Modelling cyclists‘ behaviour and interactions at urban intersections

vorgelegt von

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Abstract

The number of cyclists in Germany is increasing yearly, but infrastructure has failed to adapt to this growth. E-bikes are becoming more common, resulting in more speed differences on bicycle paths. In addition, manoeuvrable e-scooters and large cargo bikes also share the bicycle path with conventional bicycles and e-bikes. Bicycle paths are mostly narrow and it is difficult to manoeuvre without interaction with other cyclists. Little is known about the causes of bicycle-bicycle accidents. Due to the limited availability of accident data, real-life observational data can be used to gain a better understanding of bicycle-bicycle interactions.

This dissertation aims to provide a more comprehensive understanding of how cyclists interact with each other by presenting an overview of interaction patterns, descriptions of interactions, and initial modelling approaches. The data used for this thesis were collected over several weeks at different intersections in Braunschweig, Germany. At these intersections, the trajectories of road users were recorded by using camera systems.

The thesis demonstrated that there are three primary categories of cycle interactions at intersections: overtaking, oncoming, and crossing. Surrogate Measures of Safety were utilised as criticality metrics to assess the degree of criticality of the interactions between cyclists in the scenarios. Route choice, speed during the interaction, lateral distances during the interaction and longitudinal distances before the interaction were analysed in order to subdivide the oncoming and crossing scenarios into further sub-scenarios. In addition, it was investigated how often cyclists adhere to the rules in the observation data (correct direction of travel, respecting right-of-way, bicycle path use) and how they themselves rated their cycling behaviour in a survey. The results of the analysis demonstrate that instances of deviant behaviour in particular can precipitate critical situations. The observed bicycle path is notably narrow, rendering it difficult for two cyclists to ride side-by-side. In the event that a cyclist travels in the incorrect direction on the bicycle path, there is an inherent risk of collision with another cyclist travelling in the wrong direction. Such an incident could result in injury.

It is therefore of the utmost importance to educate children at an early age about cycling rules. Signs, pictograms or additional illuminations in critical areas of a bicycle path can alert cyclists that they are cycling in the wrong direction. In the crossing scenario, the installation of additional traffic lights could be considered to clarify the right-of-way.

The study underlines the serious potential of conflicts of cyclists at intersections and the need for further research in this area. Parameter distributions can be used in the future to develop measures for mitigating cyclist conflicts or to simulate and plan infrastructure more effectively and safely.

Zusammenfassung

Seit Jahren nehmen die Radverkehrsstärke und Fahrzeugtypen auf Radwegen in Deutschland stetig zu. Neben konventionellen Fahrrädern steigt sowohl der Anteil an schnelleren E-Bikes, als auch die Menge an wendigen E-Scootern und breiten Lastenrädern auf Radwegen. Da die Radverkehrsinfrastruktur nicht mitgewachsen ist, sind die vorhandenen Radwege häufig zu schmal, um eine interaktionsfreie Begegnung von Radfahrenden zu ermöglichen. Über die Ursachen von Fahrrad-Fahrrad-Unfällen ist wenig bekannt. Aufgrund der geringen Verfügbarkeit von Unfalldaten können reale Beobachtungsdaten genutzt werden, um ein besseres Verständnis über Fahrrad-Fahrrad-Interaktionen zu erlangen.

Ziel dieser Arbeit ist es, Fahrrad-Fahrrad-Interaktionen an Kreuzungen zu analysieren und mögliche Konflikte zu identifizieren. Dazu wurden Videoaufzeichnungen und Trajektorien verschiedener Zeiträume mit und ohne Radweg an Kreuzungen in Braunschweig, Deutschland untersucht.

Bei der Analyse wurden drei Hauptszenarien identifiziert: Entgegenkommen, Kreuzen und Überholen. Die Kritikalität der Interaktionen wurde mit Hilfe von Metriken, den Surrogate Measures of Safety, untersucht. Routenwahl, Geschwindigkeiten während der Interaktion und laterale Abstände während, sowie longitudinale Abstände vor der Interaktion wurden analysiert, um die Szenarien Entgegenkommen und Kreuzen in weitere Unterkategorien einzuteilen.

Anhand von Realdaten wurde untersucht, wie oft sich Radfahrende an Verkehrsregeln halten und in einer Umfrage bewerteten Radfahrende ihr eigenes Fahrverhalten. Im Anschluss konnten erste Modellierungsansätze entworfen werden. Die Ergebnisse zeigen, dass insbesondere regelwidriges Verhalten zu kritischen Situationen führen kann. Ein schmaler Radweg erschwert das Nebeneinanderfahren der Radfahrenden, so dass es beim Szenario Entgegenkommen vor allem kritisch ist, wenn beide Radfahrende auf dem Radweg fahren. Beim Szenario des Kreuzens zwischen Radfahrenden besteht das größte Risiko, wenn die Vorfahrtsregel missachtet wird.

In allen Fällen ist es von größter Bedeutung, Kinder frühzeitig zu schulen. Schilder, Piktogramme oder eine mögliche zusätzliche Beleuchtung kritischer Bereiche von Radwegen können Radfahrende darauf hinweisen, dass sie den Weg in die falsche Fahrtrichtung befahren und andere vor ihnen warnen. Im Szenario des Kreuzens könnte die Installation zusätzlicher Ampeln in Betracht gezogen werden. Aber auch hier müssten sich Radfahrende an Regeln halten, um kritische Interaktionen oder Unfälle zu vermeiden.

Die Arbeit zeigt das Potential für kritische Interaktionen an Kreuzungen zwischen Radfahrenden in Deutschland auf und stellt Parameterverteilungen zur Verfügung, welche in Zukunft genutzt werden können, um Maßnahmen zu entwickeln, Fahrrad-Fahrrad-Konflikte zu entschärfen oder Infrastrukturen genauer zu simulieren und zu planen.

Acknowledgments

Das Thema Radfahren beschäftigt mich schon sehr lange. Egal, ob der Weg zur Schule, Wege zu Freunden oder Ausflüge in die Natur - das Fahrrad ist ein tolles Fortbewegungsmittel. Seitdem ich mich im Rahmen meiner Dissertation mit Radfahrendenverhalten beschäftigt habe, fallen mir im Alltag deutlich mehr Konflikte und kritische Situationen auf als zuvor. Aufgrund meiner Arbeit habe ich einen anderen Blick auf Situationen auf dem Radweg entwickelt, welche mit Sicherheit auch nach fünf Jahren Fahrrad-Fahrrad-Forschung weiterhin Forschungsfragen bei mir aufwerfen werden. Dank meiner Tätigkeit am DLR hatte ich auch die Möglichkeit an nationalen und internationalen Konferenzen teilzunehmen und Teile meiner Dissertation mit anderen Forschenden zu teilen, dabei zeigte sich stets großes Interesse an Radfahrendeninteraktionen, denn viele hatten zuvor nie wirklich darüber nachgedacht.

Meine Dissertation ist kein Fingerzeig auf böse Radfahrernde, sondern soll vielmehr einen Einblick in das Verhalten von Radfahrenden an Kreuzungen mit und ohne Radweg geben. Einen Einblick in etwas, was wir als Radfahrernde jeden Tag erleben und worüber wir uns doch selten Gedanken machen. Ich freue mich, einen Überblick in die Verhaltenswelt des Radverkehrs geben zu können und die Forschung im Bereich der Fahrrad-Fahrrad-Interaktionen voranzutreiben. An dieser Stelle möchte ich mich bei einigen Personen bedanken, die mich motiviert und inspiriert haben.

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Preliminary Remarks

Special Terms

In this dissertation, the term ‘bicycle path’ is used because these routes were constructed with the primary intention of being used by two-wheeled vehicles. Based on cycling conferences (Velo-City, ICSC), cyclists do not ride ‘bikes’ because motorcyclists also do so. Cargo bikes, trikes and other vehicles for the bicycle paths would be excluded by ‘bicycle’. The number of wheels on the bicycle path is irrelevant, so the term ‘cyclist’ is used for the people in this study. The study looks at all types of bicycles on the bicycle path and does not distinguish between cargo bikes, bicycles or e-bikes.

Despite the fact that the differences between the groups were not analysed in this thesis, it is important to ensure that no one is excluded.

Citation

Sources are cited before the end of the sentence if the source refers to the sentence, and after the end of the sentence if the source refers to the paragraph.

Data used

The thesis was written at the German Aerospace Center e. V. (DLR) in the Institute of Transportation Systems. The data used was collected as part of various projects mentioned in this thesis. I analysed the data statistically and carried out the survey independently. The observation data are not freely available.

Earlier Publications

Earlier versions of the content presented in this study have appeared in peer-reviewed journals, lectures, or posters. Minor revisions and adaptations have been made to ensure coherence with the overall structure and argumentation of this study. Parts of the publications are included in this study and are primarily related to Section 4.

Section 4.1 builds on:
Leschik, C.; Gimm, K.; Irizar Da Silva, I. & Junghans, M. (2024). Interactions among cyclists riding the wrong way on the bicycle path. *Traffic Safety Research, 7*, e000072, Paper: https://doi.org/10.55329/bkjn8897

and
Leschik, C.; Gimm, K.; Irizar Da Silva, I. & Junghans, M. (2023). *Interactions among cyclists riding the wrong way on the bicycle path*. ICSC 2023 in Den Haag, The Netherlands, Poster: https://elib.dlr.de/199495/

Section 4.2 is adapted from:
Leschik, C.; Zhang, M. & Gimm, K. (2024). *Investigating of interactions between crossing cyclists at a signalised intersection based on trajectory data*. ICSC 2024 Imabari, Japan, Lecture: https://elib.dlr.de/211072/
and
as of 8 April 2025, the corresponding paper remains under review in IATSS and was originally submitted on 31 January 2025.

Section 4.3.1 incorporates material from:
Leschik, C.; Zhang, M.; Klitzke, L. & Gimm, K. (2024). *Comparison of overtaking behaviour between cyclists, and between motorised road users with cyclists*. Velocity 2024 in Ghent, Belgium, Poster: https://elib.dlr.de/205996/

The following publications also include trajectory analyses related to bicycles but were not addressed in detail in this study:
Leschik, C.; Zhang, M. & Gimm, K. (2024). Analysis of stopping behaviour of cyclists at a traffic light-controlled intersection using trajectory data [version 2; peer reviewed]. The Evolving Scholar - BMD 2023, 5th Edition, Paper: https://doi.org/10.59490/65e0736e3d3955984cdf53a6
and
Leschik, C.; Zhang, M. & Gimm, K. (2023). *Analysis of stopping behaviour of cyclists at a traffic light-controlled intersection using trajectory data*. BMD 2023 5th Edition in Delft, The Netherlands, Poster: https://elib.dlr.de/198377/

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List of Abbreviations

ADAC Allgemeiner Deutscher Automobil-Club e. V. (General German Automobile Club)

AIM Anwendungsplattform Intelligente Mobilität (Application Platform for Intelligent Mobility)

AOI Area Of Interest

BMDV Bundesministerium für Digitales und Verkehr (Federal Ministry for Digital and Transport)

Destatis Deutsches Statistik-Informationssystem (Federal Statistical Office of Germany)

DLR Deutsches Zentrum für Luft- und Raumfahrt e. V. (German Aerospace Center)

EFA Empfehlungen für Fußgängerverkehrsanlagen (Recommendations for Pedestrian Traffic Facilities)

ERA Empfehlungen für Radverkehrsanlagen (Recommendations for Bicycle Traffic Facilities)

FGSV Forschungsgesellschaft für Straßen- und Verkehrswesen (German Road and Transportation Research Association)

GIDAS German In-Depth Accident Study

MiD Mobilität in Deutschland Studie (Study of Mobility in Germany)

NC Normal Way Cyclist

PET Post Encroachment Time

pPET Predicted Post Encroachment Time

RASt Richtlinien für die Anlage von Stadtstraßen (Guidelines for the Design of Urban Roads)

SMoS Surrogate Measures of Safety

SMP Scenario Mining Platform

StVO Straßenverkehrsordnung (German Road Traffic Regulations)

SUMO Simulation of Urban Mobility

TASI TrAffic Situation Analysis and Interpretation

TTA Time To Arrival

TTC Time To Collision

WWC Wrong Way Cyclist

Glossary

AIM Application Platform for Intelligent Mobility: A large-scale research platform by the German Aerospace Center (DLR) in Braunschweig, Germany covering various aspects of traffic research. It includes test areas, labs, simulators, and research vehicles to develop and test innovative mobility solutions in realistic environments. (Knake-Langhorst and Gimm, 2016)

Crossing Cyclists whose paths intersect in space and time, either in front of or behind one another.

Encounter Two cyclists follow their route without influencing each other. Either there was no reaction (e.g., swerving) in the observation data, or they were so far apart that it can be assumed that they were travelling uninfluenced. Of course, this does not rule out the possibility that the cyclists saw each other at an early stage and still travelled differently than they normally would if they were alone.

Geisterradler Directly translated, 'ghost cyclists' are cyclists who cycle in the wrong direction and are referred to in this study as WWC. In some studies the term also includes cycling on the footpath (in both directions).

Infrastructure The fundamental physical and organisational facilities and systems supporting transportation, including roads, footpaths and bicycle paths.

Interaction Cyclists change their route because of another cyclist. This means taking evasive action, changing speed or coming very close to the other cyclist.

NC Normal Way Cyclist: A cyclist cycling on the bicycle path in the legal direction of travel. This includes turning onto the pedestrian path or cycling on the pedestrian path in the legal direction of travel in relation to the bicycle path. Cycling on the pedestrian path is generally permitted in the observation locations of this study.

NETEDIT A visual network editor in SUMO where the input is selected from a menu.

Oncoming Cyclists approaching head-on from the opposite direction.

Overtaking A cyclist overtakes another cyclist on either the left-hand or right-hand side.

Research Intersection A traffic intersesction in 38106 Braunschweig, Germany equipped with radar and stereo camera sensors to record detailed data on motorised and non-motorised road user behaviour. It is part of the Application Platform for Intelligent Mobility (AIM).

SMoS Surrogate Measures of Safety are various measures used to assess road safety. The advantage is that driving and riding behaviour can be examined in critical situations without the need for accident data.

SUMO Simulation of Urban Mobility: Open source software for microscopic traffic simulation in urban areas. It enables detailed modelling of means of transport for research and traffic planning. Developed by the German Aerospace Center (DLR).

TASI TrAffic Situation Analysis and Interpretation: Python library for managing, processing, and analysing traffic movement data (trajectory data) from various sources such as infrastructure sensors and vehicles.

Trajectory The route or path a road user follows through space and time, representing their actual movement during travel.

Unfallatlas An online platform by the German Federal Statistical Office providing mapped data on traffic accidents with personal injury.

WWC Wrong Way Cyclist: A cyclist cycling on the bicycle path in the wrong direction of travel. This includes turning onto the pedestrian path or cycling on the pedestrian path in the wrong direction of travel in relation to the bicycle path. Cycling on the pedestrian path is generally permitted in the observation locations of this study.

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1 Introduction

Analyses in large cities in Germany have indicated that more than 40% of car journeys are less than 5 km long. According to the study of UBA (2024), bicycles are the fastest means of transport for this distance. Moreover, cycling promotes health as it requires physical movement and is also environmentally friendly and cheap compared to motorised traffic. (UBA, 2024)

In 2023, the total number of bicycles in Germany was approximately 84 million, representing an approximate 11% increase from 2019 and an over 25% increase from 2005 (Statista, 2025a; ZIV, 2024). In 2023, over 84 million people lived in Germany. The majority of individuals own at least one bicycle, and there is a growing tendency towards ownership of additional bicycles, often referred to as 'second bicycle' or 'third bicycle'. (ZIV, 2024) The number of bicycles sold declined from 2022 to 2023, with 2.4 million bicycles sold in 2022 and 1.9 million sold in 2023. In 2023, the number of e-bikes sold in Germany exceeded that of bicycles for the first time (in 2022 2.2 million e-bikes were sold, versus 2.1 million in 2023). Despite a decline in demand, the bicycle trade has only experienced a modest decline due to elevated e-bike prices. While the number of cargo bikes in 2023 appears relatively modest at approximately 190,000 bicycles, this represents a 14.5% increase compared to 2022. (iwd, 2024)

The Mobilität in Deutschland Studie (Mobility in Germany study; MiD) is a nationwide household survey commissioned by the Bundesministerium für Digitales und Verkehr (Federal Ministry for Digital and Transport; BMDV). At the time of writing, the latest MiD data for 2023–2024 were not available. According to MiD data between 2002 and 2017, both the proportion of cyclists and the number of trips and kilometres travelled increased significantly in this time. The average number of trips per day is 2.4 with an average total distance of 9.3 km, and cycling in urban areas increased from 9% to 15%. One third of the population uses a bicycle at least once a week, mainly for commuting. The cyclist population in Germany is characterised by seasonal fluctuations, with a greater proportion of cyclists and longer distances travelled during the summer months (3 km per trip in winter vs 4.4 km per trip in summer). (MiD, 2019)

Additionally, the population of Germany is increasing at a steady rate, increased from 83.17 million people in 2019 to 84.67 million people in 2023 (Statista, 2025b); this implies that there will be a greater number of individuals interacting with one another on the roads in the future. Furthermore, the composition of modes of transport on the bicycle path is undergoing a transformation. The number of e-bikes is rising, resulting in notable discrepancies in velocity compared to conventional bicycles without motors. The presence of e-scooters and pedelecs also has an impact on this phenomenon. The number of cargo bikes is likewise increasing, necessitating significantly more space on the bicycle path.

According to Allgemeiner Deutscher Automobil-Club e. V. (General German Automobile Club; ADAC), every third bicycle path in Germany's federal state capitals is already too narrow and does not meet the minimum width of 1.60 m (ADAC, 2020). It can therefore be expected that the number of conflicts will increase not only on bicycle paths but also on road lanes for all-vehicle traffic in areas where there is no cycling infrastructure and on footpaths if the cycling infrastructure is too narrow or the road is perceived as too dangerous for cycling.

Table 1: Overview of the German population, number of bicycles owned and bicycle-bicycle accidents for the years 2006 and 2017–2023 (Destatis, 2007, 2018, 2019, 2020, 2021, 2023; Statista, 2025a, 2025b). -: Data for these years were not available at the time of the study.

Year	**Number of German population in million**	**Number of German bicycles in million**	**Number of bicycle-bicycle accidents in %**
2006	82.31	67.00	8.4
⋮	⋮	⋮	⋮
2017	82.79	73.50	8.7
2018	83.02	75.50	9.6
2019	83.17	75.90	9.6
2020	83.16	79.10	11.3
2021	83.24	81.00	10.8
2022	83.12	82.80	-
2023	83.46	84.00	-

In 2020 there were 92,273 cycling crashes in Germany, including 426 fatal accidents or rather fatal crashes. Although the number of fatal crashes decreased by 4.3% compared to the previous year, the number of cyclists had increased by 5.6%. Crashes with cars accounted for 71.9% of accidents, while 11.3% of accidents involved multiple cyclists, and this trend is rising (2006: 8.4%; 2017: 8.7%; 2018 and 2019: 9.6%). (Destatis, 2007, 2018, 2019, 2020, 2021) There was a decrease in the number of accidents between cyclists from 11.3% in 2020 to 10.8% in 2021. At the end of January 2020, the 'World Health Organisation' (WHO) declared a public health emergency, which the WHO declared ended in early May 2023

(Statista, 2024). It remains unclear how the global COVID-19 pandemic affected bicycle-bicycle accidents, as no accident data for such cases since 2022 was available at the time of writing.

An overview of the development of the population (Statista, 2025b), the number of bicycles owned (including e-bikes; Statista, 2025a) and the number of bicycle-bicycle accidents, all referring to Germany, is shown in Table 1.

Given that the number of bicycles continues to increase and the potential for this to overload cycling infrastructure, it is important to understand how cyclists interact with each other. This includes an understanding of how cyclists overtake each other, how cyclists react to wrong-way riders, and how cyclists adapt to each other when crossing. With a sufficiently large sample of data from these three scenarios, cyclists' behaviour can be described descriptively and modelled to allow for measures to improve infrastructure and the modelling of cyclists' real traffic behaviour through simulations. These data can also be used for scenario-based testing of automated driving functions. The aim of this work is thus to realistically describe and depict the traffic behaviour of cyclists. Particular attention is paid to the following three scenarios:

- Oncoming: Cycling in the opposite direction
- Crossing: Cyclists who are coming from different directions and who cross each other at the same point
- Overtaking, side-by-side or convoy: Cycling in the same direction

Different types of cyclists are identified and described within the scenarios. By realistically depicting behaviour, modelling of cyclist trajectories can be improved, and measures can be taken to improve infrastructure.

This thesis addresses the following overarching research question:

How do cyclists interact close to an intersection, and what dangers can arise?

In order to answer the research question, this thesis is divided into different sections, which are presented below. Firstly, a literature review was conducted (Section 2), which addresses the regulations and infrastructure for cyclists (2.1-2.2). It elucidates the circumstances under which cyclists should utilise the bicycle path, and how they should act on intersections. Subsequently, existing bicycle accident statistics are analysed (2.3). The principle of analysing video data and its advantages is explained in Section 2.5, given the low number of reported accidents and high number of unreported accidents. Finally, an insight into a simulation software is given in Section 2.6.

In Section 3, the methodology of traffic observation using video data is presented in more detail. Firstly, an insight into the selected measurement locations is given (3.1) and the data processing (3.2) is explained in more detail. In addition, the tools used (3.3) and the traffic analysis of the bicycle-bicycle interaction scenarios (3.4) are explained. Finally, the data quality is considered in more detail (3.5).

The results are summarised in Section 4. At the time of the study, a large dataset (with different time periods) was analysed to find different interaction scenarios between cyclists at the Research Intersection and the Intersection in the 30 km/h zone. The results of the oncoming (4.1) and crossing (4.2) scenarios are presented in more detail in Section 4, including descriptions of behavioural patterns and parameters from the video data, survey results, a discussion, a conclusion and a limitation section for each scenario. The scenario of overtaking (4.3.1), which was observed less frequently, is dealt with at the end. General analyses of the survey are analysed in Section 4.4.

In Section 5, the scenario of crossing cyclists is used as an example to demonstrate how the SUMO simulation can map scenarios using the determined parameters.

Section 6 deals with general limitations for intersections and the measurement of cyclists.

In Section 7 the conclusion and discussion take place, the research question is answered and an outlook on further research (7.1) is given.

2 Literature Review

Current studies deal primarily with overtaking behaviour and the crossing of cars and cyclists at intersections. The interaction behaviour of cyclists between themselves is rarely considered.

This chapter presents an overview of the legal framework for cyclists on the bicycle path as well as current statistics and previous research. The chapter is divided into a general overview of the legal basis for cyclists (2.1) and sub-sections concerning the legal stipulations for oncoming, crossing, and overtaking scenarios (2.1.1- 2.1.3). Next, Section 2.2 outlines infrastructure rules, such as bicycle path width (2.2.1) and two-way bicycle paths (2.2.2). Section 2.3 discusses bicycle accident statistics in Germany in general (2.3.1); bicycle accident statistics for the oncoming, crossing, and overtaking scenarios (2.3.2); as well as statistics from other countries (2.3.3). Section 2.4 presents the statistics and literature on work dealing with bicycle accidents in the scenarios. Section 2.5 details the use of data when little or no accident data is available and how critical situations can be investigated using trajectories (2.5.1) and video annotation (2.5.2). Section 2.6 examines the simulation of bicycle traffic and Section 2.7 is a summary that goes into more detail about the research question and the next steps to answer it.

2.1 Legal Situation

In Germany, there are various types of bicycle paths. These can be located on the carriageway next to motorised traffic or may be separated; in the latter case, bicycle paths are usually next to the footpath or joined with it.

If a German bicycle path is marked with the signs 237 (special path for cyclists, Figure 1A), 240 (joint footpath and bicycle path, Figure 1B), or 241 (separate footpath and bicycle path, Figure 1C), the cyclist must ride on the bicycle path and may not use the roadway. Exceptions apply if paths are unusable, such as due to snow or ice on the bicycle path. In these cases, the cyclist may bypass the bicycle path on the roadway but must return to the bicycle path once possible. If the condition of the bicycle path would require frequent switching between the bicycle path and the road, the cyclist may ride on the road. (ADAC, 2024c)

Figure 1D shows the sign 244.1 for a ‘Fahrradstraße’ (‘bicycle street’). Cars and motorcycles may be allowed to use it if it is clearly marked. However, if they are allowed to do so, they must not obstruct, endanger or jostle cyclists when riding side-by-side. (ADAC, 2024a)

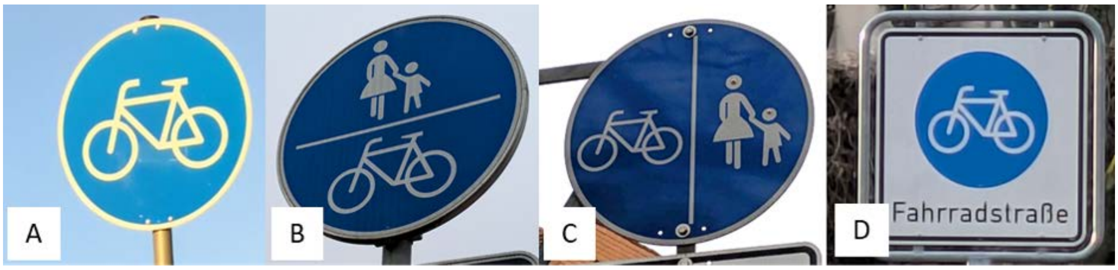


Figure 1: Traffic signs 237 (A), 240 (B), 241 (C) and 244.1 (D)

The supplementary sign 1022-10 (Figure 2A), inscribed with the word 'frei' ('bicycle free'), enables cyclists to utilise thoroughfares and pathways that are typically inaccessible to them, such as one-way streets or footpaths. However, specific regulations pertain to the utilisation of a footpath under the 'bicycle free' designation. In these cases, cyclists must travel at a velocity equivalent to that of pedestrians. (Herbst, 2024)

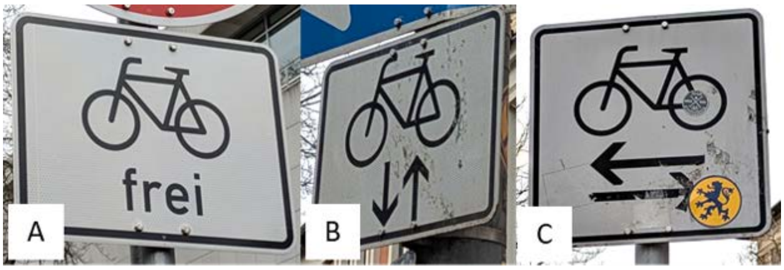


Figure 2: Additional traffic signs 1022-10 (A), 1000-33 (invalid since 1 April 2017) (B) and 1000-32 (C)

Furthermore, it is possible to permit cycling in one-way streets or bicycle paths in both directions. This is subject to the regulations set out in traffic sign 1000-32 in Figure 2C (Figure 2B is invalid since 1 April 2017 but still used).

2.1.1 Oncoming

Furthermore, bicycle paths may only be used in the signposted direction, which is often to the right-hand side of the roadway in Germany. According to § 2 para. 4 Straßenverkehrsordnung (German Road Traffic Regulations; StVO), cyclists may only use the right-hand side bicycle path if there is a bicycle path in both directions of the roadway. Furthermore, the right-hand traffic rule also applies to cyclists in Germany, though there are exceptions if this is signposted or, for example, there is a bicycle path on both sides. If not exceptionally signalled, riding in the opposite direction on the bicycle path is a criminal offence (§ 2 para. 4 StVO) in Germany, regardless of whether one hinders or endangers other cyclists (or pedestrians). Cyclists who ride the bicycle path in the wrong direction are so-called 'Geisterradler' (ghost cyclists) and are called 'Wrong Way Cyclists' (*WWC*) in this study. *WWC* disregard their duty of care and, in the event of an accident, they are at least partly up to fully responsible. In contrast, cyclists who follow the rules of § 2 StVO are referred to as 'Normal Way Cyclists' (*NC*). *WWC* endanger themselves and car drivers at, for example, intersections or when turning because car drivers do not expect cyclists to ride against the direction of traffic.

Children are an exception to these rules. In Germany, children are required to ride their bicycles on the footpath until they reach the age of 8. Between the ages of 8 and 10, children have the option of either riding on the footpath or on the bicycle path. Once they reach the age of 10, they must use the bicycle path. (ADAC, 2024c) It is prohibited for adults to cycle on the footpath. The only exception is that a parent or supervisor from the age of 16 may be allowed to accompany a child under the age of 8 who is cycling on the pedestrian path or the supplementary sign 1022-10 (free for cyclists) mentioned above (Figure 2A). (ADAC, 2024b)

2.1.2 Overtaking

In Germany, the rule for overtaking cyclists requires a sufficient distance (§ 4 StVO); this means that cyclists can be overtaken on a wide bicycle path if the overtaking manoeuvre is announced with a bell and is also noticed by the person being overtaken. No further information is given about the distance or width of the bicycle path. If there is a risk that it will not be possible to overtake safely (i.e., without touching) due to the narrow width of the bicycle path, one is not allowed to overtake. If there is a footpath next to the bicycle path (traffic sign 241 in Figure 1C), it must not be used for overtaking or passing. (ADAC, 2020)

The priority-to-the-right rule also applies on the bicycle path (§ 2 para. 2 StVO). Cycling in the middle of the bicycle path without a reason (to avoid obstacles, to keep a distance from car doors, etc.) makes overtaking more difficult and is prohibited. (ADAC, 2024c)

There is no minimum distance for overtaking on bicycle paths. Legal judgements and recommendations are presented in Section 2.4.1.

2.1.3 Crossing

The legal situation in Germany regarding the behave at intersections with traffic lights for cyclists is well regulated. 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 conditions suggests that a cyclist is 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 not be obliged to stop. The definition of this is not clear (ADFC, 2024):

a. The traffic lights for motor vehicles is placed behind the bicycle path and include it.

b. There is no waiting area between the road and the bicycle path for crossing pedestrians and cyclists to stop.

c. The bicycle path has a stop line (often not present even when stopping is required).

d. The bicycle path is 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 para. 1 sentence 1 StVO (StVO, 2013)).

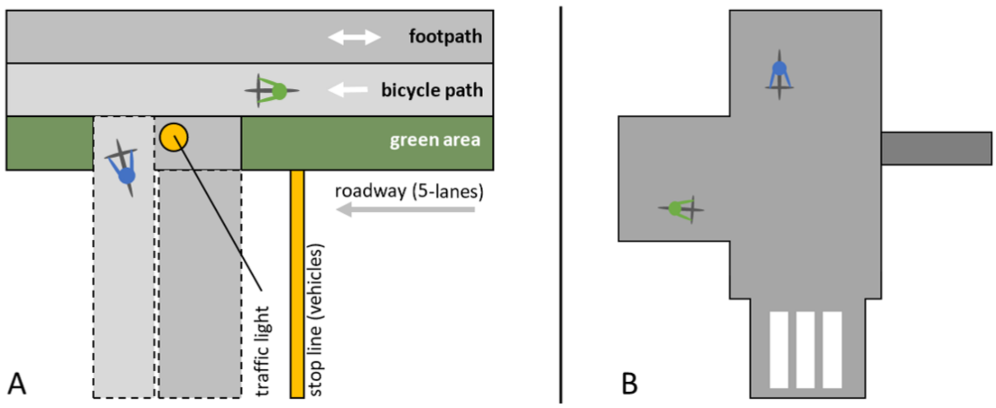


Figure 3: Schematic illustration of the analysed intersections. A: The Research Intersection, where cyclists have priority-to-the-right on the bicycle path; B: Intersection in the 30 km/h zone without a bicycle path and without traffic lights

In this study, an intersection is examined where points a–d not apply: Cyclists do not have to stop on the bicycle path, but the crossing cyclist must give way (Figure 3A). This was confirmed by the local police of Braunschweig. Furthermore, a case study of an intersection without a designated bicycle path situated within a 30 km/h zone and with priority-to-the-right is also presented (Figure 3B).

2.2 Infrastructure

It is not known exactly how many kilometres of bicycle paths there are in Germany, but the network of long-distance bicycle paths across Germany is about 12,000 km long (BMDV, 2024). Due to the available camera technology, this study focuses on the city of Braunschweig, Germany. The bicycle paths in Braunschweig comprising of 205 km of separate 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 that are attached to the main roadway, and approximately 5 km of bicycle protective lanes. Of the 205 km of separate 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) In December 2024, an evaluation was published of all bicycle paths in Braunschweig (ADFC, 2024). Around 130 km of paths do not meet the requirements, for example, because they are not at least 1.50 m wide. This means that there is always the possibility that bicycle paths will be created and removed.

The area under investigation in this study is traversed by a separated 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 (Figure 13).

2.2.1 Path Width

Germany has recommendations for cycling facilities, and the current recommendations from 2010 (ERA 2010) are being renewed in 2025. The ERA 2010 recommendations include information on the construction of bicycle paths. According to ERA 2010, a path 1.60 m wide may be sufficient for low traffic volumes, but ERA 2010 does not define 'low' in further detail. ERA 2010 recommends a path width of 2.00 m. (ERA, 2010)

The decision as to whether bicycle and pedestrian traffic can run without visible separation (i.e., a shared footpath and bicycle path) is dependent upon the number of pedestrians and cyclists per path width, in accordance with German recommendations for pedestrian traffic facilities (EFA 2002), German recommendations for bicycle traffic facilities (ERA 2010), and German guidelines for the design of urban roads (RASt 2006). There is no legal measure regulating pavement widths. The German Road and Transportation Research Association (FGSV) developed the EFA to provide guidance on the design of footpaths. The minimum recommended width for a footpath is 2.50 m, which allows 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 and their specific dimensions in Germany. While the creation of a shared foot- 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 pedestrians and NC on a shared path, and the presence of WWC can further complicate matters, particularly in situations where there is limited space for manoeuvring.

