Pedelec user study: Safety insights into an emerging vehicle

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ABSTRACT

The aim of this study is to understand the real-world use of both bicycles and Pedelecs in order to contribute to an increased road safety of both vehicle types. Due to a lack of in-depth information in the user research thus far, a quantitative user study was conducted (survey details: period June/ July 2020, countries GER, CH, NL, FR, UK and USA; participants: N = 3026, Ø age 44.07 years, 49.6 % female, bicycle or Pedelec owner).

The survey results indicate that Pedelecs compared to bicycles are used more for everyday purposes (+20 % commuting and errands), more frequently (+50 %), and more for traveling longer distances (+60 %). The riders try to compensate for their higher accident exposure by increasing their visibility in road traffic (e.g. light-reflecting vests +9 %) and by wearing a helmet (+9 %). Most accidents occur in urban areas (70 %) and at intersections (29 %), which motivates the improvement of traffic and bicycle infrastructure. Car- and truck-side systems such as turning assistants, reverse driving assistance, and dismounting warning systems can effectively mitigate potential conflicts as well. Single bicycle accidents occur second most frequently after passenger car accidents. In comparison, single Pedelec accidents are 13% less frequent, but accidents involving other vulnerable road users are more frequent. Therefore, the infrastructure should be adapted to the increasingly multimodal use and anti-lock braking systems (ABS) should be used to achieve short braking distances. In 18 % of the cases, the injured cyclists and Pedelec riders did not receive direct medical help, which can be reduced by eCall systems.

If these challenges regarding road safety are solved, the user study shows that both bicycles and Pedelecs can be established even more strongly as a sustainable and safe means of transport in the mobility mix of the future.

Keywords: Pedelec, safety, user study, accident analysis.

1 INTRODUCTION

Two-wheelers, with and without electric drive, are the means of transport of the moment. Already in the past years and again strengthened by the SARS-COV-2 pandemic since the year 2020, the bicycle industry undergoes a dynamic growth. In the future, it can be assumed that every second bicycle sold in Europe will be a Pedelec (acronym for pedal electric cycle). The prerequisite for this strong spread of the Pedelec is the increasing diffusion into different types. In 2020, according to statistics from the German two-wheeler industry association, the distribution was as follows: eCity/Urban 28 %, eTrekking 35.5 %, eCargo 4 %, eMTB 30 %, eRoad 0.5 %, and S-Pedelecs 0.5 % (Eisenberger, 2021). It should be noted that the eCargo and eMTB types have the highest growth rates, whereas the S-Pedelec has little appeal due to stricter regulation in the L1e-B class. The quality and safety awareness of buyers is encouraging, which ensures that Pedelecs are purchased with high equipment standards. This fact given in combination with the available electrical energy and computing power on Pedelecs pave the way for assistance systems to increase safety in cycling.

Bosch eBike Systems has already launched the world's first production-ready ABS (acronym for anti-lock braking system) for Pedelecs in 2018 (Bosch eBike Systems, ABS, 2021). ABS enables controlled braking even under difficult conditions. The ABS for Pedelecs was developed by Bosch, based on the already established ABS for motorcycles. The combination of front wheel ABS and rear wheel lift-off control makes Pedelec riding safer. During difficult braking manoeuvres, the braking pressure of the front brake is regulated and thus an optimum is found in the trade-off between stability and deceleration in the given riding situation. In addition to the ABS, Bosch eBike Systems launched the Help Connect feature via App as a passive safety system in 2020 (Bosch eBike Systems, Help Connect, 2021). In the event of a fall, an emergency call is made. This alerts a trained service team that is available around the clock and immediately notifies emergency services in case needed.

This manuscript examines the road safety on the market development of Pedelecs, considering both the specifics of Pedelec use, which were collected in the form of a quantitative user study, and the benefits of safety systems. In addition to the introduction, the manuscript is divided into four chapters. Chapter 2 gives an overview about the current state-of-the-art and explains the materials and methods used for gaining the results. Chapter 3 describes in detail the new insights on Pedelec usage characteristics, safety behaviour, accident experience and future role. Chapter 4 discusses the implications of the findings on Pedelec road safety and deduces recommendations for action. Chapter 5 summarizes the manuscript and draws conclusions on the presented content.

2 MATERIAL AND METHOD

2.1 Official accident statistics

The road safety of Pedelecs is essential for the long-term establishment of this mode of transport. It should be noted that in most countries, Pedelecs are not specifically included in official accident statistics or have only been included for a relatively short period of time (e.g. in Germany since 2014, (Gehlert, 2014)). Furthermore, the development of accident statistics is just as dynamic as the development of the Pedelec market, which is why short-term trends must be distinguished from long-term trends.

For example, the strong increase in accident figures according to DESTATIS[1] for bicycle and Pedelec accidents in Germany in 2018 and 2019, which can be seen in Figure 1, is basically due to a dry and warm climate (Kirsche, Lux, & Friedrich, Deutschlandwetter im Jahr 2018, 2018) (Kirsche & Friedrich, Deutschlandwetter im Jahr 2019, 2019), which leads to increased bicycle and Pedelec use. The opposite influence of climate on accident occurrence is evident in 2010, in which a very pronounced phase with wintry conditions prevailed in Germany over the year as a whole (esp. Jan.-March and Nov.-Dec.) (Kirsche & Lux, Deutschlandwetter im Jahr 2010, 2010). Such a climatic constellation causes that less bicycles and (in 2010 still hardly existing) Pedelecs are ridden and at the same time the drivers of motorized vehicles such as cars act more cautiously in traffic.

In general, the trend of bicycle accidents has been increasing for more than ten years (e.g. in Germany for bicycle and Pedelec accidents with personal injury[2] by +18% since 2004, see Figure 1), whereby the number of bicycle and Pedelec riders killed in Europe (Adminaité-Fodor & Jost, 2020) in general and in Germany (see Figure 1) in particular is at the same level as in 2004. Compared to motor vehicles, motorcycles and pedestrians, there is a need for action for bicycles and Pedelecs.

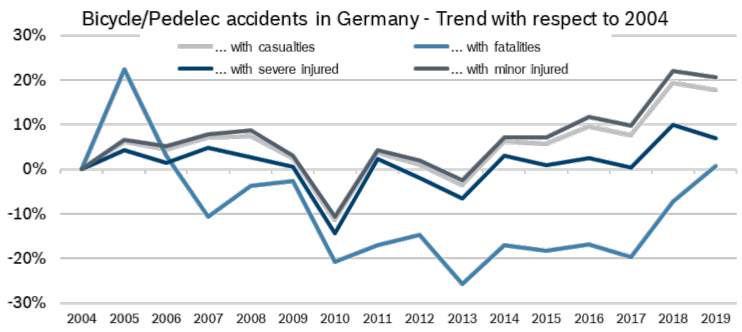

Figure 1: Official bicycle and Pedelec accidents in Germany since 2004, Source: DESTATIS

[1] German Federal Statistical Office (DESTATIS) on "traffic accidents" published annually

[2] Accidents with personal injury are those in which persons were injured or killed, irrespective of the amount of damage to property, cf. DESTATIS on "Verkehrsunfälle, Grundbegriffe der Verkehrsunfall-statistik", published on 26.03.2021.

