. The study analyses the accidents that occurred between 2008 and 2018, encompassing 17 337 accidents involving cyclists in the cities of Erfurt, Jena and Dresden in Germany. Accidents involving left-hand cyclists ranged between 12.6% and 17.8% in these three cities. The most frequent accidents occurred when turning or crossing (68%) and on bicycle paths (40%) as well as on unauthorised footpaths in the opposite direction of travel (34%). Around 10% of accidents occurred in longitudinal traffic. The majority of road users involved in accidents with cyclists (82%) are cars, but only small proportions involving other cyclists (9%) or pedestrians (6%). In 68% of cases, injuries are minor. The data also shows that approximately 60% of cyclists involved in accidents are male, while the remainder are female (40%) (other genders are not mentioned in the study). Furthermore, an observation analysis was carried out in 2019 and 2020, weekday 6–19 h video footage, at 3 accident blackspots. 4 400 cyclists were recorded, 40% of whom were riding on the left-hand side (left-hand hotspot). Cyclists met each other in 95% of the cases, of which 95% of the interactions were free of conflict. In 2.3% there was a sudden reaction by a road user and in 0.2% a strong reaction, contact could still be prevented. There was no contact during the observation period. In this amount of 2.3% and 0.2% of interactions, cyclists were the main interaction partners (46%). Lateral interaction distances between 0.5 and 1.5 m were found most frequently. In close encounters, distances of 0.25 m were also observed. In an additional analysis, a questionnaire survey was conducted at the same measurement locations during the same study period. The results indicated that 80% of respondents cycled on the left-hand side consciously and particularly carefully (95%). This finding contrasts with the statements in the questionnaire, in which the respondents stated that they did not consciously cycle the wrong way.

As outlined by Dhakal et al. (2018), the key predictors of WWC behaviour are the purpose of the journey, the length of the journey and the journey time. Furthermore, the probability of WWC was found to be lower for journeys outside of rush hour traffic than during rush hour traffic.

2.6 Countermeasures

The most common measures against WWC are visible campaigns or traffic checks at selected locations by the police. Campaigns in Germany typically include the application of neon coloured pictograms with and without text on the bicycle path, as well as the installation of posters or signs against the direction of travel. Therefore, all campaigns can only be perceived by WWC and are intended to draw their attention. Slogans like 'WWC please turn around!' (German: 'Geisterradler bitte wenden') as shown in the left of Figure 2, 'WWC endanger!' (German: 'Geisterradler gefährden!') as shown in the right of Figure 2 or 'Wrong side!' (German: 'Falsche Seite!') should cause the WWC to think about his/her cycling behaviour.

The pictograms fade after a short time and the posters also change their location regularly so that WWC might not get used to it. Cities and municipalities carry out many campaigns every year and, for example,

Figure 2 Campaign against WWC with pictogram (Schönstedt, 2015) or sign (Kurier, 2020)

also use creative campaigns to draw attention to cycling behaviour. In Bremerhaven, for instance, fruits were given to cyclists during bicycle checks—apples for correct riding behaviour and lemons in case of WWC (Motyka, 2021). The advantage of priority checks is that violations are enforced and the find may prevent another violation. However, many WWC also avoided the conversation when the police check was already visible in the distance. During a focus check in Regensburg, 11 WWC were checked on one day in 2021, and over 500 in two weeks in Munich in 2019 (Felbinger, 2019; Schmitt & Spethmann, 2022). 43 of 111 news items with the keyword Geisterradler dealt with the topic of campaigns against WWC.

2.7 Two-way bicycle path

A study conducted by BASt (2015) employed a survey methodology to examine the comparative behaviour of cyclists utilising one-way and two-way bicycle paths. The presence of bidirectional traffic can lead to a number of issues, particularly at intersections where turning vehicles are not always aware of cyclists travelling in the opposite direction. In the case of accident clusters, no discernible difference was identified between the incidence of accidents occurring in areas where left-hand traffic was against the regulations (on a one-way bicycle path in the wrong direction) and those where it was permitted (in a two-way bicycle path). It is recommended that bidirectional cycling should only be permitted in exceptional cases, given the increased risk of accidents at intersections and crossroads.

The study by Methorst et al. (2017) reaches a comparable conclusion. Similarly, the probability of accidents between cyclists and motorists was found to be larger on two-way bicycle paths than on one-way bicycle paths, due to motorists failing considering the direction of travel. The authors rejected the hypothesis that two-way bicycle paths increase cyclist safety. In the Netherlands, cars encounter cyclists more frequently than in other countries, given that 27% of all journeys are made by bicycle and 72% of bicycle paths are already open to both directions. However, motorists do not pay attention to cyclists travelling in the opposite direction, resulting in a higher incidence of accidents at unsignalised intersections. The authors highlight the necessity for two-way bicycle paths to have a certain width in order to avoid head-on collisions with bicycles or mopeds.

