THE "TYPICAL" CAR-CYCLIST COLLISION UNDER THE MICROSCOPE: A GIDAS-BASED ANALYSIS OF THE PREVALENT CRASH SCENARIO

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ABSTRACT

In a world where reducing the carbon footprint is crucial, riding carbon-neutral vehicles such as bicycles or pedelecs is a sustainable and thus desired way of transport. Since motorized and unmotorized bicycles are missing any protective body, their riders are part of the vulnerable road users (VRUs). In order to increase the attractivity of transport by bicycle and pedelec, providing traffic safety for this group must be ensured.
To get a better understanding of cycle crashes, this paper's objective is to deduce the most important crash types of collisions of cyclists with passenger cars. By obtaining the characteristic details of these crashes, strategies for crash avoidance can be derived.
The **data source** used for the results presented in this paper is GIDAS (German In-Depth Accident Study). GIDAS is a unique database as the input data is provided by experts on crash reconstruction who join the police at the crash site and record the crash in great detail. 8497 relevant crashes involving bicycles, captured from 2000-2021, were evaluated.
The **methodology** consists of the evaluation of the two most common crash types regarding speed distributions and contact points of the crash opponents, street layout, driver intent, traffic density, and visual conditions.
The **results** show that the most common crashes are two crossing crash types accounting for nearly a third of all crashes between cyclists and drivers of motorized vehicles. Both of these crash types are characterized by the cyclist riding on the designated cycling infrastructure, while in the more common one, the cyclist goes against the expected direction for the crash opponent.
For the selected crash types, the results also show that more than half of crashes occur at junctions, predominantly where the driver has to yield. Most crashes occur during turning right maneuvers at low traffic densities and speeds below 13 kph. The evaluation of the car driver's maneuvers performed in the last second before the crash indicates a black spot in driving-off situations. In more than 70 % of the cases, the contact point with the cyclist is at the front.
The data, analyzed in detail in the **discussion**, points towards the theory that drivers tend to "fail to look" at cyclists coming from the right and "look but fail to see" cyclists from the left. Furthermore, cyclists crossing from the right might not be expected in right-hand traffic.
A general **limitation** of official crash data sources based on police reports is a high underreporting rate of bicycle crashes. Using the German crash database, also certain bias towards countries with similar traffic infrastructure must also be assumed. This is further analyzed in the discussion.
The **conclusions** drawn from this study show that cycling infrastructure remains of the highest importance and needs to be designed in accordance with the human factor in traffic. Also, communication between involved parties can contribute largely to tackling the most dominating crossing crash types, i.e., virtually enhancing the cyclist's visibility for other traffic participants.

INTRODUCTION

In a world where reducing the carbon footprint is crucial, riding carbon-neutral vehicles such as bicycles or pedelecs is a sustainable and thus desired way of transport. Going by bike or pedelec also helps reduce traffic congestion in urban areas. Cycling in road traffic, however, involves dangers not present in other kinds of transport: crashes often lead to severe injuries due to the marginal to non-existing structural protection in collisions. As a consequence, cyclists are classified with the so-called vulnerable road users (VRUs) [1]. Due to the high crash risk, cyclists often tend to avoid certain routes or journey times [2].

Hence, preventing crashes and making cycling safer is an important step towards inclusive mobility. To prevent crashes, detailed knowledge about collisions and their causes is necessary. For example, to develop advanced driving assistance systems (ADASs) targeting crashes with VRUs, information about the expected speed of said VRU and the vehicle speed before impact is required.

Related Works

For a while, in crash research, car-cyclist collisions became a focus of attention, for example;

Summala et al. investigated car-cyclist crashes in Helsinki and found that the most dominant ones are those where the driver had to cross a cycle path while turning right and collided with a cyclist coming from the right [3]. They also showed that drivers turning right are focused on traffic from the left and fail to perceive cyclists coming from the right.

Car-cyclist crashes from the driver's perspective have also been investigated by Gohl et al. within the EU-funded PROSPECT project [4]. The authors defined use cases by analyzing the prevalent GIDAS crash types and ranked these based on frequency and injury severance. They identified the right turn subsets of two specific crash types, *UTYP 341 & 342*, as the fifth and first most relevant crashes. Referencing previous works (e.g., Summala et al.), they postulated that in crashes where the cyclist came from the right, the driver "failed to look", whereas in crashes where the cyclist came from the left, the driver "looked but failed to see" the cyclist.

The analysis of car-cyclist crashes for autonomous emergency braking (AEB) testing has been the subject of the CATS project. Within the project, Op den Camp et al. researched the main crash scenarios and demonstrated that the crossing scenarios are dominant throughout several European countries [5]. Uittenbogaard et al. later researched the crash parameters built on the selected crossing scenarios, showing, amongst others, that vehicle speed contributes to crash severity while cyclist speed does not [6].

During the European SAFE-UP project, Balint et al. determined safety-critical scenarios for VRUs in road traffic using the German In-depth Accident Study (GIDAS) pre-crash matrix (PCM) dataset [7]. The work contains an analysis of the last seconds of car-cyclist collisions, especially under the aspect of adverse weather conditions. They also identified the scenarios with cyclist crossing from the left and the right while the car approaches a junction as the most relevant.

Further studies outside of Europe are addressing the relevance of cyclist crossing crashes: E.g., MacAlister and Zuby demonstrated that straight-crossing crashes account for the highest number of car-cyclist crashes and the second highest number of fatalities in the USA [8]. Beck et al. analyzed cyclist crashes in Victoria, Australia, and found that crossing-path crashes are the second most common car-cyclist collision, just after crashes where both parties traveled in opposing directions [9].

Contribution

This work ties in with previous efforts to obtain more details about car-cyclist crashes. We aim to explore the most common crash scenarios between cyclists and cars using data from the GIDAS to be able to parametrize safety functions in later works. As already revealed in previous works, collisions where the car driver had to give way to a cyclist crossing on a cycleway are dominant in car-cyclist crashes: crashes where the cyclist came from the left (the far side in right-hand traffic) constitute 8 %, and crashes, where the cyclist came from the right 20.9 % of all collisions, making these the two most frequent crash scenarios.

In the following study, we focus on these two most common scenarios to not dilute the crash situation's characteristics with those of other scenarios. Yet, we differentiate the direction the cyclist is coming from as well as crash severity. In particular, we center on outlining the specifics of the "typical" crash, which occurs at junctions, in great detail to derive exact scenarios for developing and testing new ADASs. We reveal the similarities of car-cyclist crashes, for example, that most occur during the car turning right and into light traffic. We demonstrate that collisions

occur at relatively low speeds and that the car's speed increases the chance of severe injuries. Eventually, in accordance with previous works, we assume that drivers in turning maneuvers "fail to look" at cyclists coming from the right but "look but fail to see" cyclists from the left.
This work was inspired and influenced by the analysis of crashes in Europe performed within the SECUR project [10]. The SECUR publication focuses on identifying the main crash scenarios, aggregating similar crash types into groups, and analyzing characteristics of the identified scenarios, including but not limited to car-cyclist crashes. With the focus on describing the most common car-crash scenario for safety function development, we briefly share the methodology for identifying the characteristics of the relevant scenarios before focusing on a very particular subset of the car-cyclist crashes, the crash types *UTYP 341* and *UTYP 342*. The present work is, therefore, an extension of the SECUR study to provide further insights into two distinct and prevalent types of cyclist crashes and the differences between them.
The structure of the paper continues with Methodology, which contains a description of the GIDAS data set we used and the methodology we applied. Subsequently, in Results, we present the findings of our study. We discuss similarities and differences between the crashes as well as the applied methodology in Discussion. In Conclusions, we summarize our contribution and give an outlook on our follow-up research.

METHODOLOGY

The aim of the work is to sketch the "typical crash" between cars and cyclists as mentioned in Introduction. In the first step, we selected the most common crash scenario as described in Data source and scenario selection. Based on the selected subset, we analyzed the specifics of the most common crash scenario as described in Evaluation of selected crash cases. By fixating the analysis on a sole scenario instead of summarizing similar scenarios in groups, we aim to receive more precise results for the selected scenario. Since the study aims to get more insights into crashes for the development of novel safety functions, we mainly focused the evaluation on the car's perspective.