Figure 2 and Figure 3 show the age distribution of bicycle and Pedelec users (Nobis & Kuhnimhof, 2019) as well as the age distribution of riders who were involved in accidents and killed in Germany according to DESTATIS. Older riders on bicycles and Pedelecs are at increased risk of fatal accidents. Furthermore, the use of bicycles is very similar across all age groups, with a noticeable difference among schoolchildren (10-19 years). In contrast, Pedelec use varies greatly across age groups and is found primarily in the age group 50 years or older. The age distribution of users of bicycles and Pedelecs coincides with the age distribution of riders involved in accidents, which leads to the following conclusions:

- The general accident risk correlates with use (independent of age).
- The risk of a fatal accident correlates with age (independent of use)

Consequently, it is necessary to (1) understand the actual use of bicycles and Pedelecs in detail, and (2) identify further age-specific risk factors in order to deduce recommendations for action. The aim of this paper is to give new insights on these questions through the results of a detailed user study and thus contribute to an increased road safety of bicycles and Pedelecs.

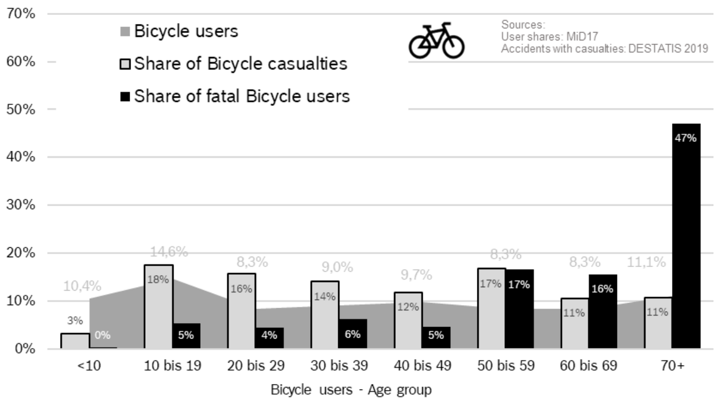

Figure 2: Age distribution of bicycle casualties and users, according to DESTATIS and (Nobis & Kuhnimhof, 2019)

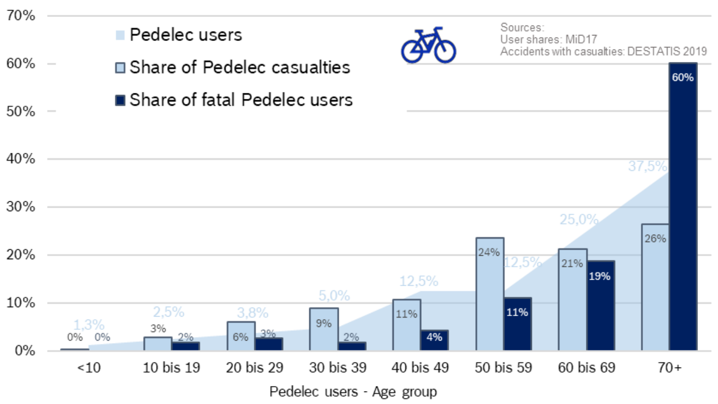

Figure 3: Age distribution of Pedelec casualties and users, according to DESTATIS and (Nobis & Kuhnimhof, 2019)

2.2 User study

The user study conducted by Bosch eBike Systems is a quantitative online study, which was carried out in the months of June and July of 2020[3] in six countries: Germany (GER, N = 519), Switzerland (CH, N = 499), Netherlands (NL, N = 501), France (FR, N = 503), United Kingdom (UK, N = 503), and United States of America (USA, N = 501). The N = 3026 participants (average age 44.07 years, 49.6 % female; see Figure 4), who were required to own one or more bicycles or Pedelecs at the time of the survey, were recruited with the help of an external panel provider according to the demographic characteristics of adults aged 18-70 years in each country. Of the sample, 23 % lived in a village setting (n < 10 thousand inhabitants), 29 % in a small town (10 thousand inhabitants ≤ n < 100 thousand inhabitants), 21 % in a medium-sized city (100 thousand inhabitants ≤ n < 500 thousand inhabitants), 15 % in a large city (500 thousand inhabitants ≤ n < 1 million inhabitants), and 12 % in a metropolis (n ≥ 1 million inhabitants) at the time of the survey. At the time of the survey, 93.2 % of the participants owned a bicycle and 31.8 % owned a Pedelec, although the distribution of bicycle types differs between bicycles and Pedelecs according to the actual differences in penetration (see Figure 5). In the analysis of the sample, it becomes clear that the Pedelec, like the bicycle, now penetrates all age groups. The average age of the Pedelec riders (48.35 years) is only slightly higher than that of the bicycle riders (44.63 years). The sample described above, whose data was ultimately evaluated by internal experts, can be considered representative overall.

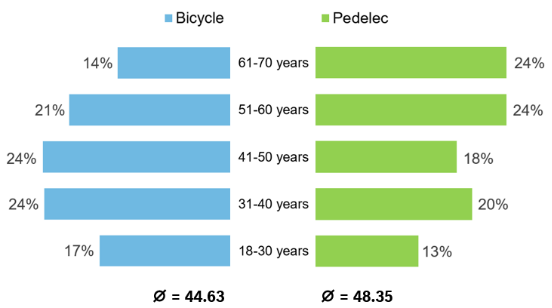

Figure 4: Age distribution of the sample (N = 3026)

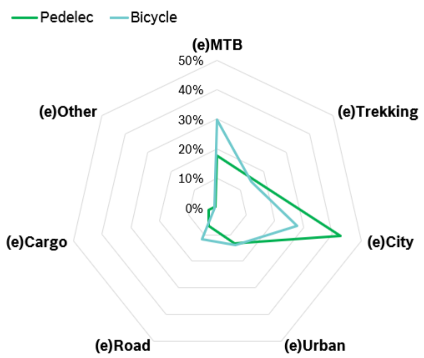

Figure 5: Bicycle type distribution over sample (N = 3026)

[3] An influence of the SARS-COV-2 pandemic on the results, especially with regard to the extent of use, cannot be ruled out, although at the time of the survey, significant mobility- and safety-changing factors (e.g., so-called "lockdown" measures) were less pronounced in the European countries than in 2020 as a whole.