In their study, UDV (2023) employed a variety of accident statistics to compare the safety of two-way and one-way bicycle paths for cyclists and pedestrians. The accident rate on two-way bicycle paths is 1.5 accidents per area and per five years and 0.9 for one-way bicycle paths, which makes one-way bicycle paths almost twice as safe. Furthermore, it was reported that there is a higher incidence of accidents involving pedestrians and cyclists on bicycle paths with a width of less than 1.60 m. In contrast, in case of bicycle paths with a width of 2.50 m or more, hardly accidents involving pedestrians and cyclists occur. It is therefore recommended that two-way bicycle path is not implemented, particularly in areas with a high volume of pedestrian traffic.

A study conducted by Egeskog (2019) revealed that the behaviour of cyclists when encountering oncoming traffic on a 3 m and 2.4 m wide bicycle path is largely similar to that observed when cycling without oncoming traffic. The perception of safety is significantly influenced by a width of 2 m.

2.8 Limitation

A globally transferable method to decrease the number and the effects of WWC is difficult to implement, as both, the rules and the infrastructure, differ from country to country. For example, there are wide bicycle paths that can be used on both sides, where the issue of cyclists riding the wrong way may be irrelevant. This study is limited to a bicycle path at a certain location at an urban German intersection, where cycling in both directions of the bicycle path is forbidden.

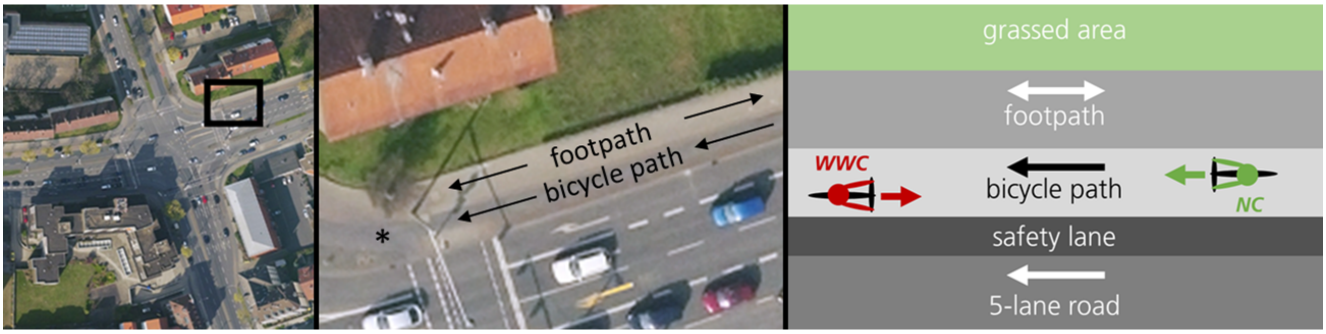

Figure 3 Left: satellite image of AIM Research Intersection (black: area of interest for this analysis); middle: zoom into the AOI with * for the straight AOI after the curve to the left; right: sketch of the study area of interest

3 Method

WWC can be identified locally with the assistance of traditional on-site observation, as is conducted by the police. The use of sufficiently accurate GPS data and a digital map with stored permitted directions of travel enables the identification of WWC (Luan et al., 2020; Dhakal et al., 2018). Furthermore, the detection of WWC via cameras is a viable method. Trajectory data from traffic observations in Braunschweig, Germany (e.g. route, speed, distance) as well as video annotation for verification and additional information (e.g. demographic data) were used to analyse interactions between NC and WWC.

3.1 Traffic observation

The observation took place at the Application Platform for Intelligent Mobility (AIM) Research Intersection in Braunschweig, Germany (Figure 3, left). This large-scale research facility is an instrumented intersection that records trajectory data with 20 fps with 14 stereo-cameras at a traffic signal-controlled crossing with bicycle and footpaths (Figure 3, middle and right). Trajectory data contained information about GNSS-based timestamp, location (UTM), velocity, acceleration, road user type (e.g. pedestrian, bicycle, car) and size of each detected road user (Knake-Langhorst, 2022). The following section provides a brief overview of the image processing techniques employed to derive trajectory data. The objects are captured through the utilisation of stereo video signal processing, which is based on spatial correlation. This enables the calculation of distances within the image through the use of the Hamming distance (disparity). Furthermore, temporal correlation is employed, which entails the linking of identical pixels in successive images (optical flow). The linking of disparity measurements in consecutive images allows the speed of pixels to be measured directly. Subsequently, the position and speed of the traffic participants are derived (Arndt, 2021; Talukder & Matthies, 2004). The accuracy is expected to be better than 25 cm of deviation in average per trajectory. In tests with vehicles equipped with high-precision positioning systems, the lateral deviation was found to be, on average, one digit.