Data source and scenario selection

The analysis is based on the GIDAS database, containing a representative set of injury crashes in Germany since 1999 [11]. Experts who join the police at the crash site record extensive data about the crashes and reconstruct the course of events. Subsequently, the record containing up to 3500 data fields, including information about the crash type, vehicles, injuries, and environment, is saved in the database. For example, the crash type (GIDAS field *UTYP*) denotes the situational circumstances that led to the crash [12]. The level of detail in this database is considered unique in the world.
For our study, we focused on 8497 relevant crashes between 2000 and 2021, where the first collision of a passenger car, delivery van, or mini bus occurred with a cyclist (see also table 1). The crash types were then attributed to crash scenarios, combining collisions with a similar course of events. A first evaluation of the frequencies of the aforementioned scenarios showed that two very similar crash types are the most common: the collisions between cars in front of a junction that had to yield for crossing traffic with cyclists crossing on a cycleway (see also table 2). With a frequency of 1776 crashes (20.9 %), the cyclist coming from the right (*UTYP 342*) is the more common, while in 682 crashes (8 %), the cyclist comes from the left (*UTYP 341*) (compare fig. 1). In both cases, the cyclist has the right of way. Together, these account for 28.9 % of all car-cyclist injury crashes. Sorting instead by the highest share of crashes with killed and severely injured (KSI), *UTYP 342* also ranks 1st with 269 (14.6 %) out of 1837 KSI crashes, whereas *UTYP 341* ranks 4th with 127 (6.9 %) crashes.

Table 1.
Selected GIDAS crashes

Subset	Count	% of car-cyclist crashes
Car-Cyclist crashes	8497	100 %
... thereof UTYP 341 & 342	2458	28.9 %
... thereof urban crashes	2426	28.6 %
... thereof KSI crashes	392	4.6 %

Table 2.
Frequency distribution of the five most common car-cyclist crash scenarios

Rank	Rank KSI	Scenario	included UTYPEs	Count	Count KSI
1st	1st	before junction / car has to yield / cyclist from the right (on cycleway)	342	1776	275
2nd	4th	before junction / car has to yield / cyclist from the left (on cycleway)	341	682	127
3rd	10th	junction / turning right / cyclist in same direction on cycleway	243, 285[1]	560	61
4th	7th	junction / car has to yield / cyclist from left (on road)	301-303, 311, 312, 352	474	91
5th	2nd	junction / car has right of way / cyclist from the left (on road)	261, 271, 321, 322, 331, 332, 353, 355	416	142

[1] Cyclist hit on left side

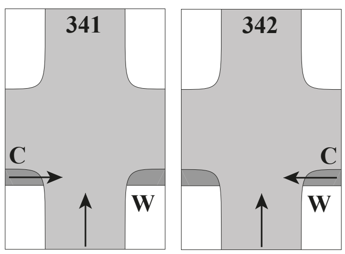

Figure 1. Schematic drawing of UTYP 341 and 342 as defined in [12]. **C** ***marks the cycleway and*** **W** ***marks that the car has to give priority to the crossing traffic.***

Due to the similar nature of the crash scenarios *UTYP 341* and *UTYP 342*, we centered the following analyses on both types. Since 2426 or 98.7 % out of the 2458 crashes of the selected type and a predominant part of cyclist crashes, in general, occur in urban areas, we considered solely urban crashes in our evaluation.

Evaluation of selected crash cases

To get more details about the situational circumstances at the crash site, we performed a frequency analysis of the GIDAS data fields depicted in table 3 in *RStudio* [13] using the subset of cyclist crashes described in Data source and scenario selection. In each evaluation, non-applicable values or entries where no data was encoded were filtered out, reducing the size of the dataset. Furthermore, among the crash reconstruction data (REKO), we utilized the fields describing the speed over time in the last seconds before the crash (see also table 3). The data are split into sequences that denote a single action of one of the participants involved in the crash. For this, we linearly reconstructed the speed over time for each segment. After that, we attributed the labels *Accelerating* (Accel.), *Braking* (Brake.), *Constant speed* (Const.), and *Standstill* (Stand.) to each sequence, depending on the difference in speed of the last segment to the current segment. A speed below 3 kph is considered as *Standstill*. The sequences were then normalized so that they range from $t = -4s$ to the point of time of the crash, $t_0 = 0s$. Finally, we split the normalized sequences into intervals of 0.1 s duration.
We also considered using GIDAS PCM records which already provide time-sampled data for each road user involved in the crash. As we compared these to our reconstruction of speed profiles using the *REKO* record, it turned out that the speed profiles of the *REKO* data are a good approximation of the PCM data, so there is no benefit of using the PCM data instead. On the contrary, since there are more than twice as many records available in *REKO*, we gain better insights into the crash occurrence by using this source instead.
The fields *BRPX* and *BRPY* were used to reconstruct the collision points between cyclist and car.

Table 3.
Evaluated GIDAS data fields

Records	Name	Description
BEFRAG	ABSICHT	Intention of action before crash
BETEIL	ANTSCH	Share of fault for the crash
	URSAMT1	Official cause of the crash
STRASSE	SICHTBV	Presence of permanent or non-permanent visual obstructions
	SICHTV	Kind of visual obstruction if present
UMWELT	STFUHO	Crash location
	TZEIT	Time of day regarding light conditions
	VKREG	Traffic regulation at crash site
	VSTUFE	Traffic density at time of crash
REKO	BRPX	Point of first contact of both opponents
	BRPY	
	SEQT	Duration of the sequence
	TREAKTV	Time in sequence until reaction
	TSYNC	Start of sequence regarding to global time
	V0	Speed at begin of the sequence
	VK	Speed at the end of the sequence / the collision

RESULTS

The first subsection of this chapter, Environmental circumstances, contains the analysis results using the records *BEFRAG*, *BETEIL*, *STRASSE*, and *UMWELT*, as introduced in Evaluation of selected crash cases. Subsequently, Collision speeds concentrate on the speeds at the time of the collision and the seconds before. Contact points finally addresses the point where the cyclist collided with the car.

Environmental circumstances

The analysis of the **crash location**, depicted in fig. 2, shows that more than half of the crashes occur at junctions: with 52.7 %, the share of these crashes is just slightly higher for *UTYP 341* crashes than the 51.6 % corresponding to *UTYP 342* crashes. The same applies to KSI crashes, with 53.9 % and 51.5 %. The difference in crashes at crossings and property entrances is more notable: 30.6 % (KSI: 32.0 %) of the crashes where the cyclist came from the left occurred at crossings, as opposed to 24.1 % (KSI: 24.6 %) of cases where the cyclist came from the right. In contrast, 13.9 % (KSI: 10.2 %) of the *UTYP 341* and 21.7 % (KSI: 21.7 %) of the *UTYP 342* crashes occurred at property exits.

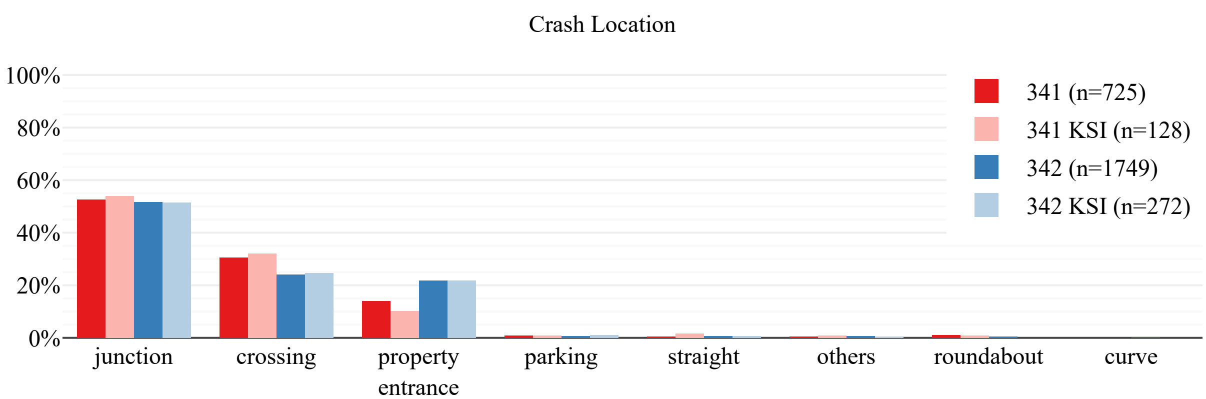

Figure 2. Frequency distribution of the crash location.