A study by Bjørnskau et al. (2016) examined the recommended minimum and maximum widths of bicycle paths in 15 countries. The minimum width is between 1.20–1.50 m, with 66% recommending 1.50 m. Maximum widths of 2.00–2.50 m are found in countries with a strong bicycle culture, such as the Netherlands and Denmark. Egeskog (2019) investigated the perception of safety in relation to bicycle path width by conducting a study with 13 people on a test track. The results demonstrated that cyclists position themselves significantly closer to the curb of the bicycle path when the width is less than 2.40 m, especially when encountering oncoming cyclists. This tendency is interpreted as risk compensation, as cyclists attempt to minimise the risk of a collision. The speed of cyclists showed no significant differences between different widths of the bicycle path. The distance between oncoming cyclists decreases as the width of the bicycle path decreases. At a width of 1.80 m, the average lateral distance between cyclists is only around 0.25 m. An additional width of over 2.40 m of the bicycle path does not bring any meaningful advantages for perceived safety or the possibility of overtaking, unless the width enables safe overtaking manoeuvres with oncoming cyclists.

A study by Schepers et al. (2023) also analysed bicycle path widths with 24 participants and supplementary observation measurements on real bicycle paths. It was found that larger bicycle path widths resulted in cyclists riding further away from the kerb and maintaining a greater distance from oncoming cyclists. The study recommended a lateral distance of 0.50 m between cyclists to ensure safe encounters.

2.2.2 Two-Way Bicycle Path

BASt (2015) employed a survey methodology to compare the 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, there was no discernible difference between the incidence of accidents occurring in areas where left-hand traffic was against the regulations (where a cyclist was going in the wrong direction on a one-way bicycle path) and those where it was permitted (on a two-way bicycle path). It is recommended by BASt (2015) that bidirectional cycling only be permitted in exceptional cases given the increased risk of accidents at intersections and crossroads.

Methorst et al. (2017) reached a comparable conclusion that the probability of accidents between cyclists and motorists was greater on two-way bicycle paths than on one-way bicycle paths due to motorists failing to consider the direction of travel. The authors therefore rejected the hypothesis that two-way bicycle paths increase cyclist safety. In the Netherlands, cars encounter cyclists more frequently than in other countries, which is unsurprising given that 27% of all journeys are made by bicycle and 72% of bicycle paths are open to both directions. However, motorists oftentimes do not pay attention to cyclists travelling in the opposite direction, resulting in a higher incidence of accidents at intersections without traffic lights. Methorst et al. (2017) highlighted the necessity for two-way bicycle paths to have a certain width in order to avoid head-on collisions with bicycles or mopeds.

UDV (2023) employed a variety of accident statistics to compare the safety of one-way and two-way bicycle paths for cyclists and pedestrians. The accident rate on two-way bicycle paths is 1.5 accidents per area per five years versus 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, bicycle paths with a width of 2.50 m or more rarely witness accidents involving pedestrians and cyclists. It is therefore recommended by UDV (2023) that a two-way bicycle path is not implemented, particularly in areas with a high volume of pedestrian traffic.

Eriksson et al. (2019) revealed that the behaviour of cyclists when encountering oncoming traffic on a 3 m and 2.4 m bicycle path is largely similar to that observed when cyclists do not face oncoming traffic. The perception of safety is significantly influenced when a path has a width of 2 m.

2.3 Bicycle Accident Statistics

The following is an overview of cycling accidents in Germany. The GIDAS (German In-Depth Accident Study) accident database contains accident data for Dresden and Hannover (German cities with more than 500,000 inhabitants). Traffic accidents involving personal injury are collected in anonymised form and made available in the GIDAS database. Detailed parameters are recorded for each accident. Due to the regionally collected data, the representativeness for Germany as a whole may be somewhat limited. The complexity of the details of each accident makes analysis difficult, so the evaluation is not trivial. In addition, the database is not open source and is limited to two cities. (GIDAS, 2025) The GIDAS database was not used in the following analysis.

A selection of online news is compared with Deutsches Statistik-Informations-system (Federal Statistical Office of Germany, Destatis) statistics, and cycling accidents are examined in detail using the Unfallatlas (Accident Atlas). Cycling accidents in other countries are also presented. The online news search is based on Google News (2024) and is intended to provide additional details that cannot be found in Destatis or the Unfallatlas (e.g., reasons for the accident, age or gender).

2.3.1 General Bicycle Accidents in the Media and Statistics in Germany

A search was performed on Google News to obtain an overview of bicycle accidents mentioned in online media (Google News, 2024). Google News does not reflect the total number of accidents but can nevertheless give insight into the current accident situation. To gain an overview of the total number of accidents mentioned, a Google News search was carried out on 1 August 2024 with the German tags 'Unfall' (accident) and 'Fahrrad' (bicycle) and compared with accident statistics for 2021 (Destatis, 2023). For the sample, 107 articles were analysed, of which about 66% ($n = 71$) were matching articles about bicycle accidents. The remaining articles were blocked by a paywall, duplicate articles, or general articles without specific reference to accidents. The articles cover a period of four months (April–July 2024). In comparison, Table 2 compares the Destatis values from the entire year 2021.

Table 2: Types of accidents involving cyclists. Comparison between Google News (4 months) and Destatis 2021 (1 year) (Destatis, 2023; Google News, 2024)

Accident type	Google News in %	Destatis for the year 2021 in %
Alone	16.9	28.7
Bicycle-motorised traffic	78.6	71.7
Bicycle-bicycle	12.5	10.8
Bicycle-train	1.8	Not specified
Bicycle-pedestrian	7.1	6.6

About 63% ($n = 40$) of the accidents in the articles which specified severity ($n = 64$) were serious or fatal. Generally, news coverage tends to prioritise significant incidents (e.g., those related to infrastructure flaws or issues with turning aids, etc.) or those incidents that capture public interest. In addition, both news and official statistics under-report accidents that have not been officially reported, which means that the number of unreported accidents or accidents where the people have come to an agreement will be very high.

Turning accidents ($n = 18$) were the most common type of accident between cyclists and motorised traffic mentioned in Google News, followed by accidents with an unexplained cause ($n = 12$) and crossing the road ($n = 9$). Other accident types with less than six cases were crossing, overtaking, riding side-by-side, or pulling out of a parking space. Furthermore, the consumption of alcohol was identified as a contributing factor in four additional cases. There were only two bicycle-bicycle accidents during the analysed period, four of which were due to oncoming traffic and one due to overtaking. In the case of one unexplained accident, it is suspected that an oncoming cyclist was also to blame.

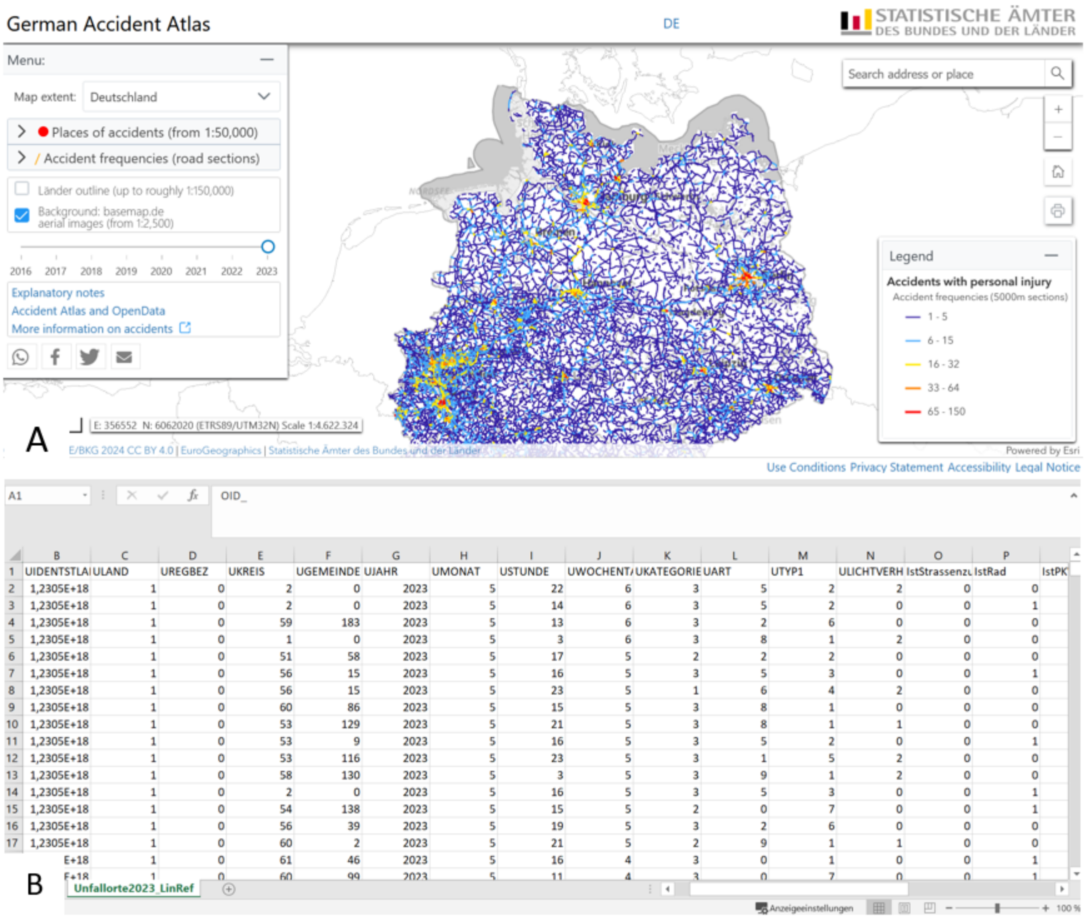
The statistics of Destatis are compiled objectively and neutrally. Destatis collates and publishes all data and statistics from all federal states in Germany and publishes them, including data on road accidents. According to Destatis (2023) data, accidents between bicycles and motorised traffic are mainly caused by incorrect use of the road, turning, parking in and out, and other errors. In 2021, there were 8,264 bicycle-bicycle accidents and 12 fatalities (Destatis, 2023).

2.3.2 Unfallatlas

The Unfallatlas is a compilation of data on road accidents collated by the Federal and State Statistical Offices of Germany and Destatis. The data is derived from police reports and presented in an online map format (Figure 4A) that allows users to interact with the information. Alternatively, the data can be downloaded as Open Data (Figure 4B). The Unfallatlas is updated annually with new accident data from the previous year. The data for all German federal states has been fully available since 2021. The statistics do not include accidents where the police were 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 mapped and made usable. (Unfallatlas, 2024)

The Open Data can be filtered according to accident categories and types. (Metadata on Unfallatlas (2024)). Relevant filters for the following analysis are the type of road user (bicycle with *IstRad*, pedestrian with *IstFuss*, car with *IstPKW*, ...), the accident type (*UART*), and the accident category (*UTYP1*). Where *UART* describes the type of collision (e.g., side collision, collision with oncoming traffic) and *UTYP1* describes the category of accident (e.g., turning, intersection).

The methodology and filters are elucidated in greater detail below. The filters employed for the analysis are highlighted in colour.



	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
1	UIDENTSTLA	ULAND	UREGBEZ	UKREIS	UGEMEINDE	UJAHR	UMONAT	USTUNDE	UWOCHENT	UKATEGORIE	UART	UTYP1	ULICHTVERH	IstStrassenzu	IstRad
2	1,2305E+18	1	0	2	0	2023	5	22	6	3	5	2	2	0	0
3	1,2305E+18	1	0	2	0	2023	5	14	6	3	5	2	0	0	1
4	1,2305E+18	1	0	59	183	2023	5	13	6	3	2	6	0	0	0
5	1,2305E+18	1	0	1	0	2023	5	3	6	3	8	1	2	0	0
6	1,2305E+18	1	0	51	58	2023	5	17	5	2	2	2	0	0	0
7	1,2305E+18	1	0	56	15	2023	5	16	5	3	5	3	0	0	1
8	1,2305E+18	1	0	56	15	2023	5	23	5	1	6	4	2	0	0
9	1,2305E+18	1	0	60	86	2023	5	15	5	3	8	1	0	0	0
10	1,2305E+18	1	0	53	129	2023	5	21	5	3	8	1	1	0	0
11	1,2305E+18	1	0	53	9	2023	5	16	5	3	5	2	0	0	1
12	1,2305E+18	1	0	53	116	2023	5	23	5	3	1	5	2	0	0
13	1,2305E+18	1	0	58	130	2023	5	3	5	3	9	1	2	0	0
14	1,2305E+18	1	0	2	0	2023	5	16	5	3	5	3	0	0	1
15	1,2305E+18	1	0	54	138	2023	5	15	5	2	0	7	0	0	1
16	1,2305E+18	1	0	56	39	2023	5	19	5	3	2	6	0	0	0
17	1,2305E+18	1	0	60	2	2023	5	21	5	2	9	1	1	0	0
	E+18	1	0	61	46	2023	5	16	4	3	0	1	0	0	1
	E+18	1	0	60	99	2023	5	11	4	3	0	7	0	0	1

Figure 4: Data from the Unfallatlas. A: Map representation (self-made screenshot from Unfallatlas (2024)); B: Section of the Open Data accident locations 2023 (own screenshot of accident locations 2023 - CSV format [zip])

Road users can be selected in binary form (0 for no and 1 for yes). When filtering by bicycle (*IstRad* = 1) and all other road users are excluded (*IstFuss* = 0, . . .), it is unclear whether it is a bicycle-bicycle accident or a single bicycle accident. For this, further filters must be set, such as *UART* (Table 3). *UART* 2, 3, 4, and 5 can be used to analyse bicycle-bicycle accidents. The data from the remaining categories is not relevant for further analysis (collisions with stationary road users, objects, conflicts with pedestrians, or single vehicle accidents).

Table 3: Possible *UART* values and meaning. Coloured entries are used to find bicycle-bicycle accidents.

UART Value	Meaning
1	Collision with another vehicle which starts, stops, or is stationary (parked vehicle, stopped without reference to the accident)
2	Collision with another vehicle moving ahead or waiting (stopped and possibly involved in an accident, unidirectional)
3	Collision with another vehicle moving laterally in the same direction (side-by-side or changing lanes)
4	Collision with another oncoming vehicle (oncoming)
5	Collision with another vehicle which is turning into or crossing a road (turning or crossing)
6	Collision between vehicle and pedestrian (with pedestrian)
7	Collision with an obstacle in the carriageway (obstacle, trees, stones, wild animals)
8	Leaving the carriageway to the right (leaving the road, other person can ride away without contact)
9	Leaving the carriageway to the left
0	Accident of another kind (U-turn, domestic animals, failure, ...)

Table 4: Possible *UTYP1* values and meaning. Coloured entries are used to find bicycle-bicycle interactions in combination with *UART*.

UTYP1 Value	Meaning
1	Riding accident (loss of control, inappropriate speed, misjudgement before the accident)
2	Accident caused by turning off the road
3	Accident caused by turning into a road or crossing it
4	Accident caused by crossing the road
5	Accident involving stationary vehicles
6	Accident between vehicles moving along in carriageway
7	Other accident

After filtering *UART* for categories 2, 3, 4, and 5, the number of accidents remaining for the example year 2021 is 6,844 (years 2016–2023 are in Table 5). In addition, a distinction is made between different categories of accident *UTYP1* (Table 4).

The following cyclist-cyclist interactions can be derived from the accident data:

- Cycling in convoy: Collision with another vehicle moving ahead (or waiting) and between vehicles moving along in carriageway (*UART* 2 + *UTYP1* 6)
- Cycling side-by-side or overtaking: Collision with another vehicle moving laterally in the same direction and between vehicles moving along in carriageway (*UART* 3 + *UTYP1* 6)
- Oncoming cyclist: Collision with another oncoming vehicle and between vehicles moving along in carriageway (*UART* 4 + *UTYP1* 6)
- Crossing cyclist: Collision with another vehicle which turns into or crosses a road, that is, accident caused by turning off the road or caused by turning into a road or by crossing it and between vehicles moving along in carriageway (*UART* 5 + *UTYP1* 2, 3, 6)

Table 5 shows the total number of accidents from 2016 to 2023 and for the four previously filtered cyclist-cyclist scenarios: convoy, overtaking, oncoming, and crossing. In addition, the number of cyclist-cyclist fatalities was counted. The accident class *UKAT* sums up the injury status from one killed to three slightly injured. In the case of the example year 2021, the number of relevant accidents is reduced from 6,844 (only filtering *UART*) to 3,589 after filtering with *UART* and *UTYP1*.

It is important to note that the accident data for Germany has only been complete since 2021. Prior to this, the federal state of Mecklenburg-Vorpommern was not included in the data set. Consequently, the accident data from 2016 to 2020 are incomplete and underrepresented for Germany.

Overall, the number of accidents increased from 2016 to 2019. In the period between 2020 and 2021, which was characterised by the global COVID-19 pandemic, the number of accidents decreased and stagnated. In 2022 and 2023, the total number of accidents returned to the pre-pandemic level. The situation is somewhat different for bicycle-bicycle accidents. The total number of bicycle-bicycle accidents has increased over the eight-year period between 2016 and 2023, with a decrease only in 2021. The reduction in the number of accidents varies by category, with 13% fewer oncoming accidents and 15% fewer collisions in 2021 compared to the period before the pandemic. For crossing accidents, the reduction was only 9%. The largest reduction in bicycle-bicycle accidents was in side-by-side cycling or overtaking, which dropped by over 18%. Due to COVID-19 restrictions, people may have ridden less in groups or kept greater distances from others.

Over all the years (from 2016 to 2023), the most common types of bicycle-bicycle accidents were with oncoming traffic (30.7%–36.4%) and crossing (32.16%–38.01%), followed by riding side-by-side or overtaking (17.56%–21.31%) and riding in a convoy (10.17%–12.04%).

The majority of accidents occurred in urban areas, such as Hamburg or Berlin, and in conurbations in the south and west of Germany. It is notable that only few incidents were documented in rural regions situated in the centre, east, and north of Germany (Figure 5). No discernible patterns emerge in the accumulation of accidents of a specific scenario type depending on the region.

Table 5: Accident data from the Unfallatlas. Total number of all accidents as well as the number of bicycle-bicycle accidents of the scenarios convoy, overtaking, oncoming, and crossing, and the number of fatalities per bicycle-bicycle scenario.

Year	**Total of all**	**Total cyclist-cyclist**	**UART 2 + UTYP1 6**	**Fatal**	**UART 3 + UTYP1 6**	**Fatal**	**UART 4 + UTYP1 6**	**Fatal**	**UART 5 + UTYP1 2, 3, 6**	**Fatal**
2016*	151,673	1,688	198	0	300	1	571	1	619	1
2017*	195,229	2,289	267	1	402	1	811	2	809	0
2018*	211,868	3,006	346	3	586	2	984	1	1,090	1
2019*	268,370	3,635	373	0	700	1	1,215	3	1,347	1
2020*	237,994	4,120	496	1	854	0	1,265	0	1,505	2
2021	233,208	3,589	422	0	699	2	1,104	3	1,364	3
2022	256,492	4,341	476	2	842	0	1,452	9	1,571	3
2023	269,048	4,867	495	1	1,037	3	1,770	3	1,565	3

* Data from federal state of Mecklenburg-Vorpommern, Germany, is missing in the Unfallatlas database.

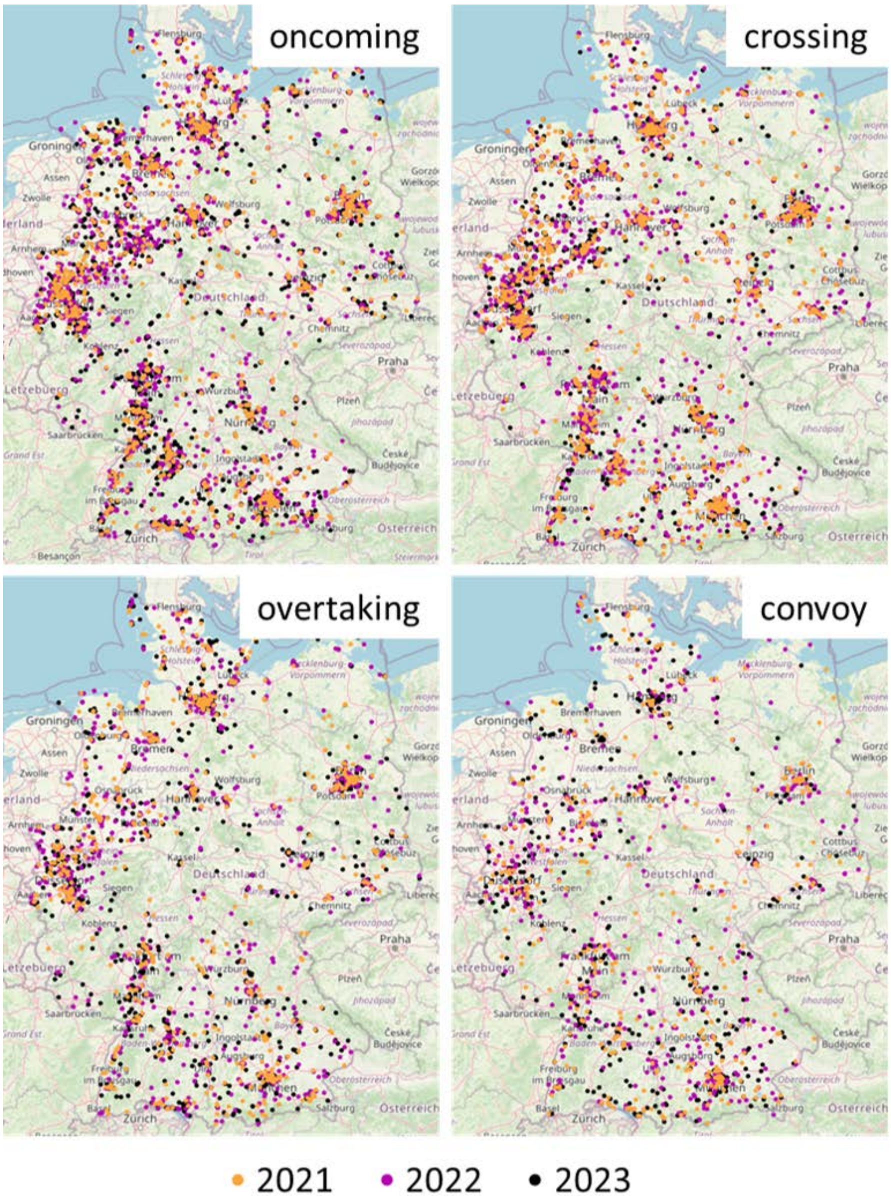


Figure 5: Time and spatial distribution of bicycle-bicycle accidents per scenario (oncoming, crossing, overtaking and convoy) for each year (2021–2023) from Unfallatlas visualised with QGIS 3.20 'Odense'

The ADFC Fahrradklima-Test (ADFC Cycling Climate-Test, (ADFC, 2023a)) is a survey researching cyclists' experiences, with around 245,000 people participating in 2022. The survey is not considered to be representative as it is open to everyone but is specifically aimed at cyclists. However, it is a great help to cities and municipalities because of the high participation rate. (ADFC, 2023b)

The survey divides cities by population and combines the survey results with grades to produce a ranking. Table 6 shows the classes by population with the corresponding best-rated and worst-rated cities in each class. Cities only appear in the rankings if they reach a minimum number of respondents within their respective class. Bicycle-bicycle accidents were identified from the Unfallatlas (2024) for each city. On the one hand, it is noticeable that there are more accidents in the cities with the best cycling conditions than in the cities with poor cycling conditions. This is probably because there are generally more people who cycling in cities with good ratings. On the other hand, the number of accidents increases with the number of inhabitants, which also suggests that more cyclists lead to more accidents.

Table 6: German cities ranked by number of population and first (↑)/last (↓) city in their class (ADFC, 2023a). In addition, bicycle-bicycle accidents are shown for the year 2023 (Unfallatlas, 2024).

City population class (in thousands)	City	Number of bicycle-bicycle accidents 2023
< 20	↑ Wettringen	2
	↓ Windhagen	0
20–50	↑ Baunatal	0
	↓ Kulmbach	0
50–100	↑ Nordhorn	13
	↓ Lüdenscheid	0
100–200	↑ Erlangen	30
	↓ Remscheid	0
200–500	↑ Münster	87
	↓ Krefeld	12
> 500	↑ Bremen	89
	↓ Essen	4

2.3.3 General Bicycle Accidents in the Media and Statistics outside Germany

Analogous interactive accident maps comparable to the German Unfallatlas are available in other countries. The Netherlands has developed an interactive map that provides statistical data on incidents resulting in property damage, injury, or death. The accidents can be filtered by age and by vulnerable or non-vulnerable road users. However, it is not possible to see how many bicycle-bicycle accidents there are because, in addition to bicycles, vulnerable road users also include e-scooters or motorbikes, for example. The data set comprising reported accidents is collected by private individuals using a dedicated mobile application (MobielSchadeMelden, 2024), which is integrated into the map. Accident data is also reported by the police and insurers (Figure 6A). (STAR, 2025)

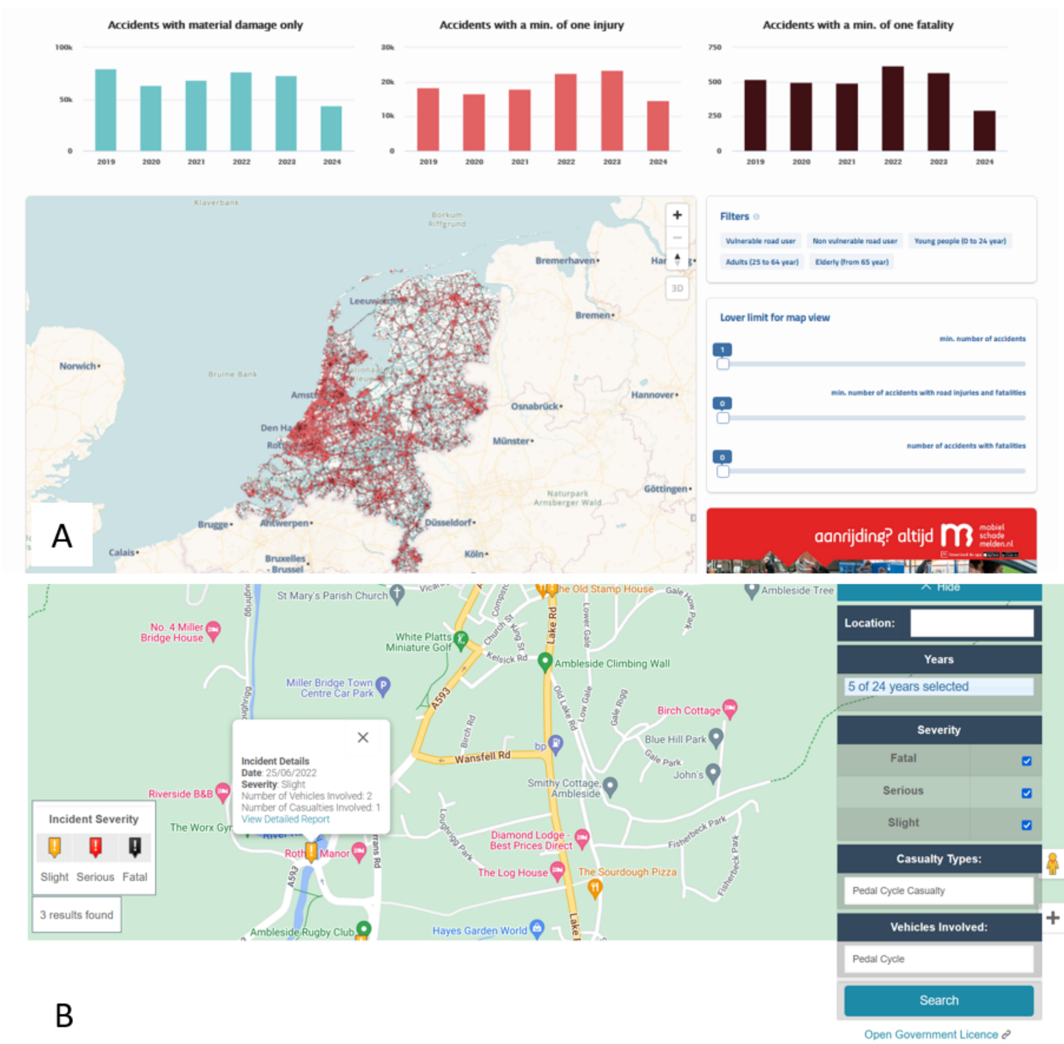


Figure 6: Accident data from A: STAR homepage (STAR, 2025) (own screenshot from STAR (2025)) and B: CrashMap (2024) (own screenshot from CrashMap (2024))

In the Netherlands in 2022, the number of deaths exceeded 700, representing an increase of over 150 deaths compared to 2021. Of these, 291 were cyclists, representing an increase of 84 deaths compared to 2021. The number of cyclists killed exceeded that of car drivers (2022: 225). (CBS, 2023)

Figure 7: Accident data from A: CycleStreets (2024) (own screenshot from CycleStreets (2024)) and B: ARDD (2024) (own screenshot from ARDD (2024), key: Road Trauma Australia 2022)

Moreover, the United Kingdom provides an interactive map that is accessible at no cost; however, users are required to pay a fee to access collision reports. The data are published by the Department for Transport and are sourced from the police. They are recorded using the STATS19 accident report form. STATS19 is a system for recording road accident data in the United Kingdom. The map allows the user to filter accidents by year and by accident severity (fatal, serious, slight). Furthermore, the casualty type and vehicles involved can also be filtered. For instance, an accident involving a bicycle can be selected under casualty type, while the option 'pedal cycle' can be chosen under vehicles involved. Nevertheless, it remains uncertain whether a motorised vehicle was involved given that the accident reports are subject to a charge (Figure 6B). (CrashMap, 2024)

Another website that utilises accident data from the United Kingdom is Bikedata (2024) (Figure 7A). The advantage of this site over CrashMap (2024) is that detailed reports can be viewed. The site can be filtered in a multitude of ways, including by the presence of pop-up bicycle paths, path widths, thefts, collisions, and so forth. However, it is not possible to filter by bicycle-bicycle accidents. Instead, each accident can be selected individually for further analysis. The data displayed on the map is derived from STATS19 collision data and other sources (CycleStreets, 2024). In the United Kingdom, the number of cyclists on the road has increased by 50% between 2004 and 2022. In 2022, 91 cyclists lost their lives, 4,056 were seriously injured, and 11,546 were slightly injured. Of these incidents, 46% involved two-vehicle collisions between a cyclist and a car. (GOV.UK, 2023)

Additionally, other countries make their accident data accessible, albeit not in the form of an interactive map. Instead, it is presented in tabular form, as exemplified by Canada with the National Collision Database Online (NCDB), or in the format of a dashboard, as in the case of Australia with the Australian Road Deaths Database (ARDD) (ARDD, 2024; NCDB, 2024, Figure 7B).

All providers aim to draw attention to locations that have a high incidence of accidents. By ensuring that each individual is able to use the system with ease, greater visibility is achieved. This allows cities to exert a targeted influence and implement improvements, while citizens are able to adapt their travel routes accordingly.

2.4 Bicycle Accident Statistics for Oncoming, Overtaking, and Crossing Scenarios

To gain a better understanding of bicycle accidents, news reports and papers were analysed as well as the legal framework for the scenarios of overtaking, oncoming, and crossing.

2.4.1 Overtaking

The issue of overtaking manoeuvres on narrow bicycle paths or in mixed traffic with motorised vehicles is particularly problematic. To complete the overtaking manoeuvre as quickly and safely as possible, it is necessary to estimate how much faster one has to ride. However, it is also important to leave space for the overtaking cyclist as they pose a danger in the event of accidental swerving.

In Germany, there is no regulation pertaining to the overtaking distances between cyclists, unlike between cyclists and motorised traffic. It is a legal obligation to overtake on the left. However, the cyclist must not swerve onto the footpath if the footpath and bicycle path are separate (see Section 2.1).

According to Table 5 (Section 2.3.2), there was a sustained increase in bicycle-bicycle accidents involving side-by-side riding or overtaking from 2016 to 2020. It is unclear from the data whether cyclists were riding side-by-side or an overtaking manoeuvre was taking place. In 2023, the number of accidents reached four digits for the first time ($n = 1,037$) and the highest number of cyclist fatalities since 2016 ($n = 3$).

The literature mainly contains studies on overtaking behaviour between cyclists and motorised traffic. Due to high speeds and cyclists' vulnerability, accidents in these circumstances are particularly critical. Drivers must not only concentrate on the overtaking manoeuvre of the bicycle traffic but also on oncoming traffic. In doing so, the distance of 1.50 m (in town) and 2.00 m (out of town) required in Germany between motorised vehicle and bicycle is often not maintained in order to leave enough space for oncoming traffic.

However, there are similar problems for cyclists. Overtaking manoeuvres often take place on narrow infrastructure, leaving little space to turn and increasing the risk of cyclists' handlebars touching. In addition, cyclists may approach from the opposite direction during the overtaking manoeuvre (legally and illegally), increasing the risk of a collision.

