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Traffic safety of electric bicycles

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Wilhelmstraße 43/43G, 10117 Berlin
Postfach 08 02 64, 10002 Berlin
E-Mail: unfallforschung@gdv.de
Internet: www.udv.de
Facebook: www.facebook.com/unfallforschung
Twitter: @unfallforschung
YouTube: www.youtube.com/unfallforschung

Editor: Dr. rer. nat. Tina Gehlert
Layout: Franziska Gerson Pereira
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Introduction

The number of electric bicycles has increased in recent years and continues to increase both in Germany and elsewhere [1]. For example, 410,000 e-bikes were sold in Germany in 2013 (Figure 1). The unique feature of these bikes is their electric motor. The German legislation distinguishes between pedelecs (pedal electric cycles), s-pedelecs and e-bikes, depending on the type and power of the motor:

1. A pedelec is a bicycle with motor assistance of up to 250 watts that is only engaged when the cyclist is pedaling and cuts out at a speed of 25 km/h. Motor assistance is permitted without pedaling at speeds of up to 6 km/h. A pedelec is legally classified as a bicycle. That means the pedelec user can use the cycling infrastructure and does not need a driving license or motor liability insurance. Wearing a cycling helmet is recommended but not mandatory.
2. The more powerful s-pedelec provides motor assistance of up to 500 watts to a pedaling cyclist and cuts out at 45 km/h. It is classified as a moped. S-pedelec users are therefore subject to the same conditions as moped riders: above all, that means they need a license, a helmet and a vehicle registration, and they may only use the road infrastructure.
3. An e-bike with power on demand provides motor assistance of up to 500 watts and at speeds of up to 20 km/h without pedaling. It is classified as a moped and is therefore subject to the restrictions described above.

The majority of electric bicycles in Germany are pedelecs, which have a market share of about 98%. Only 2% to 3% of electric bicycles are s-pedelecs or e-bikes with power on demand.

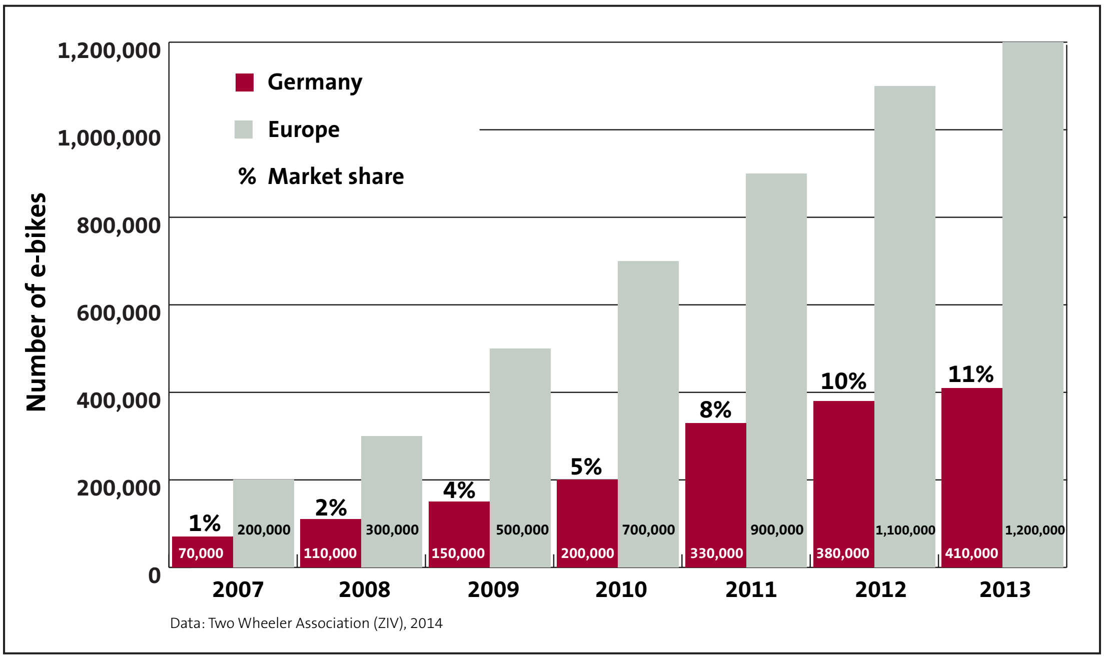

Figure 1:
Development of the market for electric bicycles

The growing number of electric bicycles and the possibility of higher speeds give rise to concerns about road safety, in particular the risk of crashes and accidents. In Germany, pedelecs have only been included as a separate vehicle category in the accident statistics since 2014. Reliable accident statistics will therefore not be available before 2017. In Switzerland, electric bicycles have been included separately since 2011. The initial results show that pedelec accidents are more serious than conventional bicycle accidents. People aged 45 and older are particularly affected [2]. However, these results may not be transferable, since the Swiss legislation permits electric bicycles with motor assistance of up to 1,000 watts.