Fig. 3 shows the frequencies of **rules of the road** at the crash site. With 74.5 % of crashes with the cyclist coming from the left (*UTYP 341*) and 68.5 % with the cyclist coming from the right (*UTYP 342*), in the majority of the crashes, the car driver had to give way. The frequencies for *UTYP 341* and *342* KSI crashes differ slightly (74.2 %/64.9 %). 10.6 % (cyclist from left) and 13.3 % (cyclist from right) of the crashes occurred at property entries and exits with no significant difference in KSI crashes (9.7 %/13.5 %). Stop signs were present in 6.3 % and 9.9 %, respectively, of the crashes or 4.8 % and 11.6 %, respectively, of the KSI crashes. Traffic lights were present at 4.9 % and 4.3 % for crashes of all severities and 7.3 % and 5.4 % for KSI crashes.

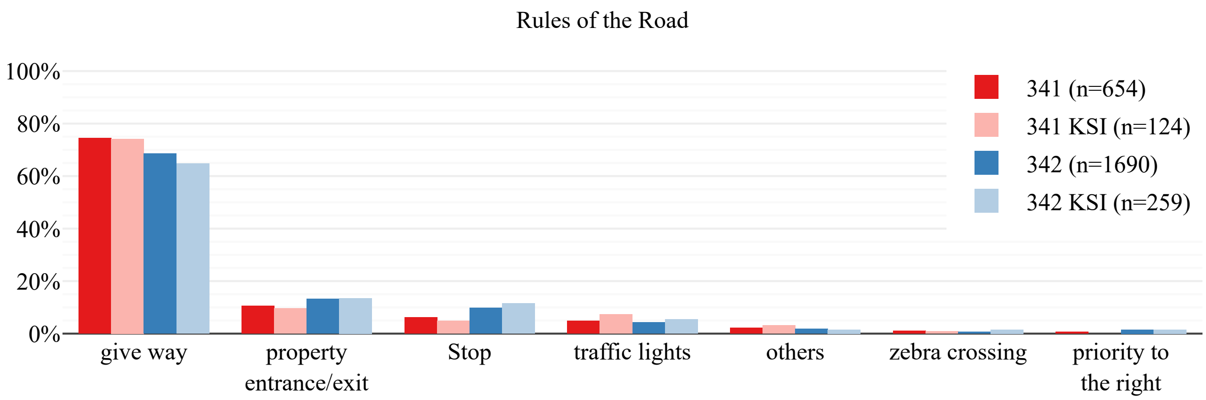

Figure 3. Frequency distribution of rules of the road at the crash site. Categories with a frequency of $< 1\%$ are not shown.

The **intent of the car driver** is depicted in fig. 4 for situations where the cyclist intented to go straight over the crossing. For other intents of cyclists, there are less than 1 % of cases for each *UTYP 341* and *UTYP 342*.
In most of the crashes and regardless of the *UTYP*, the car driver wanted to turn right: this was the car driver's intent in 66.8 % of the collisions with the cyclist coming from the left. This intent is even more pronounced for the collisions with the cyclist coming from the right, with 89.0 %. The KSI crashes' frequencies are distributed similarly (61.7 %/87.6 %). Turning left was the second most common intent of the driver with 21.0 % and 7.5 %, respectively, of all crashes and also 26.7 % and 9.0 %, respectively, of the KSI crashes. The car driver wanted to go straight in 11.9 % (KSI: 10.0 %) of the *UTYP 341* crashes and 3.4 % (KSI: 3.4 %) of the *UTYP 342* crashes. In a single KSI crash with the cyclist from the left (0.3 % of all; 1.7 % of KSI), the driver was parking.

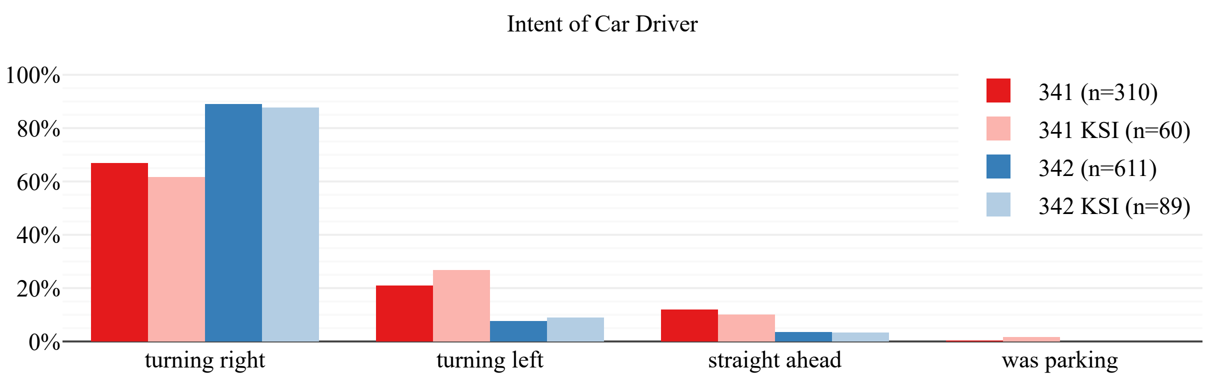

Figure 4. Frequency distribution of the intent of the car driver before the crash when the cyclist intended to go straight ahead. Intents with a frequency of $< 1\%$ are not shown.

The evaluation of the **traffic density** at the time of the collision, as depicted in fig. 5, shows that most crashes occur in light traffic, with 42.4 % (*UTYP 341*) and 44.4 % (*UTYP 342*) of the crashes of any given severity. The numbers for KSI crashes are even slightly higher, with 45.4 % and 46.4 %. In 35.6 % of the collisions with the cyclist coming from the left and 35.1 % of the collisions with the cyclist coming from the right, there were cars on the street just occasionally. For KSI crashes, these numbers are slightly lower (32.8 % and 31.8 %). In 20.3 % (KSI: 21.0 %) of the

UTYP 341 and 19.0 % (KSI: 19.7 %) of the *UTYP 342* collisions, while there was dense traffic on the road, it was still possible to drive the maximum allowed speed. Collisions between cyclists and cars were rare when there was slow-moving traffic or traffic jam (all below 2 % each).

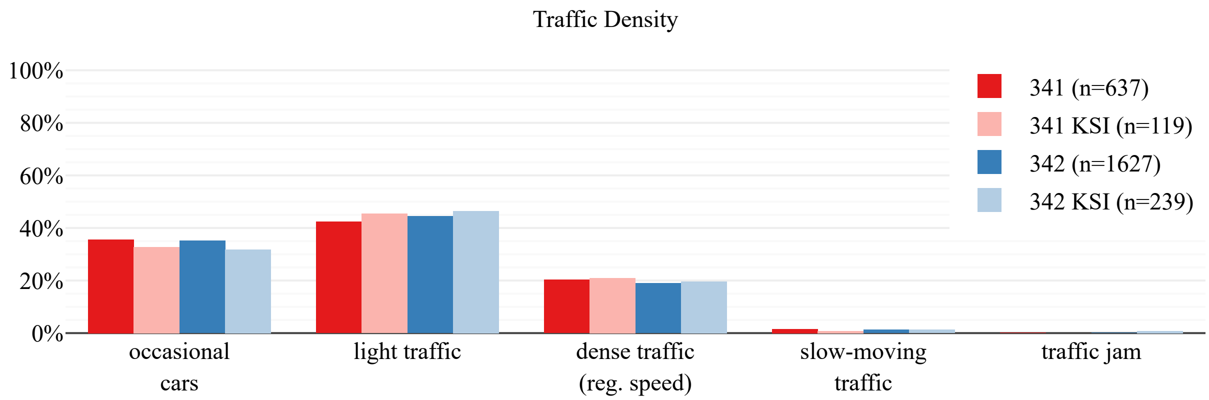

Figure 5. Frequency distribution of the traffic density at the time of the collision.