3 RESULTS

The results presented are divided into four subsections. The first subchapter deals with bicycle and Pedelec use in general, whereas the second subchapter focuses on the safety behaviour of users in particular. Subchapter three focuses on accident experience and compares this with the usage characteristics found. The concluding fourth subchapter looks into the future and shows the potential role of the Pedelec in the mobility mix.

3.1 Usage characteristics

Bicycle and Pedelec usage characteristics are presented in this subsection based on categories: trip characteristics, route profiles, and environmental conditions.

3.1.1 Trip characteristics

The starting point for the analysis of bicycle or Pedelec use is the question about the use cases that respondents do by bicycle or Pedelec:

"What are the specific occasions/ situations you are using your bike/ Pedelec?"

The results of the study are shown in Figure 6, where it is striking that Pedelecs are used more frequently for commuting (+19 %) and errands (+13 %) than bicycles. Conversely, Pedelecs are used less as sports equipment than bicycles (-14 %).

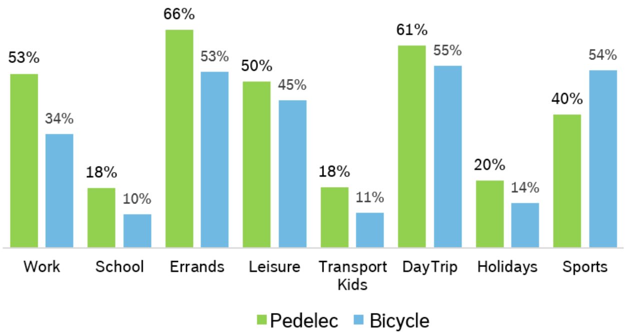

Figure 6: Use cases of bicycle and Pedelec (N = 3026)

The results indicate greater use of the Pedelec as an everyday vehicle compared to the bicycle. This can be proven by the questions about frequency of use and distance typically travelled:

"Do you ride a Pedelec more often (in terms of frequency of use) than a "regular" bicycle?"

"How many kilometres do you travel approximately on your bike/ Pedelec per year on average (i.e., sum of all distances)?"

The survey results show that Pedelecs are used more frequently (+67 %) and for longer distances (+60 %) than bicycles across all countries. It is interesting to note the strong difference in absolute distances travelled between the individual countries (see Figure 7). In NL, followed by GER and FR, the greatest distances in absolute terms are covered by bicycle and Pedelec.

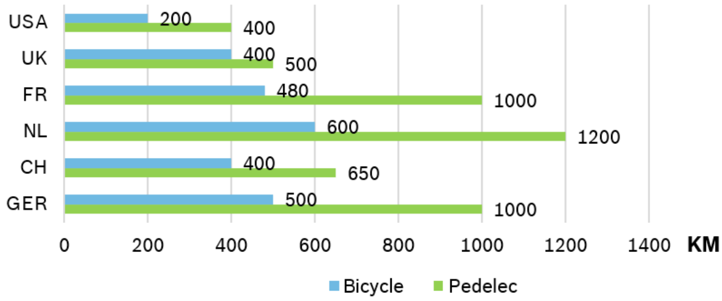

Figure 7: Mileage of bicycle and Pedelec in km per year (median, N = 3026)

3.1.2 Route profiles

The survey results regarding route profiles were similar to a large extent between bicycle and Pedelec. Of interest are the results to the questions about topography and sub-terrain, i.e., road surface:

> "What type of terrain do you predominantly ride on when you travel the routes by bicycle/ Pedelec?"

> "What types of surfaces are you predominantly traveling on when you travel the routes by bicycle/ Pedelec?"

Most trips are made with both types of vehicles on flat surfaces (see Figure 8) and on asphalt (see Figure 9). Pedelecs are used slightly more often (+6 %) in hilly topography, but less on trails (-6 %). The latter finding is consistent with the reduced use of Pedelecs for athletic use compared to bicycles from the use case analysis. The former finding is consistent with similar studies (Dozza, Werneke, & Mackenzie, 2013) and can be seen as a consequence of the increased use of Pedelecs as an everyday vehicle, in which route choice is more limited than for recreational trips (e.g. commuting or shopping).

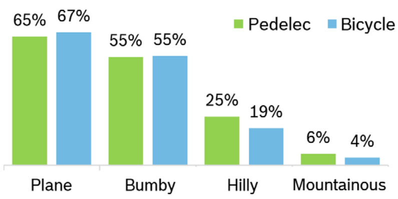

Figure 8: Topography of bicycle and Pedelec trips (N = 3026)

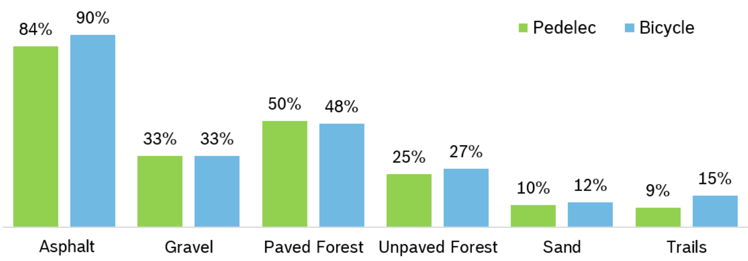

Figure 9: Road surface of bicycle and Pedelec trips (N = 3026)

3.1.3 Environmental conditions

Based on the results of the trip characteristics and route profiles, it can be assumed that due to the use of the Pedelec as an everyday vehicle, it is subject to a higher exposure to challenging environmental conditions. The two relevant questions in this context about the season and weather conditions during bicycle and Pedelec use confirm this assumption:

> "At what time of year do you ride your bicycle/ Pedelec at least occasionally?"

> "In which of the following weather conditions do you ride your bicycle/ Pedelec at least occasionally?"

Bicycles and Pedelecs are used to a comparable extent in good weather conditions (see Figure 10) and in the seasons of spring (88 % to 87 %), summer (94 % to 92 %), and fall (75 % to 77 %). According to Figure 10, bad weather conditions such as especially rain (+5 %), fog (+8 %), and changing conditions (+6 %) expose Pedelec riders more often than bicycle riders. Due to the modal shift towards Pedelecs for commuting, Pedelecs are also more likely to be used in winter conditions than bicycles (37 % to 31 %).