As no legal basis exists for overtaking manoeuvres between cyclists, the following legal rulings were examined. The following three judgements were made in the case of overtaking manoeuvres. In 2017, the Higher Regional Court of Hamm ruled that an overtaking distance of about 30 cm is too small. Fluctuations in riding cannot be ruled out and can easily lead to a conflict (Haufe, 2023). In 2018, the Berlin Court of Appeal ruled in a conflict between two cyclists and considered 1 m to be sufficient (Verlag Beck, 2018). In 2021, the Higher Regional Court of Oldenburg ruled that 1.50 m between cyclists (as between cyclists and motor vehicles) does not have to apply because bicycle paths are too narrow and referred to mutual consideration (§ 1 StVO) (Deubner Recht, 2021). Mutual consideration means that road users are always careful not to harm, endanger, obstruct or harass anyone.

A secondary investigation was conducted on 1 September 2024 utilising the keywords 'Fahrrad' (bicycle) and 'Unfall' (accident) in Google News. The resulting newspaper articles pertaining to overtaking collisions are collated in Appendix A.3 in Table 14 and Table 15. Eleven accidents were identified between 2023 and 2024, including three accidents involving side-by-side riding and two accidents involving riding in a column. The victims of the accidents were over 50 years of age in approximately 72% of cases, whereas 55% of the other party involved in the accident was under 50 years old. The victims and the responsible parties were evenly split between genders, and the victims were injured in every case, two of them fatally. The opponents were injured in seven out of 11 cases, with no information provided in three cases. The following reasons were identified for the accidents:

- Side contact and fall.
- The overtaking cyclist wanted to turn left, and the overtaken cyclist collided with the overtaker because the cyclist being overtaken tried to turn and did not indicate a turn.
- The cyclist in front braked and the cyclist behind could not stop.
- The cyclist in front also wanted to overtake and collided with the overtaking cyclist behind them.

Conflicts in the same direction of travel were very rarely found in studies and therefore seldomly analysed (Van der Horst et al., 2014).

Mohammed et al. (2019) conducted an observational study of overtaking behaviour in New York City, the United States. A total of 34 overtaking manoeuvres were analysed through cluster analysis, with lateral distances and speeds used to delineate the phases of overtaking. Mohammed et al. (2019) acknowledged the absence of a predetermined formula for quantifying the number of data sets required for a cluster analysis, but they noted that 34 interactions is a low number.

2.4.2 Oncoming

Oncoming bicycle traffic can occur both legally and illegally. In Germany, there are few legal two-way bicycle paths (Section 2.2.2), and these must meet a certain minimum width to ensure safe passage. Accidents can occur if cyclists are careless, do not keep to their path, or the overtaking width is restricted due to overtaking manoeuvres or infrastructure damage.

Illegal oncoming scenarios pose an increased risk of accidents as they are often not anticipated and there is frequently insufficient space on bicycle paths for cyclists to pass each other safely. In these cases, very small distances are maintained or evasive manoeuvres are carried out (e.g., moving onto the footpath).

WWC endanger themselves and car drivers, for example, at intersections or when turning if the driver did not expect a cyclist from the direction of travel. However, traffic is also constantly increasing on bicycle paths, and most bicycle paths are already too narrow. If an *NC* encounters a *WWC*, this can sometimes be fatal.

Unfortunately, no official statistics are kept of oncoming situations for Germany, although they often lead to critical encounter situations or accidents. According to traffic accident statistics in Braunschweig for 2021 (Braunschweig, 2021), illegal riding in the opposite direction was the second leading cause of accidents involving cyclists, representing 13% of cases. Among the causes of road accidents with injuries caused by cyclists, illegal riding in the wrong direction of travel accounted for 9% of cases.

A further search was conducted on 1 September 2024 for the keywords 'Fahrrad' (bicycle) and 'Unfall' (accident) on Google News, with the resulting newspaper articles pertaining to oncoming collisions being collated in Appendix A.2 in Table 12 and Table 13. The search yielded 19 oncoming accidents between 2020 and 2024 in Germany, along with a single case in Austria. In 74% of cases, the victim was male. Also in 74% of cases, the other party involved in the accident was male, although in two articles gender was not mentioned. Furthermore, in approximately 50% of cases, the victim was over 50 years old, and a similar figure applies to the age of the other party involved in the accident, although in some cases age was not stated. In 10 out of 19 cases, minor to serious injuries were reported for the other party involved, while for the accident victims, 15 out of 19 cases involved minor to serious injuries, with 5 victims dying. Accidents involved the following situations:

- Both cyclists attempted to swerve, resulting in a collision.
- During an overtaking manoeuvre, the cyclist travelling in the opposite direction was struck.
- While passing each other, one of the cyclists lost their balance.
- Influence of alcohol.

Currently, only observation studies shed additional light on such situations. These studies have demonstrated that the proportion of irregular use of the bicycle path in the wrong direction of travel varies widely. In the case of separate bicycle paths, 20% of 39,000 observed cyclists go the wrong way, with values scattering between 8% and 50% for each study area (Alrutz et al., 2009). Alrutz et al. (2009) also indicated that in 5% of cases cyclists adopt the pedestrian walkway to overtake other cyclists or to avoid oncoming wrong-way cyclists. In Huemer and Vollrath (2014), 16% of 2,549 observed cyclists went the wrong way due to time savings and convenience.

Bjørnskau et al. (2016) studied cycling in Oslo, Norway, and found that eight out of 10 cyclists used the bicycle path in the right direction and almost all wrong-way riders used the footpath. The most common conflicts were near accidents caused by something blocking the bicycle path (e.g., due to parked vehicles). In 2015, Bjørnskau et al. (2016) conducted a survey in Norway of 4,300 cyclists. The survey revealed that 11% of these cyclists had already been in a bicycle accident, with 3.5% in an accident with another cyclist and 12% in an incident with a ghost cyclist (similar to *WWC*). (Bjørnskau, 2005)

Sørensen et al. (2022) indicated that wrong-way riders in Denmark are mainly found at intersections, but this varies greatly depending on the location (0%–33%). *WWC* were most frequently detected at peak times. According to their study, the risk of conflict is seven times higher for *WWC* than for cyclists in the correct direction of travel. The majority of cyclists deliberately cycle in the wrong direction and know it is illegal (90%); their reasons include shorter distances, seeking the fastest route, or attempting to avoid crossing the road.

On 6 July 2023, a search for the keyword 'Geisterradler' (cyclist cycling in the wrong and forbidden direction, also known as ghost cyclists) on Google News returned 111 entries. Among these were seven posts about accidents with *WWC*, including three with cyclists, three with cars, and one with a pedestrian. 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 recommendation to wear a helmet has been identified as a significant contributing factor to the incidence of severe head injuries. A review of newspaper articles provides an incomplete overview of the accident statistics. It is reasonable to conclude that the number of unreported accidents involving *WWC* is significantly higher as smaller accidents are not reported.

A guideline on *WWC* was developed in a larger study of Große and Böhmer (2021) and causes for misuse were sought. In this study of Große and Böhmer (2021) ghost cycling includes both left-hand riding and riding on footpaths. In addition to safety, the length and duration of the route are also important for cyclists; ignorance of the rules plays a subordinate role for misconduct. Infrastructure also plays an important role, especially multi-lane roads, bridges, gradients, surfaces, and traffic light circuits. Due to the way accidents were reported, Große and Böhmer (2021) had to read texts and wrong-way riders had to be singled out separately. 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 the 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%) were cars, with only small proportions involving other cyclists (9%) or pedestrians (6%). In 68% of cases, injuries were minor. The data also shows that approximately 60% of cyclists involved in accidents were male, while the remainder were 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, three accident blackspots. A total of 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 cases, of which 95% of the interactions were free of conflict (no encounter or controlled reaction). In 2.3% there was a sudden reaction by a road user and in 0.2% a sharp reaction, where contact could still be prevented. There was no contact during the observation period. In these 2.3% and 0.2% of interactions, cyclists were the main interaction partners (46%). Interaction distances between 0.5 and 1.5 m were chosen 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 respondents stated that they did not consciously cycle the wrong way.

Kerbs are a frequently used means of separating different paths. A study from Austria revealed that a kerb was involved in one in 10 of approximately 250 bicycle accidents. Accidents are often unintentional and do not occur when riding up or down the kerb. (Zuser, 2023) In the Netherlands, 14% of 670 single-vehicle accidents were related to a conflict with a kerb (Schepers and Klein Wolt, 2012). Last but not least, kerbs can act as a demarcation between the road and bicycle path or bicycle path and footpath, but they also create barriers, such as for older people.

Countermeasures

The most common measures against wrong-way cycling are visible campaigns or priority checks by the police. Campaigns include the application of neon-coloured pictograms with and without text as well as the installation of posters or signs. All campaigns can only be read in the direction of travel of the *WWC* and are intended to catch their attention. Messages like ‘Ghost cyclists are endangering others’ (‘Geisterradler gefährden!’), ‘If you are reading this, you are cycling on the wrong side' ('Wenn Du das liest, radelst Du auf der falschen Seite!'), 'Ghost cyclists please turn around' ('Geisterradler bitte wenden!'), and 'Wrong side!' ('Falsche Seite!') should cause the *WWC* to think about their riding behaviour (Figure 8A-C). The sprayed-on pictograms fade after a short time and the posters change location regularly so that *WWC* do not become used to them. Cities and municipalities carry out many campaigns every year and also use creative campaigns to draw attention to riding behaviours. In Bremerhaven, for example, fruit was distributed to cyclists during bicycle checks in September 2022, with apples for correct riding behaviour and lemons for *WWC* (Nordsee-Zeitung, 2022).

Figure 8: Campaign against *WWC* with pictogram (A: shz (2015)) or sign (B: KURIER (2024) and C: own source)

The advantage of priority checks is that violations are punished and fines may act as a deterrent to future violations. It is not uncommon for *WWC* to avoid police checks when they become aware of them from a distance. During a focus check conducted in Regensburg in 2021, 11 *WWC* were issued warnings, and over 500 warnings were issued in two weeks in Munich in 2019 (Münchener Zeitung, 2019; TVA Ostbayern, 2021). A total of 43 of the 111 news items with the keyword 'Geisterradler' dealt with the topic of campaigns against *WWC*.

2.4.3 Crossing

A second investigation was done on 1 September 2024. The keywords used were 'Fahrrad' (bicycle) and 'Unfall' (accident) in Google News. The resulting newspaper articles about crossing collisions are listed in Appendix A.4 in Table 16 and Table 17. A total of six accidents were identified in 2023 and 2024. In each incident, the victim sustained injuries, and in one case, fatalities occurred. The underlying causes of these accidents were as follows:

- Failure to acknowledge the right-of-way.
- Swerving and emergency braking led to a fall.
- Accident when turning.

A study of 148 bicycle-bicycle crashes in the Netherlands from Schepers (2014) found that approximately 12% of all crashes occurred while crossing. However, no additional details were provided concerning the manifold characteristics and causes of the scenario of crossing cyclists. 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, Berghoefer and Vollrath (2023) examined the behaviour of cyclists at various sections of a route. At an unsignalised intersection, some cyclists disregarded the right-of-way. However, it is not clear whether this behaviour would also apply in reality.

Zhang and Theisen (2024) found evidence that cyclists were more likely than car drivers to violate the right-of-way at an intersection in a 30 km/h zone.

Van Biezen (2018) performed an empirical investigation on two intersecting bicycle paths, one which had priority markings and one which did not. 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 the right-of-way. Van Biezen (2018) concluded that the implementation of priority markings has a positive influence on the priority behaviour of cyclists.

2.5 Analysis of Critical Situations without Accident Data

Statistics pertaining to bicycle-bicycle accidents lack the requisite precision regarding the circumstances of the accident and underlying causes. Furthermore, there are considerably more instances of conflict than accidents; as such, by undertaking a detailed analysis of the interactions and conflicts that occur, a great deal can be learnt about the manner in which individuals cycle and the circumstances under which accidents occur.

As early as 1935, Greenshields et al. (1935) examined traffic capacity in the United States with the assistance of a camera, determining the speed of road users by measuring the frame rate. The analysis of movement paths, or trajectories, was facilitated by the use of objects motions through space as a function of time. In the context of using trajectories, a road user can record their path, for instance using GPS, or their path can be determined by external measurements, such as cameras.

Cameras allow long-term observation. Temporary observations only show a short period of time, so daily patterns or the influence of e.g., weekdays or seasons cannot be shown. Trajectories also have the advantage that analysis can be done automatically, rather than having to manually search through data. In addition, trajectory analysis can be used to define or find parameters that do not depend on the subjective opinion of an expert. The Research Intersection offers the possibility of recording traffic behaviour over a longer period of time and analysing the behaviour of road users using trajectory analysis.

2.5.1 Trajectory Analysis

Trajectories are defined as the paths an object travels in space when moving. They describe how the position of an object changes over time. Trajectories can be generated using time and coordinate information. With this data, it is possible to trace paths, and with the information of many trajectories, patterns can be identified and paths can be predicted.

Given the infrequency of accidents and the consequent paucity of data for analysis, the Hydén accident pyramid approach (Figure 9) is an appropriate methodology to investigate near misses (Hydén and Linderholm, 1984). The pyramid posits a correlation between the frequency and severity of accidents. The occurrence of fatal accidents is the least frequent. The base of the pyramid is formed by a large number of normal traffic flows and a multitude of near misses.

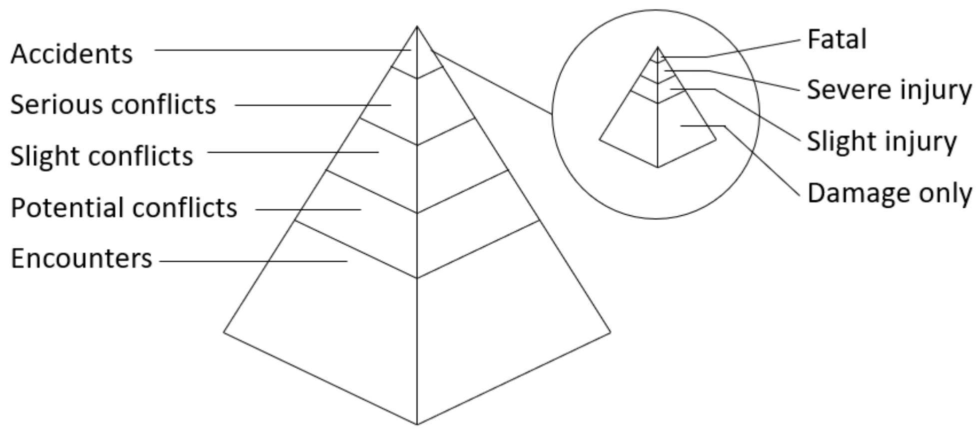


Figure 9: Accident pyramid by Hydén (adopted from (Hydén and Linderholm, 1984))

The analysis of near misses can provide insights into potential accidents, thereby enabling the prevention of accidents before they occur. By analysing traffic flow, conclusions can be drawn about the safety of the infrastructure (e.g., whether roads are sufficiently visible, whether speeds are excessive, and whether roads are cleared promptly enough).

The criticality metrics (Surrogate Measures of Safety (SMoS) or Surrogate Safety Measures (SSM)), which were also utilised in the present work, are presented in Section 3.3.1.

2.5.2 Video Annotation

Trajectory analysis provides a robust foundation for the examination of riding behaviour. However, the data does not invariably disclose the rationale behind specific behaviours. In video annotation, interactions with obstacles or other road users can be excluded. Furthermore, the occurrence of certain accelerations or close interactions can be ascertained, and their truth can be distinguished from measurement errors. Additionally, video annotation can be utilised to discern cooperative behaviour (e.g., head movements, hand signals), helmet usage, and gender.

As stated in the BASt (2021) report, approximately 26% of cyclists wore helmets in 2020. This assertion can be verified with video annotation techniques. Video annotation was employed in rural areas of Brandenburg, Germany, to ascertain a helmet-wearing rate of 26% of commuter and leisure cyclists and 100% helmet-wearing rate for racing cyclists (Leschik et al., 2023).

The video material in this study has been modified to reduce the resolution of faces and number plates, rendering them unrecognisable. This has implications for the accuracy of gender and age assessment, which is often challenging to determine with certainty. In inclement weather conditions, such as during rain, and when subjects are wearing hoods, the confirmation of helmet use cannot be guaranteed.

2.6 Bicycle Simulation

Recent years have seen an increased demand for the simulation of bicycle traffic. Planners specialising in bicycle traffic and representatives of cities and municipalities are keen to alter or redesign infrastructure, and they therefore require information on traffic flow and turning movements. Furthermore, there is a scientific need to understand the manner in which cyclists interact. To this end, it is essential that simulations are as realistic as possible.

In a study, Maciejewski (2010) compared the microscopic traffic flow simulation systems ‘TRansportation ANalysis and SIMulation System’ (TRANSIMS, 2025), ‘Simulation of Urban MObility’ (SUMO, 2025) and ‘Verkehr In Städten -

SImulationsModell' (VISSIM, 2025). The study found that all three systems have different advantages and disadvantages. For example, VISSIM provides accurate tram modelling, but it is slow and commercially licensed. In the field of transportation research, the utilisation of simulation tools such as VISSIM (2025) has emerged as a prevalent approach in the study of cycling behaviour. Veraart (2024) demonstrated a methodology for simulating cyclists and pedestrians, encompassing cyclists using both conventional bicycles and e-bikes. However, the model's capacity to generate a realistic simulation is contingent upon the extensive customisation of its parameters. Enhanced adaptation of the Time To Collision (TTC) remains unattainable.

However, both SUMO and TRANSIMS are free to use, open source and the code is modifiable. The SUMO system is particularly well-suited for detailed microscopic simulations of individual traffic scenarios, while TRANSIMS offers advantages in the integrated analysis of large-scale traffic systems and activity patterns. (Maciejewski, 2010) Another simulation tool that can be used to simulate cycle traffic in a transport network is 'Multi Agent Transport Simulation' (Horni et al., 2016), which has a lower computational cost and can therefore be used well for large networks.

Rivoirard et al. (2024) sought to simulate bicycle traffic at intersections with the objective of formulating effective traffic management strategies. To this end, they utilised pre-recorded GPS data to differentiate between slow, medium, and fast bicycle traffic in France. The modelled traffic flows in SUMO exhibited a high degree of correlation with those measured at a counting station. Ma and Luo (2016) modelled acceleration behaviour in relation to GPS data in Sweden. Their study distinguished between acceleration, deceleration, and constant speed, and the analysis enabled clear identification of speed profiles. The investigation revealed a significant impact of gender and agility on acceleration behaviour. The authors recommended that future analyses focus more on the interaction behaviour between cyclists. Pérez Castro (2023) examined the requirements for microscopic models. Using video recordings and the resulting trajectories of individual cyclists from Sweden, Pérez Castro (2023) emphasised the need for a large amount of data and the determination of bicycle types and models for interactions between road users to predict interactions. However, the influence of weather, environment, and culture was also taken into consideration.

Kaths (2023b) presented an open source tool, 'RoadUserPathways', for analysing movement patterns. When used to examine intersections in Germany, it revealed deficiencies in the actual routes used compared to the observed trajectories. Nevertheless, this tool can provide initial counts and turn-off relationships for planners. In addition to vehicle models, pedestrian models have been utilised to map cyclist behaviour. Kaths (2023a) developed a model for non-track-bound road users, such as bicycles, with the objective of providing greater flexibility to cyclists, though further data collection is necessary for validation. For this, the Python package CyclistModel used with the 'Traffic Control Interface' (TraCI) in SUMO. In the original study Twaddle (2017) recorded video data at four intersections in Germany and developed a tactical behaviour model enabling the prediction of infrastructure choice, direction of travel, red light behaviour, and turning behaviour. The use of the model at intersections with traffic lights is mentioned as a limitation, and the author notes that there is no differentiation of bicycle types. Furthermore, the transmission of the model to other intersections and countries is unclear. The author concludes that there is a need for research into interactions with other road users.

The simulation software utilised in this study is SUMO (more details in Section 3.3.2). The software is open source, which allows for straightforward customisation of parameters.

2.7 Summary and Research Question

This literature review shows that, on the one hand, there are clear rules for cyclists, such as the right direction of travel on the bicycle path depending on the signage, or overtaking only on bicycle paths that are wide enough for two cyclists. On the other hand, it is not always clear what is wide enough and who has the right-of-way at intersections with bicycle paths. Bicycle-bicycle accidents are rarely reported, resulting in a high number of unreported accidents. Detailed information about the course of the accident is rarely available. The media tend to focus on serious accidents, while the number of conflicts without serious damage remains unknown. Based on the available accident data and the lack of information on accident sequences, this study answers the following research question:

How do cyclists interact close to an intersection, and what dangers can arise?

This question will be answered with the help of traffic observations, which are explained in more detail in Section 3 below. Based on the literature review, conflicts arise during oncoming, crossing, overtaking and side-by-side cycling. Section 4 presents and evaluates the results of the traffic observations using trajectory analyses for the scenarios and provides an outlook.

3 Methodology

Cycling data can be collected through a variety of methods. These include the use of traffic censuses and measurement devices, such as induction loops, and GPS devices (smartphones or additional devices) or additional sensors on the bicycle. Additionally, traffic observation with camera systems can collect naturalistic bicycle traffic data, which is especially helpful for analysing traffic behaviour on the microscopic level. 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. Braunschweig is located slightly north of the centre of Germany. It has a population of about 255,000 (as of December 2023). (Braunschweig, 2025)

The present section is divided into two parts. The first section details traffic observation at the Research Intersection, which was utilised for all scenarios. The second section presents the intersection in the 30 km/h zone, which was also used for the crossing scenario. Data processing is described in Section 3.2, followed by the tools used (Section 3.3), the traffic analysis procedure (Section 3.4), and the data quality (Section 3.5).

3.1 Traffic Observation

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

The following is an introduction to the existing infrastructure at Deutsches Zentrum für Luft- und Raumfahrt e. V. (German Aerospace Center; DLR), including possible recording locations and measurement techniques. Large-scale facilities include the Research Intersection (Section 3.1.2) and the Mobile Structures (Section 3.1.3) used for this work.

3.1.1 Test Bed Lower Saxony

In the field of automated and connected vehicles, the availability of robust and adaptable test facilities represents a significant asset. The DLR is constructing the 'Testfeld Niedersachsen' (Test Bed Lower Saxony), a test facility which is funded by the Niedersächsischen Ministerium für Wirtschaft, Arbeit, Verkehr und Digitalisierung (Lower Saxony Ministry of Economics, Labour, Transport and Digitisation) and the Niedersächsisches Ministerium für Wissenschaft und Kultur (Lower Saxony Ministry of Science and Culture) using resources from the European Regional Development Fund (ERDF) and the State of Lower Saxony. Financial and personnel support are provided by the following project participants: ADAC Niedersachsen/Sachsen-Anhalt e. V., Continental AG, IAV GmbH, NORDSYS GmbH, Oecon Products & Services GmbH, Siemens AG, Volkswagen AG, and Wolfsburg AG. An open research and development platform is being created that will enable a unique and comprehensive combination of different test and trial possibilities, ranging from simulation through to routes in public spaces. (DLR, 2024)

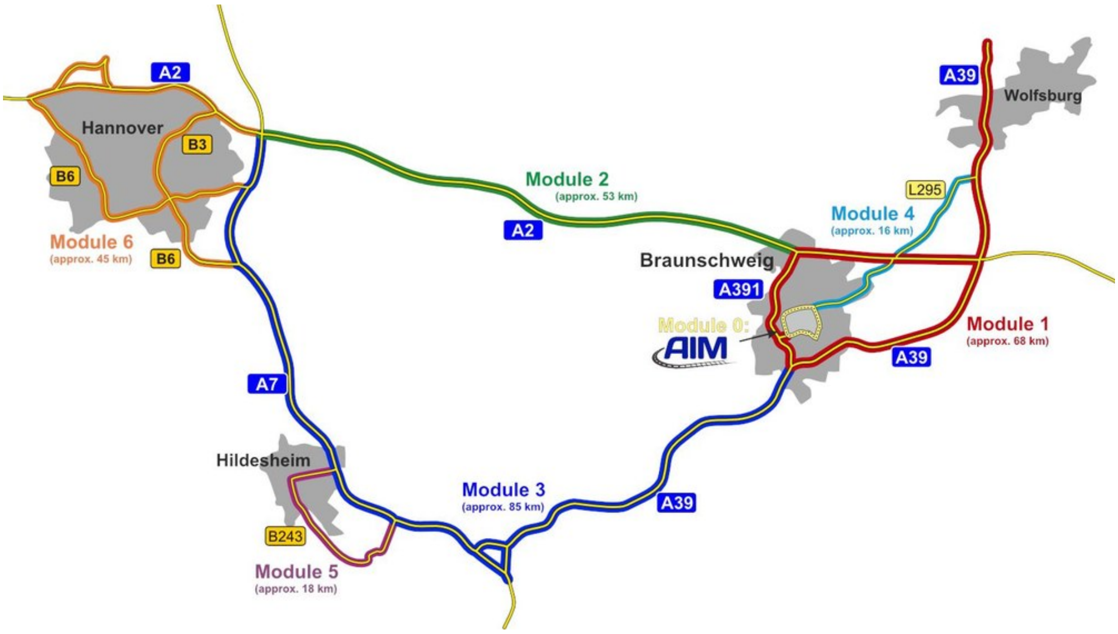


Figure 10: Test Bed Lower Saxony © DLR

The Test Bed Lower Saxony includes sections of the A2, A7, A39, and A391 motorways as well as parts of the federal and state roads B3, B6, B243, and L295 (Figure 10). In addition, it incorporates the established routes of the Application Platform for Intelligent Mobility (AIM) (DLR, 2024).

Application Platform for Intelligent Mobility (AIM)
The AIM has been constructed by the Institute of Transportation Systems of the DLR in Braunschweig, Germany. Its purpose is to provide support and conduct research and development in the field of intelligent mobility. The facility comprises a number of large research infrastructure facilities providing a wide range of services. These include simulation environments, test tracks, and field instruments. One of the services is the AIM Research Intersection. (Knake-Langhorst and Gimm, 2016)

3.1.2 Research Intersection

As part of the AIM, an intersection in 38106 Braunschweig was converted into a Research Intersection in 2014 (with a view extension of the cameras in 2021). An existing intersection was equipped with sensor systems (radar, mono, and stereo cameras). The Research Intersection is located on the northeastern corner of the inner ring road of Braunschweig (Easting 604770.98, Northing 5792792.04, UTM Zone 32U). This is an instrument for the detection and assessment of traffic behaviour at a large and complex urban intersection with conflicting traffic flows. (Knake-Langhorst and Gimm, 2016) It is controlled via traffic lights, with lanes designated for vehicles and separate lanes for pedestrians and cyclists. Federal Highway 4 runs in a south-to-west direction from Hagenring to Rebenring. Brucknerstraße runs in a northward direction, and Hans-Sommer-Straße runs to the east (Figure 11A).

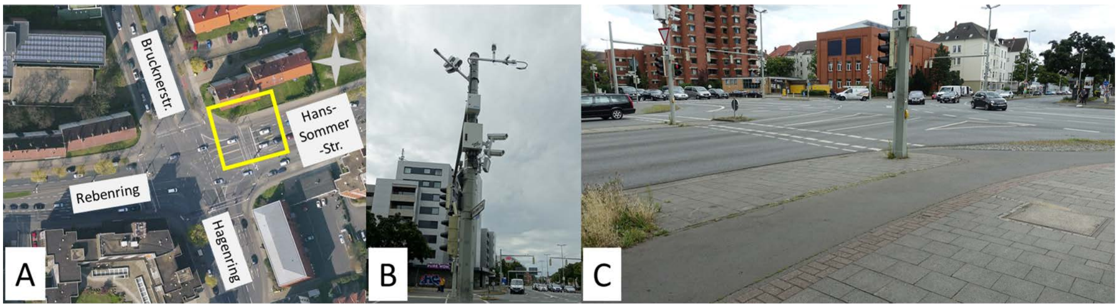


Figure 11: Research Intersection in Braunschweig, Germany (modified © DLR). A: Orthophoto; B: Measurement technology (stereo video system and IR flash); C: Pedestrian view of the Research Intersection looking southeast

There are seven lanes to the west, east, and south and five lanes to the north. A variety of university facilities are situated to the north and west of the intersection. In 2016, the XCYCLE project included the installation of supplementary measurement technology at the Research Intersection (Knake-Langhorst, 2016). This comprised the deployment of the TraffiTower 2.0 from Jenoptik in the northeast and north of the intersection (Figure 12A and Figure 12B). The additional positioning of the sensors enables the detection of road users on the footpath and bicycle path in the northeast and north in particular (Figure 12C).

A separate footpath and bicycle path are provided in all arms of the intersections (Figure 11C). The bicycle path is surfaced with asphalt, while the footpath is paved. There is no kerb or similar feature between the two paths. The bicycle paths may only be used in the direction of travel.

There are 14 vertical stereo video systems and IR flashes at the intersection (Figure 11B shows one of the 14 video systems). Videos are recorded in a reduced resolution so that neither faces nor license plates can be recognised. Data contains information about Global Navigation Satellite System-based timestamp (GNSS-based timestamp), location (in Universal Transverse Mercator; UTM), velocity, acceleration, road user type (e.g., pedestrian, bicycle, car), and size of each detected road user (Knake-Langhorst, 2022).

Area of Interest (AOI)

The area used for the following analyses is called the area of interest (AOI; Figure 12A and C).

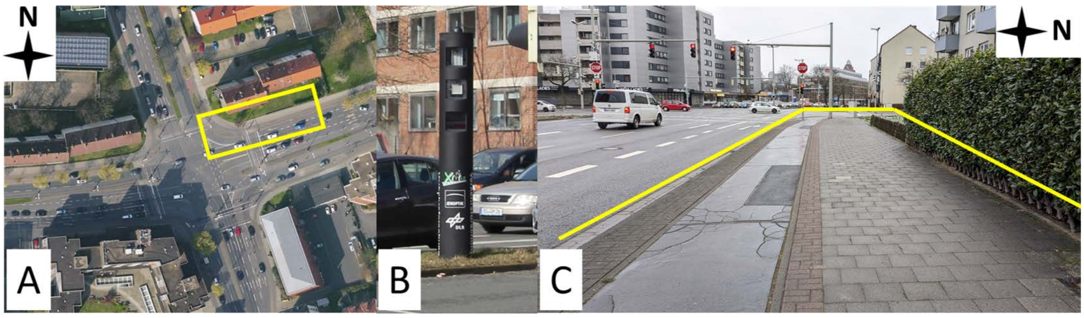


Figure 12: Area of interest (AOI). A: AOI marked in yellow (modified © DLR); B: Additional video system TraffiTower 2.0 (© DLR); C: View as a pedestrian on the AOI

The view into the arm is deeper than at all other arms, allowing for a greater depth of vision.

For cyclists travelling from the east to the west, the last crossing is approximately 180 m away, which means these cyclists can reach a high speed. The bicycle path is in total approximately 1.60 m wide, with an asphalt surface measuring approximately 1.35 m.

Paved paths to the left (0.57 + 0.11 m) and right (0.29 + 0.11 m) of the bicycle path make it appear wider (Figure 13). On the side of the path, next to the bicycle path there is a high kerb, and there is a fence next to the footpath. The AOI is approximately 25 m long and straight. Given the narrow width of the bicycle path and the absence of obstacles along the footpath, it is highly probable that cyclists will utilise the latter (Figure 13).

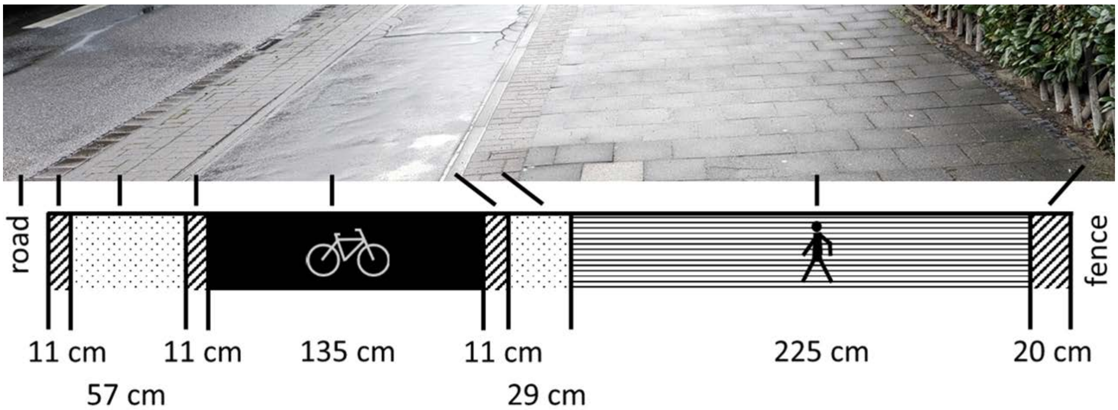


Figure 13: Definition and dimensions of the various paths

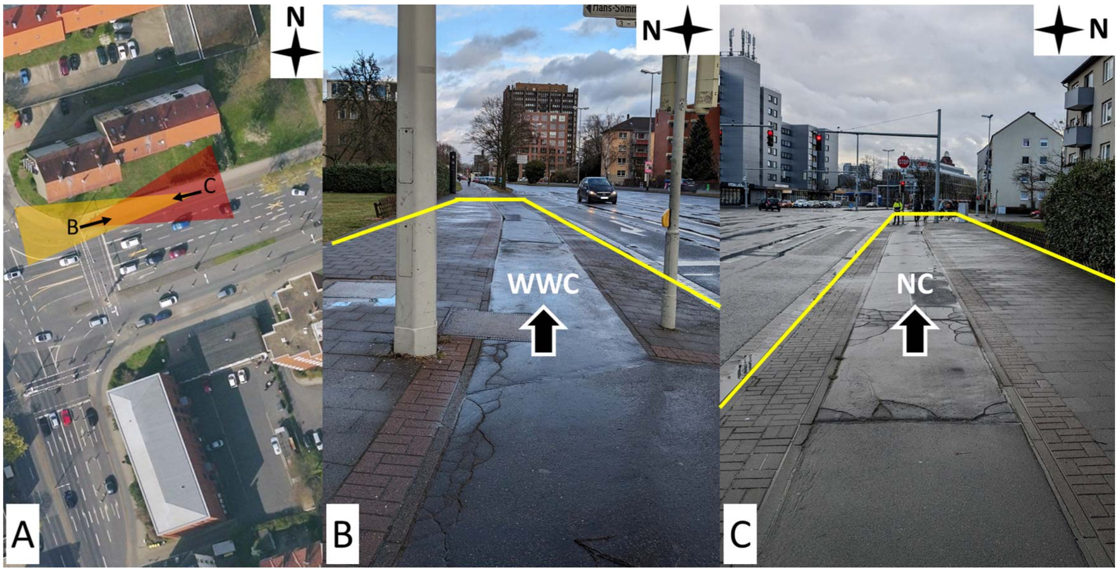


Figure 14: Study area with viewing cones (A, modified © DLR). Foot- and bicycle path from the position of *WWC* (B) and *NC* (C)

Figure 14 shows the bicycle path from the point of view of a *WWC* (B) as well as the bicycle path from the point of view of an *NC* (C). The bicycle path seems to be in poor condition. Random observations showed no influence of the surface on keeping on route or heavy puddle formation. The trajectories are described descriptively and classified according to possible groups. Examples within the scenarios and analysis approaches could be overtaking (Figure 15A), oncoming (Figure 15B), and crossing (Figure 15C).