As shown in fig. 6, most crashes between cyclists and cars occur during daylight, as the analysis of **daylight conditions** at the time of the crash indicates. While 76.1 % of *UTYP 341* crashes and 71.4 % of KSI crashes occurred during daylight, the percentage of these collisions is even higher within the *UTYP 342* scenario, with 88.5 % of crashes and 91.0 % of KSI crashes. A fraction of 15.9 % (KSI: 19.0 %) of *UTYP 341* crashes occurred at night, whereas only 5.7 % (KSI: 3.0 %) of *UTYP 342* crashes occurred without any daylight. Twilight conditions were present in 8.0 % of *UTYP 341* crashes and 5.8 % of *UTYP 342* crashes of any severity, and 9.5 % and 6.0 %, respectively, of KSI crashes.

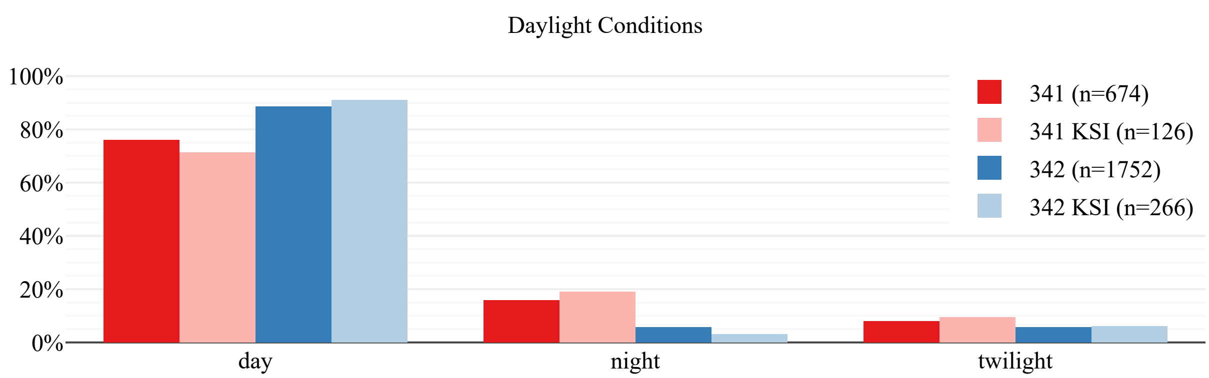

Figure 6. Frequency distribution of daylight conditions at the time of the collision.

The evaluation of **visual obstructions** from the driver's perspective (depicted in fig. 7) shows that, in most cases, there was no obstruction in the line of sight. The fraction of crashes without obstruction is higher for those with the cyclist coming from the left (72.0 %) than for those with the cyclist coming from the right (62.1 %) and higher for all crashes than for KSI crashes only (64.5 % and 55.8 %, respectively). In the cases where the view was obstructed, the most common issues were structural circumstances, e.g., buildings, vegetation, or hills, with 19.0 % of collisions with the cyclist coming from the left and significantly more collisions with the cyclist coming from the right (32.3 %). In KSI crashes, these were present in 21.5 % and 35.1 % of the cases. Parking vehicles play a role in 4.4 % of *UTYP 341* and 4.0 % of *UTYP 342* injury crashes, as well as 5.4 % and 7.1 % of KSI crashes. Other circumstances are not of significant matter.

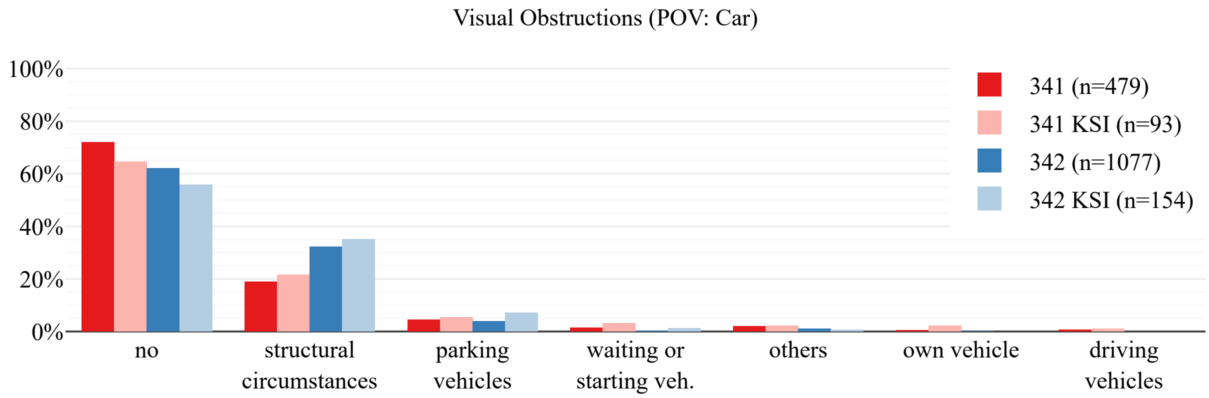

Figure 7. Frequency distribution of visual obstructions seen from the perspective of the driver.

The analysis of the **share of fault for the crash** (depicted in fig. 8) shows that in 87.2 % of crashes of *UTYP 341*, the cyclist had no responsibility for the crash. In contrast, in *UTYP 342* crashes, the cyclist was not even partially at fault in 35.6 % of crashes. The KSI crashes show similar numbers, with 91.7 % and 29.4 %. In only 10.0 %, the cyclist coming from the left was partially at fault for the crash, but in 60.2 %, the cyclist coming from the right was partially responsible. For the KSI crashes, again, the numbers are alike at 5.6 % and 65.2 %. When coming from the right, the cyclist was determined to be at the main fault in 3.2 % of crashes of all severities and 4.5 % of KSI crashes. Other constellations were present in less than 2 % each.
Subsequently, an analysis of the official cause of the crash yields further details: considering only the collisions where the cyclist's share of responsibility was not labeled as "not at fault" or no data was encoded, leaving only crashes where the cyclist was to blame partially, in 82.1 % of the *UTYP 342* collisions, the cyclist was wrongfully riding on the road or cycleway, e.g., riding in the wrong direction (not depicted). For *UTYP 341* crashes, in only 24.5 %, the cyclist was riding illegally on the road/cycleway.

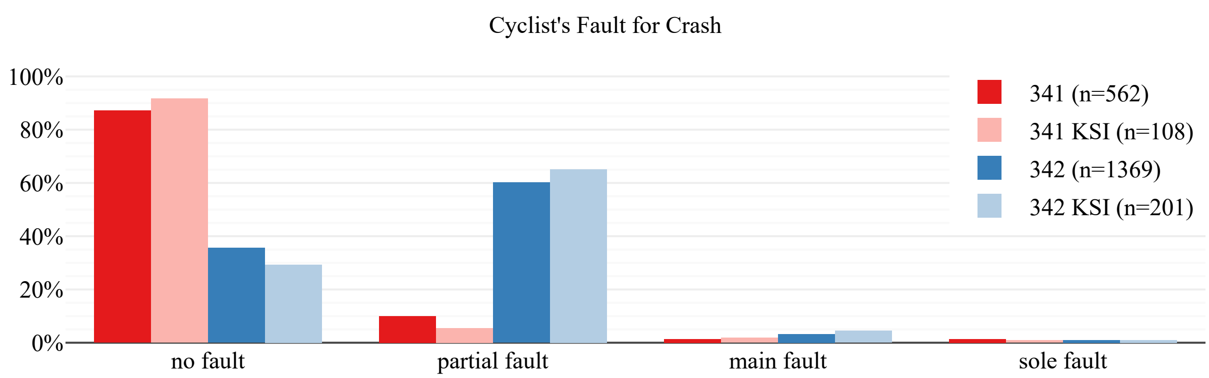

Figure 8. Frequency distribution of the cyclist's share of the fault for the crash.

Collision speeds

Fig. 9 shows the distribution of the **cars' speeds at impact**. More than half of the cars have a speed between 3 kph and 13 kph at the time of collision with the cyclist. In 95.9 % of the *UTYP 341* and 98.3 % of the *UTYP 342* crashes, the speed was 28 kph or less. Considering KSI crashes only, the speed was equal to or below 28 kph in 91.7 % and 95.5 % of the collisions, respectively.