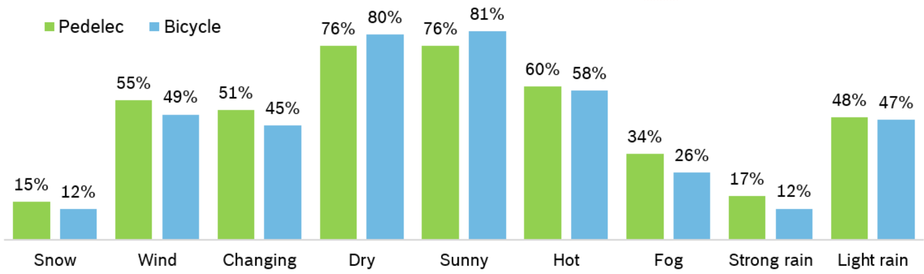

Figure 10: Weather conditions for bicycle and Pedelec use (N = 3026)

From the survey results on the riding profiles, it can be summarized that Pedelecs are used more than bicycles for everyday purposes, are used more frequently, are used to travel longer distances and are used more independently of the weather. Due to the associated higher exposure to accidents, the next subchapter is devoted to the safety behaviour of users.

3.2 Safety behaviour

The safety behaviour is analysed based on the user's accident anxiety and riding behaviour adaption, the used safety products, and the readiness for preventive maintenance.

3.2.1 Accident anxiety and riding behaviour adaption

The survey result regarding...

> "How worried are you about being involved in an accident with your bike/ Pedelec?"

... shows a high level of uncertainty among users. Only 21 % of the respondents for bicycles and 24 % for Pedelecs consider their individual accident risk to be low, whereas 39 % of the respondents for both bicycles and Pedelecs consider their individual accident risk to be high. The pronounced subjectively perceived uncertainty of bicycle and Pedelec riders has a considerable influence on their riding behaviour, as the survey results show in response to the following question:

> "To what extent does your concern about being involved in an accident with your bicycle/e-bike influence your driving behaviour?"

According to Figure 11, cyclists particularly avoid certain routes (53 %), weather conditions (52 %), high speeds (42 %) and certain journey times (38 %) in response to concerns about accidents. Apart from avoiding high speeds (also 42 %) and reducing motor assistance by choosing a suitable riding mode (17 %), avoidance behaviour is less pronounced among Pedelec riders than among cyclists (difference of 7 % to 11 %), which can be explained by the use of the Pedelec as an everyday vehicle. Pedelec riders do not have the possibility to avoid certain weather conditions, routes, or riding times.

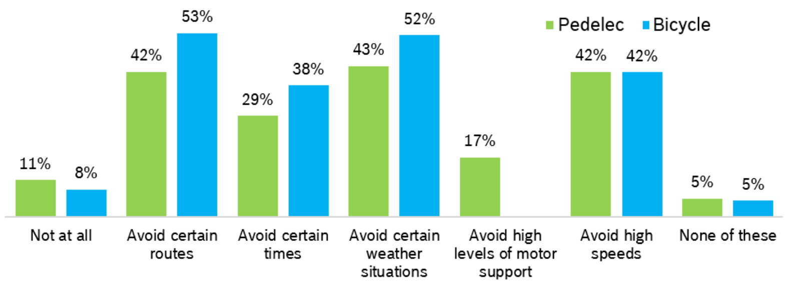

Figure 11: Adaptation of cycling and Pedelec riding behavior across all countries (N = 2357)

The comparison of the individual countries is interesting (cf. Figure 12). In NL, for example, where the bicycle is already the most established everyday vehicle and the cycling infrastructure is the most developed (Castro, Kahlmeier, & Gotschi, 2018), 42 % of respondents perceive the risk of accidents as low, while at the same time adapting their cycling behaviour significantly less. For example, only 31 % of respondents avoid certain routes and only 19 % avoid certain driving times. It follows that a high subjective safety of users can go hand in hand with the use of bicycles and Pedelecs as everyday vehicles, provided that the general conditions are bicycle- and Pedelec-friendly.

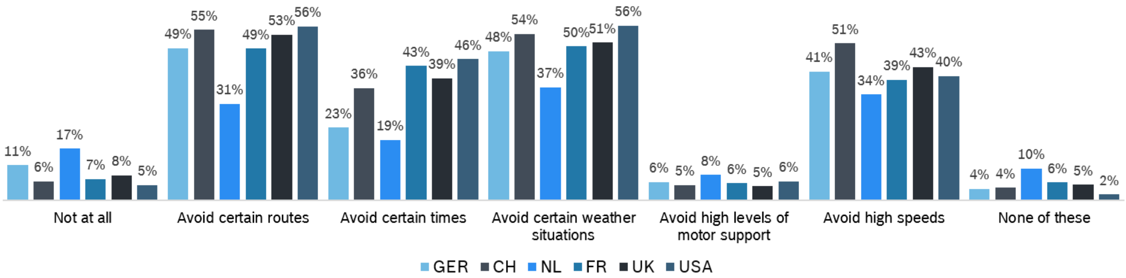

Figure 12: Adaptation of bicycle and Pedelec riding behavior for individual countries (N_{GER} = 405, N_{CH} = 389, N_{NL} = 293, N_{FR} = 417, N_{UK} = 434, N_{USA} = 419)

3.2.2 Used safety products

Due to the subjective uncertainty in combination with limited possibilities to adapt the riding behaviour, especially among Pedelec riders, the question arises whether and in what form the respondents make use of safety products such as a helmet. The survey result to the question...

"How often do you wear the following products while riding your bike/ Pedelec?"

... shows that Pedelec riders generally use safety products on their vehicle (e.g. +14 % rear view mirrors) and on themselves as riders more often than cyclists (cf. Figure 13). The respondents across all countries state that they always wear a helmet on their Pedelec (+4 %) and often wear a helmet (+5 %) compared to their bicycle[4]. A similar picture emerges for the use of both light-reflecting waistcoats (+5 % always and +4 % frequently) and clothing with sewn-in light reflectors (+3 % always and + 6 % frequently). These data suggest that Pedelec riders, due to their subjectively perceived uncertainty in combination with their increased exposure to accidents, try to reduce their individual accident risk by increasing their visibility in road traffic and by wearing a helmet.

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[4] The figures for bicycles and pedelecs in GER (33% of respondents always wear a helmet) are in line with the figures collected by (Nobis & Kuhnimhof, 2019) (34% of respondents always wear a helmet).