A total of 256 hours of video material, recorded between 8–10 February 2022 (50 hours), 18–28 October 2022 (108 hours) and 26 April–2 May 2023 (98 hours), was analysed with interactions occurring most frequently between 6 a.m. and 6 p.m. No interactions between NC and WWC were found after 8 p.m. and before 6 a.m.

It is only permitted to ride on the bicycle path in the direction of travel. This bicycle path is around 1.60 m wide (FRISBI, 2023), although the effective width is approximately 1.35 m. Paved paths to the left and right of the bicycle path make it appear wider (Figure 4).

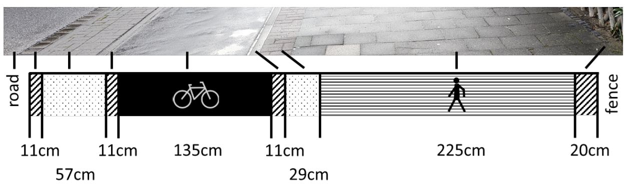

Figure 4 Dimensions of the various paths

On the road side, next to the bicycle path, there is a high kerb, and there is a fence next to the footpath. The width of the bicycle path makes it difficult for two cyclists to ride next to each other or to overtake. Therefore, most WWC take the footpath (see results in section 4). The area of interest (AOI) is approximately 25 m long and straight. The bicycle path is narrow

Figure 5 Study area: foot- and bicycle paths from the perspective of WWC (left) and NC (right)

and the adjacent footpath can be used without obstacles (Figure 5). Figure 5 shows the bicycle path from the point of view of the WWC (left) approximately from the position of the star-sign in Figure 3 (middle), as well as the bicycle path from the point of view of the NC (right). The bicycle path seems to be in poor condition. Random observations showed no influence of the surface on keeping the route or heavy puddle formation.

The cyclists were observed to be unaffected at all times. There were no indications of incorrect direction of travel, as shown in chapter 2.2, and there were no police checks. The AIM Research Intersection has been in place since 2014, so the influence of this can also be categorised as low.

3.2 Traffic analysis

The whole data process is shown in Figure 6, which includes all necessary processing steps from data recording, detection of direction of travel, separation of NC and WWC to interaction analysis.

The direction of travel was determined using polygons. Associated NC and WWC were clustered into different interaction types, depending on where NC or WWC were riding at the beginning and during the interaction. The Euclidean distances between the object centres of the interacting couples were computed. The identified interactions were checked manually in the video. Further information such as helmet use, age, gender or hands on the handlebars were annotated. Assuming that the bicycles maintained their direction and speed when passing each other, small data gaps were interpolated linearly. Interaction pairs where one or both trajectories were corrupted were ignored. Sometimes passing each other took place outside the detection area. These interaction pairs were also not used. The impact on pedestrians was not analysed in this study. Care was taken to ensure that pedestrians did not interfere with the cyclists' interactions. The interaction can be represented graphically in three phases. Figure 7 shows them of this passing manoeuvre as an outline.

Phase 1 describes the switching process, in which the WWC crossed from the bicycle path to the footpath. Phase 2 contains the process when NC and WWC passed each other, with NC riding on the bicycle path and WWC riding on the footpath. In phase 3, the WWC switched from the footpath back to the bicycle path. Phases 1 and 2 could be observed properly in the AOI. In many cases, phase 3 could not be observed due to the restrictions of the field of vision of the cameras.

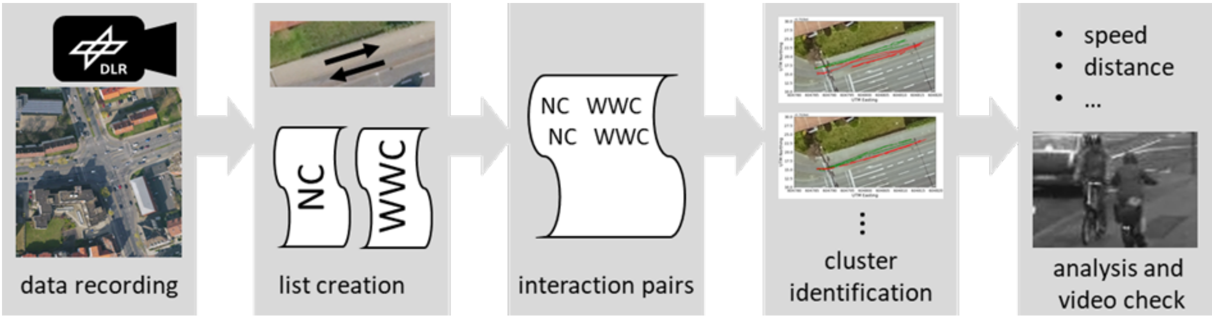

Figure 6 Outline of the analysis procedure from data recording (left) to data clustering and analysis (right)