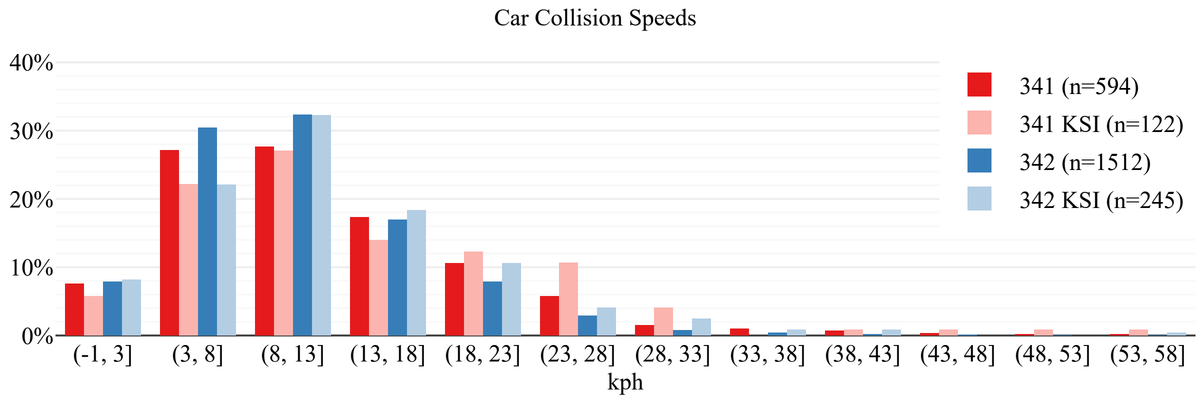

Figure 9. Frequency distribution of the cars' speeds at the time of the collision. One UTYP 341 and one UTYP 341 KSI crash each in bin [78, 83) are not shown.

In comparison, fig. 10 represents the distribution of the **cyclists' speeds at impact**. Compared to cars, the speed of cyclists is higher at the time of the collision: More than 60 % of the cyclists had a speed of 8 kph to 18 kph just before the collision. Above 90 % of cyclists were riding with a 23 kph maximum, and more than 97 % with a 28 kph maximum, both including the KSI cases. It is noticeable that the higher collision speeds are primarily present when the cyclist was riding along the usual driving direction: In ca. 26 % of *UTYP 341* crashes, the cyclist was going 18 kph to 28 kph, whereas in less than 13 % of *UTYP 342* crashes the cyclist was going this speed. The collision speeds of KSI crashes are similarly distributed as all injury crashes.

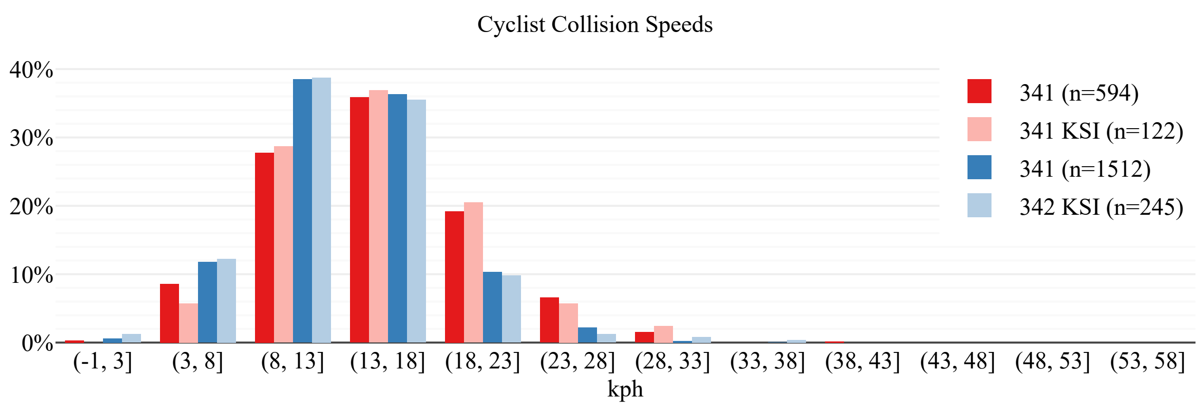

Figure 10. Frequency distribution of the cyclist speed at the time of the collision.

Fig. 11 shows the distribution of **maneuvers conducted by the driver in the last four seconds** before the collision. The data originates from the crash reconstruction and subsequent assignment in intervals, as described in Evaluation of selected crash cases. If data was unavailable for this interval, the related interval is marked as "unknown". There is good data availability for the last 0.9 s before the impact: data could be reconstructed in more than 80 % of cases. Two seconds before the impact, not more than 40 % is available. For the *UTYP 342* crashes, only one fifth of the crashes had data recorded at $t = -3.9\ s$.

With 39.5 %, more drivers in *UTYP 342* crashes were accelerating in the last tenth of a second compared to the 33.2 % of *UTYP 341* participants. In contrast, more drivers were braking before colliding with the cyclist from the left (27.0 %) compared to crashes with the cyclist coming from the right (21.0 %). In both crash types, a rise in braking maneuvers can be seen in the last 0.5 s before impact. In *UTYP 342* crashes, more drivers stood still once in the last seconds before impact compared with *UTYP 341* crashes, with a maximum of 20.6 % vs. 13.7 % at $t = -1.5\ s$. At $t = 0\ s$, the constant velocity driving maneuver is slightly more frequent in *UTYP 341* crashes (33.6 %) than in *UTYP 342* crashes (30.6 %). The distribution of maneuvers of KSI crashes is similar to the distribution of all injury crashes except for more constant driving and less acceleration maneuvers in *UTYP 341* crashes.

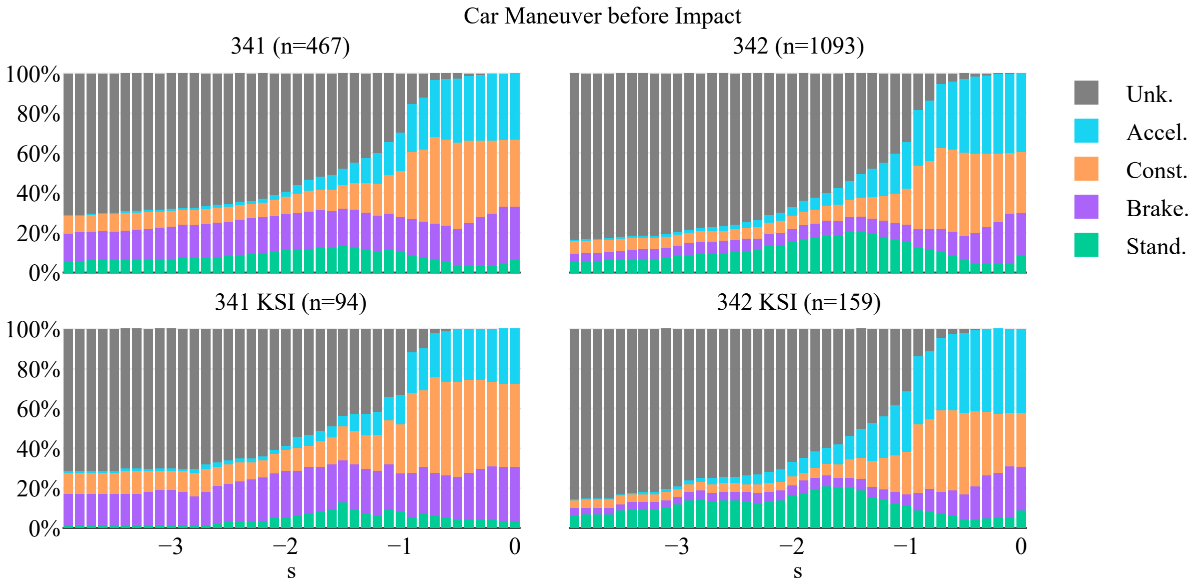

Figure 11. Frequency distribution of the cars' maneuvers in the last four seconds before the collision.

Due to the declining availability of reconstructed speed for $t <= -1\ s$, the focus during the following analysis lies only on the last second before the collision. Fig. 12 depicts the analysis of the **cars' speeds during the last second** before the impact, clustered into the three maneuvers accelerating, constant speed drive, and braking.