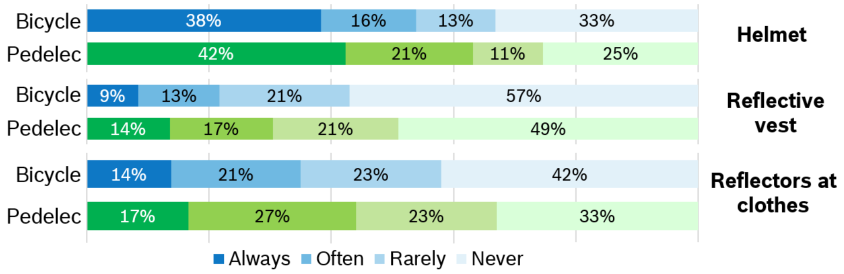

Figure 13: Safety products worn when using bicycle and Pedelec (N = 3026)

3.2.3 Preventive maintenance

In addition to the safety products used, the maintenance of the bicycle or Pedelec is another effective safety measure. The readiness for maintenance as well as the type of maintenance were surveyed with the following questions:

"How regularly is your bike/ Pedelec maintained?"

"And who usually carries out the maintenance on your bike/ Pedelec?"

The survey result for both questions is very encouraging, especially for the Pedelec. 67 % of respondents follow the typical manufacturer recommendation to service the Pedelec at least once a year. Maintenance is carried out by trained experts in specialist shops by 54 % of respondents. Compared to the Pedelec, the results for the bicycle with 55 % annual maintenance interval and 38 % maintenance by specialist dealers are lower but seem justified due to the lower frequency of use and mileage.

3.3 Accident experience

The following subchapter presents the accident experience by the respondents. Of the entire sample, in response to the question...

"Have you ever been involved in an accident yourself as a rider of a bicycle/ Pedelec?"

... 15 % of the respondents stated that they had been involved in a bicycle ($A_{ccident,\ Bicycle}$ = 317; 14.5 %) or Pedelec accident ($A_{ccident,\ Pedelec}$ = 127; 15.2 %) at least once. The accident analyses presented in the following are based on the statements of this subset of the total sample ($A_{ccident}$ = 444) and present the course of the accident, starting from the trip purpose, through the environmental and traffic conditions, to the consequences and recording of the accident.

3.3.1 Trip purpose

The use cases for bicycle and Pedelec use that preceded the accident were surveyed with the following question:

"For what specific occasion were you using a bicycle/ Pedelec when this most recent accident involving you as a bicycle/ Pedelec rider occurred in terms of time?"

The study result shows that the distribution of use cases for bicycle and Pedelec largely coincides with the identified distribution of use cases for all bicycle and Pedelec trips, as expected (cf. Figure 14 with Figure 6). Pedelec riders have more accidents in everyday situations than cyclists. In addition to commuting to work (+14 %), the transport of children (+17 %) is particularly noticeable. However, this does not mean that transporting children is dangerous. With a Pedelec, this is merely made easier and is used more than with bicycles, as the electric drive compensates for the weight of the children and a possible trailer. Thus, (ADAC, 2021) recommends that users enquire at specialist retailers whether and how child seats and trailers are possible with the respective Pedelec model. In addition, children should always wear a suitable helmet.

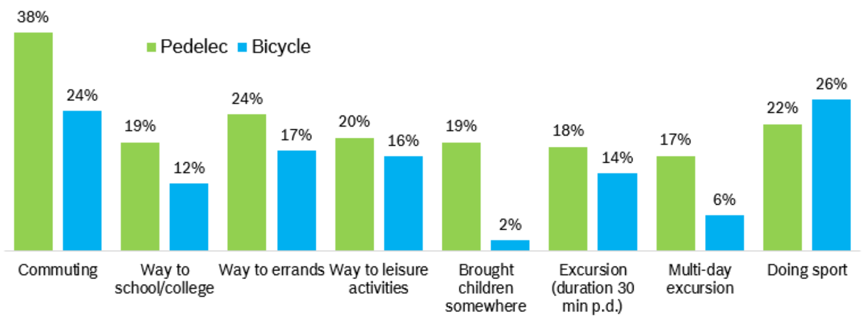

Figure 14: Use cases of bicycle and Pedelec with accident consequences (N = 444)

In line with the identified use cases, Pedelec riders were asked...

"At what time of day did the last accident with you as a bicycle/e-bike rider occur?"

... were involved in an accident more evenly throughout the day (30 % in the morning, 40 % at midday, 25 % in the evening and 5 % at night) and thus more frequently in the morning (+8 %) and in the evening (+4 %) compared to cyclists.

3.3.2 Environmental conditions

When asked about the location, road surface and weather conditions at the time of the accident....

"Where did this last accident with you as a cyclist/ Pedelec rider happen?"

"Can you remember the road surface of the location of your last accident with you as a cyclist/ Pedelec rider?"

"What were the weather conditions like at the time of the last accident involving you as a cyclist/ Pedelec rider?"

... the study results coincide with the accident exposure caused by Pedelec use as an everyday vehicle in urban areas. Most accidents occur in urban areas (70 %) and at intersections (29 %). Correspondingly, 74 % of all accidents occur on asphalted roads. As already known from the analysis of the usage characteristics (cf. Chapter 3.1), the weather can be classified as unproblematic for the majority of bicycle and Pedelec accidents. However, the higher accident exposure of Pedelecs to bad weather conditions due to their more weather-independent use cannot be neglected, cf. Figure 15. The greatest differences to bicycles are an accident frequency in light (+15 %) and heavy (+16 %) rain.

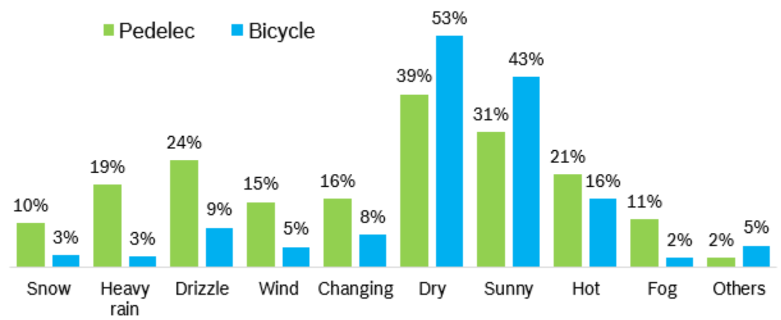

Figure 15: Weather conditions for bicycle and Pedelec accidents (N = 444)

3.3.3 Traffic conditions and accident recording

In addition to the use cases and environmental conditions, the traffic conditions, in particular the collision opponent, as well as the accident recording by the police are also important for the accident analysis. It is known from the latter that accidents involving vulnerable road users (VRUs) are heavily under-reported (Wegman, Zhang, & Dijkstra, 2012). This under-reporting limits the validity of official accident statistics and prevents a representative picture of accident occurrence, which in turn makes it difficult to deduce recommendations for action to increase road safety.

The question of the collision opponents...

"Were other road users involved in the most recent accident with you as a cyclist/ Pedelec rider?"