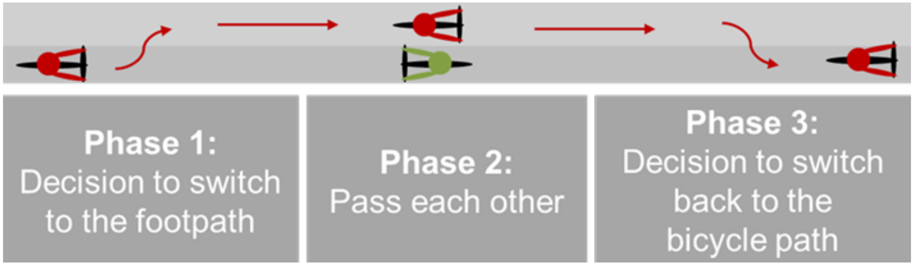

Figure 7 Considered interaction phases in the AOI in the case that NC rode on the bicycle path and WWC changed from the bicycle path to the footpath

4 Results

19 352 bicycles could be counted in the data, and 12% of those were WWC. In the final dataset, 169 trajectory pairs of NC—WWC interactions remained for analysis in the AOI (Figure 3, middle and right). During validation and plausibilisation of the interaction pairs in the video images, gender, age range and helmet use were estimated and annotated. It appeared that 61% of the NC and 75% of the WWC were male. WWC seemed less likely to wear a helmet (7% of men and 12% of female).

4.1 Interaction

The first step of the analysis was to examine, which patterns occurred (i.e. path change, passing and overtaking) during the interactions. Also, it was checked whether similar patterns occurred after passing the interaction partner. All cases were compared between NC on bicycle path or footpath and WWC on bicycle path or footpath. Each case occurred at least once. The largest proportion of 21% WWC was found on 18 October 2022, 6–7 a.m. and 26 April 2023, 6–7 p.m.

In the following, the term ‘straight’ is always used when the WWC trajectory was straight and the WWC remained on either the bicycle path or the footpath. The term ‘crossing’ was used to express the change between bicycle path and footpath. A distinction is made for the WWC as to whether it changed to the footpath before the interaction or to the bicycle path after the interaction. In Table 1, the resulting data is shown for each interaction on the respective infrastructure (footpath or bicycle path) for NC and WWC.

In Figure 8 the different clusters of encounter situations corresponding to Table 1 are shown. The green lines represent NC cycling from east to west and the red lines represent WWC cycling from west to east. In 110 (65.1%) cases, the WWC was on the footpath and the NC on the bicycle path, and both remained (straight). This was the most frequent case and also the safest for interaction between cyclists, because uncontrolled short-term evasive manoeuvres were less likely to occur (Figure 8, case 1.1). In 14.2% of the cases, the second most common occurrence was that WWC initially rode on the bicycle path and decided to switch to the footpath (crossing) before interacting with the NC (Figure 8, case 1.2).

NC and WWC interacted less frequently together on the bicycle path (straight: 11.8%, crossing: 4.1%). Nevertheless, this interaction was the most dangerous of all, because NC and WWC came closest to each other compared to all other cases. It harbours the largest collision risks, as the bicycle path was only 1.60 m wide. The distance between the handlebars was very