For *UTYP 341* crashes where the car was **accelerating** in the actual interval, the median speed was 5.78 kph (Q1: 4.48 kph, Q3: 9.24 kph) at one second before the impact and 10.0 kph (Q1: 8.0 kph, Q3: 15.0 kph) at impact. Median speeds for *UTYP 342* are similar, while quartiles are lower with 5.33 kph (Q1: 4.0 kph, Q3: 7.13 kph) at $t = -1\ s$ and 10.0 kph (Q1: 7.0 kph, Q3: 12.0 kph) at $t = 0\ s$. There is no significant difference for acceleration crashes in speeds between KSI and all injury crashes.

In the group of the cluster of **braking** intervals before the crash, speeds are higher: the median for the interval at $t = -1\ s$ is 17.76 kph (Q1: 14.54 kph, Q3: 21.74 kph) for *UTYP 341* and 17.1 kph (Q1: 12.03 kph, Q3: 21.5 kph) for *UTYP 342* crashes. At $t = 0\ s$, the medians for intervals are 12.0 kph (Q1: 7.0 kph, Q3: 17.0 kph) for *UTYP 341* and 10.0 kph (Q1: 7.0 kph, Q3: 15.0 kph) for *UTYP 342*. KSI crashes show higher speeds over the last second before the impact: for *UTYP 341* collisions, especially at $t = -0.7\ s$, the speed is notably higher with 19.8 kph (Q1: 14.98 kph, Q3: 28.62 kph) compared to 16.4 kph (Q1: 12.6 kph, Q3: 22.4 kph) for all injury crashes. *UTYP 342* KSI crashes have similar speeds to all injury crashes.

The intervals with **constant speed** have the following properties: The reconstructed speed intervals of 341 crashes are slightly higher than for 342 crashes. For example, the speed at $t = -1\ s$ is 15.0 kph (Q1: 10.0 kph, Q3: 22.0 kph) compared to 12.0 kph (Q1: 9.0 kph, Q3: 20.0 kph) and the speed at $t = 0\ s$ is 13.0 kph (Q1: 8.0 kph, Q3: 20.0 kph) compared to 10.0 kph (Q1: 8.0 kph, Q3: 15.0 kph). The speeds for the KSI crashes exceed the speeds of their respective crashes of all injuries as well.

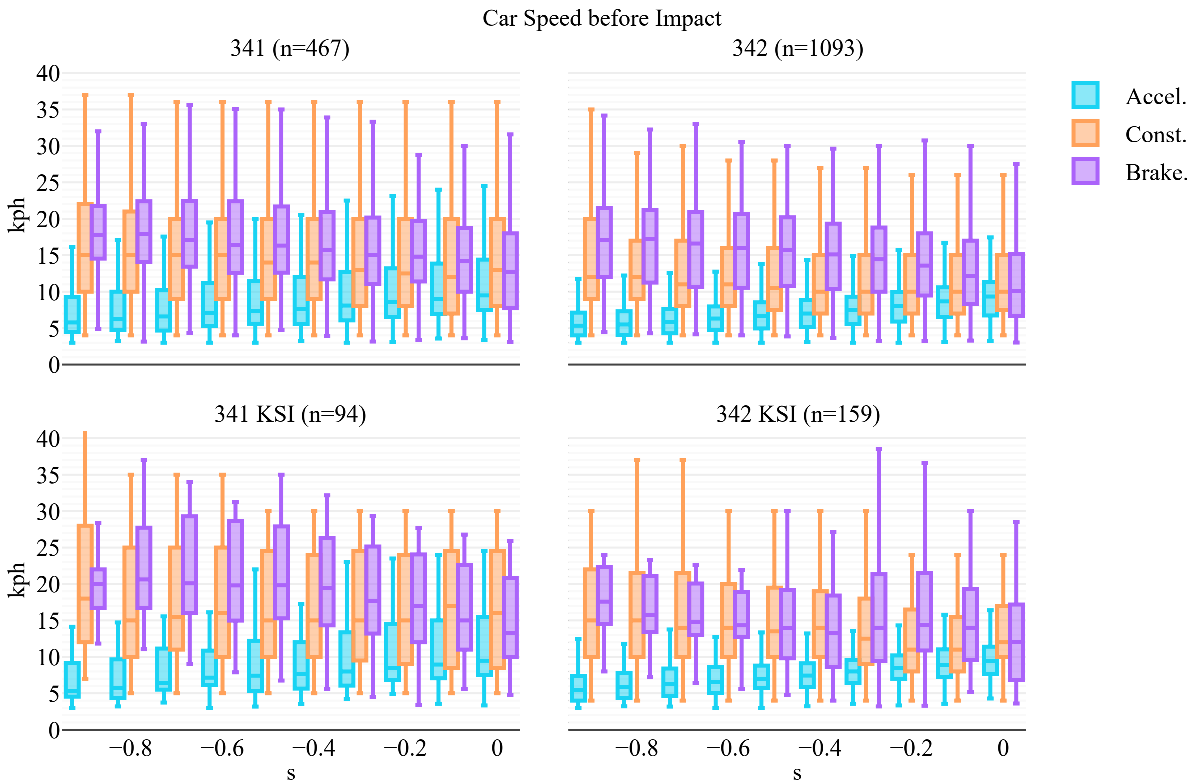

Figure 12. Box plots of the cars' speeds in the last second before the collision, grouped by maneuver performed in the particular interval.

Contact points

Fig. 13 represents the **first contact points** between cyclist and car for *UTYP 341 & 342* collisions. These are measured in centimeters from the point at the very front of the vehicle's longitudinal axis. Compared to the predominantly centered contact point in *UTYP 342* collisions, the majority of contacts in *UTYP 341* crashes are located more to the left with a maximum at −70 cm, which is where the headlight is located. Additionally, with 27.4 %, significantly more cyclists collided with the side of the car compared to 14.0 % in *UTYP 341* crashes. Most collisions into the side were recorded right at the front of the vehicle for *UTYP 342* crashes, but around 50 cm to the rear for *UTYP 341* crashes. KSI crashes occurred under very similar conditions regarding all aforementioned aspects. Only the share of contacts at the vehicle's side is slightly shifted towards the front.

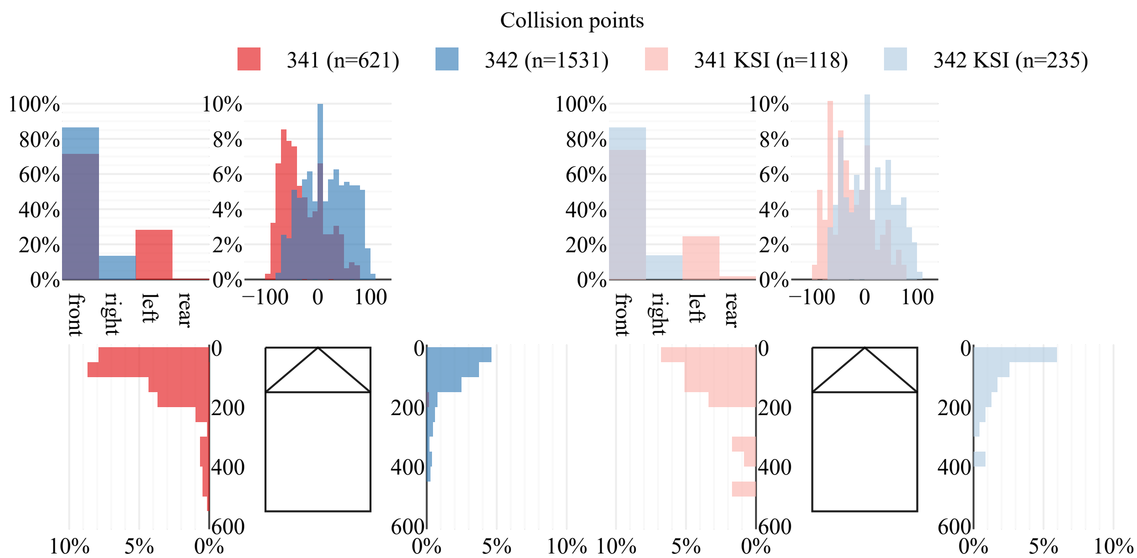

Figure 13. Distribution of first contact points of the cyclist at the car. Two UTYP 341 collisions at the rear not displayed.