... showed that for both bicycle and Pedelec, motor vehicles (bicycle and Pedelec both 47 %) and passenger cars in particular (bicycle 39 % and Pedelec 36 %) were the most frequent collision opponents. It was also noticeable that Pedelecs are involved in 13 % fewer single-vehicle accidents than bicycles, whereas Pedelecs collide 12% more often with other bicycles or pedestrians. The lower proportion of single-vehicle accidents can be explained by the predominantly urban use of the Pedelec on a road with good grip (see previous section on environmental conditions), but also shows, as determined for example in (Schepers, Klein Wolt, Helbich, & Fishman, 2020) or (Twisk, Stelling, Van Gent, De Groot, & Vlakveld, 2021), that the Pedelec is easy to control (supported for example by a good technical state). On the other hand, the confined traffic space and the resulting lack of opportunities for VRUs to avoid each other seems to be critical.

Due to the deviating distribution of the collision opponents as well as Pedelec-specific trends such as the increased use of leasing offers, which in some cases contractually require the police to record the accident, the following question is of particular interest:

"Were the police called at your last accident involving you as a bicycle/Pedelec rider?"

The study result shows that in 79 % of bicycle accidents the police were not notified and consequently the accident was not recorded in the official accident statistics. In contrast, the under-reporting rate for Pedelec accidents is significantly lower by 24 % and amounts to 55 % in absolute terms. These different under-reporting rates show another problem area in accident research in the context of bicycles and Pedelecs. If the under-reporting rates of both vehicle types differ, comparative statements based on official accident statistics are difficult. This applies in particular to accidents with low injury severity of the participants, as is often the case in solo accidents of VRUs as well as in accidents of VRUs among themselves. The latter also explains the discrepancy between the collision opponents shown in DESTATIS and the collision opponents found above.

3.3.4 Accident consequence

The injury severity determined in this user study based on the following question....

"What were the consequences for you personally of the last accident with you as a cyclist/ Pedelec rider in terms of time?"

... shows Figure 16. As expected, the average injury severity is lower for bicycles and Pedelecs when corrected for age in comparison to the official accident statistics according to DESTATIS. The higher proportion of seriously injured Pedelecs compared to bicycles (+7 %) is also striking, which can be explained by the higher accident exposure of the Pedelec as an everyday vehicle, especially in urban areas (in particular collisions with other road users). Compared to the official accident statistics presented in Chapter 2.1, the age factor does not have an effect here, as the sample for bicycles and Pedelecs is almost equally distributed in the respective age categories. The explanation for the higher proportion of non-injured Pedelec users than bicyclists is the better technical condition of Pedelecs, as well as the greater riding experience of Pedelec users, e.g. as commuters.

Another interesting question regarding the consequence of accidents is:

"At the time of the last accident involving you as a cyclist/ Pedelec rider, were your injuries directly treated?"

The study result shows that of the cyclists and Pedelec riders involved in accidents, 36 % received no help, 23 % received first aid and 41 % received subsequent medical care. Compared to Figure 16, the difference between non-injured and non-assisted riders is 18 %.

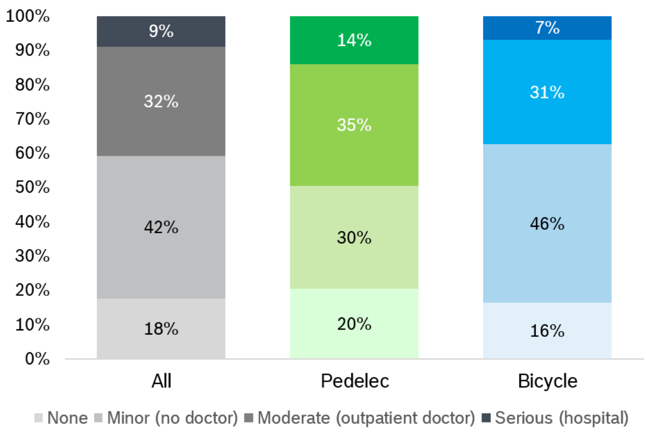

Figure 16: Injury severity in bicycle and Pedelec accidents (N = 444)

3.4 Future role

The following subchapter analyses the planned and actual modal shift to the Pedelec, as well as the planned and actual distances travelled with the Pedelec. In addition, the views and wishes of the participants are presented, which can be understood as recommendations for action to establish the Pedelec even more strongly as a sustainable and safe means of transport in the mobility mix of the future.

3.4.1 Modal shift

The study results to the questions…

"Which of the following means of transport do you think can replace the Pedelec?"

"And which distances that you used to travel by car do you now do with your Pedelec?"

... show that the expected benefits of respondents who do not yet own a Pedelec and the actual benefits of respondents who already own a Pedelec are largely the same, see Table 1 and 2.

What is striking in the evaluation of the modal shift is the clear preference to replace the conventional bicycle with a Pedelec. Consequently, more mixed traffic is to be expected on the traffic infrastructure in general and on the cycling infrastructure in particular. In addition, it can be assumed that some of the bicycles will continue to be owned but will be used significantly less than before (cf. use cases in chapter 3.1).

Table 1: Modal shift from selected modes of transport to Pedelec (N = 3026)

Substitution of…	Expectation	Reality	Difference
Bicycle (conventional)	**60 %**	**59 %**	-1 %
Scooter and Moped	39 %	39 %	0 %
Second passenger car	23 %	24 %	+1 %
First passenger car	18 %	20 %	+2 %

The evaluation of the distances previously travelled by passenger car and now by Pedelec shows that the expectations of future Pedelec users are significantly lower than the distances actually travelled. Remarkable are the marked distances of >10 km, which are covered by 46 % of the Pedelec owners. This result, in combination with the application cases found, underlines the use of the Pedelec not only as an intra-urban, but also as an inter-urban commuting vehicle and motivates the expansion of cycle paths.

Table 2: Substituted distances from car by Pedelec (N = 3026)

Distances formerly travelled by passenger car …	Expectation	Reality	Difference
<1 km	17 %	9 %	**-8 %**
1-5 km	42 %	30 %	**-12 %**
5-10 km	49 %	49 %	0 %
10-20 km	24 %	32 %	**+8 %**
>20 km	9 %	14 %	**+5 %**

3.4.2 User views and wishes

The views and wishes of the participants asked in the user study were asked in a closed form via pre-formulated statements, which the respondents could agree with:

"To what extent do you agree with the following statements?"

The statement "I would like to see better cycle lanes" received the highest level of agreement at 69 %, which fits with the general weakness identified by the user study: traffic and cycling infrastructure. Another 56 % agree with the statement "I wish there was a better charging infrastructure for eBikes", which underlines the use of the Pedelec as an everyday vehicle, as well as the frequent use and long distances of Pedelecs. 55 % of the respondents agree with the statement "I would like to see politics promote eBike riding more" and see politics as responsible for improving the framework conditions for Pedelecs.