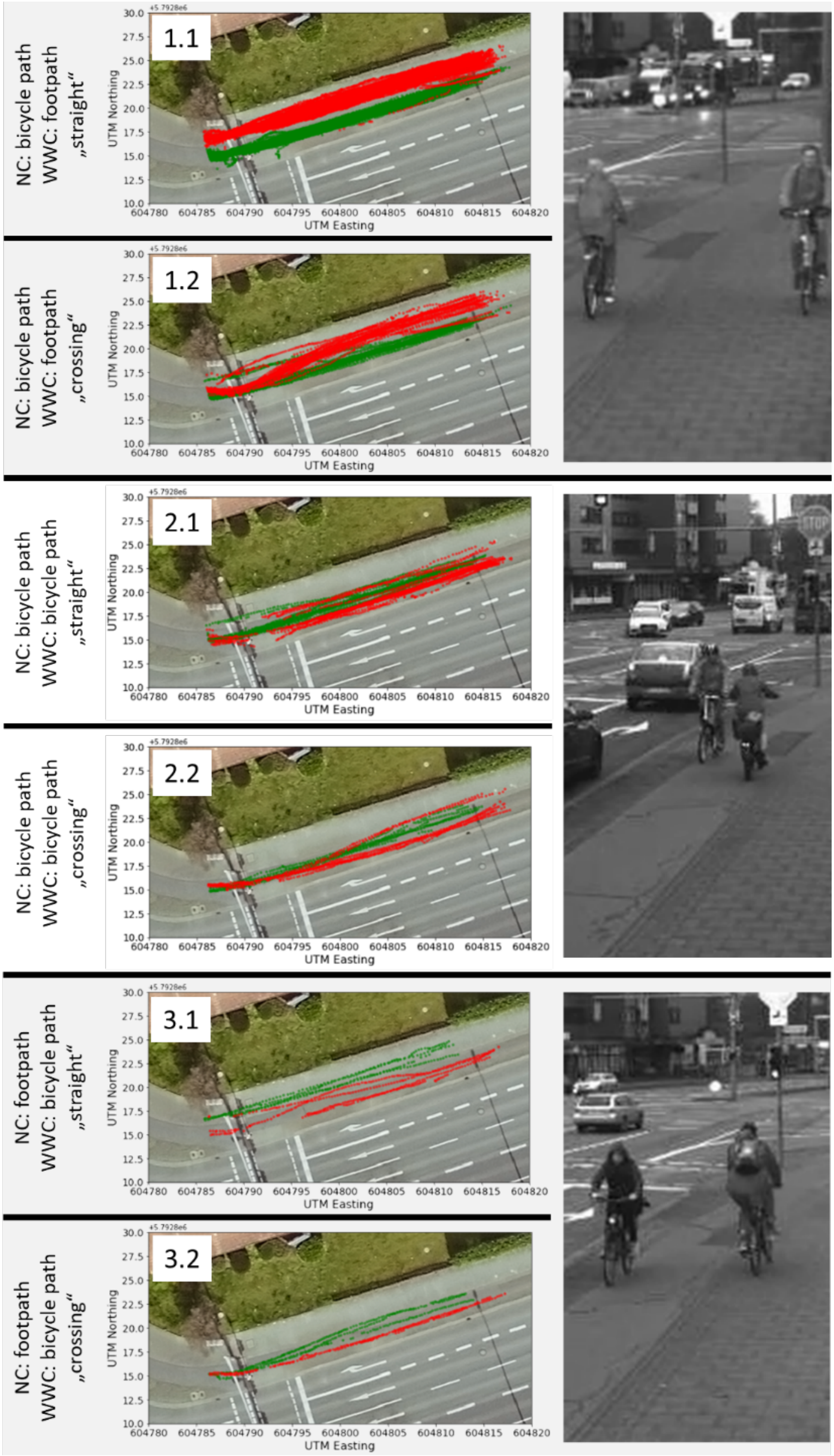

Figure 8 Types of interaction between NC and WWC: cases 1.1 and 1.2: NC on bicycle path and WWC on footpath; cases 2.1 and 2.2: NC and WWC on the bicycle path; cases 3.1 and 3.2: NC on footpath and WWC on bicycle path

Table 1 Scenarios of 77 interacting cyclist pairs

No.	NC	WWC	Type	Number of cases	dmin,mean | dmin [m]	NC v | [m/s]	WWC |v| [m/s]
1.1	Bicycle path	Footpath	Straight	110 (65.09%)	2.29 ± 0.04 | 1.42	5.12 ± 0.13	4.39 ± 0.11
1.2			Crossing	24 (14.20%)	2.14 ± 0.07 | 1.50	5.21 ± 0.24	4.76 ± 0.19
2.1	Bicycle path	Bicycle path	Straight	20 (11.83%)	2.38 ± 0.49 | 0.68	4.98 ± 0.25	4.63 ± 0.16
2.2			Crossing	7 (4.14%)	1.65 ± 0.09 | 1.48	5.44 ± 0.27	5.00 ± 0.30
3.1	Footpath	Bicycle path	Straight	4 (2.37%)	2.50 ± 0.17 | 2.16	6.21 ± 0.59	4.93 ± 0.39
3.2			Crossing	3 (1.78%)	1.43 ± 0.39 | 0.68	4.56 ± 0.45	4.90 ± 0.34

Note: with speed |v|, mean of minimum distance between the cyclists during interaction $d_{min,mean}$ and type 'straight' or 'crossing' for changing path, with ± for standard deviation.

small and the slightest swerve could lead to an accident (Figure 8, cases 2.1 and 2.2). In 2.4% (straight) and 1.8% (crossing) of cases, the WWC rode on the bicycle path and the NC on the footpath or swerved onto it (Figure 8, cases 3.1 and 3.2). In doing so, they gave up their legal right of way on the bicycle path in the right direction and adopted the footpath instead. In these cases, both cyclists committed an offence, the WWC used the bicycle path in the wrong direction and the NC the footpath (see Table 1). The scenario of NC and WWC travelling on the footpath only occurred once during the period and is not shown.