DISCUSSION

Discussion of results

Summarizing the findings in Results, we can draw a picture of the ”typical crash” between cars and crossing cyclists at junctions with similarities, as well as notable differences between the collisions with the cyclist coming from the left (*UTYP 341*) and the right (*UTYP 342*):

<u>Similarities between crashes</u> **More than half of the crashes occur at junctions**. Next to that, for *UTYP 341* crashes, the share of crashes at crossings is more than twice as high for collisions at property entrances. However, *UTYP 342* crashes occur nearly as often at crossings as at property entrances.
”Give way” is the most dominant of the rules of the road at the crash site, with two thirds to three quarters of the collisions. Property entrances/exits, stop signs, traffic lights, and others play a minor role in these crashes. Between the *UTYP 341* and *UTYP 342* crashes, there is only little difference in the distribution. A slight shift toward more crashes at stop signs and property exits can be noticed for *UTYP 342* collisions.
Most crashes are turning right crashes: In nearly 90 % of the cases with the cyclist coming from the right, the car driver wanted to turn right at the junction. Other actions, therefore, only constitute slightly more than 10 % of the crashes. With the cyclist coming from the opposite side, the most common intent of the car driver is turning right as well, but here, in one third of the crashes, the driver intended to turn left or go straight ahead.
Nearly all crashes occur at low traffic densities: In about 4 out of 5 collisions, there was light traffic or only occasional cars on the road at the time of the crash, similarly distributed for crashes with the cyclist coming from left and right.
The crashes are mostly daylight crashes: While nearly 9 out of 10 *UTYP 342* crashes occur during daylight, the number for *UTYP 341* crashes is moderately lower, with 3 out of 4 crashes.
Visual obstructions are present in one third of collisions: In most crashes, no visual obstructions were on site. Yet, if there was an obstruction present, it is more likely to be in the crashes with the cyclist coming from the right than from the left, more likely for KSI crashes, and more likely to be a structural circumstance than a temporary obstacle such as a parking or waiting vehicle.
Collisions occur at relatively low speeds and while the car is accelerating: more than half of the crashes show a car’s speed of 13 kph or below, and in more than 90 % of the cases, the speed is 28 kph or less. However, the analysis of the maneuvers performed in the last second before the collision shows that accelerating was the most common action.

Cyclists are most often hit by the car's front bumper: in 70.4 % of the *UTYP 341* and 85.2 % of the *UTYP 342* crashes, the collision point between cyclist and car was recorded at the car's front. In crashes where the cyclist came from the right, the share of impacts to the side of the vehicle is comparatively lower, and the contact point is more centered at the front bumper – both facts indicate that the car reached the cyclist at a later point in time compared to the crashes where the cyclist came from the left.

Differences between crashes **Crashes where the cyclist comes from the right are more frequent:** compared to the crash type *UTYP 341*, the related *UTYP 342* crash occurs 2.6 times more frequently.
The cyclist coming from the right might not be expected on this side: as shown in Environmental circumstances, in more than 60 % of the collisions, the cyclist was ruled to be at least partially responsible for the crash. In over 80 %, the reason was the wrongful use of the cycleway against the prescribed driving direction, meaning that the driver of the car could not have expected the cyclist to come from this direction.
Drivers "fail to look" at cyclists coming from the right and "look but fail to see" cyclists from the left: crashes, where data shows that reduced visibility could play a role, are more present in the *UTYP 341* group. For example, as seen in fig. 6, the collision ratio at night is nearly three times as high as in the *UTYP 342* crashes. It is also notable that *UTYP 342* crashes are almost entirely turning-right crashes. When the driver wanted to turn left or go straight over the crossing and therefore had to also look for traffic coming from the right, notably fewer crashes occur when the cyclist comes from the right. Following the work of Summala et al., we assume that once the driver is forced to look right to avoid collisions with other cars, the cyclist is perceived as well [3]. Visual obstructions are also more present in *UTYP 342* crashes, thus blocking the chance of seeing the cyclist coming from the right in time.
Crashes with the cyclist coming from the right occur at lower speeds: in *UTYP 342* crashes, the (collision) speed of the cyclist is lower compared to the opposite crash scenario. We suppose that cyclists might drive slower, purposely knowing that they are not expected by the cars' drivers when coming from that direction. The speed of the cars is also lower before and at the time of the collision, and drivers are more often accelerating again after standing still. The share of crashes at stop signs is higher compared to *UTYP 341* crashes, indicating that the driver had stopped or was about to stop before the collision. Additional time gained by slower maneuvers could have prevented the crash by decreasing the chance of overlooking the cyclist coming from the left, while in *UTYP 342* crashes, the two participants still collided, backing the thesis that the cyclist from the right is not seen at all due to visual obstructions or the drivers' omission to look right.
The cyclist's speed at the time of the collision does not affect the severity. In contrast, the car's speed does: A comparison of the speeds of both cyclist and car with the speeds for KSI crashes shows that there were not significantly more severe injuries or deaths when the collision speed of the cyclist was higher. However, the distribution of the collision speed of the car is visibly shifted to higher speeds for KSI crashes compared to all injury crashes.

Comparison to related works

As mentioned in Related Works, this work shares its methodology to some extent with the SECUR publication [10]. However, it focuses on a subset of a certain type of cyclists crashes within the group of crashes in the SECUR so-called "accident scenarios" *Straight Crossing Path – Left & Right Direction Bicyclist (SCP-LD-BC & SCP-RD-BC)*. It is obvious to compare the characteristics of the *UTYP 341* and *UTYP 342* crashes with these accident scenarios. Since the SECUR publication focuses on KSI crashes, only these are considered in the following comparison:
Compared to 50 % of the crashes in the SCP-LD-BC group and 55 % of crashes in the SCP-RD-BC group, in 74.2 % of the *UTYP 341* and 64.9 % of the *UTYP 342* KSI collisions, the car driver had to yield. Structural visual obstructions were present in 17 % (30 % presence of obstructions times 57 % structural obstructions) for SCP-LD-BC and 24 % (35 % times 69 %) for SCP-RD-BC compared to 21.5 % and 35.1 % in our analysis. Reported traffic densities were similar (sporadic or light traffic was present in 80 % for both SCP-LD-BC and SCP-RD-BC vs. 78.2 % and 78.2 %), as well as daylight conditions (80 % and 87 % vs. 71.4 % and 91.0 % crashes during daylight.) This indicates that the *UTYP 341 & 342* crashes are especially prone to visual obstructions in comparison to the larger group of crashes in similar constellations, and required yielding by the car driver is more common than other forms of rules of the road, such as stop signs or traffic lights.
The work's results align with the results of Summala et al., who analyzed car-cyclist crashes from 1987 to 1989 in Helsinki and found that the prevalent crash type is one where the cyclist came from the right and the car driver

wanted to turn right [3]. The crashes studied also showed low traffic densities. The authors also assumed that measures reducing the speed at the intersection and, thus, providing the driver more time increases the chance to see the cyclist and hence avoid the collision.

Gohl et al. state that in crashes where the cyclist came from the right, the driver ”failed to look” into the cyclist's direction, whereas in crashes where the cyclist came from the left, the driver ”looked but failed to see” the cyclist [4]. Our findings, for example, the high share of right-turning maneuvers in *UTYP 342* crashes and the comparatively higher proportion of visual obstacles confirm their statements. Their finding that drivers pay less attention when they expect the other party to comply with traffic regulations also backs up our result that the cyclist riding on the wrong lane and, therefore, crossing the car's path from the right might not be expected.

Using the data from several European countries, Uittenbogaard et al. highlighted that whether a cyclist is severely injured or killed is influenced by the car's speed at the time of impact, not by the cyclist's speed [6]. Our data also revealed similar results but for severe versus slight injuries.

Limitations of this study

In the present study, we solely used the famous GIDAS dataset as the basis for our evaluation. This data, collected in two cities in Germany, is as representative as possible of German crashes according to the data's providers due to sampling and weighting mechanisms [14]. Yet, the results cannot be projected directly onto other nations' crash occurrences. Especially the frequency of the selected crash scenarios, *UTYP 341 & 342* presumably differs from country to country, e.g., due to other road infrastructure, traffic rules, or driver education. Other works proved that, e.g., in Hungary, the most common crash scenarios are those in the longitudinal direction [15]. Though, there is also a high relevance of crossing scenarios in France, Italy, the Netherlands, Sweden, the UK [5], Australia [9], and the USA [8], as previous works have demonstrated. We, hence, suppose that the underlying principles of these crashes are similar in other countries. For example, it can be assumed that drivers turning right often focus on traffic from the left; therefore, cyclists from the right are not noticed. This has also been shown by similar works in Finland [3].