Despite these user views and desires, as well as the previously perceived low level of safety, 62 % agree with the statement "I think eBikes are good". Another 58 % affirm the statement "eBikes can describe a solution to the traffic problem in cities" and 56 % agree with the statement "eBikes are environmentally friendly". The acceptance for the Pedelec with all its advantages is consequently given among the respondents.

4 DISCUSSION

4.1 Cycling safety

Since the spread of Pedelecs will still increase significantly, the course of the accident figures is also very variable. Furthermore, a comparison with bicycles based on official accident statistics - due to the different under-reporting rates (cf. chapter 3.3) - can only be an approximation. In such a comparison between bicycles and Pedelecs, it makes sense to relate the accident figures to other parameters, e.g. to the number of vehicles used and their mileage (cf. chapter 3.4).

Since bicycles and Pedelecs are not registered in most countries and thus also in GER, it is not possible to directly conclude on the vehicle fleet size in the field. Considering an average use of seven years (Juris, 2021), it is possible to determine the fleet size in the field based on the annual sales figures[5].

In Figure 17, it can be seen how the stock of bicycles is continuously decreasing over the last few years and being replaced by Pedelecs. Furthermore, a trend reversal in the total stock (bicycles plus Pedelecs) can be observed from 2015 onwards. The increase is due to the growing popularity of Pedelecs. It can be assumed that bicycles will continue to be replaced by Pedelecs in the coming years and that new user groups for Pedelecs will also be developed.

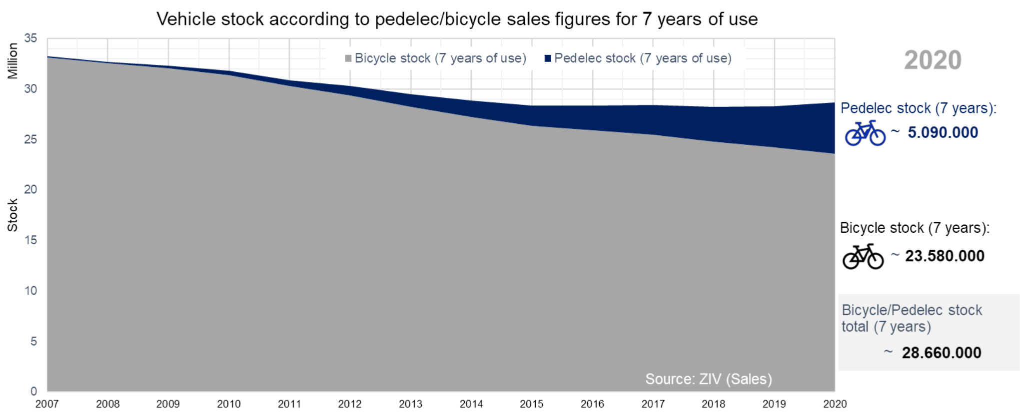

Figure 17: Vehicle stock according to sales figures of Bicycle and Pedelec based on 7 years of use

The evaluation of accidents with personal injury according to DESTATIS in GER in 2019, in relation to every 100k vehicles in the field[6], shows that significantly fewer accidents with personal injury per 100k vehicles occur with Pedelecs than with bicycles (cf. Table 3). This is remarkable because the average mileage, as determined in chapter 3.1, is not included in this analysis.

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[5] Sales figures of bicycles and Pedelecs according to the German two-wheeler industry association (ZIV), cf. https://www.ziv-zweirad.de/presse-medien/pressemitteilungen/

[6] Stock figures and mileage for motorized two-wheelers and passenger cars according to vehicles registered with the German Federal Motor Transport Authority (KBA)

The distance travelled plays an important role when considering accident frequency, as a vehicle that travels significantly longer distances typically has a higher accident exposure, as can be seen in the example of the passenger car. As the user study shows, Pedelecs are used for significantly longer distances compared to bicycles (in GER, for example, factor 2, cf. chapter 3.1)[7]. Table 4 below shows the calculated number of accidents with personal injury per billion vehicle km. When using the average mileage for GER (see above as well as KBA), the risk for bicycles is about a factor of 3 higher than for Pedelecs. Pedelecs are at a level like that of motorised two-wheelers.

Table 3: Accidents regarding vehicle stock in GER in 2019

Involvement of …	Accidents with causalities	Vehicle stock	Accidents with causalities per 100k vehicles
Pedelec	10.806	5.090.000	212
Bicycle	77.480	23.580.000	329
Two-wheeler (with license plate)	26.938	4.506.410	598
Passenger car	236.675	47.715.977	496

Table 4: Accidents regarding vehicle stock and average mileage in GER in 2019

Involvement of …	Mileage per year per vehicle in km	Total milage in billion km	Accidents with causalities per 1 billion km
Pedelec	1.000	5,1	2.123
Bicycle	500	11,8	6.572
Two-wheeler (with license plate)	2.218	10,0	2.695
Passenger car	13.602	649,0	365

For the derivation of recommendations for action, it can be concluded that measures to increase road safety should focus equally on bicycles and Pedelecs, even if the vehicle-specific risk is lower for Pedelecs. The lower accident risk with Pedelecs can be justified on the basis of the user study with the following aspects:

- Predominantly new vehicles, as the trend towards Pedelecs is still young and leasing offers have a fixed term (cf. chapter 3.3).
- Regular maintenance, as most Pedelec manufacturers and suppliers of electric drives recommend a maintenance interval of one year at a trained specialist dealer (cf. chapter 3.2)
- High-quality components, as there is a high willingness to pay for Pedelecs, especially due to the substitution of expensive means of transport in the course of the modal shift (cf. chapter 3.4).

[7] Further studies in this context show that the values determined in the user study for the Pedelec are rather conservative (cf. e.g. (Castro, Alberto, & et al., 2019)), while those for the bicycle are rather optimistic (cf. e.g. (Castro, Kahlmeier, & Gotschi, 2018)).

- Active lighting devices, as a direct energy supply via the battery of the electric drive as well as switching on and off via the human-machine interface of the Pedelec is possible. Especially in bad weather conditions (see chapter 3.1), lighting devices can make a significant contribution to road safety (DEKRA, 2020).