4.2 Distance and velocity

The average Euclidean distance d_{mean} between interacting NC and WWC was approximately 2.14 m. In 27 cases d was even less than 2 m. The smallest distance was d_{min} = 0.68 m.

On average, 11% WWC (n = 7 598) were detected. With more than 20% the proportion of WWC was the largest between 6–7 a.m. NC and WWC did not always interact in the same way. WWC most often drove on the footpath and did not have an observable influence on the NC. Table 1 visualises the measured variables: column $d_{min,mean}$ quantifies the1 minimum distance during interaction; in column |v| the speeds of both, NC and WWC, are shown during interaction. NC and WWC can ride on the bicycle path or footpath. It appeared that in 70 of 169 cases the bicycle path was used, and in seven cases both adopted the bicycle path at the same time. There were no examples found, where both rode on the footpath. Within the area of interest, it occurred that NC and WWC first changed paths before they passed each other (Table 1 crossing). Otherwise, NC and WWC kept their path during the interaction (Table 1 straight). In each situation the speed of the WWC was lower than of the NC except case 3.2. In three of nine of the crossing cases, it appeared that WWC had already cycled along the footpath before reaching the AOI (compare Figure 3middle). In six cases, the WWC was already on the bicycle path. In the remaining five crossing cases, the WWC was not detected until the path change. It appeared, that the WWC switched from the bicycle path to the footpath approximately 14.4 m ± 3.7 m before the interaction. When riding on the bicycle path at the same time, small distances were measured. In one case NC and WWC rode on the footpath. As the WWC trajectory was too short, the interaction point could not be determined.

4.3 Model

In most cases, the NC was riding on the bicycle path (n = 161, 95,3%). This amount of data makes it possible to set up a tree of possible interactions and to describe the individual interactions. The result of the interaction behaviour of WWC encountering a NC on the bicycle path is shown in Figure 9. Cases that occurred less than five times are not shown.

Case 1.1: In 68.3% of the cases, NC rode most frequently on the bicycle path while the WWC was already on the footpath (straight). The NC passed legally and unaffected by the WWC on the bicycle path. The WWC rode on the footpath and the interaction between WWC and NC were not critical, but it could not be ruled out that the WWC possibly could have interacted with pedestrians.

Case 2.1: When WWC and NC remained on the bicycle path was one of the least observed cases (n = 20, 12.4%), but it can lead to critical interactions (Figure 9, red bubble). The smallest distance measured for NC and WWC on the bicycle path was d_{min} = 0.68 m (see Table 1).