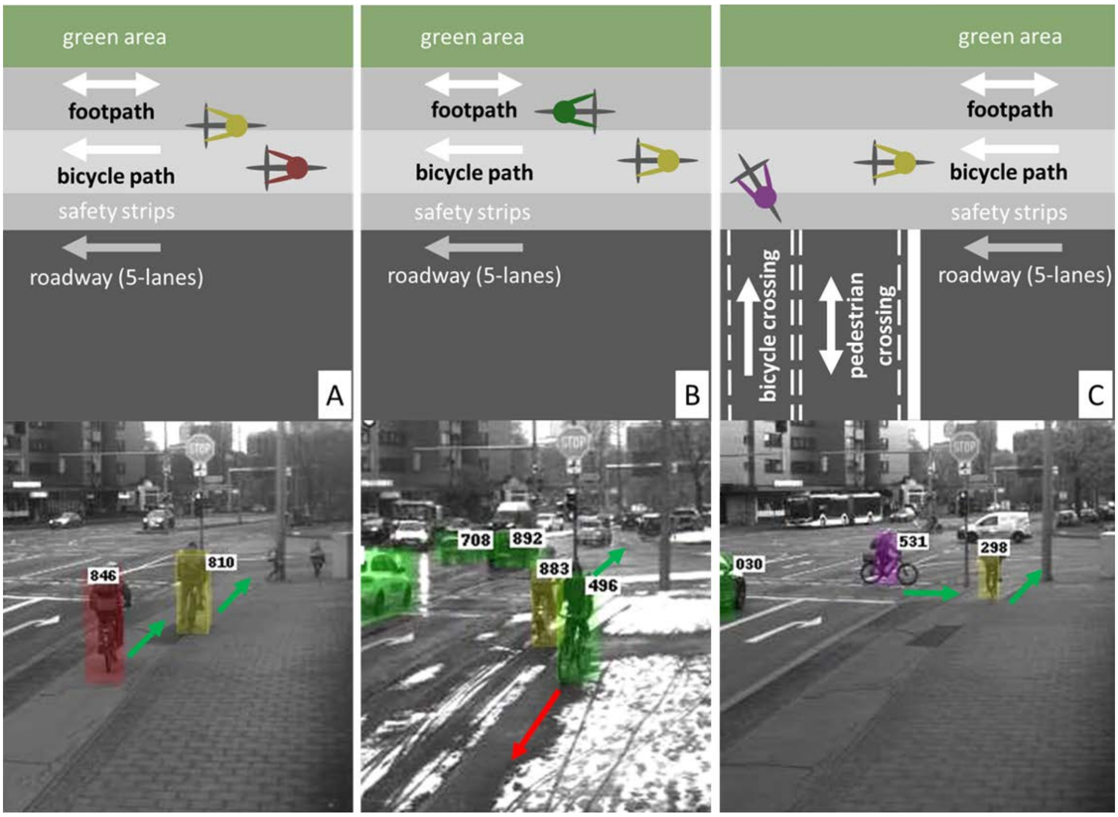


Figure 15: Interactions on the bicycle path. Sketch and example image for overtaking (A), oncoming (B), and crossing (C)

3.1.3 Intersection in the 30 km/h Zone

For reference data without bicycle infrastructure, data from the @city project is reused. The @city project was a 2017 to 2022 project to test prototype automated driving features in an urban environment. There are publications on interactions between vehicles or cyclists and other vehicles but no publications between cyclists (Quante et al., 2023; Zhang and Theisen, 2024). The study area is located on the street Bültenweg in Braunschweig, Germany. This campaign with a data collection took place from 18 to 28 September 2019.

One camera was positioned to capture the northern area of Bültenweg (Figure 16B), while a second camera was placed to cover the southern section (Figure 16C). The collection of data was facilitated by two Mobile Structures (Figure 16A). These devices have the same hardware and software architecture as the Research Intersection, but they are portable. The mast is equipped with two stereo cameras and an IR flash for illumination at night.

The intersesction 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 Bültenweg in 38106 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 desire line that is not a classified road. There is a zebra crossing in the south.

Figure 16: Place of measurement on the street Bültenweg, Braunschweig, Germany. A: One of two Mobile Structures (© DLR) with viewing direction of B to the north; C: Viewing direction to the south, with Mobile Structure of Figure A in the background

3.2 Data Processing

This section provides a brief overview of the image processing techniques employed to derive trajectory data. The data processing is the same for both measuring sites and is described below for the Research Intersection. The process of recording was initiated at a frequency of 10 Hz. The object list is estimated and updated at a frequency of 20 Hz.

Objects are captured using 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 and Matthies, 2004)

The approximate position of the viewing cones is shown in Figure 17 (based on Arndt (2021)). Figure 17A shows the inner area with long- and medium-range stereo video sensors. Figure 17B shows the viewing cones for the pedestrian and bicycle crossings with short-range sensors, and Figure 17C shows the viewing cones of the TraffiTower 2.0 specifically for the northeast footpath and bicycle path.

The signals are processed into voxels for each camera mast. Voxels are stereoscopic image data from a sensor system, which are compressed into volumetric 3D features. Each voxel is decomposed into eight vectorial attributes using a compactly coded representation: position, velocity vector, filtered velocity vector, acceleration vector, observable surface, evaluation metrics, measurement error, and optical classification result.

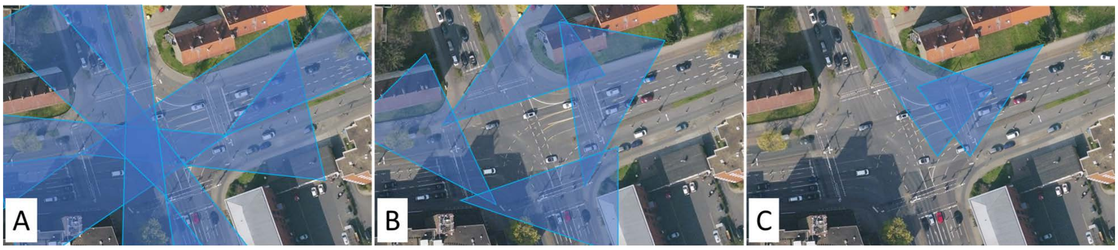


Figure 17: Locations of the masts and viewing areas of the mounted stereo cameras. A: In the inner area; B: At the pedestrian fords; C: Locations of the TraffiTower 2.0 in the north-east area (based on Arndt (2021) and modified © DLR)

The recorded voxels are grouped into free-form fans. Objects are classified as belonging together based on the voxels of a free-form fan. The object detection system is designed to detect and track rigid bodies (vehicles) as well as objects with a cylindrical or other deviating shape. Possible object classifications are Bicycle, Narrow Vehicle, Passenger Car, Pedestrian, Truck, Van, as well as Background and Unknown. A bounding box is defined as a minimal surrounding cuboid that completely encloses an object within a three-dimensional space. Subsequently, the bounding box is plotted on the object in the video to verify the size and shape of the recognised object. The quality of the bounding box is adversely affected if the outer edges of an object deviate significantly from a rectangle or if the object is moving at a low speed. Consequently, the reliability of the system is severely compromised when the object is at rest. Since 2020, an additional weather station has been installed in the south crossing arm, enabling the recording of meteorological data, emissions, and environmental parameters. These include wind direction and speed, solar radiation, air temperature, carbon monoxide, and water film thickness.

The Research Intersection gathers data from road users on a continuous basis (24 hours a day, seven days a week). This allows for the analysis of recordings irrespective of meteorological conditions, time of day, day of the week, or other variable conditions. 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 an average deviation of one digit in cm.

3.3 Tools

A range of tools were utilised in the evaluation process. This section introduces the Surrogate Measures of Safety (SMoS), which have the capacity to divide the trajectory data into critical interactions. Additionally, the interaction simulation tool SUMO is presented. Finally, the questionnaire is presented as a tool for evaluating the observed interactions.

The trajectories of the detected traffic participants and video material with augmentation of the bounding box were stored in a PostgreSQL database. In the initial level of processing (pose processing), infrastructural data is processed for the purpose of measuring individual objects. The 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. (Klitzke and Schicktanz, 2024) Parts of the analysis in this thesis are then be implemented in TASI so that they can be reused.

3.3.1 Surrogate Measures of Safety

The use of SMoS enables the analysis and evaluation of road safety. No accident data is required for analysis, but critical situations and near misses can be evaluated using metrics. This enables the assessment of road sections or intersections in terms of their safety without the need to wait for accidents to occur. Different SMoS are used to evaluate different conflicts, but each type of SMoS has different strengths. Examples of frequently used SMoS are shown in Table 7.

The Time To Collision (TTC) is often used for vehicles travelling towards or behind each other. The Post Encroachment Time (PET) is used for vehicles crossing each other. BASt (2017) identifies a lack of standardisation of threshold values for SMoS, and there is a paucity of long-term studies on the correlation between SMoS and accident data. Observation period is a crucial factor as short observation times can lead to high variances in estimates. The TTC performs poorly on non-linear trajectories, such as those of cyclists. BASt (2017) also note a limitation in the capacity of SMoS to capture stress or long-term changes.

Table 7: Three frequently used Surrogate Measures of Safety (SMoS) and their criticality values

SMoS	Meaning	Unit	Classified as critical
Post Encroachment Time (PET)[A, C]	Degree to which they miss each other	s	$PET < 2$ s[F]
Expected Post Encroachment Time ($pPET$)[D, E]	Expected degree to which they miss each other	s	$pPET < 3$ s
Time To Collision (TTC)[B, C]	Time left before the crash	s	$TTC < 1.5$ s[G]

[A]Allen et al., 1978; [B]Hayward, 1972; [C]Laureshyn et al., 2010; [D]Rasch et al., 2025; [E]Yastremska-Kravchenko et al., 2022; [F]Van der Horst, 1991; [G]Lu et al., 2005

PET

The PET is employed in instances where two vehicles intersect. The first vehicle departs from the intersection at time t_0 (Figure 18A), while the second vehicle enters at time t_1 (Figure 18B). The temporal difference between these two instants is utilised to calculate the PET value (see Formula 3.1).

$$PET = t_0 - t_1 \tag{3.1}$$

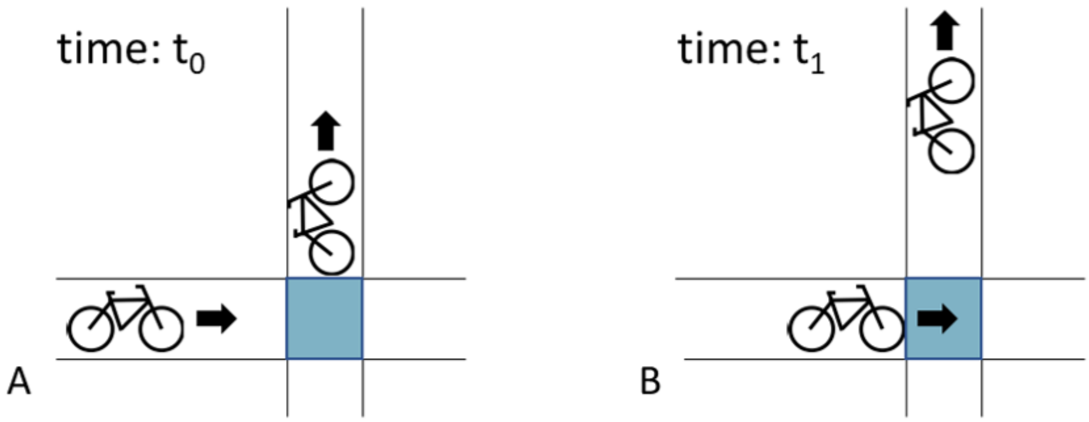


Figure 18: Sketch of the calculation of the PET at time t_0 (A) and t_1 (B)

It is evident that the PET value is directly proportional to the criticality of the interaction; that is, the higher the PET value, the less critical the interaction.

This is because the road users only pass each other or because one or both road users have already created space by braking or taking evasive action.

The PET is capable of assuming both positive and negative values, contingent upon the prioritisation of the road user in question. Consequently, a PET of +3 s or -3 s can subsequently be utilised not only to determine the criticality of the situation but also to ascertain which road user crossed first (based on the mathematical sign).

pPET

If the paths of two trajectories do not intersect, the *predicted PET* ($pPET$) can be used as a metric. Assuming that both crossing trajectories maintain a constant heading and speed, the $pPET$ in this study is calculated as follows: The intersection point is calculated where the trajectories are expected to meet if they maintain their current speed. The distance from the current position of the objects to the intersection point is then calculated. The distance vectors are normalised and the velocity is projected. The result is the component of the velocity that points in the direction of the intersection point. The Time To Arrival (TTA) for each object is calculated by dividing the distance to the intersection by the projected speed. The difference between the TTA of the two trajectories is the $pPET$. A smaller $pPET$ value indicates a potentially more dangerous situation, as the trajectories would arrive at the intersection almost simultaneously.

TTC

To calculate the TTC, it is necessary for both road users to be on a collision course. The TTC is a continuous variable that calculates the time before a collision occurs based on speed and distance travelled.

The TTC is employed principally in situations involving direct forward movement by road users. The magnitude of TTC is directly proportional to the relative triviality of the interaction.

3.3.2 Simulation of Urban MObility

Simulation of Urban MObility (SUMO) is an open source microscopic traffic simulation software developed by the DLR and introduced in 2001 (Alvarez Lopez et al., 2018). SUMO enables the realistic simulation of large-scale traffic networks, including various road users such as pedestrians, cyclists, and public transport. The software is scalable and can be used for transport networks of various sizes. SUMO can be used via the command line, via graphical user interfaces (SUMO GUI and NETEDIT), as well as via programming interfaces such as TraCI (Traffic Control Interface) with Python. (Alvarez Lopez et al., 2018)

In this work, SUMO 1.20.0 was used via graphical user interfaces (SUMO GUI and NETEDIT). The components of the SUMO system are described below.

NETEDIT
NETEDIT facilitates the editing of road networks and the incorporation of supplementary information, including right-of-way regulations, routes, velocities, and vehicle classifications. The software enables the customisation of traffic light sequences and intersection layouts, with the ability to specify customisation down to edges, nodes, and lanes. Nodes represent intersections or intersections where multiple edges intersect.

SUMO GUI
The SUMO Graphical User Interface (SUMO GUI) is the visual representation of the traffic simulation. The previously defined traffic network on NETEDIT can be loaded and controlled here (start, stop).

Bicycles in SUMO
In SUMO it is possible to simulate different road users in one place at the same time. There is currently no movement model implemented for cyclists. When simulating a road user as a cyclist, the following parameters are set and can be adjusted later:

- $minGap = 0.5$ m
- $max.acceleration = 1.2$ m/s^2
- $max.deceleration = 3$ m/s^2
- $emergencydeceleration = 7$ m/s^2
- $length = 1.6$ m
- $maxspeed = 20$ km/h; this can be modified by defining vClass specific speed limit

The 'minGap' attribute describes the offset to the leading vehicle and is the minimum gap when standing (in meter). The maximum acceleration is not the maximum acceleration capability but rather the maximum acceleration a rider chooses, and the same applies to maximum deceleration. The 'emergency deceleration' attribute is the maximal physically possible deceleration for the class. The 'length' attribute describes the length of the vehicle itself. The 'max speed' attribute is the vehicle's (technical) maximum velocity (in m/s).

In 2024, there were two methods available for the purpose of simulating cyclists in SUMO. First, cyclists could be regarded as narrow vehicles that adhere to established vehicle models. Alternatively, cyclists could be considered as fast pedestrians. Pedestrians possess numerous degrees of freedom, including the ability to turn around on the spot, thereby demonstrating a high degree of flexibility in their movement. In contrast, vehicles are confined to following a designated lane and consequently exhibit a reduced degree of flexibility in their behaviour. However, this flexibility is comparable to that observed in cyclists traversing a bicycle path. Therefore, cyclists are simulated as narrow vehicles in this work.

Bicycle-bicycle scenarios in SUMO

Given the absence of any cyclist model in SUMO, the simulation and interaction of this particular user group is not a possibility. Bicycles are therefore simulated as narrow, slow vehicles or as fast pedestrians.

Road users in SUMO demonstrate strict adherence to the established rules. Consequently, the presence of *WWC* is non-existent in this environment. Cyclists, on the other hand, are confined to the designated direction of travel along their designated bicycle path. The introduction of a second lane for cyclists travelling in the opposite direction would be a prerequisite for the facilitation of *WWC*. Additionally, the implementation of a rule allowing for the use of footpaths during swerving manoeuvres would be necessary.

The same applies to overtaking. Overtaking on a bicycle path is only possible if the bicycle path is divided into a separate lane.

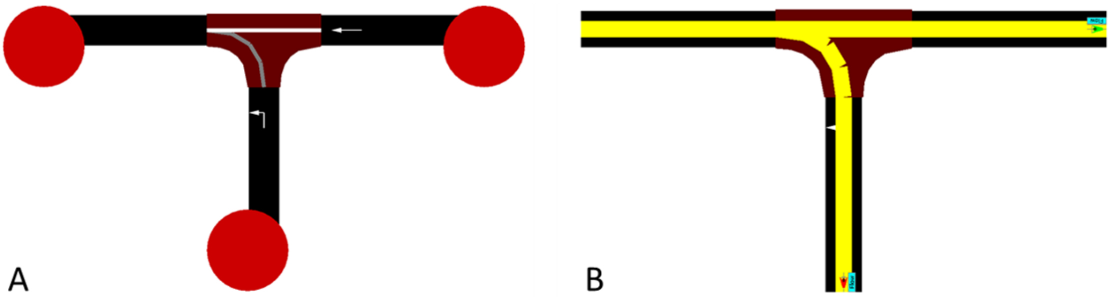


Figure 19: T-intersection in the SUMO simulation software NETEDIT. A: Nodes and edges with intersection; B: Possible routes for green vehicle (east to west) and red vehicle (south to west) intersection (own screenshots from the SUMO NETEDIT version 1.20.0)

In the crossing scenario, the existing crossing of vehicles can be utilised. In the example of the Research Intersection, a T-intersection is created in SUMO that has three corners, three edges, and a crossing point (Figure 19A). With respect to the routes, the two most frequently travelled routes (Section 4.2.1) were also selected in SUMO. Vehicles can travel from east to west and from south to north. Vehicles can meet at the crossing point (Figure 19B).

In principle, a rule can be defined for the crossing point. If the rule is applied from priority-to-the-right, initially all parties in the simulation will adhere to it. The internal attribute of the crossing point type is: right-before-left.

However, it is possible to modify this rule. An intersection without a priority-to-the-right rule (type: unregulated) would lead to a high number of accidents and is not used because priority-to-the-right rule applies at the Research Intersection. In addition, three parameters were used in the simulation to be able to ignore the right-of-way:

- $jmIgnoreFoeSpeed$ (default 0 m/s)
- $jmIgnoreFoeProb$ (default 0)
- $jmIgnoreJunctionFoeProb$ (default 0)

The attributes jmIgnoreFoeProb and jmIgnoreFoeSpeed are utilised jointly. The velocity of the attribute is configured to the maximum permissible value. Only vehicles that are moving at a speed below or equal to the specified value can be disregarded. The attribute jmIgnoreFoeProb delineates the probability of circumventing the right-of-way rule and will be refined based on the outcomes of this study. The final parameter guarantees that vehicles that have already entered the intersection can also be ignored.

The speed distribution of cyclists is controlled by the speedFactor, which employs the truncated normal distribution: normc (mean, dev, min, max).

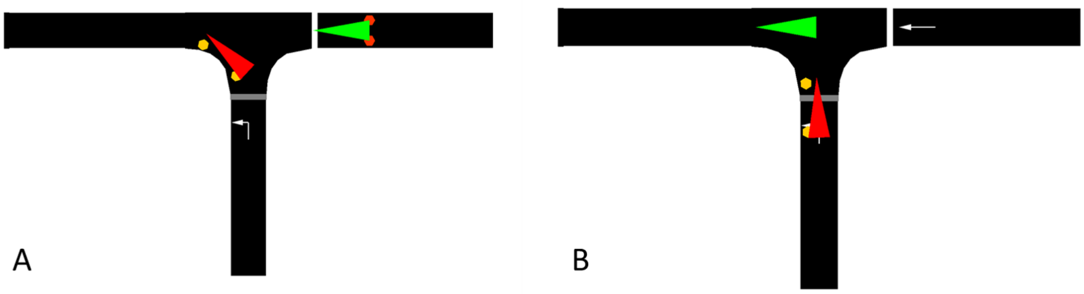


Figure 20: T-intersection in the SUMO simulation software SUMO GUI. Cyclist (red) takes the right-of-way (A) or gives the right-of-way (B).

The function under analysis draws a normal distribution for both lanes from the given speed distribution, with the speed distribution itself being adjusted to real observation data at the conclusion of the analysis. It is possible to execute the network in the SUMO GUI, which can result in the collection of additional SMoS values. An example of the SUMO GUI for the intersection is illustrated in Figure 20.

The incorporation of narrow vehicles as bicycles results in the concomitant display of vehicles within the simulation.

The SSM device is utilised for the purpose of calculating the *predicted PET* ($pPET$). In this context, the ego and the foe vehicle represent two discrete entities.

- ego vehicle = vehicle with SSM device that creates the output
- foe vehicle = vehicle in conflict with ego vehicle

In the scenario depicted in Figure 20, the absence of a direct intersection point is notable. However, the vehicle from the south merges into the lane, indicating that in this instance, only the $pPET$ can be calculated. In the observed case of cyclists from the south and north crossing the footpath, a four-leg intersection is formed, enabling the determination of a PET.

Like the control of random events, SUMO uses the Mersenne Twister algorithm. This algorithm can be reproduced by default and can be made non-reproducible by using the option `--random`. This option uses the system time to create a seed. A seed starts the random number generator. A fixed seed can be used to make randomness that can be reproduced.

The utilised and modified values are presented in Section 5.

Limitations

The simulation is subject to certain limitations. First, there is an absence of a suitable bicycle model, and therefore narrower vehicles were used and adapted. In principle, collisions cannot be avoided unless the software is adapted. As these are narrow vehicles, they always ride in the middle of their lane. Cyclists should move further to the right. Cyclists have more degrees of freedom than vehicles but less than pedestrians. Cyclists lose some freedom of movement when simulated as a narrow vehicle. This is sufficient for some calculations. However, certain evasive manoeuvres cannot be mapped with it.

3.3.3 Survey

The aim of the survey was to gather subjective data in addition to the objective traffic observation data to understand the reasons for identified behaviour patterns, such as not respecting the right-of-way. The online questionnaire was created using SoSci Survey (Leiner, 2024). Participants were contacted directly and the survey was shared in a cycling forum.

The questionnaire consisted of seven pages, of which respondents had to complete six, 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 data processing
- General riding behaviour
- Query about previous wrong-way riding behaviour
- If the respondent had ridden the wrong way at least once, they received the *WWC* questionnaire; if 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 how participants found out about the survey and a free text field for comments

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

The survey pages can be found in the Appendix A.5.

3.4 Traffic Analysis

This section presents the various approaches to analysing the three scenarios of oncoming, overtaking, and crossing.

3.4.1 Oncoming

The recorded trajectories were filtered by *NC* and *WWC*. The whole process from data recording to analysis is shown in Figure 21. 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 before and during the interaction. The Euclidean Distances between the object centres of the interacting couples were computed. All the identified interactions were checked manually in the video. Further information such as helmet use, age, gender, or hands on the handlebars were annotated. The video material was recorded in reduced quality, which means that information about age and gender can only be determined very imprecisely and in some cases is based on assumptions. Assuming that the bicycles maintained their direction and speed when passing each other, small data gaps were interpolated linearly.

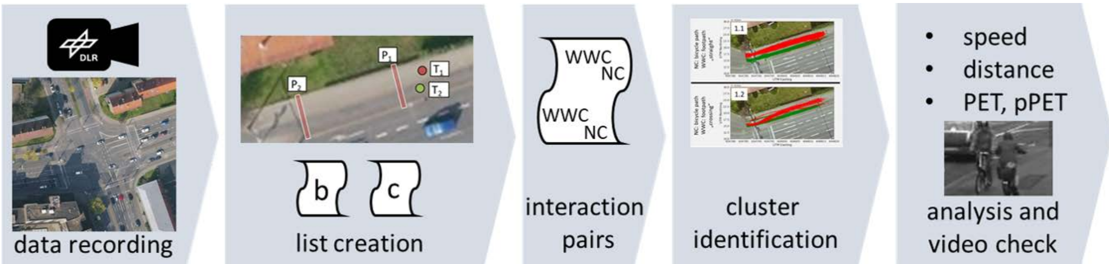


Figure 21: Analysis plan for the oncoming scenario. Outline of the analysis procedure from data recording (left) to data clustering and analysis (right)

Interaction pairs where one or both trajectories were too short or incomplete were ignored. Sometimes passing 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 cyclist's interaction.

3.4.2 Overtaking

In the recorded trajectories, a list of pairs intersecting two defined polygons is analysed to find overtaking interactions. The process is illustrated in Figure 22.

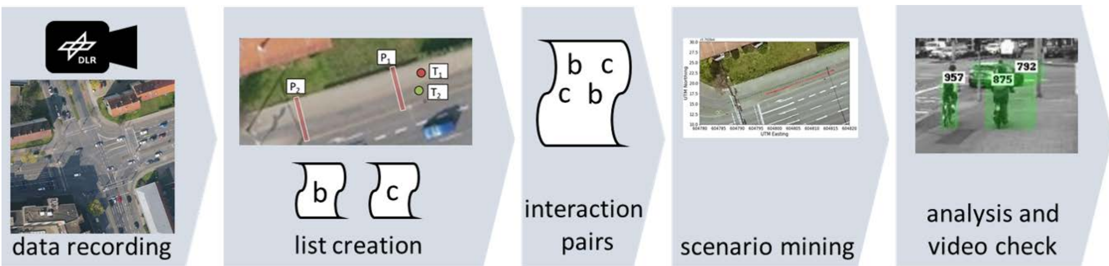


Figure 22: Analysis plan for the overtaking scenario. Outline of the analysis procedure from data recording (left) to scenario mining and analysis (right)

Two polygons along the bicycle path were selected for the purpose of recording overtaking manoeuvres. In step 1, trajectory 1 crosses polygon 1 at a specific time ($t_{1,1}$). A second trajectory also crosses polygon 1 at a time ($t_{1,2}$). Subtraction of the times from each other reveals the order in which the polygon was crossed

by the two cyclists (example calculation in Formula 3.2). If the intersection of the trajectories in polygon 1 is less than 5 s, the pair is examined further. In step 2, trajectory 1 crosses polygon 2 ($t_{2,1}$) and trajectory 2 also crosses it ($t_{2,2}$). Here, subtraction can also be used to find out which cyclist first crossed the polygon (example calculation in Formula 3.3). In the final step, the signs from polygon 1 are compared with those from polygon 2 to determine whether an overtaking manoeuvre has taken place, whether the cyclists are travelling in a column, or whether they are travelling side-by-side (or whether the overtaking manoeuvre is still in progress).
An example calculation:

- Trajectory 1 crosses polygon 1 at 08:35:03 and trajectory 2 at 08:35:05.

$$t_{1,1} - t_{1,2} = -2\,s \tag{3.2}$$

- Trajectory 1 crosses polygon 2 at 08:35:18 and trajectory 2 at 08:35:14.

$$t_{2,1} - t_{2,2} = +4\,s \tag{3.3}$$

Following the alteration in sign, it can be deduced that an overtaking manoeuvre must have occurred, a fact that is corroborated by the video annotation. In the absence of a change in sign, it can be inferred that the cyclists are riding one behind the other. A minimal temporal separation can be interpreted as evidence that they are riding in close proximity to each other.

In comparison to the oncoming scenarios, it was not possible to interpolate the incomplete trajectories. This was due to the presence of too many changes in direction during the overlap that occurred behind and next to each other that could not be interpolated.

3.4.3 Crossing

It was checked when a trajectory intersected the area of interest and whether another trajectory also intersected it within 3 s using polygons. 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 handlebars or half the length of the bicycle. Common length and width dimensions are 1.90 m and 0.70 m (ADFC, 2020). The complete data process is illustrated in Figure 23, which encompasses all the requisite processing steps from data recording, direction of travel detection, and interaction analysis.

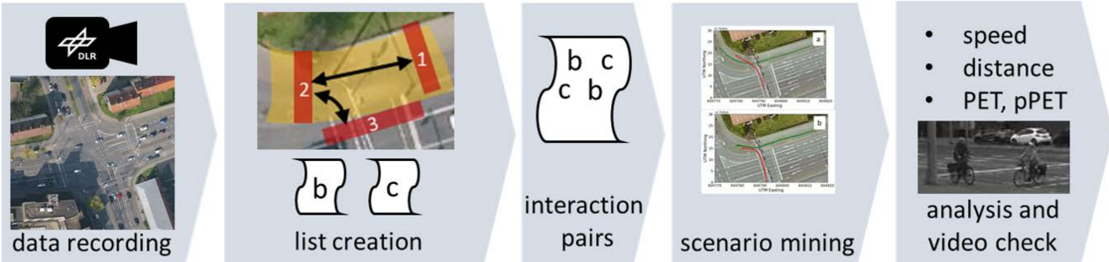


Figure 23: Analysis plan for the crossing scenario. Outline of the analysis procedure from data recording (left) to analysis (right)

The proximity of cyclists while crossing was also assessed by calculating the *PET* and *pPET* and by calculating the minimum distances between cyclists as members of the SMoS. For each crossing scenario, the *PET* is calculated as a measure to evaluate the situation in terms of traffic safety (Allen et al., 1978). The *PET* is used when two road users intersect. The ego user leaves the intersection point at time t_0, while the second user enters at time t_1. The difference in time forms the value for the *PET*. Euclidean distances between the object centres of the interacting couples were computed, and the identified interactions were checked manually in the video. If the trajectories did not cross, for instance because of swerving, no *PET* was calculated. Assuming both crossing cyclists maintained constant headings and velocities, there is the possibility to calculate the *pPET* for each moment of time. Interaction pairs were excluded when 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.

3.5 Data Quality

The measurement data was not collected for the purpose of analysing bicycle-bicycle interactions but rather was repurposed from other projects (KI Data Tooling (KDT, 2025), SAVeNoW (SAVeNoW, 2025), @city (atCITY, 2025) and STADT:up (STADT:up, 2025)). The recordings remain suitable for evaluation due to the accurate detection of cyclists in their designated locations. However, from 18 to 28 October 2024, no video data was available, precluding the possibility of a retrospective interaction check. The detection of pedestrians is only possible to a limited extent, and e-scooters cannot be detected at all, meaning that the influence of other road users on bicycle interactions could only be checked in the video material.

The quality of the data is limited, particularly in instances where two cyclists approach each other. Objects are detected with a delay and occasionally are lost from view for a moment, resulting in gaps in the trajectories. A review of the video material suggests that oncoming cyclists continue on their course. Consequently, it was possible to interpolate the gap. Smaller lateral deviations would not have been recorded due to the accuracy of the system. During overtaking manoeuvres, a brief sequence of close cycling, cut out, overtaking, and cut in is observed. In this instance, interpolation is not applicable, as the trajectory could not be mapped. When crossing, the trajectories are detected with high precision until the point of encounter as they originate from different directions and do not overlap with each other. Smaller gaps in the trajectories during the crossing can be effectively interpolated upon review of the video material.