It is important to emphasise that despite the lower vehicle-specific risk of Pedelecs, potential safety-enhancing measures should - if possible - be addressed directly. First and foremost these are:

- Transport infrastructure, as Pedelecs have a higher accident exposure due to their use as everyday vehicles and the lack of infrastructure to adapt their driving behaviour (cf. chapter 3.1). In particular, the multimodal use of traffic space should be taken into account, a continuous cycle path network with sufficient cycle path width[8] should be created and intelligent traffic infrastructure solutions (e.g. "green wave" concepts) should be implemented (cf. chapter 3.2).
- Short-term transport infrastructure measures can be (1) the opening of cycle paths outside built-up areas for so-called S-Pedelecs[9] in order to make inter-urban commuting safer until the completion of cycle lanes (cf. Chapter 3.4) and (2) increasing the usability of the cycle infrastructure, e.g. by making appropriate clearing and gritting concepts available for winter conditions (cf. Chapter 3.1, (DEKRA, 2020) and (ADAC, Radfahren im Winter, 2021)).
- Helmet recommendation, especially for older users, as they have a limited physical capacity (e.g. balance problems) and the consequences of accidents are more serious (e.g. higher vulnerability) (Malczyk, 2015). The importance of recommending helmets for older people is also underlined by the results of the survey in (Nobis & Kuhnimhof, 2019), which coincides with the user study presented here (cf. chapter 3.2), but also shows the helmet-wearing rate across the age of the riders. For example, the helmet wearing rate decreases sharply for the over 50s and ends at a low 22 % for the over 80s who always wear a helmet (compared to the average of 34 % across all age groups).
- Riding training, especially for new and returning riders, as they are often inexperienced riders with insufficient riding experience - see also (ADAC, Sicher auf dem Pedelec unterwegs, 2021). Examples include dealing with complex traffic situations in urban areas or the use of Pedelecs regardless of weather conditions (see chapter 3.1). Furthermore, the newcomers are not yet used to the newer technology, e.g. brakes.

4.2 Vehicle based systems

The electrical energy present in Pedelecs offers new functional possibilities, such as on-site safety systems, which are divided into active and passive safety systems. Passive safety systems serve to protect against serious injuries in the event of an accident. They reduce the risk of injury and mitigate the consequences of an accident. Examples of passive safety systems already available on bicycles or Pedelecs are the helmet, the airbag (Hövding, 2021) and eCall systems, such as the Help Connect feature from Bosch eBike Systems. The latter addresses, among others,

[8] Cf. for GER (ADAC, Test: Sind Radwege breit genug?, 2021).
[9] Light motorized vehicles of category L1e-B, with motor assistance up to 45 km/h, limited assistance ratio

the 18 % of cyclists and Pedelec riders who were injured but did not receive direct help, as identified in chapter 3.3.

Active safety systems help to avoid accidents and make a preventive contribution to road safety. The most popular example is ABS, which stabilises the vehicle in critical situations and optimises deceleration. The primary aim of ABS is to prevent wheel lock-up, which often occurs with uncontrolled wheels due to over-braking on slippery surfaces and/or in bad weather conditions (see chapter 3.2). Due to the unfavourable ratio of centre of gravity height to wheelbase, the additional function of rear wheel lift-up control (RLC) is of particular interest for Pedelecs in case of over-braking on non-slippery surfaces (see chapter 3.3). The aim of RLC is to reduce the risk of an endo (acronym for end over front) around the vehicle's transverse axis during braking. In the case of Pedelecs, the special challenge arises that the risk minimisation of an endo must also function optimally in hilly topography (cf. chapter 3.1). Assuming a full ABS penetration on Pedelecs in the field up to every third crash involving a Pedelec could be avoided in Germany (cf. (Moennich et al.)). ABS with the additional function RLC are available on the Pedelec market from (BluBrake, 2021) and Bosch eBike Systems.

In addition to Pedelecs, other motorised road users (e.g. cars, trucks) should also push for vehicle systems to protect VRUs. The focus should be on conflict situations in the intersection area (see chapter 3.3). The legal obligation to fit turning assistants[10] as standard equipment on trucks and buses from 2022 is to be welcomed (EU, 2019), although a retrofitting requirement would be desirable. Also to be welcomed are the activities of EuroNCAP, which are increasingly raising the requirements for automated emergency brakes (AEB) in the event of an imminent collision with VRUs (EuroNCAP, 2021). Due to the challenging driving task during parking, an increasing spread of parking assistants with emergency braking function (cf. e.g. (ADAC, Test: Parkassistenten mit Notbremsfunktion, 2021)) as well as dismounting warning systems (cf. e.g. (ADAC, Ausstiegswarner, 2021)) are recommended. In this context, it is also interesting to see which future safety potentials result from connecting the traffic participants and infrastructure (cf. e.g. (Uittenbogaard & et al., 2021)).

[10] Turning Assistant, which detects VRUs in front of and beside the vehicle and warns driver when turning.

5 CONCLUSIONS

The motivation for conducting the quantitative user study was a partially unclear accident situation, caused by limited official statistics based on police reports. In particular, it was assumed that accidents with collisions and high injury severity were overestimated. The aim of the study was to obtain a more representative view of bicycle and Pedelec safety by interviewing users. The focus was to examine safety fears and safety behaviour, as well as accident experiences.

The results of the study show that Pedelecs compared to bicycles are used more for everyday purposes, more often in terms of frequency, more to cover long distances and more in all weather conditions. Due to the associated higher exposure to accidents and the lack of possibilities to adapt their riding behaviour, Pedelec riders try to reduce their individual accident risk by increasing their visibility in road traffic and wearing a helmet.

For both bicycles and Pedelecs, motor vehicles and commercial vehicles are the most frequent collision opponents. It is striking that Pedelecs are less involved in single vehicle accidents than bicycles, whereas Pedelecs collide more frequently with other bicycles or pedestrians. The lower proportion of single-vehicle accidents can be explained by the fact that Pedelecs are primarily used in urban areas on roads with good grip and that they are easy to handle (new, high quality and regularly maintained vehicles). Critical, on the other hand, seems to be the cramped urban traffic space and the associated potential for conflict with motorised traffic, as well as the multimodal use of the cycling infrastructure with a lack of possibilities for VRUs to avoid each other.

Furthermore, the study results show that in 79 % of bicycle accidents and in 55 % of Pedelec accidents, the police were not notified and consequently the accident was not included in the official accident statistics. The high and at the same time different under-reporting rates motivate studies such as the one presented here and point to a new problem area in accident research in the context of bicycles and Pedelecs. If the under-recording rates of both vehicle types differ, comparative statements based on official accident statistics are difficult.

The presented user study shows that bicycles and Pedelecs are basically used in a similar way in many respects. For this reason, measures to increase road safety should be oriented first and foremost to the needs of bicycles, as they are more widespread and have a higher accident risk in terms of both number of users and mileage. In addition, Pedelecs, which are increasingly used as everyday vehicles, can use the additional available electrical energy and computing power to make the Pedelec even safer through vehicle safety systems.

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