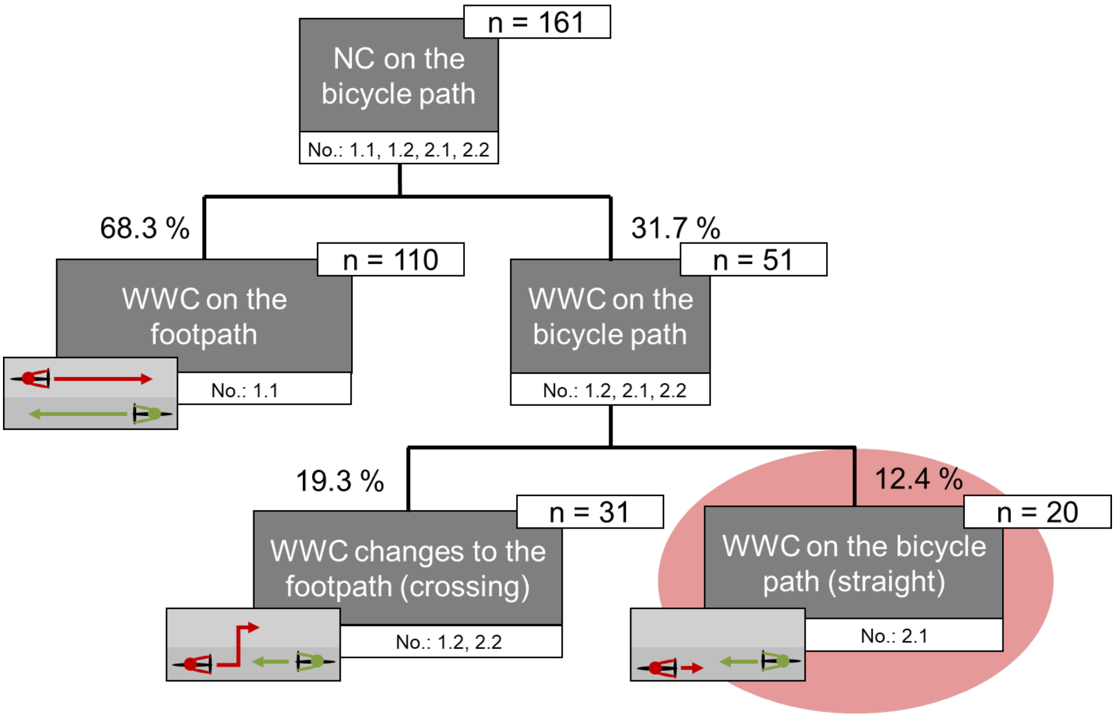

Figure 9 Possible interactions of WWC when NC rides on the bicycle path

Cases 1.2 and 2.2: In another scenario the NC rode on the bicycle path and the WWC initially rode on the bicycle path, but decided to switch to the footpath before the interaction and, if necessary, to switch back to the bicycle path after the interaction (crossing with 19.3%).

The phases 1 and 2 shown in Figure 7 occurred 14 times. The average distance between the change from bicycle path to the footpath and the interaction was 18.17 m ± 3.75 m. In five observed cases all three phases could be recorded. The distance between change and interaction was 15.58 m ± 5.04 m. After the interaction, the change back to the bicycle path took place after 4.43 m ± 1.95 m.

If the first straight section of the infrastructure after the local curve was taken as the starting point of this study, the change from bicycle path to footpath (phase 1) took place after 6.08 m ± 1.83 m in all 19 cases (see the black asterisk in middle of Figure 3).

5 Discussion

This study focused on the analysis of how WWC adapted their behaviour when NC and WWC passed each other. For this purpose, 256 hours of real trajectory data were recorded and analysed regarding NC and WWC interaction at an urban intersection. During the recording period, 169 interaction pairs of NC and WWC remained in the final data set for detailed analysis.

It was found that with a WWC rate of 12% this study confirmed other studies (Alrutz et al., 2009; Huemer & Vollrath, 2014; Große & Böhmer, 2021). WWC seemed less likely to wear a helmet (7% of men and 12% of female), which could indicate that WWC are more willing to take safety risks. The results could indicate that if one rule is broken, others are added or that WWC are generally more willing to take risks. It is necessary to conduct further research in order to ascertain whether the use of the bicycle path as a WWC is influenced by gender or helmet use.

The obtained results showed that WWC often rode on the footpath and avoided conflicts with NC. It also appeared that a small proportion of WWC adopted the bicycle path at the same time and passed by very closely and potentially dangerous. An explanation could be that WWC were aware of their wrong behaviour and thus, adapted to the situation as safely as possible. In the case of WWC that stayed on the bicycle path, it was not entirely clear whether they did not know that it was illegal or whether they did not care about such dangerous situations. Some NC swerved onto the footpath in order to mitigate the situation. An explanation could be that they insisted on their rights and also stayed on the bicycle path, which led to almost 11% of critical interactions. WWC rode most frequently on the footpath (approximately 80%), which was prohibited, but they therefore avoided the interaction with another NC. WWC were slower on average in comparison to NC, which might be affected by local curve they passed before entering the field of observation. The reason for this could also be to ride more safely, because of the awareness that he/she was riding in the wrong direction.

Reasons for wrong-way cycling are for instance the claim to save time, for instance due to detours. The lack of knowledge was found as a reason too (Große & Böhmer, 2021). Campaigns can help to raise awareness of the rules. However, education is not enough to completely prevent wrong-way cycling. In future, it will be important to take measures to prevent WWC. As rules and signs only help to a limited extent, infrastructural adjustments should be considered. As it will hardly be possible to avoid WWC in the short term, and campaigns only help briefly and locally, it is important to better understand and model WWC.