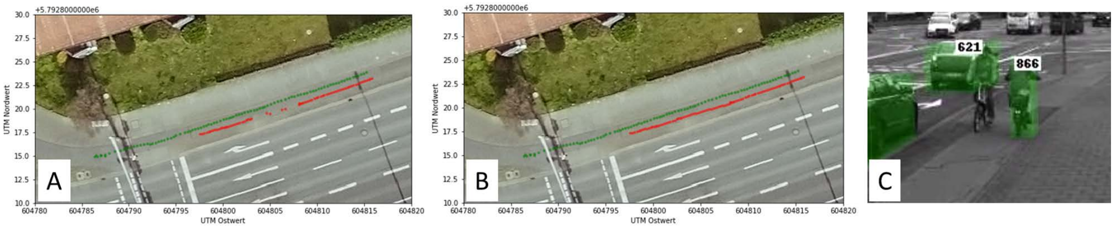


Figure 24: Example of interpolation for the oncoming scenario. A: Before interpolation with example image (C) and after interpolation (B). Green dots: *NC*, red dots: *WWC* (A and B modified © DLR)

Figure 24 presents a good example of interpolation during the oncoming manoeuvre. Figure 24C shows that the *WWC* was not detected. Prior to the interpolation process (as depicted in Figure 24A), the calculated distance was 1.86 m. This is because when the two vehicles were operating in close proximity, the *WWC* remained undetected. Consequently, a point on the trajectory that was further away was utilised, as opposed to the situation where the two cyclists were not at the same height. Following the interpolation, the calculated lateral distance was 0.92 m (see Figure 24B). It should be noted that, due to the necessity of utilising the centre coordinates of the objects in the calculation, the distance between the centre of the handlebar and the point of interest, approximately 0.35 m, had to be subtracted. Thus, the distance during the interaction was 0.57 m, which is possible with additional measurement uncertainty and when considering Figure 24C. It is possible that cyclists on the track were not detected and therefore not included in the analysis. The number of unreported cases is unknown given that not all of the video material was available because the system experienced intermittent video data failures. Moreover, the reduced image quality of the video annotation caused an inaccurate estimation of age and gender. Consequently, the age was categorised into only three groups: young, middle-aged, and old. Distinctions between third gender were generally not possible, so the binary gender classification may also contain some misinterpretations.

4 Results

This section presents the results for oncoming, crossing and overtaking as another scenario.

Table 8: Overview of all data sources used with time periods and the number of interactions found therein

Scenario	Data set Overview	Hours	Interactions found
Oncoming	**Research Intersection** **KI Data Tooling** (KDT, 2025): 8–10 Febuary 2022 (50h) **SAVeNoW** (SAVeNoW, 2025): 18–28 October 2022 (108h) **STADT:up** (STADT:up, 2025): 26 April–2 May 2023 (98h)	256	169
Crossing	**Research Intersection** **KI Data Tooling** (KDT, 2025): 8–10 Febuary 2022 (37h*) **SAVeNoW** (SAVeNoW, 2025): 18–28 October 2022 (108h) **STADT:up** (STADT:up, 2025): 26–27 April 2023 (26h)	171	120
	Intersection in the 30 km/h zone **@city** (atCITY, 2025): 18–28 September 2019 (240h)	240	35
Overtaking	**Research Intersection** **KI Data Tooling** (KDT, 2025): 8–10 Febuary 2022 (50h) **SAVeNoW** (SAVeNoW, 2025): 18–28 October 2022 (108h) **STADT:up** (STADT:up, 2025): 26 April.–2 May 2023 (98h)	256	12
	Intersection in the 30 km/h zone **MMoNK** (MMoNK, 2023): 14 September 2021 (8h)	8	104

* Without nighttime

Table 8 shows an overview of all data sources used, the analysed time periods and the interactions found therein. The exact results are described for oncoming in Section 4.1, for crossing in Section 4.2 and for other interactions (especially overtaking) in Section 4.3.1.

4.1 Oncoming

A total of 19,352 cyclists were counted in the data, and 12% of those were *WWC*. In the final data set, 169 trajectory pairs of *NC*-*WWC* interactions remained for analysis in the AOI (Figure 12A in Section 3.1.2). During validation and plausibility checks 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 women wore helmets).

4.1.1 Interaction

The first step of the analysis was to examine which patterns occurred (i.e., path change, passing, and overtaking) during the interactions. Additionally, it was checked whether similar patterns occurred after passing the interaction partner. All cases were compared between *NC* on the bicycle path or footpath and *WWC* on the bicycle path or footpath. Each case occurred at least once. The largest proportion of *WWC* (21%) was found on 18 October 2022 from 6 to 7 AM and 26 April 2023 from 6 to 7 PM. In this research, the term ‘straight’ is always used when the *WWC* trajectory was straight and the *WWC* remained on either the bicycle path or the footpath, whereas the term ‘crossing’ is used to denote a change between bicycle path and footpath. A distinction is made for *WWC* who changed to the footpath before the interaction versus those who changed to the bicycle path after the interaction. Table 9 lists the data for each interaction on the respective infrastructure (footpath or bicycle path) for *NC* and *WWC*. Figure 25 depicts the clusters of encounter situations corresponding to Table 9. 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 the safest for interaction between cyclists because uncontrolled short-term evasive manoeuvres were less likely to occur (Figure 25, case 1.1). The second most common occurrence (14.2% of cases) was that the *WWC* initially rode on the bicycle path and decided to switch to the footpath (crossing) before interacting with the *NC* (Figure 25, case 1.2).

4.1.2 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% of WWC ($n = 7,598$) were detected. The proportion of WWC was largest from 6 to 7 AM (20%). 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 9 visualises the measured variables: column $d_{min,mean}$ quantifies the minimum distance during interaction, and in column v presents the speeds of both NC and WWC during interactions. NC and WWC can ride on the bicycle path or footpath. In 70 of 169 cases the bicycle path was used, and in seven cases both WWC and NC adopted the bicycle path at the same time. There were no examples of both riders riding on the footpath. Within the AOI, NC and WWC sometimes first changed paths before they passed each other (Table 9 type crossing). Otherwise, NC and WWC kept their path during the interaction (Table 9 type straight). In each situation the speed of the WWC was lower than of the NC, except in Figure 25 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. 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. WWC switched from the bicycle path to the footpath approximately 14.4 $\pm$ 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 (not shown in Table 9). As the WWC trajectory was too short, the interaction point could not be determined.

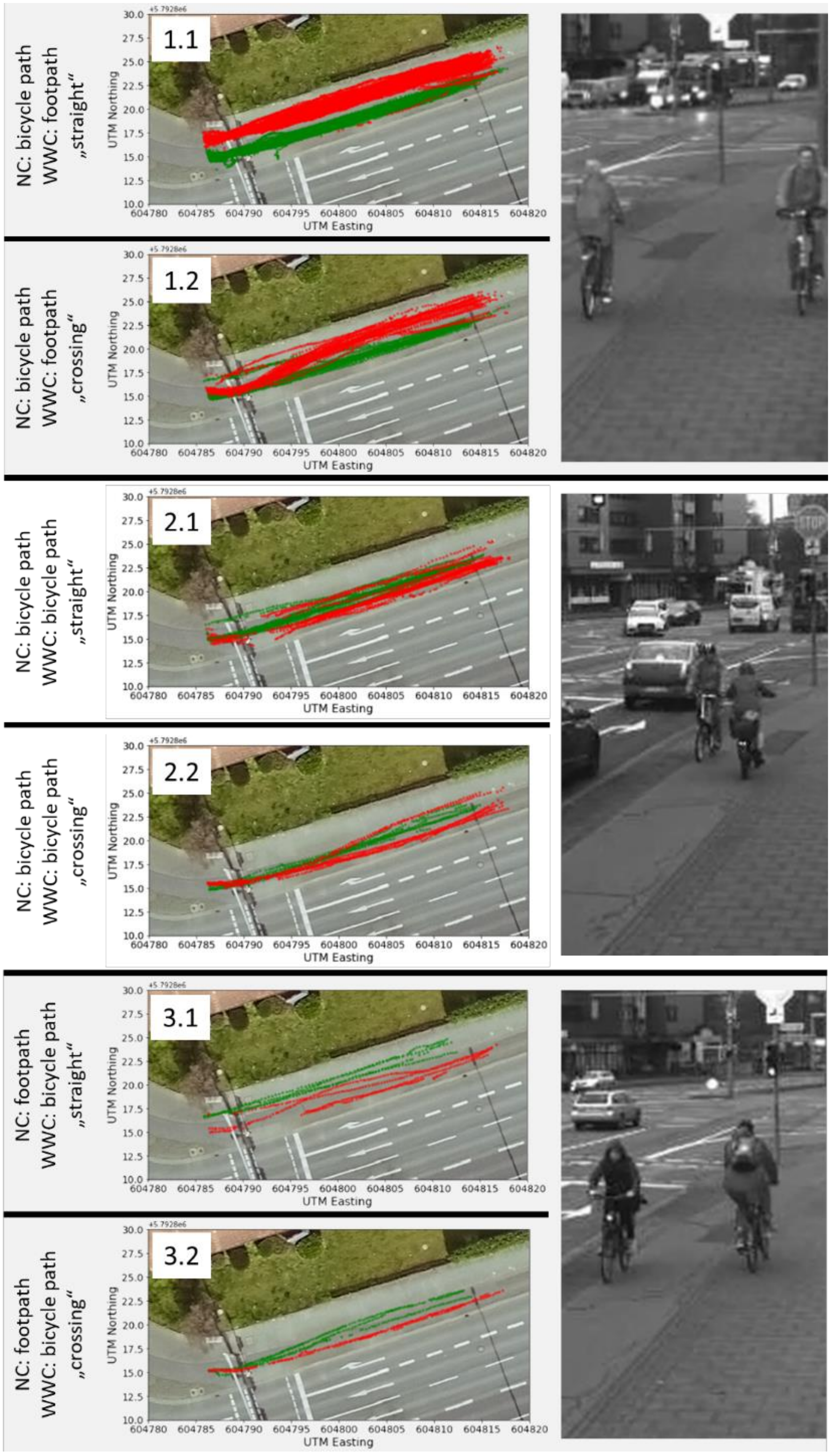


Figure 25: Types of interaction between *NC* and *WWC*: cases 1.1 and 1.2: *NC* on bicycle path and *WWC* on footpath; cases 2.1 and 2.2: *NC* and *WWC* on the bicycle path; cases 3.1 and 3.2: *NC* on footpath and *WWC* on bicycle path (modified © DLR)

Table 9: Scenarios of 168 interacting cyclist pairs 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. One case where *NC* and *WWC* rode on the footpath is not shown.

No.	**NC**	**WWC**	**Type**	**Number of cases**	$d_{min,mean}$ **in m**	d_{min} **in m**	$\|v\|$ **in m/s**	
							NC	**WWC**
1.1	bicycle path	foot-path	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	foot-path	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

4.1.3 First Model

In most cases, the *NC* was riding on the bicycle path ($n = 161$, 95.3%). This 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 *NC* on the bicycle path is shown in Figure 26. Cases that occurred less than five times are not shown.

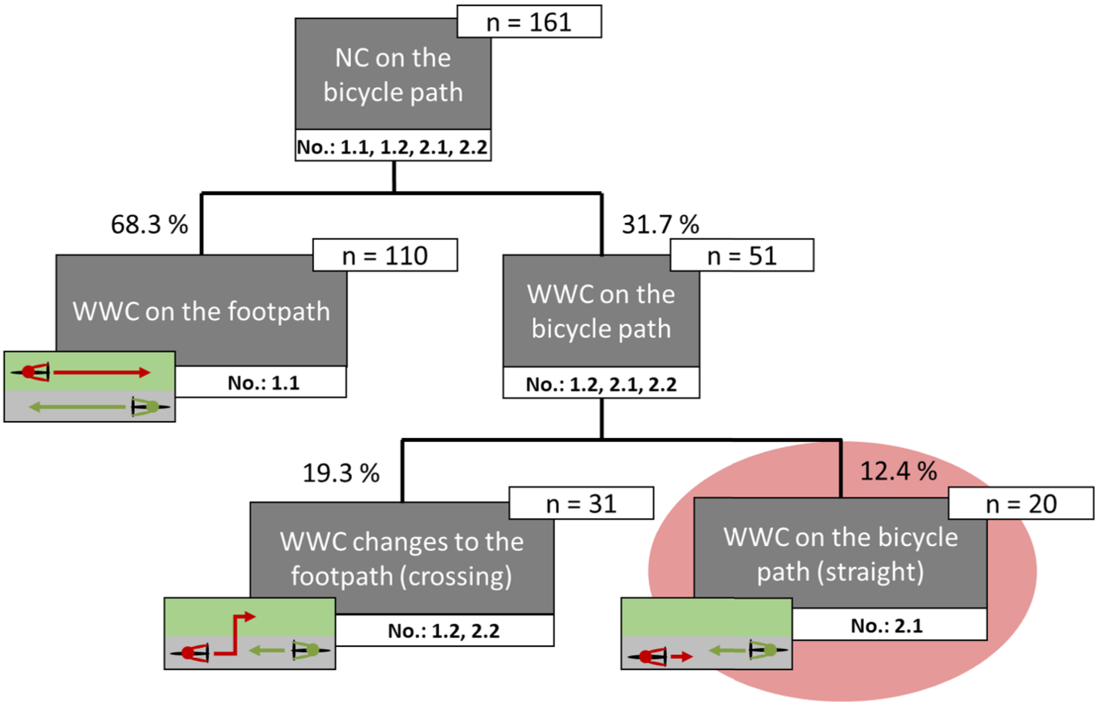


Figure 26: Possible actions of *WWC* when *NC* rides on the bicycle path. Red bubble shows possible critical cases.

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

Case 2.1: *WWC* and *NC* remaining on the bicycle path was one of the least observed cases ($n = 20$, 12.4%), but it can lead to critical interactions (Figure 26, red bubble). The smallest distance measured for *NC* and *WWC* on the bicycle path was $d_{min} = 0.68$ m (see Table 9).

Cases 1.2 and 2.2: In another scenario *NC* rode on the bicycle path and *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 red bubble is the most critical case, when both cyclists are on the bicycle path and the lateral distance between them is the smallest of all cases. Of all the cases, this is the least common, but has the highest risk of falls and conflicts.

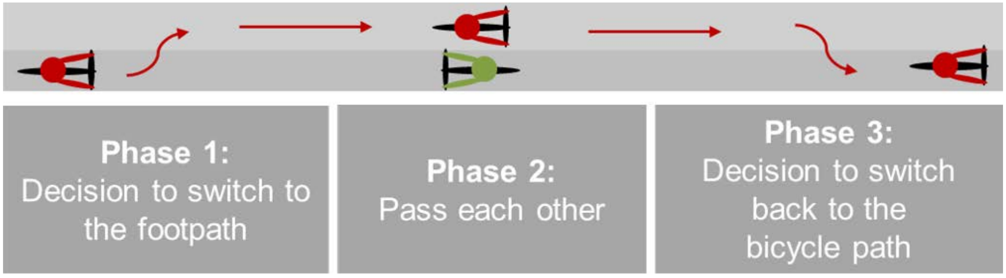


Figure 27: Considered interaction phases in the AOI in the case that *NC* (green cyclist) rode on the bicycle path and *WWC* (red cyclist) changed from the bicycle path to the footpath

Phase 1 describes the switching process of *WWC* crossing from the bicycle path to the footpath. Phase 2 describes the process of *NC* and *WWC* passing each other, with *NC* riding on the bicycle path and *WWC* riding on the footpath. In phase 3, *WWC* switch from the footpath back to the bicycle path.

Phases 1 and 2 could be observed within the AOI, but in many cases phase 3 could not be observed due to restrictions on the cameras' field of vision. Phases 1 and 2, as shown in Figure 27, occurred 14 times. The average distance between the change from bicycle path to the footpath and the interaction was 18.17 $\pm$ 3.75 m. In five observed cases all three phases were recorded. The distance between change and interaction was 15.58 $\pm$ 5.04 m. After the interaction, the change back to the bicycle path took place after 4.43 $\pm$ 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 $\pm$ 1.83 m in all 19 cases.

4.1.4 Helmet Usage

During validation and plausibility checks of the interaction pairs in the video images, gender, age range, and helmet use were estimated and annotated. A difference between *NC* and *WWC* could be identified in 130 interaction pairs, but approximately 5% of helmet use and age could not be estimated for *NC* due to video resolution, camera perspective, contrast, and illumination. Figure 28 gives the annotation for *NC* and Figure 29 for *WWC*. It appears that 61% of *NC* and

75% of *WWC* were male, while 7% of male and 12% of female *WWC* wore a helmet. There were five cases of one-handed *WWC* (due to, e.g., mobile phone use, carrying objects, hand in pocket).

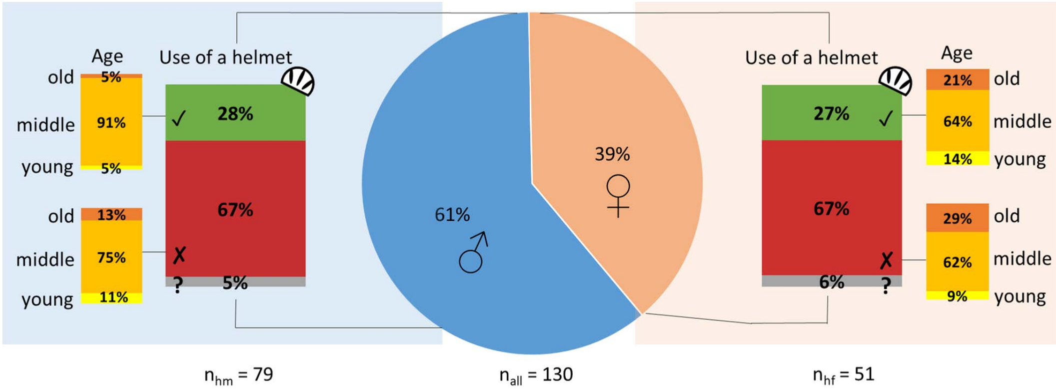


Figure 28: Video annotation at the Research Intersection. Age, gender and helmet use of (*NC*) with the total number n_{all} of cyclists and the number of helmet usage for male n_{hm} and female n_{hf} cyclists

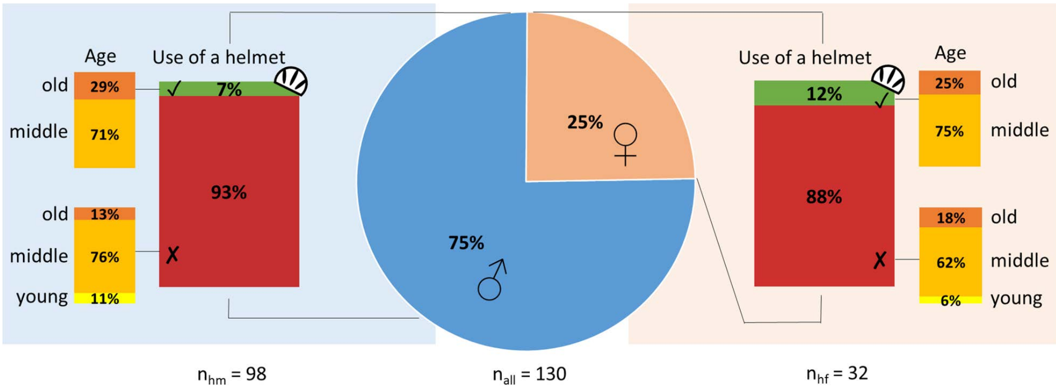


Figure 29: Video annotation at the Research Intersection. Age, gender and helmet use of (*WWC*) with the total number n_{all} of cyclists and the number of helmet usage for male n_{hm} and female n_{hf} cyclists

A comparison with the survey in Section 4.4.2 shows that 47% of respondents wear a helmet.

4.1.5 Survey

In the survey, 88% of respondents indicated that they had previously ridden in an incorrect manner at least once (Figure 30). The predominant rationale cited for this behaviour was the desire to save time and distance (110 responses). It should be noted that respondents were permitted to select multiple answers in the survey. Additionally, the open-text field was utilised on 27 occasions, providing supplementary reasons for these behaviours (Appendix A.1). The most commonly cited reasons for this practice included the use of bicycle paths in the wrong direction for brief distances due to the absence of alternative routes, the inability to change lanes due to safety concerns, and the unavailability of crossing aids. Additionally, the lack of planned alternatives due to ongoing construction sites was identified as a contributing factor.

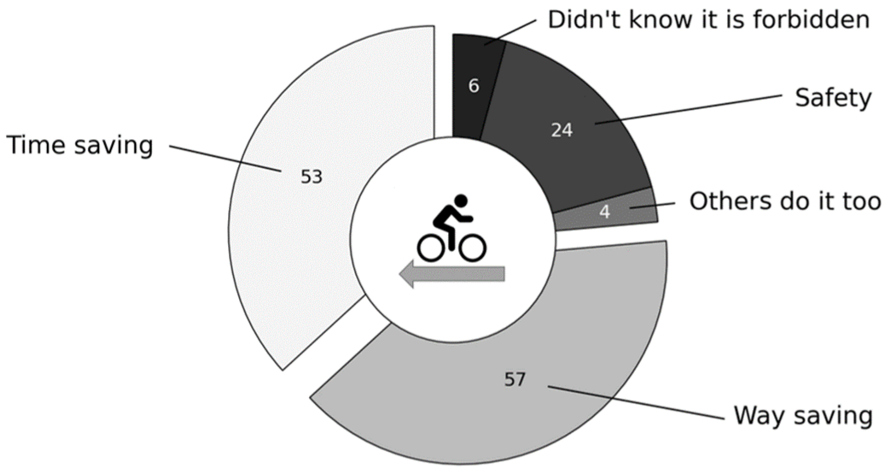


Figure 30: Reasons for cycling in the wrong direction of travel

In terms of infrastructure, a clear distinction emerges depending on whether the *WWC* uses the bicycle path with or without oncoming traffic.

A total of 72% of *WWC* ride on the bicycle path without the presence of oncoming traffic. In contrast, when oncoming traffic is present, only 30% of cyclists stay on the bicycle path, and 59% use the footpath (Figure 31).

In the event of the *WWC* coming into contact with another oncoming cyclist, what would be the consequence in terms of speed and distance? Does the *WWC* not have any awareness of the oncoming cyclist? In the survey, 75% of *WWC* respondents stated that they would slow down if there is an oncoming cyclist, and none indicated that they would increase their speed. With regard to distance, 84% of respondents stated that they would increase their distance, while only 2% stated that they would decrease it (Figure 32).

Evaluation of *NC* is underrepresented as only 16 respondents stated that they never ride in the wrong direction. However, 62.4% of these respondents also stated that they reduce their speed when encountering a *WWC*, while around 50% stated that they maintain their distance. In contrast, 7% of *WWC* indicated that they reduce their distance when encountering NC. When confronted with a WWC, 81% of NC respondents continued to use the bicycle path, while only 3 respondents (19%) used the footpath (Figure 33).

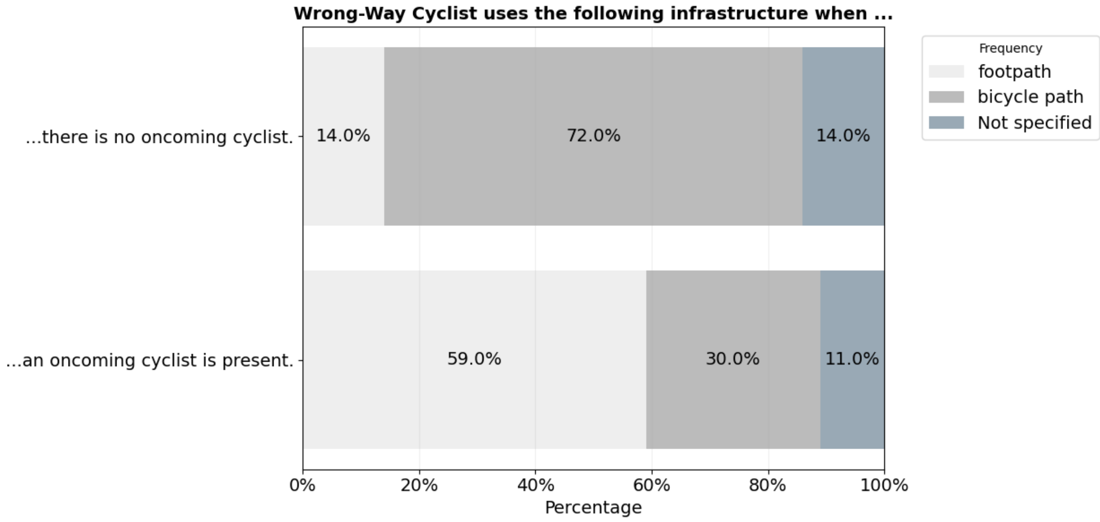


Figure 31: Use of infrastructure depending on whether there is an oncoming cyclist

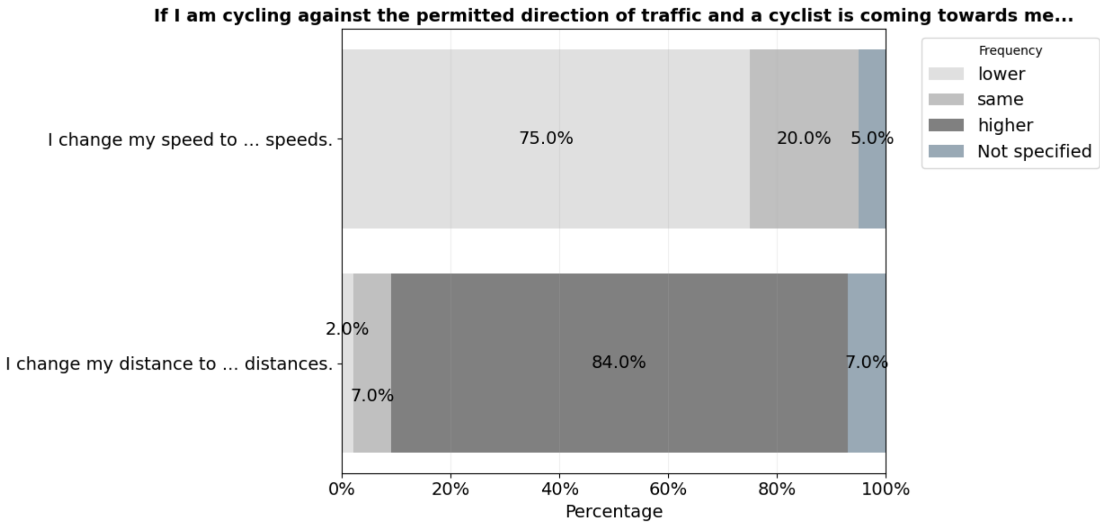


Figure 32: Speed change WWC when meeting an oncoming NC

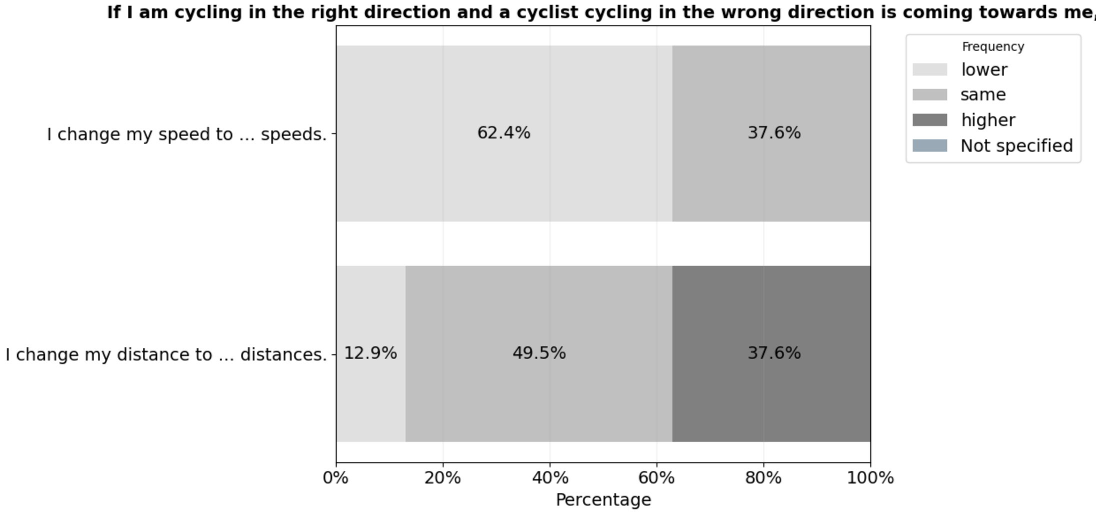


Figure 33: Speed change *NC* when meeting an oncoming *WWC*

4.1.6 Discussion

This study focuses on how *WWC* adapt their behaviour when *NC* and *WWC* pass 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 between *NC* and *WWC* remained in the final data set for detailed analysis.

Of the 169 interaction pairs, the *NC* rode most frequently on the bicycle path and the *WWC* on the footpath (n = 134). Distances of 1.50 m were mostly maintained during the interaction. *NC* and *WWC* were observed second most frequently on the bicycle path (n = 27). The speed of *NC* and *WWC* was sometimes higher at closer distances than in the case of the *WWC* cycling on the footpath. These interactions, where both *NC* and *WWC* cycle on the bicycle path, are particularly critical, especially when bicycle paths are very narrow.

In the survey, 88% of respondents stated that they had already been a *WWC* to save time or distance. Here, 72% of respondents cycle on the bicycle path when there is no *NC* nearby and only 30% stay on the bicycle path when there is an oncoming *NC*. However, it can be assumed that these 30% of respondents may come into conflict with an *NC* on the bicycle path. 75% of respondents stated that they reduce their speed when a *NC* is oncoming. The observation data also showed that *WWC* cycle more slowly than *NC*. It can therefore be assumed that *WWC* are aware of their situation and are therefore slowing down their speed deliberately.

A total of 130 interaction pairs could be annotated and analysed according to helmet use. Among *WWC*, 12% wore helmets, aligning with the findings of other studies (e.g., Alrutz et al. (2009), Große and Böhmer (2021) and Huemer and Vollrath (2014)). The results also reveal that *WWC* often rode on the footpath to avoid conflicts with *NC*. A small proportion of *WWC* used the bicycle path at the same time as *NC* and passed by them very closely and critically. An explanation for this choice 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* who stayed on the bicycle path, it was not entirely clear whether they did not know that it was illegal or did not care about such dangerous situations. Some *NC* swerved onto the footpath to mitigate the situation. This may have been due to a desire to insist on their right-of-way and to stay on the bicycle path, and these scenarios characterised almost 11% of safety-critical interactions.

The results could indicate that if one rule is broken others are added, or that *WWC* are generally more willing to take risks. In support of this, *WWC* seemed less likely to wear a helmet (with only 7% of male and 12% of female *WWC* exhibiting helmet use). *WWC* rode most frequently on the footpath (approximately 80% of interaction cases), which is also prohibited, but they also avoided interaction with *NC* in this way. *WWC* were on average slower in comparison to *NC*; this may have been due to a curve they had to pass before entering the AOI. *WWC* may also go more slowly to ride more safely due to awareness of riding in the wrong direction. Further research is necessary to ascertain whether *WWC*' use of the bicycle path is influenced by gender or helmet use. Helmet use among male *NC* was 28% versus 27% for females (Figure 28), which corresponds to BASt (2021) and a rural observation study from Leschik et al. (2023). According to the survey, 47% of respondents wear helmets. Given that some respondents also acknowledged being *WWC*, this high rate of helmet use can be attributed to the fact that the survey was disseminated primarily among individuals interested in bicycles via cycling-related mailing lists.

Reasons for wrong-way cycling include the desire to save time and lack of knowledge (Große and Böhmer, 2021). Campaigns can help to raise awareness of the rules, but education is not enough to completely prevent wrong-way cycling. In the future, it is important to take measures to prevent *WWC*. As rules and signs only help to a limited extent, infrastructural adjustments should be considered. Given the impossibility of fully preventing *WWC* in the short term, it is important to better understand and model *WWC* to avoid bicycle-bicycle conflicts and to plan safer bicycle paths.

It is not evident that the widening (two-way bicycle path) of the 1.60 m bicycle path described in this study would be a beneficial course of action. Distances of 2.36 m were identified as the minimum required for both cyclists to ride on the bicycle path safely (Table 9, case 2.1). Subtracting 0.35 m for half the handlebars 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 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 Egeskog (2019), which indicate that cyclists perceive the presence of oncoming traffic only when the bicycle path width is less than 2.40 m. There are no statistics on whether wider bicycle paths cause fewer accidents. However, it can be assumed that there is more space for interaction when the bicycle path is wider, and therefore there is more space for lateral movements. There are also no statistics on whether wider bicycle paths lead to more incorrect behaviour (e.g., more *WWC*). However, it can be assumed that wider bicycle paths that are not two-way bicycle path give the feeling that there is enough space and therefore encourage *WWC*. This should be researched in the future, as well as how to mark two-way bicycle path to prevent, rather than encourage, *WWC*. It should further be noted that even a bicycle path 2.40 m in width does not provide sufficient space for cyclists to overtake or navigate oncoming traffic safely when the width of the handlebars 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. 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 or a change of traffic guidance markings or signalling) and thus higher costs. Moreover, Methorst et al. (2017) demonstrated that two-way bicycle paths are not accident-free. Still, two-way bicycle paths 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 to mitigate conflicts with *WWC*.

For *NC* at the Research Intersection, the last intersection is 180 m away, and thus they have the option of riding at a higher speed in the AOI, unless they already see the red traffic light and choose to stop. In contrast, *WWC* either come from one of the fords or have to ride around a curve first. As such, there is a possibility that the *WWC* go more slowly due to the infrastructure and not only because they know they are doing something wrong.