Since records are only added to GIDAS if the crash is rated as an injury crash, we do not have any information about the milder crashes without injuries. Also, due to the significant underreporting of crashes with cyclists [16, 17], data might be skewed toward the crashes that are reported. This includes especially crashes with low injury severity, while in contrast, crashes with pedelecs are relatively more often reported [2].

CONCLUSIONS

This work's goal lies in exploring the most common crash scenario between cars and cyclists and its characteristics. Therefore, using the GIDAS database, we first identified the crashes where the car collided with a crossing cyclist riding on a cycleway as the most significant crashes with a share of 28.9 % of all car-cyclist collisions. In the subsequent analysis, we then focused on these crashes but discriminated between the cases where the cyclist came from the left and the cases where the cyclist came from the right, as well as between crashes with all levels of injuries and crashes with killed and severely injured (KSI).

The most common crashes between cyclists and cars, as recorded in the GIDAS data set, can be described as crashes with light injuries at junctions where the car driver disregarded the right of way of the crossing cyclist. The car driver intended to turn right and merge into light traffic while the rules of the road required yielding. In the significantly more common case, the cyclist came from the right and was partially to blame for the crash for riding in the wrong direction. Most of the collisions occurred in daylight and without visual obstructions. The car's speed was less than or equal to 13 kph, and the cyclist's speed was less than or equal to 18 kph. In the last second before the collision, the car was accelerating or driving with nearly constant velocity. At the collision, the cyclist made first contact with the front of the car.

We demonstrate that besides similarities in environment and course of events of the crash, there are few features distinguishing the collisions with the cyclist coming from the left and the right: for instance, we assume that, in right-hand traffic, the driver ”fails to look” at the cyclist from the right and ”looks but fails to see” the cyclist from the left. The circumstance that a cyclist coming from the right might not be expected could contribute to these collisions. It is noticeable that comparatively fewer crashes occur in a situation where the driver had to look right, i.e., turning left or driving straight over a crossing. Our work also shows that the cyclist's severity of injuries is only influenced by the car's, not the cyclist's speed.

The present results highlight the need for measures reducing crashes with cyclists, especially in crossing situations. This includes well-designed traffic infrastructure protecting cyclists at junctions and crossings or avoiding crossing situations of these parties at all, but also novel in-vehicle safety applications making the driver aware of cyclists and, in general, VRUs in critical situations. Since Vehicle-to-everything (V2X) communication does not require line-of-sight conditions, systems based on this technology could support creating awareness of VRUs in the near future [18].

By means of the results presented, our follow-up work will consist of developing these novel safety applications based on vehicle-to-everything communication to avoid these types of crashes. The results will help us to understand the crash occurrence between cars and cyclists and allow us to determine requirements and derive parameters for aforementioned applications.

REFERENCES

[1] European Parliament, Council of the European Union. (2018, January 9). Directive 2010/40/EU of the European Parliament and of the Council of 7 July 2010 on the framework for the deployment of Intelligent Transport Systems in the field of road transport and for interfaces with other modes of transport (Text with EEA relevance) [OJ L 207 6.8.2010]. Retrieved June 4, 2021, from https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=CELEX:02010L0040-20180109

[2] Maier, O., Hattula, S., Schneider, S., Mönnich, J., & Lich, T. (2021–November 12). Pedelec user study: Safety insights into an emerging vehicle [11]. *Proceedings of International Cycling Safety Conference 2021*.

[3] Summala, H., Pasanen, E., Räsänen, M., & Sievänen, J. (1996). Bicycle accidents and drivers' visual search at left and right turns [Journal Article]. *Accident Analysis & Prevention*, *28*(2), 147–153. https://doi.org/10.1016/0001-4575(95)00041-0

[4] I. Gohl, A. Schneider, J. Stoll, M. Wisch, & V. Nitsch. (2016–November 4). Car-to-cyclist accidents from the car driver's point of view. *Proceedings of International Cycling Safety Conference 2016*. https://doi.org/10.5281/zenodo.1135194

[5] Op den Camp, O. M., Ranjbar, A., Uittenbogaard, J., Rosen, E., & Buijssen, S. (2014–November 19). Overview of main accident scenarios in car-to-cyclist accidents for use in AEB-system test protocol. *Proceedings of International Cycling Safety Conference 2014*.

[6] Uittenbogaard, J., van Montfort, S., et al. (2016–November 4). Overview of main accident parameters in car-to-cyclist accidents for use in AEB-system test protocol. *Proceedings of International Cycling Safety Conference 2016*.

[7] Bálint, A., Labenski, V., Köbe, M., Vogl, C., Stoll, J., Schories, L., Amann, L., Sudhakaran, G. B., Huertas Leyva, P., Pallacci, T., Östling, M., Schmidt, D., & Schindler, R. (2021). SAFE-UP Deliverable D2.6: Use Case Definitions and Initial Safety-Critical Scenarios. Retrieved November 27, 2022, from https://www.safe-up.eu/s/SAFE-UP_D2_6_Usecasedefinitionsandinitialsafety-criticalscenarios_.pdf

[8] MacAlister, A., & Zuby, D. S. (2015–September 11). Cyclist Crash Scenarios and Factors Relevant to the Design of Cyclist Detection Systems. *2015 IRCOBI Conference Proceedings*, 373–384.

[9] Beck, B., Stevenson, M., Newstead, S., Cameron, P., Judson, R., Edwards, E. R., Bucknill, A., Johnson, M., & Gabbe, B. (2016). Bicycling crash characteristics: An in-depth crash investigation study [Journal Article]. *Accident; analysis and prevention*, *96*, 219–227. https://doi.org/10.1016/j.aap.2016.08.012

[10] Cornec, L., Unger, T., Rössler, R., Feifel, H., Hermitte, T., Page, Y., Puller, N., & Mousavi, M. (2023–April 6). Analysis of the European Car Road Accidents for the Identification of the Main Use Cases for a Significant Road Safety Improvement Through V2X. *Proceedings of the 27th ESV Conference*.

[11] *About GIDAS – Methodology*. (2022). Verkehrsunfallforschung an der TU Dresden GmbH. Retrieved December 10, 2022, from https://www.gidas.org/about-methodology-en.html

[12] Unfallforschung der Versicherer (Ed.). (2016). Unfalltypen-Katalog: Leitfaden zur Bestimmung des Unfalltyps. *Gesamtverband der Deutschen Versicherungswirtschaft e. V.* Retrieved October 8, 2022, from https://www.udv.de/resource/blob/80022/89b4d80028aacf8cab649d3a3c6157a0/unfalltypenkatalog-data.pdf

[13] R Core Team. (2018). R: A Language and Environment for Statistical Computing.

[14] *Welcome to GIDAS*. (2022). Verkehrsunfallforschung an der TU Dresden GmbH. Retrieved December 10, 2022, from https://www.gidas.org/start-en.html

[15] Glász, A., & Juhász, J. (2017). Car-pedestrian and car-cyclist accidents in Hungary [PII: S2352146517303666]. *Transportation Research Procedia*, *24*, 474–481. https://doi.org/10.1016/j.trpro.2017.05.085

[16] Maier, O., Pfeiffer, M., Wehner, C., & Wrede, J. (2015–September 16). Empirical Survey on Bicycle Accidents to estimate the Potential Benefits of Braking Dynamics Assistance Systems [09]. *Proceedings of International Cycling Safety Conference 2015*.

[17] Madsen, T. K. O., András Várhelyi, Evelien Polders, Sofie Reumers, Pau Hosta, Bibiloni, D. J., Alia Ramellini, Niels Agerholm, & Lahrmann, H. S. (2018). *Assessment of Safety of VRUs Based on Self-Reporting of Accidents and Near-Accidents*. European Commission * Office for Official Publications of the European Union.

[18] Feifel, H., Erdem, B., Menzel, M., & Gee, R. (2023–April 6). Reducing Fatalities in Road Crashes in Japan, Germany, and USA with V2X-enhanced-ADAS. *Proceedings of the 27th ESV Conference*.