It is not evident that the opening up (two-way bicycle path) of the 1.60 m wide bicycle path described in this study would be a beneficial course of action. In the present study, distances of 2.36 m were identified as the minimum required for both cyclists to ride on the bicycle path safely (Table 1, no. 2.1). Subtracting 0.35 m for half the steering wheel position, as measurements were taken from centre to centre, results in a lateral distance of less than 1.70 m. However, due to the inherent error tolerance associated with the measurement and comparison with the video material, it can be assumed that the 1.60 m bicycle path width is not sufficient, as this is the preferred lateral distance. If we assume that the bicycle path is 2.40 m in width, it would be possible to maintain this distance without having to ride on the border of the bicycle path. This is consistent with the findings of the study conducted by Egeskog (2019), which indicates that cyclists perceive the presence of oncoming traffic only when the bicycle path width is less than 2.40 m. It should be noted that even a bicycle path of 2.40 m in width does not provide sufficient space for cyclists to overtake or navigate oncoming traffic safely when the width of the handlebar is 0.70 m. The combined width of the cyclists and their handlebars already occupies 2.10 m of the path, leaving only 15 cm of lateral clearance for overtaking and oncoming cyclists. This is also inadequate. A bicycle path width of 2.40 m is a minimum requirement. In the interests of safety, cyclists must wait until oncoming traffic has passed before overtaking. Allowing cycling on both sides of the road could be a good option, but might require a re-design of intersections (e.g. less space for cars and more space for cyclists, a change of traffic guidance markings or signalling) and thus, higher costs. Nevertheless, Methorst et al. (2017) have shown that these two-way bicycle paths are not accident free. However, it can assist in the avoidance of conflicts between cyclists on road sections without intersections. Another option is the implementation of a wider one-way bicycle path serving to mitigate conflicts with WWC.

The number of interactions between WWC and NC is insufficient to confirm or refute the occurrence of accidents. During the analysis, no accidents occurred in the AOI. The establishment of a causal relationship between conflicts and accidents requires the analysis of larger data sets.

In any case, it is important to separate pedestrian and bicycle traffic without creating barriers. Shifting bicycle traffic to the road would make it much less attractive to cycle the wrong way, but also to cycle in general.

6 Conclusion and future projects

The results of this study showed that interactions between NC and WWC showed different characteristics. In many cases, WWC and NC rode already separately on footpaths and bicycle paths long before interaction with each other. In other cases, WWC switched to the footpath approximately 14 m before the interaction took place, which can be explained by the awareness of the NC approaching, and avoiding adopting the same narrow bicycle path. In a few cases, the WWC stayed on the bicycle path, accepting that a close encounter between NC and WWC was going to happen. Additionally, some WWC switched back to the bicycle path after interaction. In all of these behavioural patterns, except the case NC adopted the footpath and WWC remained on the bicycle path, speeds of WWC were considerably lower than those of NC. An explanation of this could be that due to the narrow bicycle infrastructure WWC were aware of their wrong behaviour and thus, reduced speeds. In the same way, NC also seemed to be aware of their wrong behaviour when they adopted the footpath, which led to lower speeds of the NC, too. In general, the speeds of

WWC were very similar among all switching patterns.

Further analyses of the trajectories could provide more information about when cyclists avoid or keep their path and, if necessary, at what distance a speed is maintained or adjusted.

We expect that riding behaviour and specifically WWC—NC interactions differ depending on type and width of bicycle path as well as of the bicycle type and the cyclists themselves. Further investigations should be carried out to compare riding behaviour on larger areas of interest, different transportation infrastructure and among different bicycles and rider types. In the future, additional data will be collected and analysed applying further suitable metrics of traffic conflict technique in order to determine behavioural and kinematic patterns of interacting cyclists for developing reliable tactical and operational cycling models for safety simulation purposes. In this way, a digital twin can not only help to map the state of reality more accurately, but also to test and optimise new types of infrastructures and bicycle types. Further data must be collected and analysed in order to be able to make further statements about these types of interaction and to check whether clusters have been overlooked. Furthermore, it should be checked whether the distribution remains the same or whether underrepresented clusters gain in importance.

The influence of weather conditions was not analysed. Puddles or paths that are poorly cleared of snow can also lead to changes in the riding behaviour of NC and WWC. It is possible that puddles are avoided and paths are used where there is snow to prevent the risk of falling. It would be beneficial for further studies to investigate the influence of WWC and NC in the presence of pedestrian traffic, given that WWC are not free to ride onto the footpath. A survey is currently being planned in the AOI to find out why cyclists are WWC in this area. The survey may provide information on whether WWC are aware that they need to slow down or swerve and why they sometimes may not do so.

However, the transferability of the results to other arms of this specific interaction and even other locations is limited and has to be verified in future observations. We can expect the behaviour of cyclists to be similar, especially on separated bicycle paths and footpaths in Germany. The findings may change if the bicycle infrastructure has other constructional characteristics, for instance, if the width of the bicycle paths increase. Transferability to other countries will very likely lead to different results due to the differences in construction, traffic rules, etc.

CRediT contribution statement

Claudia Leschik: Conceptualization, Data curation, Formal analysis, Investigation, Software, Supervision, Visualization, Writing—original draft, Writing—review & editing. **Imanol Irizar da Silva:** Data curation, Software, Writing—review & editing. **Kay Gimm:** Conceptualization, Visualization, Writing—review & editing. **Marek Junghans:** Conceptualization, Supervision, Writing—review & editing.

Declaration of competing interests

The authors report no competing interests.

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