The number of interactions between *NC* and *WWC* are insufficient to identify patterns in 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.

It cannot be excluded that the interactions observed as critical were not experienced as critical by the cyclists. It is possible that the cyclists were consciously adapting to the situation and deliberately interacted at close distances that the observational data identified as potentially dangerous. On the other hand, many distances are so close that the apparent control during the interaction can lead to contact or a fall if there are bumps in the road or if one of the cyclists is not paying attention.

In the 2023 german Fahrrad-Monitor (Bicycle Monitor) survey, around 4,000 people aged between 14 and 69 were asked about their mobility habits. Respondents said they felt safe on more than 90% of routes where cars and pedestrians are separated (including on-road bicycle lanes separated by bollards). Roads where cyclists have to share the road with motor vehicles were rated as the least safe. (BMDV, 2025) 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. Rumble strips, such as those placed on roads, could remind *WWC* that they are travelling in the wrong direction, but this should not be noticeable to cyclists travelling in the right direction. In addition, they need to be placed in key locations and not present a hazard if there is snow or ice. There is also a risk that cyclists will avoid them and use the footpath instead.

LED solutions could also be used to indicate the right direction of travel on the bicycle path. LED solutions could illuminate green for *NC* and red for *WWC* at defined points on the bicycle path to indicate to cyclists that they are cycling in the legal or illegal direction. There are already companies that install lighting technology in the ground to make bicycle paths more visible, or to warn vehicles with red lights not to drive into oncoming traffic (GIFAS, 2025; LaneLight, 2025). Pilot projects could help to test and develop this technology on the bicycle paths.

For rental e-scooters, geofencing automatically limits speed in certain areas. For example, in designated zones in London, United Kingdom, e-scooters can travel at a reduced speed of around 12 km/h (STANDARD, 2024), or riding may be completely disabled. Such a system could at least also reduce the speed of rental e-bikes and make riding in the wrong direction unattractive. This would require detecting both the direction of travel and the position. In addition, the braking should be announced or a warning given so that the speed reduction does not cause an accident. According to DRISI (2020), in addition to e-scooters, some United States cities are already using geofencing to limit the speed of e-bikes. The approach is practical for rental bicycles, but for private bicycles, it can only be implemented with significant effort (due to legal requirements that need to be verified). However, if the trend shifts towards rental bicycles, geofencing could be an effective solution to reduce misbehaviour. If all bicycles were also connected via V2X (Vehicle-to-everything, wireless real-time communication), it would also be possible to warn a cyclist from another cyclist crossing the bicycle path, for example.

4.1.7 Limitations

A globally transferable method to decrease the number and the effects of *WWC* is difficult to implement as the rules and 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.

Moreover, proximity to the intersection is a factor that has the potential to restrict overtaking manoeuvres. It is conceivable that cyclists may be required to halt or turn or that they have just commenced their journey. Further studies should be conducted on an open stretch of bicycle path. However, the addition of an intersection in particular has the capacity to engender more confusing and dangerous interactions.

Further general limitations are presented in Section 6.

4.1.8 Conclusion

For the oncoming scenario, 169 interaction pairs between *NC* and *WWC* were analysed.

The results highlight that interactions between *NC* and *WWC* have different characteristics. In many cases, *NC* and *WWC* were riding 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 awareness of the approaching *NC* and a desire to avoid occupying the same narrow bicycle path. In a few cases, the *WWC* stayed on the bicycle path, accepting that a close encounter between the *NC* and the *WWC* was going to happen. Additionally, some *WWC* switched back to the bicycle path after the interaction. In all these behavioural patterns except the case of the *NC* adopting the footpath and *WWC* remaining on the bicycle path, *WWC*' speeds were considerably lower than those of *NC*. This could be because *WWC* were aware of their wrong behaviour and thus reduced their speed. In the same way, *NC* also seemed to be aware of their wrong behaviour when they adopted the footpath, which led to lower speeds among the *NC* as well. In general, the speeds of *WWC* were similar among all switching patterns. This is consistent with the survey, which found that 75% of respondents stated they reduce their speed when an *NC* is oncoming.

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. Riding behaviour and in particular *WWC-NC* interactions are expected to differ depending on the type and width of the bicycle path as well as on the type of bicycle and the cyclists themselves. Further investigations should be carried out to compare riding behaviour within larger AOI, different transportation infrastructure, and among different bicycles and rider types. In the future, additional data will be collected and analysed via suitable metrics of traffic conflict techniques to determine the behavioural and kinematic patterns of interacting cyclists and develop reliable tactical and operational cycling models for safety simulation purposes. A digital twin can help to not only map current practices more accurately but also to test and optimise new types of infrastructure and bicycle types. Further data must be collected and analysed to better understand these interactions and to check whether clusters have been overlooked. Additionally, it should be checked whether the oncoming distribution remains the same or underrepresented clusters are gaining in importance.

The influence of weather conditions was not analysed. Puddles or snowy paths may lead to changes in the riding behaviour of *NC* and *WWC*. It would also be beneficial to investigate *NC* and *WWC* in the presence of pedestrian traffic given that *WWC* cannot ride onto the footpath.

The transferability of the results to other aspects of this interaction and even other locations is limited and must be verified through further observations. The behaviour of cyclists is expected to be similar, especially on separated bicycle paths and footpaths in Germany. The findings may change if the bicycle infrastructure has other characteristics, such as increased path width. Transferability to other countries will likely lead to different results due to differences in construction of an intersection, traffic rules, and so on.

4.2 Crossing

This section presents the results of the analysis at the Research Intersection and the associated survey, along with the comparative results for the intersection in the 30 km/h zone.

4.2.1 Research Intersection: Interaction

Figure 34A shows the number of cyclists, with *whole_FoKr* representing the total number of cyclists at the intersection and *south_FoKr* indicating the number of cyclists in the AOI. The directions of travel *NE/Efurt* for northeast to the ford in the east (a), *NE/NW* for northeast to northwest (b), and *NW/Efurt* for northwest to the ford in the east (c) are also shown in Figure 34A.

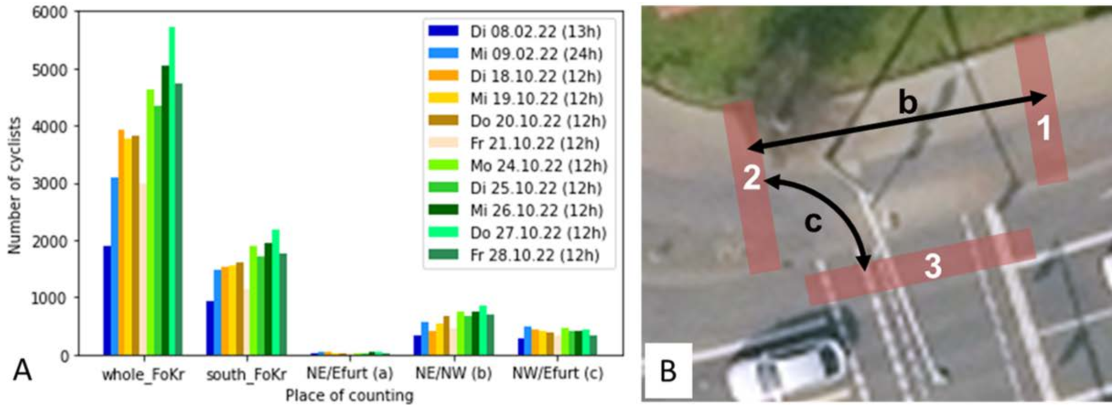


Figure 34: Crossing directions. A: The number of cyclists counted in each direction; B: The primary directions are illustrated by b and c, in conjunction with polygons 1–3, which are employed to enumerate the directions of travel (modified © DLR).

Where a, b, and c describe cycling not only in one direction but also in the opposite and the illegal direction. As there were hardly any cyclists detected on path a, only the crossing behaviour between paths b and c is examined (Figure 34B).

The colours in Figure 34A represent the measurement periods. The blue colours represent the data recorded in February 2022, the yellow to brown colours show the data recorded in October 2022, and the light to dark green colours show the second week of October 2022.

In the analysis, cyclists travelling from the east mainly crossed with those travelling from the south. 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 and potential conflicts. In total, 282 encounters were identified, within a 3 s time interval between the crossing of two trajectory paths.

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

Of the 282 encounters, 93 had a *PET* within 3 s as their trajectories intersect in the AOI. Figure 35A 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 a further 27 pairs, no *PET* could be calculated because the trajectories did not cross directly, but it was determined where they had headed, the distances between them, the $pPET$ and their speeds. Figure 35C shows trajectories that do not intersect, although the cyclist from the south merges onto the bicycle path.

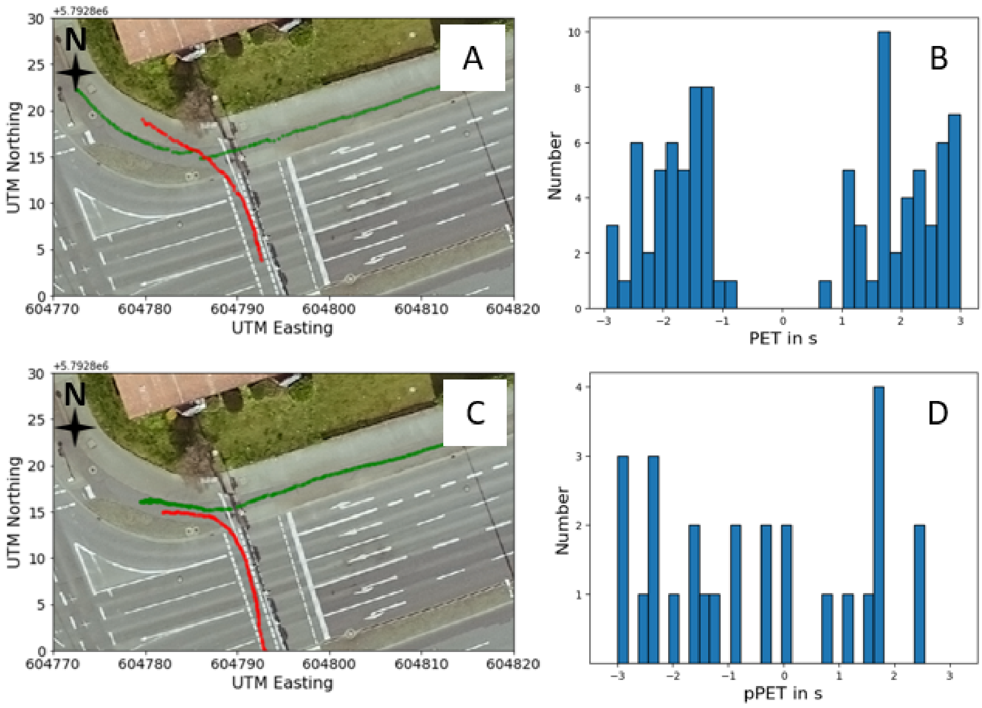


Figure 35: Interaction while crossing between cyclists with (A) and without intersection point (B) and PET with (C) and $pPET$ without (D) crossing point (A and C modified © DLR)

In the following discussion, the 120 cases with a crossing point ($n = 93$) and in which merging was observed ($n = 27$) are examined in greater detail. In 69 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 (Figure 35A). Thus, most of the cyclists from the south cut a corner not following the bicycle path. Of the cyclists coming from the east, eight continued north, four 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 respected in 50% and ignored in 50% of cases. Figure 35B shows the *PET* distribution. The distribution is similar for both sites except for a peak towards higher values in negative *PET*. These interactions happened when cyclists who had the right-of-way went first. It is unclear whether these cyclists were enforcing their right, which is why *PET* is closer to zero.

Figure 36: A: Distribution of the intersection points of two trajectories (positive *PET* in blue A_{pos} and negative *PET* in 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

There are also cases of unexplained clusters of values around 1.8 s. As illustrated in Figure 35D, 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 10. Overall, about 56% of the interactions while cyclists cross each other ($n = 93$) 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%.

Figure 36B shows an example interaction with a negative *PET* of -1.25 s: the cyclist from the east, who has the right-of-way, also rides first. Figure 36C shows a positive *PET* of 1.45 s: 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 36A_{pos} and Figure 36A_{neg}. Here, A_{pos} represents the intersection points with positive (blue dots) values, 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.

4.2.2 Research Intersection: 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 10. Table 10 distinguishes between crossing with the intersection point and calculated PET versus crossing without the intersection point and calculated $pPET$ scenarios. The minimum and mean values for PET and $pPET$ are given in Table 10.

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.

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 strictly 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 overtake a curve unless they continue on the footpath to the north. This is the group with the highest speed, reflecting that they have the opportunity to continue unhindered, even if not legally.

However, it is also the group with the greatest distances between each other, 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.

Table 10: 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
			-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
			-1.25 ($n = 18$)	-1.90 ± 0.54	3.75 ± 1.67	3.17 ± 1.19	2.42 ± 1.03
without crossing	bicycle path	bicycle path	0.00 ($n = 7$)	1.48 ± 0.98	3.54 ± 2.24	2.04 ± 0.52	2.61 ± 0.88
			-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

4.2.3 Survey

Survey 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.

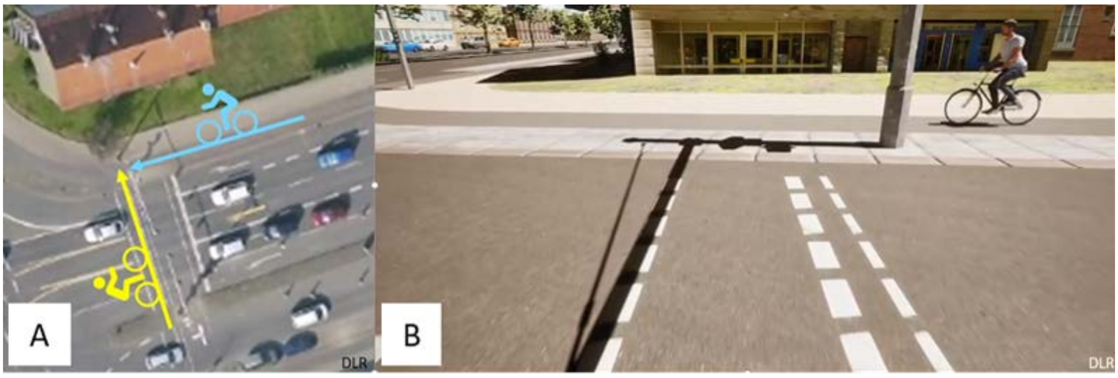


Figure 37: Orthophoto of the Research Intersection in Braunschweig, Germany. A: Crossing scenario between two cyclists (blue and yellow); B: Screenshot of an animation of the crossing scenario (viewed from the perspective of the yellow cyclist in A)

As illustrated in Figure 37A, an aerial view of the intersection is shown. In Figure 37B a screenshot from an animation is shown, showing the scene from the point of view of the yellow cyclist (in Figure 37A).

Respondents were invited to state whether they were aware of which cyclist 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 assume the right-of-way. The remaining respondents expressed a desire to attempt to reach an agreement with the other cyclist (Figure 38).

The question was initially examined during a DLR staff meeting. This non-representative survey of 100 DLR colleagues yielded a comparable outcome: 46% indicated that they would wait as a yellow cyclist (correct behaviour), 42% would ride (illegal behaviour), and 12% did not know (see legal situation for crossing in Section 2.1.3).

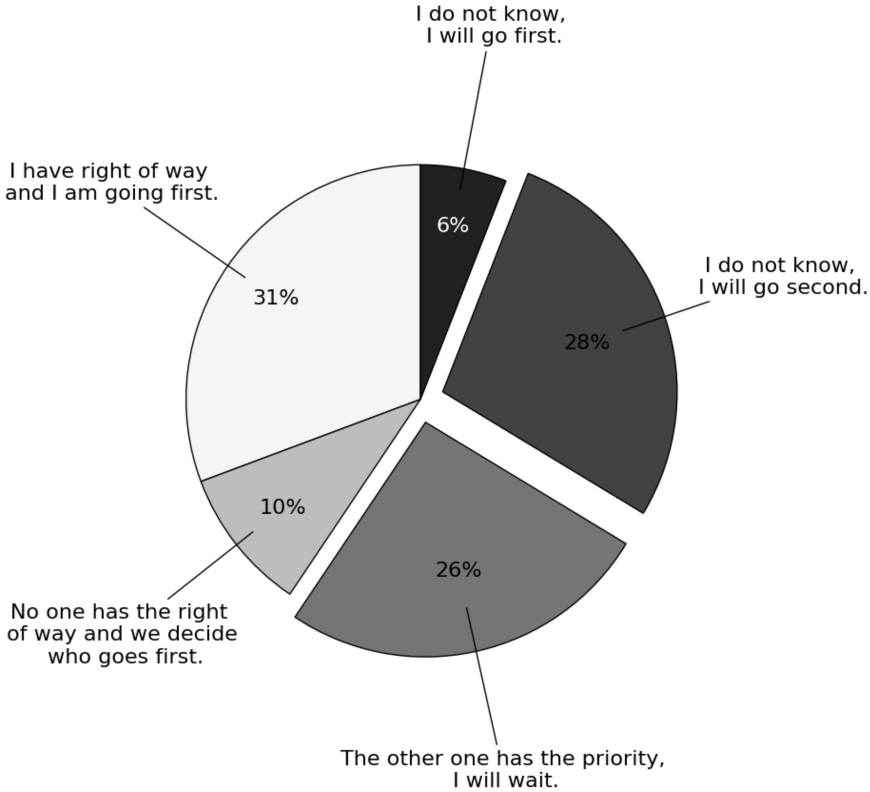


Figure 38: Results for the question of how to act as the yellow cyclist and another cyclist (blue) crosses the path

4.2.4 Intersection in the 30 km/h Zone

It is important to note that not every possible crossing relationship was observed within the designated measurement period (18 to 28 September 2019). Figure 39 presents a visual representation of the detected riding directions, while Table 11 shows the observed combinations of riding interactions.

During the observation period, 57 encounters were detected at the intersection in the 30 km/h zone. Of these, 35 had a *PET* due to the unambiguous crossing situation. Table 11 details 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. The most common case observed was a cyclist travelling from north to south (b_1). This cyclist should have given way to the second cyclist, who was either travelling from west to north or from west to south. In both cases, the priority was not given in 43% and 53% of cases, respectively. The direction of travel of the cyclist who must yield the right-of-way is marked in colour in Table 11.

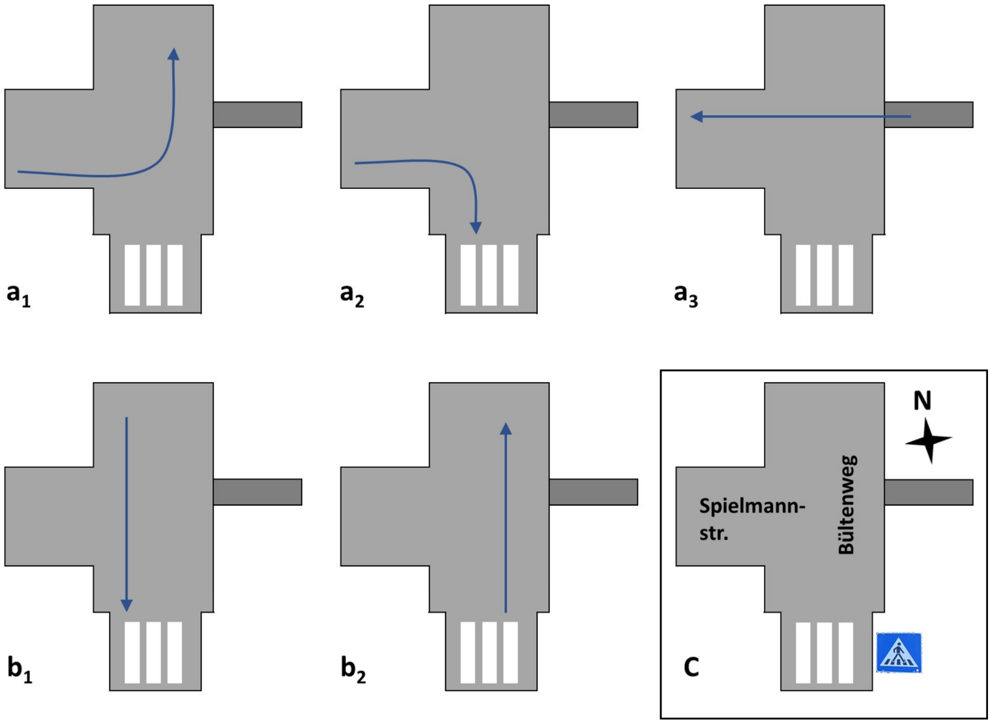


Figure 39: Riding relationships detected during the measurement period (18 to 28 September 2019)

In most cases the PET is around ± 3 s and therefore not in the critical interaction range. Only in the case of a_3/b_1 is the PET below 2 s, although the number of cases observed is not meaningful.

Figure 40: Examples of interactions by cyclists for cases A: a_3/b_1, B: a_1/b_1, and C: a_2/b_1. Arrows indicate the right-of-way. Yellow: Cyclist has right-of-way, Red: Cyclist must give way

Table 11: 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 No. is the number of cases found

Direction a	**Direction** b	**No.**	**Priority taken**	PET_{mean} **in s**	$\|v\|$ **in m/s**	**Priority given**	PET_{mean} **in s**	$\|v\|$ **in m/s**
a_1 (WN)	b_1 (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
	b_2 (SN)	2	0	–	–	2	-2.46 ± 0.26	a: 6.50 ± 0.92 b: 4.00 ± 1.67
a_2 (WS)	b_1 (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
a_3 (OW)	b_1 (NS)	2	1	-1.96	a: 4.38 b: 6.72	1	1.08	a: 4.33 b: 2.62

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 priority has been taken. Only in case a_3/b_1 does this not apply. This case also differs from the others because there is no official road in the east but rather a desire path. Nevertheless, the number of observed cases involving this particular direction of travel is not significant.

Figure 40 shows example situations for different interactions. Figure 40A, the cyclist coming from the east takes the right-of-way illegally (PET = -1.96 s). In Figure 40B, the cyclist coming from the west has the right-of-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 Figure 40C, 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 interactions between cyclists crossing each other (n = 35) had a PET between -2 and 2 s. No events were detected in the area of interest at the intersection in the 30 km/h zone with a PET between -1 and 1 s.

4.2.5 Discussion

This study examines the interaction while crossing between cyclists at a signalised 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 hours of real trajectory data were recorded and analysed with regard to interaction while crossing between bicycles at an urban intersection. During the period of recording, 120 encounters were identified, with 93 having a PET between -3 and 3 s as their trajectories intersect in the AOI; these were used for detailed analysis. At the intersection in the 30 km/h zone, 10 days were analysed, and 35 interactions of 57 encounters were studied. Quante et al. (2023) demonstrated that cyclists at this measuring location more frequently claimed the right-of-way over vehicles than vehicles to each other.

Of the interactions at the Research Intersection, 56% (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 PET 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, 20% (n = 35) of PET were between -2 and 2 s, with no events at -1 and 1 s. PET values were higher in the 30 km/h zone than on the bicycle path at the Research Intersection; this may be because there was more space to swerve on the road. However, speeds were also higher here. Cyclists at the Research Intersection coming from the south must make a turn unless they continue north on the footpath. This group had the highest speed, reflecting that they could 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 were higher, probably due to the design of the intersection, which has 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 could be seen early on. At the Research Intersection, however, there is also the added pressure of the traffic 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. According to the survey results, 31% ($n = 104$) incorrectly thought they had the right-of-way and would go first, while 26% knew the other cyclist had the right-of-way and would wait. Thus, the data indicates that almost 60% of respondents ($n = 59$) who believed themselves to be familiar with the rule erroneously assumed that they would have the right-of-way. Among the remaining respondents who were not acquainted with the rule, 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 results indicated a degree of inattention while cycling, which can also contribute to conflicts.

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 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 especially 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 this introduces potential bias, but the results nevertheless 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.

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 to avoid conflict. First, children need to be taught the rules of the road from an early age. Additionally, local campaigns can create more clarity for commuters. However, neither will be able to prevent the rules from continuing to be ignored. Signs could inform cyclists that they are crossing, but signs are only educational and are often ignored. It would therefore be more effective to adapt the infrastructure. Cyclists crossing the intersection during green traffic lights could be given their own merging lane, similar to that on the motorway for motorized vehicles (see Figure 41B for an example of such a lane in the Research Intersection). However, this would require space, which is often not available, or the infrastructure would have to be rebuilt at great expense.

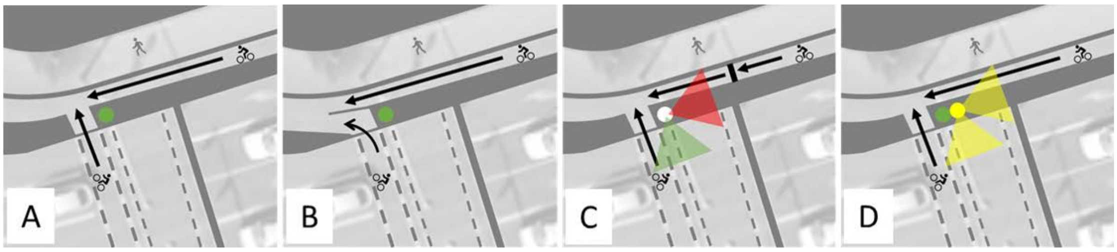


Figure 41: Research Intersection. A: Initial situation; B: Merging lane; C: Additional cycle traffic light and stop line on bicycle path; D: Flashing light

Another option would be to install a traffic light for cyclists on the bicycle path. The cycle traffic light could be installed at the same traffic light post as the crossing light. When the crossing cyclist has a green light, the cyclist on the bicycle path would have a red light and a stop line (Figure 41C). 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. If no cyclist is crossing and the cycle traffic light is still red, the traffic light is likely to be disregarded more often.

A yellow flashing light may be all that is needed to signal to cyclists on the bicycle path that another cyclist is crossing (Figure 41D). The flashing light can be linked to sensors so that it only flashes when a cyclist is actually crossing the road. However, the cyclist on the bicycle path would need to pay attention and not insist on the priority-to-the-right rule. Acceptance would be higher if there were a way of warning cyclists about crossing the road on the ford and not the cyclists on the bicycle path.

Illuminations, such as Light Emitting Diode (LED) solutions could also be used to indicate on the bicycle path that another cyclist may be crossing. One way to achieve this could be to link the LED in the bicycle lane to the bicycle traffic lights of the crossing cyclists. In this way, the LED would light up green when the crossing cyclist has a red light. And the LED in the ground of the bicycle path could flash yellow when the crossing cyclist has a green light and there is a possibility that the crossing cyclist will interact with the cyclist on the bicycle path. It will probably be even more effective if the LED only flashes when a cyclist is actually approaching the crossing. A very high detection precision is required to make the system reliable.

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 speeds for cyclists at intersections. Again, cyclists must obey the rules for a positive effect.

4.2.6 Limitations

To proceed with the analysis, it is first necessary to verify the transferability of the observed crossing behaviour. Depending on the intersection design, and in accordance with the priority-to-the-right rule, the behaviour at other intersections may or may not differ. However, the analysis is currently limited to an intersection with a priority-to-the-right rule in Germany, and further investigation is required.

Further general limitations are presented in Section 6.

4.2.7 Conclusion

Two camera-based traffic observations were used to study 120 intersection behaviours at the Research Intersection with a bicycle path, and 35 interactions were studied at an intersection in the 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 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 in cyclists' behaviours. 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% of cases. At the Intersection in the 30 km/h zone, no PET were recorded in this range. Annotation of the data revealed that cyclists stopped pedalling or swerved to defuse the situation and lead to a higher PET. While the possibility of further cooperative behaviour through eye contact cannot be discounted, this was not 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 PET 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 for another research project 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. In addition, cyclists will be interviewed on site to elucidate the results. Furthermore, additional studies should examine the impact of traffic lights on determining the priority-to-the-right rule. Depending on the traffic light phase, the rule may be disregarded. Improved education and visibility of the crossing area could help alleviate crossing conflicts.

These findings can aid in improving infrastructure and enhancing the realism of simulations. 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.

4.3 Other Scenarios

As overtaking plays an important role in accidents between cyclists, in addition to crossing and oncoming accidents, the overtaking scenario was also considered. The AOI at the Research Intersection is very close to the intersection, which means that there is an influence from the traffic lights, as well as the bend itself, which has to be taken to go north or illegally south, but also a small bend to continue west. As a result, it is not possible to enter the bend at high speed, as the intersection can cause unclear and complex situations. The following section discusses in more detail the interactions observed between cyclists travelling in the same direction.

4.3.1 Same direction of travel

In the context of the overtaking scenario, the initial analysis encompassed a period of 256 hours.

Within this data set, 12 overtaking manoeuvres were identified. To provide a point of reference, over 300 convoy (cycling in a row) trips were identified during the same period. In the context of riding in a convoy, a single case with a distance of 3 m was detected. The average distance observed was 8 m. It is noteworthy that only unaffected encounters were recorded in this setting. Unaffected encounter means that no reaction to the other cyclist was observed. Interaction means that the cyclists approach each other or adjust their behaviour because they influence each other. This behaviour was not observed during cycling in convoy.

Figure 42: Interactions in the same direction of travel at the Research Intersection. Overtaking from the left (A) or right (B), riding side-by-side (C), or riding in a convoy (D)

The analysis identified three distinct categories at the Research Intersection. The first category (Figure 42A and 42B) involved overtaking from the left or right. The second category (Figure 42C) involved riding side-by-side without overtaking. The third category (Figure 42D) involved riding one behind the other.

Research Intersection

The examination of overtaking behaviour in the area of the Research Intersection was not possible. 12 interactions is insufficient to identify clusters or patterns. The reason for the low number of interactions may be the proximity of the intersection, which could result in cyclists slowing down or stopping at red lights, thereby hindering overtaking behaviour.

For the 12 cases, an average lateral distance of $d_{mean} = 1.7 \pm 0.3$ m was calculated. The average minimum lateral distance is $d_{mean,min} = 1.4$ m. In 75% of cases, cyclists overtake legally from the left, with the cyclist being overtaken usually moving into the footpath.

Street without Bicycle Path

Piep (2023) examined the overtaking behaviour of cyclists in detail utilising a mobile measuring system from the DLR. This study was conducted in Berlin in 2021 as part of the MMoNK project, which examined the similarities and differences between e-scooters and bicycles (MMoNK, 2023). The initial measurement location, Adalbertstraße in 10999 Berlin-Kreuzberg, Germany, was selected due to the high volume of bicycle traffic on a road without a bicycle path. Piep (2023) employed the DLR software TASI (Klitzke and Schicktanz, 2024) to analyse overtaking manoeuvres and annotate video material. During the observation period (8 hours), 104 overtaking manoeuvres between cyclists and other cyclists, e-scooters, or skateboarders were analysed, of which 30 were found to occur at a lateral distance of less than 1.25 m. In 11 cases, high potential criticality was identified. The video annotation revealed an unsafe riding style on the part of the cyclists being overtaken, as evidenced by weaving or swaying during the overtaking manoeuvre. The overtaking manoeuvre was deemed critical in 11 cases due to the presence of a stationary vehicle in the cyclist's path.

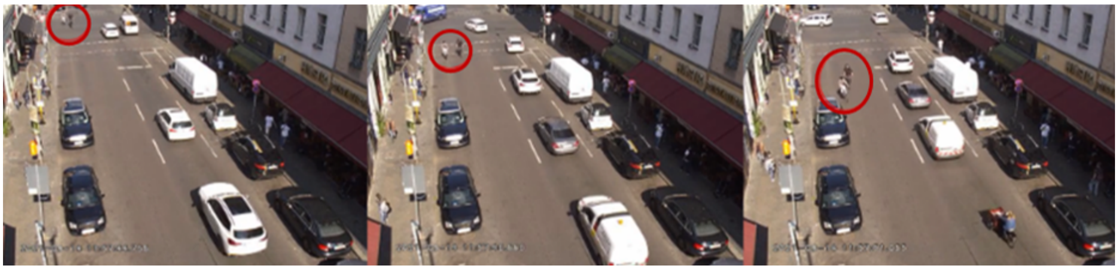


Figure 43: Overtaking manoeuvre between two cyclists with obstacle (parking car) (modified Piep, 2023)

4.3.2 Discussion

There are clear rules on overtaking in the StVO (Section 2.1.2). Riders can only overtake on the left, and it is forbidden to overtake from the right or on the footpath. If the bicycle path is too narrow, riders are not allowed to overtake. Wider bicycle paths are needed to make overtaking safer. For example, a standard cycle handlebar is 70 cm wide, and the recommended minimum width for bicycle paths in Germany is 1.60 m; this means there is an overtaking distance of 20 cm. As cyclists sway a little and inexperienced cyclists sway more, this width is not sufficient to overtake safely. The bicycle path should be at least 2 m wide so that there is more than half a metre of safety clearance.

It was not possible to examine overtaking behaviour between cyclists at the Research Intersection, and thus the sample size was insufficient for further analysis. The proximity to the intersection could be the reason for this as cyclists travelling north or illegally travelling south encounter a curve. Furthermore, cyclists can see the traffic lights and decide whether overtaking is worthwhile. It is possible that cyclists prefer to overtake on a straight, clear stretch of path. Piep (2023) also examined overtaking behaviour but in an area without a bicycle path. Over a shorter period (8 hours), more interactions between cyclists were found than on the bicycle path at the Research Intersection. This could be due to the straight and visible street as well as the wider path for overtaking. At the Research Intersection, cyclists were observed to be constrained to riding next to each other with a lateral distance of approximately 20 cm or to swerve onto the footpath, which is a limitation of the path design. The lane on the road is very wide, although it is not clear whether the overtaking cyclists were aware that a car could have overtaken them from behind. Additionally, there is the problem of obstacles that both cyclists have to pass, which could also lead to dangerous situations.

It is conceivable that additional overtaking manoeuvres occurred during this period given the inherent limitations of the Research Intersection's detection system in discerning objects in close proximity. This potential for undetected interactions could have led to deficiencies in automated detection of the scenario. The quality of the data during overtaking further complicates analysis of the 12 interactions as the gaps in the trajectories resulting from directional changes during overtaking cannot be interpolated. To analyse the overtaking scenario in greater detail, attention must be paid to the alignment of the cameras. These problems also occurred in the study by Piep (2023), where trajectories that are close together merge and can no longer be separated. One potential solution to this issue could be retraining the data and reclassifying and tracking the trajectories.

There is no way to prevent illegal and dangerous overtaking. It is possible to install a high kerb between the footpath and bicycle path, but an inattentive cyclist could fall, a pedestrian could trip, and a potential crossing would no longer be barrier-free; this therefore poses a risk to both cyclists and pedestrians. Early childhood education can help to raise awareness among cyclists. In the Netherlands, double lane bicycle paths are often used, which also allow space for oncoming cyclists and therefore more room for overtaking. Still, there is a risk of conflict with oncoming traffic. In addition, a two-lane bicycle path requires substantial space, which is often not available.

4.3.3 Conclusion

Overtaking at intersections was detected over a period of 256 hours. In the process, 12 overtaking manoeuvres were identified.

Due to the small number of interactions, the study of Piep (2023) of overtaking behaviour without a bicycle path was also examined. The results from Piep (2023) showed that, within a mere eight hours, a total of 104 overtaking manoeuvres were executed, with some exhibiting a notably close proximity in terms of overtaking distance. However, the 12 overtaking manoeuvres observed at the Research Intersection were inadequate for deriving definitive conclusions.

4.4 Survey

A survey was conducted to support and explain the interaction behaviour observed in the real data. On the one hand, this was to clarify whether the rules were known for the crossing scenario and whether the *WWC* acted consciously or unconsciously. 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 analysis.

4.4.1 General

The majority of respondents (87%) were between the ages of 30 and 59. Furthermore, over 80% of respondents were male. As illustrated in Figure 44, the distribution varies across age groups, with distinct differences observed according to gender.

4.4.2 Distraction and Helmet Use

In addition to the specific questions about the observed scenarios, the questionnaire asked how distracted they were while cycling.

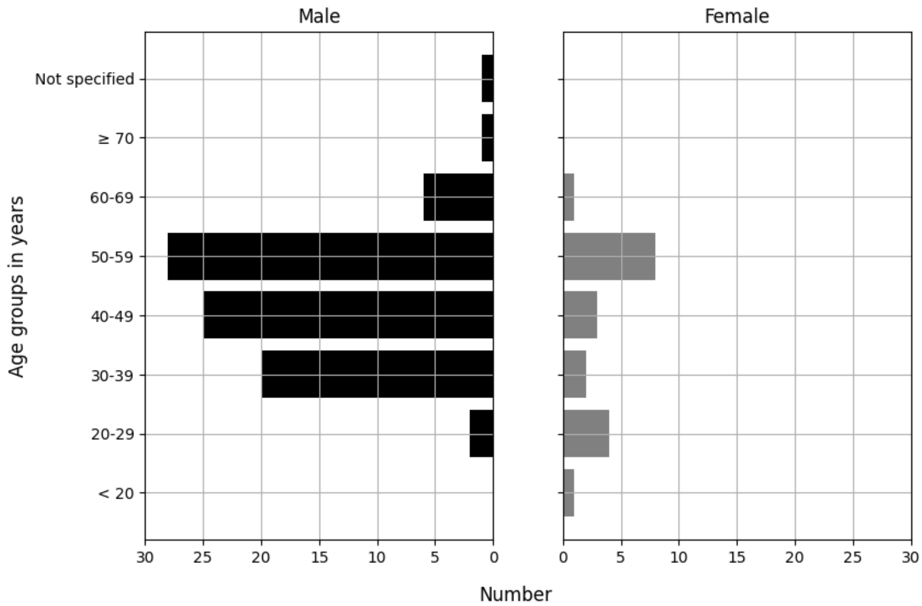


Figure 44: Age distribution in groups by gender of respondents. Two responses are not displayed as no gender was indicated (one response was for a person aged 40–49, while the other was for an unidentified age)

Rules may have been consciously disregarded, or not known, but may simply have been overlooked due to distraction. In addition to conscious misconduct, distraction can also lead to misconduct or conflicts. The statement 'I don't think about anything' shows that no one chose 'always', and only 11% chose 'often'. Respondents indicated that they think about something else 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 stated that they also think about 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 statement is illustrated in Figure 45.

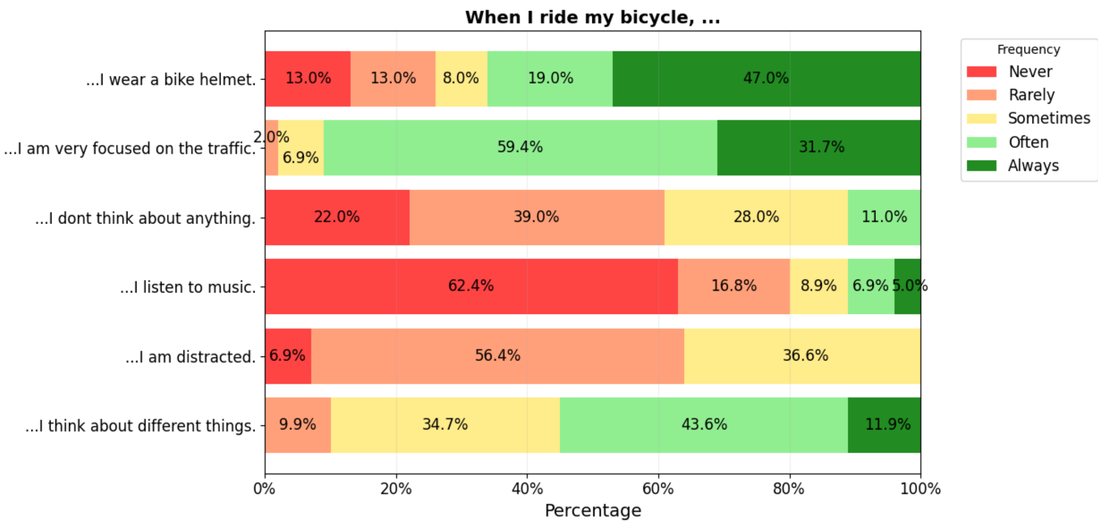


Figure 45: Survey results on attention and using a helmet when cycling

4.4.3 Discussion and Limitations

The survey was conducted between 23 October and 31 December 2024 and distributed via various mailing lists but primarily to individuals with a keen interest in bicycles. This could be a contributing factor to the significantly higher helmet usage observed, which was recorded at 47% compared to the observed rate at the Research Intersection of 23%.

The survey results also indicate that cyclists tend to be focused on traffic, but they also engage in other activities and are occasionally distracted. This tendency can potentially result in inattention and errors, both on well-known bicycle routes and particularly at new intersections, which may lead to conflicts.

The survey was meticulously designed to address oncoming traffic, with a single question on crossing. It should be pointed out, that crossing was not the study's focus. Further surveys are required to elucidate additional queries concerning bicycle-bicycle interactions. The survey's scope could be expanded to address crucial questions regarding cyclists' overtaking behaviours, such as whether they consciously choose to overtake on the footpath when the bicycle path is too narrow or whether they deliberately cross onto the footpath to avoid swerving on the bicycle path. To obtain a sufficiently large sample, future surveys should be administered more widely across Germany. The survey in this study served as a preliminary explanation of the observed cycling behaviour in real data.

Further general limitations are presented in Section 6.

4.4.4 Conclusion

The survey yielded a total of 104 usable questionnaires and was primarily designed to provide an overview of whether cyclists are aware of their actions when oncoming traffic is present or they act without thinking, as well as what they think they are doing.

When oncoming traffic is present, only 30% of cyclists stay on the bicycle path, and 59% use the footpath. This finding aligns closely with observations from actual traffic conditions, where approximately 65% of *WWC* also tend to use the footpath. Furthermore, the survey revealed that 75% of *WWC* acknowledged the importance of reducing their speed in the presence of oncoming cyclists, while an overwhelming 84% indicated a willingness to increase their distance. Additionally, 54% of survey respondents reported being aware of the necessity of waiting when crossing. This finding is consistent with the observation that right-of-way was observed in 50% of cases.

5 Modelling

In the field of modelling, the utilisation of diverse parameter distributions is contingent upon the specific scenario under consideration. This approach has been demonstrated to enhance the realism of simulations. The parameters deemed to be of fundamental significance within the context of this dissertation are delineated in Table 9 for the oncoming scenario and Table 10 for the scenario with crossing cyclists.

5.1 Modelling for Example Scenario Crossing

A simulation in SUMO was adapted for the crossing scenario. A simple crossing scenario was constructed, as described in Section 3.3.2 with the parameter from Section 4.2.2. The simulation was executed 10 times, with each iteration involving 10 runs. The resulting data set documents which road user was riding first and which $pPET$ result was achieved. The following parameters were utilised:

- $step - length = 0.1$ s
- $begin = 0.00$ and $departSpeed = max$
- $minGap = 0.20$ m
- $decel = 3$ m/s^2 and $emergencyDecel = 7$ m/s^2
- $tau = 0.6$ s
- ego: $maxSpeed = 5.54$ m/s and $speedFactor = normc(0.43, 0.22, 0.16, 1.00)$
- foe: $maxSpeed = 4.40$ m/s and $speedFactor = normc(0.41, 0.16, 0.11, 0.76)$
- foe: $jmIgnoreJunctionFoeProb = 0.5$
- foe: $jmIgnoreFoeSpeed = 10$ m/s
- random seed values: 27, 103, 221, 399, 469, 501, 656, 800, 1111, 1523

The speed is specified in x and y components in SUMO and was used as the average total speed if necessary. Notwithstanding the time step of 0.1, the $pPET$ jumps per time step were sometimes substantial, thus precluding calculation of a mean value. The selection of an interaction time point was made on the basis of the SUMO GUI display.

A total of 10 runs were initiated, with 10 seeds selected at random for retrospective evaluation. Of the 100 interactions, only 38 exhibited a $pPET$ within the range of -3 to 3 s, while eight interactions fell outside this range. In 11 instances, negative results were obtained, indicating the occurrence of accidents. For the remaining interactions, no $pPET$ could be calculated, primarily due to participants' insufficient distance from one another. In the context of SUMO, it is not feasible to ascertain who was riding first from the mathematical sign. The sign was determined using simulation and the parameter SGAPSpan. This parameter was only determined for the ego or foe vehicle at the moment of the interaction. Right-of-way could be confirmed in the SUMO GUI. To ensure comparability, negative values are displayed in Figure 46 where the cyclist from the east was designated as the primary rider. This approach enables the figure to be compared with Figure 35D of the measurement data.

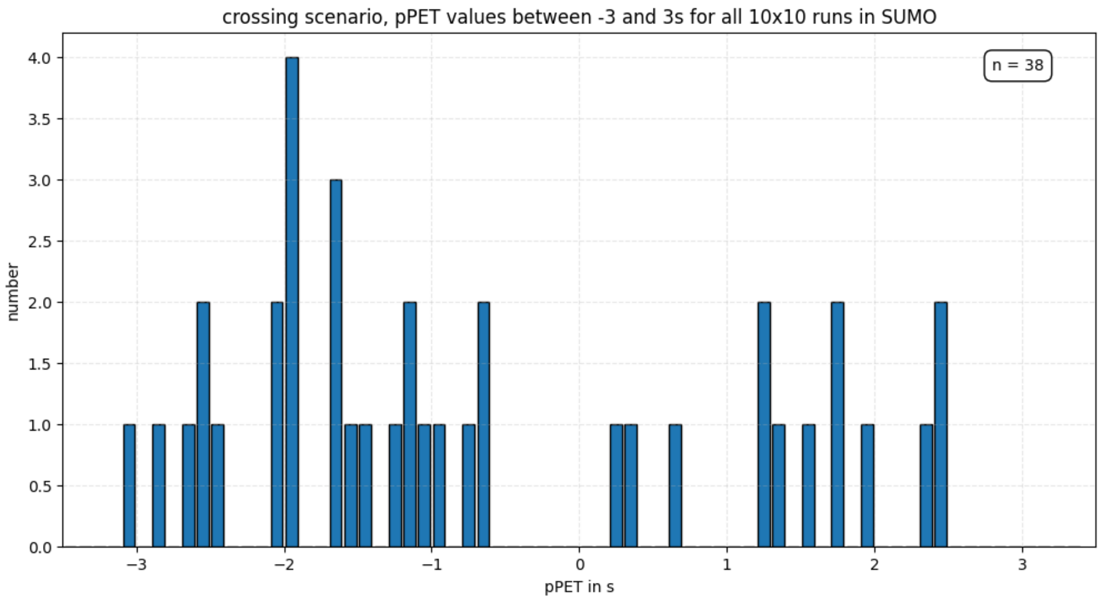


Figure 46: $pPET$ values from the SUMO simulation. Values in which the cyclist from the east is first are shown as negative, whereas values in which the cyclist from the south is first are shown as positive.

All available data from the runs were utilised with the exception of run 6, which did not contain any valid interactions for the present analysis.

In 59% of the cases, the cyclist travelling from the east was the first to arrive, and for valid $pPET$ between -3 and 3 s, this figure was 66%. A comparison of Figure 46 with Figure 35D reveals that there were fewer instances of the cyclist from the south being the first to arrive, with a closer $pPET$ to zero and a lower frequency. In all but one instance, the cyclist from the south was found to be the faster of the two.

5.1.1 Discussion

The current options in SUMO enable the modelling of intersection behaviour between cyclists if they are coming from different directions and continue on the same path. By adjusting the parameters, cyclists can ignore priority-to-the-right rules and perform risky manoeuvres, which may result in emergency braking – an occurrence that is less likely in real life. The distribution of speeds, as observed, offers a favourable opportunity for chance encounters; however, the number of those disregarding the right-of-way was observed to be higher in reality than in the simulation. Further runs would be required to achieve closer to 50% in this regard. In the simulation, behaviour when cyclists from the south go first appears to be riskier, as evidenced by a greater proportion of $pPET$ close to 0 than was observed in the real data. This discrepancy could be attributed to the assignment of aggressive riding behaviour to the cyclist from the south to ensure the right-of-way.

5.1.2 Conclusion

The simulation parameters can be readily adapted to align with the observed values in SUMO. Furthermore, there is an option to map illegal driving behaviour. However, it is important to note that emergency braking constitutes a relatively minor proportion of real-life situations and, as such, may require adjustment or even be disregarded in the context of the simulation.

The adaptation of the simulation to real data facilitates the identification of conflict points at intersections during the planning phase, thereby enabling their prevention at an early stage. It is important to note, however, that existing intersections could also be analysed and adapted in a similar manner.

6 General Limitations

This study is subject to certain limitations that may affect the ability to make comparisons regarding cycling behaviour at other measurement locations. Previous studies in this field have also been limited in that behaviours were only observed for a few days and therefore only few cases of interactions between cyclists could be detected; thus, precise description or modelling is not possible.

In addition, studies took place in good weather conditions and did not reflect the entire course of the day or week.

The bicycle path situated at the Research Intersection was in a satisfactory state of repair. There were no potholes, roots, or weeds that could interfere with cyclists. However, this may need to be considered when transferring the findings to other bicycle paths. Obstacles can influence riding behaviour and thus cause different behaviour. Figure 47 shows the various infrastructure deficiencies in other locations (Berlin and Oldenburg, Germany). As these influences have no bearing on the Research Intersection, it would not be feasible to apply them directly to a bicycle path in Berlin.

Figure 47: Roots (A), snow (B), puddles (C) on the bicycle path and a two-way bicycle path suddenly narrows (D)

The general limitations listed below may occur alone or in combination.

6.1 Location

The proximity of the intersections (Research Intersection and intersection in the 30 km/h zone) to university facilities may result in the presence of commuter traffic, particularly from students, who tend to be younger compared to the average age in the wider population. It is possible that the age of cyclists affects their cycling behaviour. However, by using different data from different time periods, this effect can be considered weaker.

The observed and analysed behavioural patterns were not tested on identical infrastructure. It is necessary in the future to ascertain whether the observed patterns can be applied to other intersections of the same design. Analyses of intersections with differing infrastructure revealed similarities, suggesting that the observed patterns may be applicable to other intersections within Germany with comparable traffic volumes. However, it is not yet possible to make any statements regarding the transferability of the results to other countries. Given the differences in infrastructure, traffic volume, and riding behaviour between countries, it can be assumed that the patterns observed in this dissertation may not be representative of those found in other countries.

6.2 Intersection Design

The Research Intersection is monitored by permanently installed cameras, which have a fixed field of view. Some cyclists can discern traffic lights with greater ease than others. This may be due to prior experience of commuter traffic, which prompts an early adaptation of behaviour and an adjustment of speed as needed. It is possible that cyclists already completed overtaking manoeuvres prior to reaching the AOI. When crossing, the route is clearly visible at an early stage, allowing sufficient time for consideration and enabling an early reaction to the interaction. However, when approaching from the opposite direction, there is a small bend before reaching the crossing area. Consequently, *WWC* only become aware of oncoming cyclists at a later stage, potentially leading to more critical situations where agile reactions are required.

6.3 Condition of Infrastructure

The condition of the infrastructure is also a significant factor in determining observed behaviour patterns. At the Research Intersection, the cycling infrastructure was deemed to be satisfactory. The potential impact of holes and the resulting formation of puddles when it rains, as well as the presence of grass or bushes that narrow the bicycle path, can be discounted. Furthermore, the infrastructure was not affected by roots. As with other cycling infrastructures, leaves and snow clearance were not carried out on a regular basis; the measurement days in this dissertation were not affected by these influences. Nevertheless, it can be assumed that both static (e.g., holes) and temporary (e.g., dirt) obstacles will have an influence on cycling patterns. Cyclists attempt to avoid obstacles and do not solely concentrate on other road users.

6.4 Weather

The measurement days in this dissertation were in both the cold and warm seasons. However, it is to be expected that cyclists behave differently in heavy rain, snow, frost or prolonged heat than under sunny and dry weather conditions. This study is unable to consider all weather conditions. However, past studies suggest stronger aggressive behaviour in warm weather, whereas in persistently cold weather the number of cyclists decreases, resulting in fewer interactions. In conditions of strong winds or gusts, there is evidence to suggest that behaviour may change. The question of whether interactions decrease because there are also fewer cyclists on the road, or whether they become more critical because cyclists react more easily to gusts and may move more to the side, remains unresolved.

Figure 48: Snow at the Research Intersection on 26 January 2019. A: Cyclist is crossing from south to north using the snowy footpath; B: Cyclist is using the snowy covered bicycle path from east to west.

Figure 48 shows the Research Intersection under snow-covered conditions. The tracks in the snow show that both the footpath and the bicycle path are used (Figure 48A). Figure 48B shows a cyclist riding very centrally on foot- and bicycle path, possibly because the bicycle path is not visible. Possible interactions on snow-covered bicycle paths should be investigated in future research.

Kenrick and MacFarlane (1986) studied the reactions of drivers in Arizona, United States of America, on Saturdays between April and August. They placed a car in front of a traffic light that was on green. Hidden observers recorded whether honking occurred and, if so, the duration and the latency until the first honk. Kenrick and MacFarlane (1986) found a linear relationship between temperature and honking. This was particularly strong for drivers with their windows open, who presumably did not have air conditioning. Another study from Wu et al. (2018) in America showed an increase in fatal accidents during heat waves. Further data collected over several years should clarify whether there is also a link between critical behaviour (riding close together, breaking the rules) and temperatures in cycling traffic. This could result in more shade from new trees or similar.

6.5 Time of Day

The data set employed in this dissertation encompasses a temporal span from the morning commute to the evening. Data analyses conducted at night were performed on a random basis, but the limited number of road users resulted in a lack of encounters. The influence of time of day should be analysed in more detail. In larger urban centres or at intersections in close proximity to events, it is possible that interactions may still be anticipated at night. It is also plausible that the patterns may deviate from those presented here due to an increased number of road users under the influence of alcohol.

In a study by Yastremska-Kravchenko et al. (2024), a distinction was made between daylight and electric light at night. The results showed that in daylight, 90% of cyclists maintained a safe lateral distance of 1.50 m already 20 m before the point of interaction. With electric light, only 75% maintained a safe lateral distance of 1.50 m before the point of interaction. However, the lateral interaction distance in daylight and electric light differed by a maximum of 20 cm, which the authors consider negligible, as a minimum distance of 1.43 m was maintained. In general a lateral distance of 1.50 m was maintained in 95% of all cases. (Yastremska-Kravchenko et al., 2024) The influence on behaviour in daylight and electric light at night should also be investigated for narrower bicycle paths.

6.6 Traffic Lights

The traffic light circuit exerts an influence on riding behaviour. The speed at which a cyclist travels may vary depending on whether the cyclist stops at traffic lights or not. Furthermore, a red traffic light at the intersection can result in less pedalling, which may facilitate overtaking manoeuvres if a cyclist has to stop immediately at a red light and the overtaking cyclist continues on the bicycle path without traffic light.

6.7 Video Data

At the Research Intersection, the video cameras at the AOI are designed with pedestrians and cyclists in mind; however, vehicles are detected and tracked more reliably in the inner area, where several video images overlap. The TraffiTower 2.0, which incorporates two overlapping video perspectives, is a superior system to individual cameras at the crossings, but lateral information is often missing. If interactions between cyclists are to be investigated, it is imperative to ensure that the camera perspective is selected appropriately for the respective desired scenario. However, it is possible that not all road users, and therefore not all interactions, are captured by the system, and therefore the data set is not complete. With a sufficiently large sample of interactions, it can be assumed that all patterns of cycling behaviour can be mapped. The Research Intersection has been in operation since 2014, and there are inconspicuously signs indicating that the intersection uses video to record traffic. The video equipment is very high up. From personal experience, the TraffiTower 2.0 is often misunderstood as a speed camera, due to its resemblance to one. It can be assumed that cyclists will behave naturally, as there is no evidence that their cycling behaviour is influenced by the cameras.

6.8 Cycle and Cyclist Type

It is important to note that not all cyclists or bicycles are identical. Electric bicycles (e-bikes) have the capacity to accelerate more rapidly, while cargo bikes are wider than standard bicycles without electric assistance. This study does not differentiate between bicycle type or rider characteristics. However, it can be hypothesised that commuters who travel the route frequently and racing cyclists utilise the route differently than people unfamiliar with the area, children, or older people. Further analyses should be conducted to ascertain how the population uses routes and how these groups differ.

Observations at the Research Intersection also showed traffic from e-scooters and cargo bikes (Figure 49). These were not included in the analysis and should be given more attention in future studies as e-scooters are very narrow and manoeuvrable and cargo bikes are significantly wider than normal bicycles and have a larger turning radius. The interaction behaviour on the bicycle path may therefore be different from that between bicycle-bicycle.

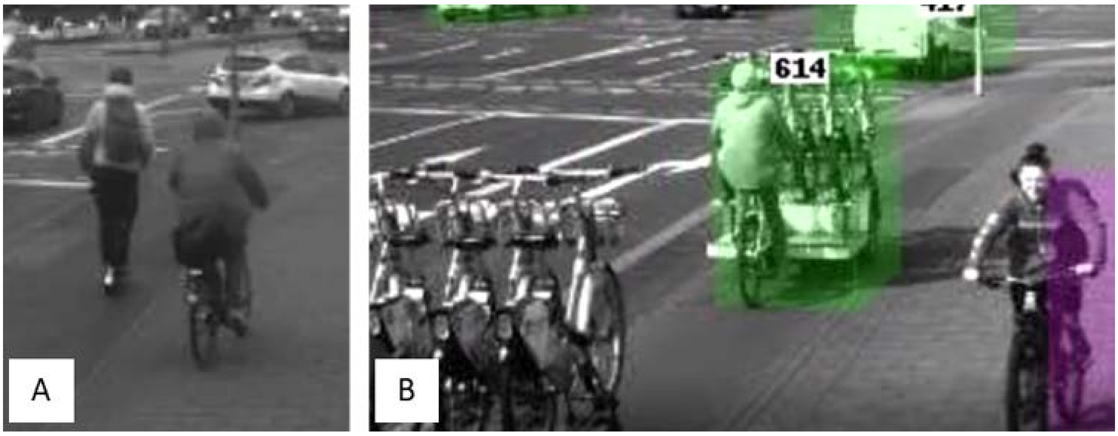


Figure 49: Other types of road users using the bicycle path observed outside of the observation period used in this study. A: E-scooter and B: Cargo bike

6.9 Other Limitations

The list of limitations is not exhaustive, but should highlight many important aspects of cycling. Another factor that can affect interactions is deer crossing. Sudden movements can cause unplanned and unpredictable evasive manoeuvres by cyclists. The same applies to dogs, cats or small children approaching or crossing the bicycle path. Litter, stones or branches lying around are also avoided to prevent damage to the bicycle and can lead to other interactions.

7 Discussion and Conclusion

This study focuses on the interaction behaviour of cyclists at and in intersections. Video data were recorded and analysed over a period of 256 hours in February 2022, October 2022 and May 2023 for oncoming and overtaking scenarios at the Research Intersection, 171 hours for the crossing scenario, and 240 hours for crossing scenario at an intersection in the 30 km/h zone in September 2019. (see Section 4)

The objective of this study was to ascertain how cyclists interact with one another while travelling in the same or different directions at an intersection.

The following scenarios were observed among cyclists cycling in the same direction: cyclists riding one behind the other, next to each other, or overtaking each other. During the observation period, over 300 cases of uncritical convoy encounters were detected, as well as 12 cases in which cyclists overtook each other. Due to the limited amount of interactions, further analysis was not possible. Furthermore, a bachelor thesis was supervised which involved the examination of a road devoid of a bicycle path for overtaking manoeuvres. Within a recorded span of eight hours, 104 overtaking manoeuvres were identified. However, due to limitations in the quality of the data (e.g, detection of all trajectories in full length), further examination for different phases (e.g., when and at what lateral distance was overtaken) and patterns was not possible. Video annotation revealed indications of critical manoeuvres, such as overtaking obstacles in close proximity or sideways wobbling.

Furthermore, this study examined the behaviour of cyclists when riding in the opposite direction, referred to as 'oncoming'. It should be noted that there is a shared bicycle- and footpath at the Research Intersection, and riding on the bicycle path in the opposite direction is prohibited. A total of 169 interactions were identified on the bicycle path, which differed depending on whether the bicycle- or footpath was used. Cycling on the footpath is critical when pedestrians are present. At the same time, the use of the bicycle path is also critical because, at a bicycle path width of 1.60 m, there is only 20 cm of space between cyclists' handlebars during oncoming scenario. In the majority of cases, the *WWC* was observed riding on the footpath, while the *NC* was riding on the bicycle path. The most critical scenario, in which both cyclists were on the bicycle path, was recorded in 20 cases. Additionally, 65% of *WWC* used the footpath. In the survey, 59% of the respondents stated that they use the footpath as a *WWC*. As outlined in Section 4, the parameters presented can be utilised to adapt a simulation for the oncoming scenario. The efficacy of this implementation, as well as its correspondence to reality, remains to be ascertained. Furthermore, the transferability of observation data to other intersections is yet to be determined.

In the context of further interactions on the bicycle path at an intersection, the act of crossing was examined using 120 interactions during the observation period at the Research Intersection. For comparison, crossing behaviour was also examined at an intersection in the 30 km/h zone without a bicycle path (35 interactions). At both intersections, the right-of-way was taken or given in 50% of cases. The *PET* was lower at the Research Intersection, possibly due to the smaller space. A survey revealed that only 54% percentage of cyclists were aware of the priority-to-the-right rule on the bicycle path, suggesting that some may not be aware of the regulations or may not adhere to them out of ignorance. Further research with a larger sample size would be necessary to ascertain the reasons for cyclists' behaviour. Given that the rule was observed in only 50% of cases in the 30 km/h zone, despite the increased clarity of its definition in comparison to that observed on the bicycle path in Germany, it can be hypothesised that cyclists are aware of their obligation to yield the right-of-way.

A SUMO simulation was conducted utilising the parameter distributions, wherein cyclists were categorised as narrow vehicles and the observed parameter distributions were employed. Subsequently, the safety metric *pPET* derived from the observation was compared with the simulation result. In a total of 100 trips, 38 encounters were evaluated. The distribution of the *pPET* is analogous to the observed data, although in the simulation southbound cyclists more frequently yielded the right-of-way with shorter interactions than was actually observed.

The present study addresses a research question by analysing video data to determine the trajectories of cyclists, with a focus on the situations in which cyclists encountered and interacted with each other.

Accident data (from police or hospital) usually only include serious accidents that have been reported. These data are incomplete due to the number of unreported accidents. Surveys are often highly self-selective and unrepresentative. Field studies differ from the real environment due to the setup and possible use of simulators or test tracks. The Research Intersection measures traffic 24 hours a day, 7 days a week and is not limited to good weather.

The aim of this work was to understand how cyclists interact on bicycle paths and whether critical situations can arise. Data from the Research Intersection was crucial to the study. Four types of interaction can be defined on the bicycle path in general: riding in a line, overtaking, oncoming, and crossing. All four types of interaction have also been classified for the whole of Germany in the Unfallatlas (see Section 2.3.2), which breaks down bicycle accidents in the years 2016–2023 according to type: riding in a line (10.17%–12.04%), overtaking (17.56%–21.31%), crossing (32.16%–38.01%), and oncoming (30.7%–36.4%).

Observation data from the Research Intersection and an intersection in the 30 km/h zone, video annotation and a survey were used to answer the following research question:

How do cyclists interact close to an intersection, and what dangers can arise?

Cyclists can encounter and interact with each other on bicycle paths in a number of ways, including when they are moving in the same direction, in opposite directions, or crossing each other. Using the bicycle path in the same direction of travel can lead to riding next to each other, riding behind each other, and overtaking. Riding next to each other is a behaviour that is subject to control, but it can also lead to conflicts, especially when riders are under the influence of alcohol. While side-by-side riding was detected in a small number of cases, it was not further analysed in this study. Convoys were detected in over 300 cases, with the smallest detected distance being 3 m and considered uncritical. In the selected AOI at the Research Intersection, riding in convoys did not lead to any critical interactions. Riding in a line directly at traffic lights, where people are braking or starting to pedal, can lead to interactions. This was not considered in this study. Overtaking manoeuvres were likewise not studied. The 12 cases of overtaking recorded are too few to draw conclusions, and the trajectories are not easy to use because they are incomplete and cannot be interpolated due to the change in direction when overtaking. The bicycle path is 1.60 m wide, leaving only 20 cm for overtaking, which can lead to critical situations if the cyclist swerves or pedestrians are disturbed. According to the Unfallatlas, the fewest accidents occur during following and overtaking manoeuvres. However, due to the number of unreported accidents, more data should be collected in the future to better understand interactions and possible accidents.

According to the Unfallatlas (see Section 2.3.2), the majority of accidents occur during oncoming or crossing, with significantly more interactions reported in both cases than when overtaking. Critical situations with oncoming traffic occur most often when both cyclists are travelling on the bicycle path, which is narrow and leaves little room for manoeuvring. Nevertheless, even when there were no pedestrians on the footpath, some *WWC* remained on the bicycle path, and *NC* also didn't swerve onto the footpath. While no accidents were recorded in the observation data, the minimum distance recorded was $d_{\min} = 0.68\,m$, representing the distance between the centres of the objects. Excluding handlebars width and considering measurement inaccuracies, these situations accounted for 11.83% of all interactions.

It is important to note that hazardous scenarios may also occur during the process of crossing, primarily because only approximately 50% of cyclists are aware of the priority-to-the-right rule. Furthermore, these rules were observed in only 50% of the interactions that were analysed. Crossing directly on the footpath enables both cyclists to travel at higher speeds, which can result in dangerous situations. The data set revealed nine cases in which the criticality metrics *PET* and *pPET* were within -1 and 1 s.

In relation to the Research Intersection, different interactions on the bicycle path were analysed (oncoming, crossing, overtaking, convoy) and at an intersection in the 30 km/h zone (crossing). The study analyses different time periods in order to get a good overview of the interaction behaviour between cyclists. It was found that in the oncoming scenario, critical interactions occur when both cyclists cycle on the narrow bicycle path. In the crossing scenario, close interactions occur when the right-of-way is not respected (at both locations). The calculated parameters were transferred to the SUMO simulation as an example and show that the interaction behaviour for crossing can already be mapped relatively well.

All in all, there are interactions at intersections that can lead to dangerous situations with no accidents occurring during this study. The analyses revealed that critical interactions were identified that were capable of leading to an accident if the cyclist was inattentive.

This study highlights the serious potential for cyclist conflicts at intersections and the need to develop mitigating measures like education or adaptation of the infrastructure.

7.1 Future Research

Cycling has become an increasingly prominent mode of transportation, with urban areas undergoing adaptations to accommodate this growing trend. New infrastructure and enhanced connectivity between cities and rural areas have been implemented to facilitate this shift.

It is imperative that future research continues to examine the behaviour of cyclists, with traffic observation providing invaluable insights into areas where traffic management is proving challenging. *WWC* have been observed to take shortcuts or utilise safer routes, suggesting the need for a re-evaluation of cycling infrastructure. This is particularly important in areas where *WWC* are prevalent as this may indicate the need for improvements to protect both *NC* and pedestrians, as well as *WWC* themselves. Conflicts when crossing can indicate unclear traffic routing that obfuscates who has the right-of-way, and these investigations can be carried out with random sample investigations. Since many bicycle accidents are not reported to the police, accident statistics do not reflect the extent of the problem, but they can give an indication of places where critical situations occur more frequently, and this can also be checked in follow-up work.

In the future, greater attention should be directed towards awareness of road traffic. Further video annotations or traffic observations may provide insights into effective strategies for managing intersections. Questions that require answers include the direction in which the cyclist looks when turning and whether they extend their arm (e.g., when changing direction). It remains unclear whether the regulations are being violated intentionally or unintentionally. It is imperative to enhance the clarity of these rules, both during childhood and through the utilisation of signs, traffic lights, and road markings, to ensure that pedestrians can navigate their environs safely and interact responsibly with cyclists.

Furthermore, greater focus is required on the incorporation of bicycle traffic simulation into traffic modelling, encompassing both motorised traffic and the behaviour of cyclists at intersections and on designated bicycle paths. This is imperative due to the varied speeds and types of bicycles and can ensure the efficient and safe utilisation of bicycle paths by all users without conflict. The successful implementation of these models can assist urban planning authorities in making optimal decisions. Furthermore, the information can be utilised for the purpose of scenario-based testing of automated driving functions (e.g., information about violation of regulations).

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Appendix

A.1 Supplementary Reasons for Wrong Way Cycling

- Avoid changing lanes
- Avoiding a traffic light phase (2 mentions)
- Only for distances less than 50 m or very short routes (4 mentions)
- There is no bicycle path in the opposite direction. (3 mentions)
- It is often the shorter route.
- Because my girlfriend wants to cycle there.
- By mistake
- Saving of distance (crossing of the main road) (3 mentions)
- There is no alternative route for the construction site. (2 mentions)
- Complicated cycle route (3 mentions)
- Avoid bad / impassable places on regular routes.
- Only when the bicycle path is blocked.
- Because it's safer (3 mentions)
- Missing crossing option

The free text box allowed more than one answer to be given, which means that some comments were also combined.

A.2 Google News for Oncoming Scenario

Table 12: General information on the accidents for oncoming scenario. The causes of the accidents are outlined in Table 13. The investigation was done on 1 September 2024. (see Section 2.4.2)

No.	Link	Date	Location	Accident Victim					Counterparty in the accident				
				Gender	Age	Bike	Helmet	Injury	Gender	Age	Bike	Helmet	Injury
1	A	30-07-2024, Tue., 19:00	Eschwege	male	13	-	yes	yes	female	55	pedelec	yes	yes
2	B	11-07-2024, Thurs., 17:50	Schwanenwik (Uhlenhorst)	male	25	-	-	serious	female	11	bicycle	-	serious
3	C	28-05-2024, Tue., 21:30	Merseburg	male	36	e-bike	-	fatal	male	62	e-bike	-	serious
4	D	04-06-2024, Tue., -	Flensburg	male	15	-	-	slight	male	63	bicycle	-	serious
5	E	05-07-2024, Fri., 16:00	Veitsbronn	male	81	pedelec	-	fatal	-	-	-	-	-
6	F	09-07-2024, Tue., -	Grenzach-Wyhlen	female	-	-	-	-	-	-	-	-	-
7	G	14-05-2024, Tue., 15:00	Kempten	male	-	racing	-	serious	male	-	-	-	-
8	H	11-01-2024, Thurs., 01:30	Berlin	male	66	no light	-	fatal	male	21	-	yes	serious
9	I	02-10-2023, Mon., noon	Schmallenberg	female	64	-	-	serious	male	70	-	-	serious
10	J	03-08-2024, Sat., 03:20	Feldkirch	female	43	e-bike	-	slight	male	≈30	older	-	-
11	K	05-07-2024, Fri., 19:00	Gräfelfing	male	84	-	no	fatal	male	9	-	-	-
12	L	15-09-2020, Tues., 14:40	Rietberg	male	74	pedelec	-	-	male	11	-	-	slight
13	M	15-03-2024, Fri., morning	Rostock	male	68	-	no	fatal	male	23	-	-	slight
14	N	11-04-2024, Thurs., 17:45	Speyer	male	58	-	yes	serious	female	9	-	-	slight
15	O	22-06-2024, Sat., 14:25	Stade	female	58	-	-	serious	male	63	racing	-	serious
16	P	24-08-2024, Sat., 00:15	Augsburg	female	31	-	-	-	male	-	-	-	-
17	Q	-, Mon., 17:00	Neuhausen	male	51	-	no	serious	male	51	-	no	-
18	R	22-07-2021, Thurs., 00:40	Gmunden	male	47	e-bike	-	-	male	42	mountain	-	-
19	S	12-04-2021, Mon., 14:20	Munich	male	24	-	-	serious	male	-	-	-	-

-: not mentioned in source; A: https://www.presseportal.de/blaulicht/pm/44151/5834158; B: https://www.mopo.de/hamburg/polizei/fahrradunfall-an-der-alster-11-jaehrige-schwer-verletzt/; C: https://www.mz.de/lokal/merseburg/schwerer-unfall-neben-b91-bei-merseburg-zwei-radfahrer-krachen-frontal-ineinander-bewusstlos-gefunden-3849889; D: https://www.foerde.news/blaulicht/zwei-verletzte-bei-fahrrad-unfall-an-der-nordstrasse.html; E: https://www.rosenheim24.de/bayern/veitsbronn-radfahrer-stirbt-nach-unfall-in-krankenhaus-93203078.html; F: https://www.badische-zeitung.de/baby-anhaenger-kippt-bei-fahrrad-unfall-bei-wyhlen-um; G: https://www.allgaeuer-zeitung.de/allgaeu/kempten/fahrrad-unfall-in-kempten-rennradfahrer-schwer-verletzt-geisterradler-fluechtet_arid-743069; H: https://www.bild.de/regional/berlin/berlin-aktuell/berlin-radfahrer-kracht-in-anderen-radfahrer-66-jaehriger-tot-86713826.bild.html; I: https://www.wp.de/staedte/meschede-und-umland/article239720311/Zwei-Schwerverletzte-nach-Ueberholvorgang-auf-dem-Radweg.html; J: https://www.vol.at/43-jahrige-nach-fahrradkollision-in-feldkirch-verletzt/8876011; K: https://www.merkur.de/lokales/wuermtal/graefelfing-ort28743/nach-fahrradkollision-84-jaehriger-graefelfinger-verstorben-12781267.html; L: https://kukon.net/rietberg/198655-fahrradkollision-im-begegnungsverkehr/; M: https://www.ostsee-zeitung.de/lokales/rostock/rostock-68-jaehriger-nach-frontalzusammenstoss-auf-radweg-gestorben-SJ7AVKD2ABEW3PB7YNC2N7TJJE.html; N: https://www.wochenblatt-reporter.de/speyer/c-blaulicht/speyer-radfahrer-muss-nach-kollision-mit-kind-ins-krankenhaus_a547985; O: https://www.tz.de/muenchen/stadt/ludwigsvorstadt-isarvorstadt-ort43328/muenchen-hauptbahnhof-paul-heyse-unterfuehrung-fahrrad-polizei-zeugen-zr-90460513.html; P: https://www.meinbezirk.at/salzkammergut/c-lokales/radfahrer-kollidierten-auf-radweg-in-gmunden_a4834108; Q: https://www.bild.de/regional/bayern/augsburg-radfahrer-fluechtet-nach-unfall-in-stadionstrasse-66cafff10f2ad15e27618014; R: https://www.abendzeitung-muenchen.de/muenchen/stadtviertel/radlunfall-auf-der-dachauer-strasse-51-jaehriger-schwer-verletzt-art-817228; S: https://www.tz.de/muenchen/stadt/ludwigsvorstadt-isarvorstadt-ort43328/muenchen-hauptbahnhof-paul-heyse-unterfuehrung-fahrrad-polizei-zeugen-zr-90460513.html

Table 13: Causes of the accidents for oncoming scenario. The general information of the accidents are outlined in Table 12. The investigation was done on 1 September 2024. (see Section 2.4.2)

No.	Accident Cause
1	The female cyclist briefly stumbled and veered too far to the left, causing both handlebars to collide.
2	A man overtook a bicycle and collided with a child.
3	They crashed head-on.
4	They were riding in opposite directions on the bicycle path next to the road and collided.
5	Presumably oncoming traffic.
6	Oncoming traffic, trailer tipped over.
7	Racing cyclist collided with *WWC*.
8	When approaching, wobbled and fell.
9	Woman wanted to overtake another cyclist and rode into a *WWC*.
10	Man could not keep his lane; despite calls, handlebars touched, both fell, man fled.
11	Combined pedestrian- and bicycle path, child came towards, collision.
12	Man encountered two children coming towards him, both swerved in the same direction.
13	Head-on collision on the bicycle path.
14	Shared pedestrian- and bicycle path, man in legal direction, children (9 and 14) coming towards him, collision and fall.
15	Collision, counterparty rode in prohibited direction and fled.
16	Counterparty rode in prohibited direction, both fell, counterparty intoxicated.
17	Both fell, man fled.
18	Man wanted to overtake two cyclists; at the second cyclist, illegal *WWC* appeared. Trying to evade, he collided with a cyclist moving in the same direction, *WWC* fled.
19	They came towards each other on the bicycle path and chose the same side to evade, collision and fall.

A.3 Google News for Overtaking Scenario

Table 14: General information on the accidents for overtaking scenario. The causes of the accidents are outlined in Table 15. The investigation was done on 1 September 2024. (see Section 2.4.1)

No.	Link	Date	Location	Accident Victim					Counterparty in the accident				
				Gender	Age	Bike	Helmet	Injury	Gender	Age	Bike	Helmet	Injury
1	A	13-04-2024, Sat., 13:00	Schmiechen	male	61	-	no	serious	male	35	e-bike	no	mild
2	B	05-07-2024, Fri., -	Offenburg	female	23	-	no	later fatal	male	25	-	no	-
3	C	21-07-2024, Sun., 13:30	Bramfeld	male	70-80	-	yes	later fatal	male	30	-	no	-
4	D	30-07-2024, Tue., morning	Berlin	female	82	-	no	serious	male	65	-	no	mild
5	E	30-05-2024, Thurs., 12:30	Dachau	male	59	e-bike	-	serious	female	58	-	serious	
6	F	09-03-2024, Sat., 15:00	Hückeswagen	male	30	-	yes	serious	female	40	-	serious	
7	G	06-07-2023, Thurs., 16:00	Delbrück	female	65	pedelec	-	mild	female	65	pedelec	yes	serious
8	H	24-08-2024, Sat., 17:53	Berglen	female	15	-	yes	serious	female	15	-	-	-
9	I	03-04-2023, Mon., afternoon	Rostock	male	43	-	yes	serious	male	-	-	-	-
10	J	15-08-2024, Thurs., 16:20	Dorsten	male	62	-	-	serious	female	79	-	-	serious
11	K	- , - , -	Flachgau	female	55	-	yes	-	male	35	racing	yes	-

-: not mentioned in source; A: https://www.schwaebische.de/regional/ulm-alb-donau/schelklingen/ein-streit-waehrend-der-fahrt-dann-kommt-s-zum-unfall-2438838; B: https://www.schwarzwaelder-bote.de/inhalt.sturz-endet-toedlich-frau-stirbt-nach-fahrrad-unfall-in-offenburg.1ed46f2a-186a-4d76-afdd-e5f7e9a90f0e.html; C: https://www.abendblatt.de/hamburg/wandsbek/article406846075/unfall-in-hamburg-radfahrer-verhakt-sich-mit-anderem-radfahrer-lebensgefahr.html; D: https://www.maz-online.de/lokales/potsdam-mittelmark/zwei-senioren-in-teltow-bei-fahrradkollision-verletzt-USUDMNSYIJ27TO6DGEXDMMXQWU.html; E: https://pfaffenhofen-today.de/87684-zwei-fahrradfahrer-schwer-verletzt-2; F: https://www.rga.de/lokales/oberbergischer-kreis/hueckeswagen/zwei-schwerverletzte-bei-fahrrad-kollision-XGL72HM7UVBWNEA6LN6HTQJ3VE.html; G: https://www.westfalen-blatt.de/owl/kreis-paderborn/delbrueck/fahrradunfaelle-frau-und-junge-schwer-verletzt-2787658; H: https://www.zvw.de/blaulicht/fahrrad-unfall-in-berglen-15-j%C3%A4hrige-schwer-verletzt-im-krankenhaus_arid-857512; I: https://www.ostsee-zeitung.de/lokales/rostock/fahrradunfall-in-rostock-radfahrer-wird-bei-ueberholversuch-schwer-verletzt-JAK55VNHFZERNH474AQ63GXNXM.html; J: https://www.lokalkompass.de/marl/c-blaulicht/79-jaehrige-radfahrerin-bei-unfall-schwer-verletzt_a1978333; K: https://www.salzburg24.at/news/salzburg/schwere-stuerze-betrunkene-radler-und-co-fahrradunfaelle-halten-salzburgs-einsatzkraefte-auf-trab-161798023

Table 15: Causes of the accidents for overtaking scenario. The general information of the accidents are outlined in Table 14. The investigation was done on 1 September 2024. (see Section 2.4.1)

No.	Accident Cause
1	Men got into a dispute while overtaking, leading to a scuffle and a fall.
2	They collided, but it's unclear whether they were overtaking each other.
3	Handlebars collided while overtaking.
4	The woman intended to stop but swerved and blocked the bicycle path, causing the man to crash as he couldn't brake in time.
5	A wild animal (deer) crossed the road. The man braked his e-bike, and the woman attempted to avoid but collided with him.
6	The man wanted to turn left, but the woman attempted to overtake and collided with him.
7	Riding side-by-side, they collided and fell.
8	Riding side-by-side, their front wheels collided, causing them to fall.
9	The man overtook and touched the woman's side, causing a fall.
10	The man overtook the woman, and they collided, causing a fall.
11	Three racing cyclists attempted to overtake a woman who was also overtaking and veered left, colliding with one of the cyclists.

A.4 Google News for Crossing Scenario

Table 16: General information on the accidents for crossing scenario. The causes of the accidents are outlined in Table 17. The investigation was done on 1 September 2024. (see Section 2.4.3)

No.	Link	Date	Location	Accident Victim					Counterparty in the accident				
				Gender	Age	Bike	Helmet	Injury	Gender	Age	Bike	Helmet	Injury
1	A	28-07-2024, Sun., 15:15	Bad Rodach	female	57	e-bike	-	mild	male	24	-	-	slight
2	B	22-11-2023, Wed., 18:30	Braunschweig	female	43	-	-	mild	3 males	-	-	-	-
3	C	30-07-2024, Tue., 15:30	Bedburg-Hau	male	23	pedelec	-	mild	male	$\approx$19	-	-	-
4	D	13-08-2024, Wed., 19:00	Traunreut	male	36	pedelec	-	mild	female	44	-	-	serious
5	E	23-06-2024, Sun., 15:30	Würselen-Alsdorf	male	55	pedelec	-	later fatal	male	59	pedelec	-	-
6	F	- , Tue., 05:15	Tettnang	male	51	-	-	mild	female	50	-	-	no

-: not mentioned in source; A: https://www.np-coburg.de/inhalt.landkreis-coburg-zwei-verletzte-bei-fahrradunfall.ff4fbf57-a1aa-478c-b368-bbce3f9d4904.html; B: https://regionalheute.de/braunschweig/unfall-mit-mehreren-beteiligten-fahrradfahrern-frau-verletzt-braunschweig-1700746652/; C: https://madeinbocholt.de/bedburg-hau-radfahrer-kollision-endet-mit-flucht-nach-streit/; D: https://www.chiemgau24.de/chiemgau/polizeimeldungen/traunreut-jochbeinbruch-nach-zusammenstoss-zwei-fahrradfahrer-bei-unfall-verletzt-93242073.html; E: https://www.aachener-zeitung.de/lokales/region-aachen/wuerselen/aachener-55-nach-zusammenstoss-zweier-pedelecs-im-krankenhaus-gestorben/14609664.html; F: https://www.schwaebische.de/regional/bodensee/tettnang/radfahrer-wird-leicht-verletzt-261019

Table 17: Causes of the accidents for crossing scenario. The general information of the accidents are outlined in Table 16. The investigation was done on 1 September 2024. (see Section 2.4.3)

No.	Accident Cause
1	Man failed to yield woman on e-bike.
2	Three men crossed a woman, men swerved, woman braked hard and fell; men fled.
3	Man on the bicycle path, another cyclist entered from a field path, collision; man on bicycle path had right-of-way, other cyclist fled.
4	Collision at an intersection.
5	Man tried to overtake multiple cyclists while another man was turning.
6	Man attempted to overtake a woman, but she turned left and they collided.

A.5 Survey

Datenschutzrechtliche Einwilligungserklärung und Informationen über die Verarbeitung personenbezogener Daten im Rahmen der Dissertation „Modeling cyclists‘ behaviour and interactions at urban intersections“ von Claudia Leschik

I. Datenschutzrechtliche Einwilligungserklärung

Das Deutsche Zentrum für Luft- und Raumfahrt e.V. (DLR) nimmt den Schutz Ihrer personenbezogenen Daten sehr ernst. Die geplante Verarbeitung Ihrer Daten zum Zweck einer Teilnahme an einer Befragung setzt Ihre zuvor erteilte Einwilligung als rechtliche Grundlage voraus. Bei der Erhebung von Forschungsdaten im Rahmen einer Dissertation am Institut für Verkehrssystemtechnik des Deutschen Zentrums für Luft- und Raumfahrt, werden Informationen zum Geschlecht und der Altersgruppe erhoben.

Ich willige ein, dass das DLR ausschließlich zu den oben genannten Zwecken die bezeichneten personenbezogenen Daten verarbeiten darf.

Meine Einwilligung erfolgt freiwillig. Ich kann sie ohne Angabe von Gründen verweigern, ohne dass ich deswegen Nachteile zu befürchten hätte. Ich kann diese Einwilligung zudem jederzeit in Textform (z. B. Brief, E-Mail) mit Wirkung für die Zukunft widerrufen. Ab Zugang der Widerrufserklärung dürfen meine Daten nicht weiterverarbeitet werden. Sie sind unverzüglich zu löschen. Durch den Widerruf meiner Einwilligung wird die Rechtmäßigkeit der bis dahin erfolgten Verarbeitung nicht berührt.

Um Ihnen eine transparente Entscheidungsfindung zu ermöglichen, möchten wir Sie mit den nachfolgenden Informationen zum Datenschutz darüber informieren, wie das DLR Ihre personenbezogenen Daten verarbeitet.

II. Informationen über die Verarbeitung personenbezogener Daten

Mit diesen Datenschutzhinweisen informieren wir Sie gemäß der ab dem 25. Mai 2018 geltenden EU-Datenschutz-Grundverordnung (DSGVO) über die Verarbeitung Ihrer personenbezogenen Daten durch das DLR sowie über die Ihnen zustehenden Rechte. Diese Hinweise werden soweit erforderlich aktualisiert und Ihnen zur Verfügung gestellt.

1. Verantwortlicher und Datenschutzbeauftragter

Verantwortlicher im Sinne der DSGVO ist das
Deutsche Zentrum für Luft- und Raumfahrt e. V. (DLR)
Linder Höhe, 51147 Köln
Telefon: +49 2203 601-0, Internet: https://www.dlr.de

Den Datenschutzbeauftragten des Verantwortlichen erreichen Sie unter:
Datenschutzbeauftragter des DLR, Linder Höhe, 51147 Köln,
E-Mail: datenschutz@dlr.de

2. Zweck für die Datenverarbeitung

Zweck der Datenverarbeitung ist die Teilnahme an einer Befragung, welche im Rahmen einer Dissertation erhoben und ausgewertet wird.

3. Datenkategorien

Im Rahmen der Verarbeitungstätigkeit werden die folgenden personenbezogenen Daten verarbeitet:

Verfahren: Befragung
Daten: Anonymisierte demografische Daten, wie Geschlecht (weiblich, männlich, divers, k. A.), Altersgruppe (unter 20 Jahre, 20-29 Jahre, …) und anonymisierte Fragen zum persönlichen Fahrverhalten (befahren des Radweges in die falsche Fahrtrichtung) sowie Verständnis über Verkehrsregeln

4. Rechtsgrundlage für die Verarbeitung

Soweit die Verarbeitung auf Grundlage einer Einwilligungserklärung erfolgt, ist Art. 6 Abs. 1 S. 1 lit. a DSGVO die Rechtsgrundlage der Verarbeitung.

5. Empfänger personenbezogener Daten

Eine interne oder externe Weitergabe personenbezogener Daten erfolgt nicht.

6. Speicherdauer

Die personenbezogenen Daten werden nur solange verarbeitet, wie dies erforderlich ist. Die anonymisierten Forschungsdaten werden entsprechend der Ordnungen zur Sicherung guter wissenschaftlicher Praxis aufbewahrt und können der wissenschaftlichen Öffentlichkeit ganz oder teilweise zugänglich gemacht werden.

Eine Speicherung kann darüber hinaus erfolgen, wenn dies durch den europäischen oder nationalen Gesetzgeber in unionsrechtlichen Verordnungen, Gesetzen oder sonstigen Vorschriften, denen der Verantwortliche unterliegt, vorgesehen wurde.

7. Ihre Rechte in Bezug auf ihre personenbezogenen Daten

Sie haben gegenüber dem DLR folgende Rechte hinsichtlich der Sie betreffenden personenbezogenen Daten. Zwecks Ausübung dieser Rechte wenden Sie sich bitte an die in Ziffer 1. angegebene Stelle. Vorbehaltlich der Bedingungen und Garantien nach Art. 89 Abs. 1 DSGVO kann es nach Art. 89 Abs. 2, 3 DSGVO zu Ausnahmen der Betroffenenrechte kommen.

Recht auf Auskunft - Art. 15 DSGVO

Mit dem Recht auf Auskunft erhält der Betroffene eine umfassende Einsicht in die ihn angehenden Daten und einige andere wichtige Kriterien, wie beispielsweise die Verarbeitungszwecke oder die Dauer der Speicherung. Es gelten die in § 34 BDSG geregelten Ausnahmen von diesem Recht.

Recht auf Berichtigung - Art. 16 DSGVO

Das Recht auf Berichtigung beinhaltet die Möglichkeit für den Betroffenen, unrichtige ihn angehende personenbezogene Daten korrigieren zu lassen.

Recht auf Löschung - Art. 17 DSGVO

Das Recht auf Löschung beinhaltet die Möglichkeit für den Betroffenen, Daten beim Verantwortlichen löschen zu lassen. Dies ist allerdings nur dann möglich, wenn die ihn angehenden personenbezogenen Daten nicht mehr notwendig sind, rechtswidrig verarbeitet werden oder eine diesbezügliche Einwilligung widerrufen wurde. Es gelten die in § 35 BDSG geregelten Ausnahmen von diesem Recht.

Recht auf Einschränkung der Verarbeitung - Art. 18 DSGVO

Das Recht auf Einschränkung der Verarbeitung beinhaltet die Möglichkeit für den Betroffenen, eine weitere Verarbeitung der ihn angehenden personenbezogenen Daten vorerst zu verhindern. Eine Einschränkung tritt vor allem in der Prüfungsphase anderer Rechtewahrnehmungen durch den Betroffenen ein.

Recht auf Datenübertragbarkeit - Art. 20 DSGVO

Das Recht auf Datenübertragbarkeit beinhaltet die Möglichkeit für den Betroffenen, die ihn angehenden personenbezogenen Daten in einem gängigen, maschinenlesbaren Format vom Verantwortlichen zu erhalten, um sie ggf. an einen anderen Verantwortlichen weiterleiten zu lassen.

Recht auf Widerspruch - Art. 21 DSGVO

Das Recht auf Widerspruch beinhaltet die Möglichkeit für Betroffene, in einer besonderen Situation der weiteren Verarbeitung ihrer personenbezogenen Daten zu widersprechen, soweit diese durch die Wahrnehmung öffentlicher Aufgaben oder öffentlicher sowie privater Interessen gerechtfertigt ist. Es gelten die in § 36 BDSG geregelten Ausnahmen von diesem Recht.

Widerruf der Einwilligung

Betroffene haben die Möglichkeit, eine einmal erteilte datenschutzrechtliche Einwilligung jederzeit mit Wirkung für die Zukunft zu widerrufen.

Beschwerde bei einer Aufsichtsbehörde – Art. 77 DSGVO

Jede betroffene Person hat das Recht auf Beschwerde bei einer Aufsichtsbehörde. In der Regel steht dafür die Aufsichtsbehörde Ihres üblichen Aufenthaltsortes oder Arbeitsplatzes oder des Sitzes des Verantwortlichen zur Verfügung.

8. Bereitstellung personenbezogener Daten

Es besteht keine Pflicht zur Bereitstellung personenbezogener Daten. Sollten diese vollumfänglich oder teilweise nicht zur Verfügung gestellt werden, ist die Verarbeitung nicht oder nur eingeschränkt möglich. Dies gilt nicht für solche Daten, die wir im Rahmen einer Einwilligung verarbeiten.

9. Automatisierte Entscheidungsfindung

Eine automatisierte Entscheidungsfindung findet nicht statt.

☐ Die Belehrung über meine Rechte aus dem Datenschutzrecht habe ich vollständig gelesen, verstanden und keine Einwände.

☐ Mir ist bekannt, dass Teilnehmer/innen unter 16 Jahren nicht zugelassen sind.

Seite 02
AG

1. Wenn ich mit dem Fahrrad fahre...

... denke ich über verschiedene Dinge nach.

○ nie ○ selten ○ manchmal ○ häufig ○ immer

... bin ich abgelenkt.

○ nie ○ selten ○ manchmal ○ häufig ○ immer

... höre ich Musik.

○ nie ○ selten ○ machmal ○ häufig ○ immer

... denke ich an nichts.

○ nie ○ selten ○ machmal ○ häufig ○ immer

... bin ich sehr auf den Verkehr um mich herum konzentriert.

○ nie ○ selten ○ machmal ○ häufig ○ immer

... trage ich einen Fahrradhelm.

○ nie ○ selten ○ manchmal ○ häufig ○ immer

2. Wussten Sie, dass das Befahren eines Radweges in beide Fahrtrichtungen nur dort erlaubt ist, wo es durch entsprechende Beschilderung ausdrücklich erlaubt wird?

- ○ Ja, das wusste ich.
- ○ Nein, das wusste ich nicht.
- ○ Weiß ich nicht.

3. Sind Sie jemals mit dem Fahrrad entgegen der vorgeschriebenen Fahrtrichtung gefahren?

- ○ Ja, mehrfach
- ○ Ja, 1-2x
- ○ Nein
- ○ Weiß ich nicht.

2 aktive(r) Filter

Filter GA02/F1
Wenn eine der folgenden Antwortoption(en) ausgewählt wurde: **1, 2**
Dann nach dem Klick auf "Weiter" direkt zur Seite **WC** springen

Filter GA02/F2
Wenn eine der folgenden Antwortoption(en) ausgewählt wurde: **3, 4**
Dann nach dem Klick auf "Weiter" direkt zur Seite **NC** springen

4. Wenn ich auf dem Radweg fahre und mir kommt ein Radfahrender entgegen, welcher in nicht erlaubter Fahrtrichtung fährt, fahre ich oft...

- ○ ... auf dem Fußweg
- ○ ... auf dem Radweg
- ○ Weiß ich nicht.

5. Wenn ich auf dem Radweg fahre und mir kommt ein Radfahrender entgegen, welcher in nicht erlaubter Fahrtrichtung fährt, fahre ich oft...

- ○ ...mit niedrigerer Geschwindigkeit als zuvor (langsamer).
- ○ ...mit gleichbleibender Geschwindigkeit.
- ○ ...mit höherer Geschwindigkeit als zuvor (schneller).
- ○ Weiß ich nicht.

6. Wenn ich auf dem Radweg fahre und mir kommt ein Radfahrender entgegen, welcher in nicht erlaubter Fahrtrichtung fährt, fahre ich oft zum anderen Radfahrenden...

- ○ ...mit geringerer Distanz als zuvor (dichter).
- ○ ...mit gleichbleibender Distanz.
- ○ ...mit höherer Distanz als zuvor (ich weiche aus).
- ○ Weiß ich nicht.

7. Wenn mir ein Radfahrender entgegenkommt, obwohl er es nicht dürfte (er nutzt den Radweg in die falsche Fahrtrichtung), fühle ich mich...

- ○ gefährdet oder gestört, denn jeder sollte sich an die Regeln halten.
- ○ unverändert, denn ich achte nicht darauf oder mir ist es egal.
- ○ unverändert, denn um Zeit oder Weg zu sparen würde ich es auch machen.
- ○ verunsichert, weil ich nicht weiß, wie ich mich verhalten soll.

1 aktive(r) Filter

Filter NC04/F1
Wenn eine der folgenden Antwortoption(en) ausgewählt wurde: **1, 2, 3, 4**
Dann nach dem Klick auf "Weiter" direkt zur Seite **KR** springen

8. Wenn ich entgegen der erlaubten Fahrtrichtung fahre und kein weiterer Verkehrsteilnehmender zu sehen ist, fahre ich am häufigsten...

- ○ ... auf dem Fußweg
- ○ ... auf dem Radweg
- ○ Weiß ich nicht.

9. Wenn ich entgegen der erlaubten Fahrtrichtung fahre und mir kommt ein Radfahrender entgegen, fahre ich oft...

- ○ ... auf dem Fußweg
- ○ ... auf dem Radweg
- ○ Weiß ich nicht.

10. Wenn ich entgegen der erlaubten Fahrtrichtung fahre und mir kommt ein Radfahrender entgegen, fahre ich oft...

- ○ ...mit niedrigerer Geschwindigkeit als zuvor (langsamer)
- ○ ...mit gleichbleibender Geschwindigkeit
- ○ ...mit höherer Geschwindigkeit als zuvor (schneller)
- ○ Weiß ich nicht.

11. Wenn ich entgegen der erlaubten Fahrtrichtung fahre und mir kommt ein Radfahrender entgegen, fahre ich oft zum anderen Radfahrenden...

- ○ ...mit niedrigerer Distanz als zuvor (dichter)
- ○ ...mit gleichbleibender Distanz
- ○ ...mit höherer Distanz als zuvor (ich weiche aus)
- ○ Weiß ich nicht.

12. Nennen Sie Gründe für das Befahren des Radweges entgegen der erlaubten Fahrtrichtung, die auf Sie zutreffen.

Bitte kreuzen Sie alle zutreffenden an.

- ☐ Ich spare dadurch Zeit.
- ☐ Ich spare dadurch Weg.
- ☐ Ich fühle mich sicherer.
- ☐ Ich wusste nicht, dass ich die Richtung nicht befahren darf.
- ☐ Weil andere es genauso machen.
- ☐ Andere Gründe: __________

Seite 06

KR

13. Betrachten Sie folgende Situation. Stellen Sie sich vor, Sie sind der gelbe Radfahrende. Sie queren die Kreuzung bei grüner Ampel und wollen weiter nach Norden fahren. Von rechts nähert sich ein Radfahrender (blau), der ebenfalls nach Norden fahren möchte. Was würden Sie tun?

Bitte klicken Sie auf den unten stehenden Link, Sie werden weitergeleitet. Die Animation dauert nur 10 Sekunden.
Link zu einer kurzen Animation mit Abbildung (mp4)
Link zu einer Abbildung (jpg)

- ○ Ich (der gelbe Radfahrende) habe Vorfahrt, also fahre ich zuerst.
- ○ Der Radfahrende in blau hat Vorfahrt, also warte ich.
- ○ Ich weiß nicht wer Vorfahrt hat, also beeile ich mich zuerst zu fahren.
- ○ Ich weiß nicht wer Vorfahrt hat, ich lasse den Radfahrenden in blau vorfahren.
- ○ Keiner hat Vorrang, wir einigen uns mit Handzeichen o. ä. wer zuerst fährt.

Seite 07

DD

14. Welchem Geschlecht ordnen Sie sich zu?

- ○ weiblich
- ○ männlich
- ○ divers
- ○ Ich möchte keine Angabe machen.

15. Welcher Altersgruppe ordnen Sie sich zu?

- ○ unter 20 Jahre alt
- ○ 20-29 Jahre alt
- ○ 30-39 Jahre alt
- ○ 40-49 Jahre alt
- ○ 50-59 Jahre alt
- ○ 60-69 Jahre alt
- ○ über 70 Jahre alt
- ○ Ich möchte keine Angabe machen.

Seite 08
Anmerkungen

16. Wie haben Sie von dem Fragebogen erfahren?

- ○ Ich wurde an einer Kreuzung angesprochen und habe den QR-Code auf Papier erhalten.
- ○ Ich habe den Link zum Fragebogen digital (Mail, Social Media,...) erhalten.

17. Anmerkungen / Sonstiges

Letzte Seite

Vielen Dank für Ihre Teilnahme!

Ich möchte mich ganz herzlich für Ihre Mithilfe bedanken. Ihre Unterstützung ist ein wertvoller Beitrag für meine Dissertation.

Ihre Antworten wurden anonym gespeichert, Sie können das Browser-Fenster nun schließen.

Claudia Leschik – 2024