Consequently, German Insurers Accident Research (UDV) and Chemnitz University of Technology carried out a large-scale naturalistic cycling study to investigate the vehicle usage, speed and road safety of users of electric bicycles in Germany. Three groups were compared: riders of i) pedelecs, ii) s-pedelecs and iii) conventional bicycles. This publication summarizes the main findings. All the results are published in research report no. 27 [3].

Content

Methodology

A field study approach was selected to collect cycling data in a realistic yet controlled setting. More specifically, we took a naturalistic approach: the participants' behavior was recorded during their daily life as unobtrusively as possible. For this purpose, video cameras and GPS and other sensors were installed on the bicycles. This methodology has already been used successfully in research into drivers' behavior [e.g. 4]. We therefore adapted the methodology for the purpose of research into the behavior of cyclists and pedelec and s-pedelec users. We developed a data acquisition system (DAS) that was fitted to the participants' bicycles. It included two video cameras, one pointing to the road ahead and one pointed at the head of the participant, GPS and wheel sensors for measuring speed, a memory card and a battery. The DAS was designed to be as unobtrusive as possible. It was switched on and off with a push of a button.

The study was carried out in the city of Chemnitz and the surrounding area. Chemnitz has a population of 249,500. There is a considerable amount of commuting from the surrounding area into the city. The study area encompassed both urban and rural areas with the terrain being quite hilly. That makes it difficult for cycling but possibly attractive for motor-assisted cycling. Currently, cycling has a modal share of only 6% [5].

There were a total of 90 participants. 49 of them were pedelec users, 10 were s-pedelec users, and 31 were ordinary cyclists. To account for potential age effects, roughly a third of the participants in each group were 40 years old or younger, a third were between 40 and 65, and another third were 65 or older. It became clear when recruiting participants from the lower age group of up to 40 that pedelecs are mainly used by older people. The average age of all participants was 52 (SD = 17.23), with the youngest being 16 and the oldest 83. According to the German Two-Wheeler Industry Association (ZIV), this reflects the age distribution of current pedelec buyers. 63% of the participants were male and 37% female. The participants used their bicycles at least three or four times per week. That was due to the fact that we made a particular effort to recruit frequent cyclists. The majority of cyclists indicated that they wear a helmet for all journeys.

Figure 2:
Pedelec with data acquisition system (left), camera views of the participant's face and the road ahead (right)

Table 1:
Sample distribution

	Bicycle	Pedelec	S-pedelec	Total
< 40 years	10	16	3	**29**
41 - 64 years	10	14	6	**30**
> 65 years	11	19	1	**31**
Total	**31**	**49**	**10**	**90**

Each participant was observed for a period of four weeks riding their own bike. In addition, participants were required to fill in a travel diary for one week to record all journeys, not just those for which they used their bike. The aim was to gather additional information, for example on the purpose of the journey and related activities. In addition, on several occasions the participants completed questionnaires about their bike usage, riding behavior and their experience of being observed (see Table 2). The observation started with the participants coming to the university's laboratory to have the DAS fitted and ended with the removal of the DAS. The four-week observation period and related measurements were scheduled between July and November 2012, depending on the participant's preference.

Table 2:
Questionnaires and content

Point in time	Content
Recruitment	▪ Sociodemographic factors ▪ Bike type ▪ Bike usage (e. g. frequency of use)
Before observation	▪ In-depthth sociodemographic factors ▪ Reasons for purchase and use ▪ Current usage ▪ Pros and cons of bike type
During observation	▪ Trip characteristics (e. g. time, purpose, accompanied, unusual/critical incidents)
After observation	▪ Perception of own riding behaviour ▪ Accidents/critical incidets during observation period ▪ Experience of naturalistic observation

A total of 4,348 journeys with a total length of 16,986 km were recorded in around 4,400 videos with a total length of over 2,300 hours. To reveal safety-related traffic situations, extensive video annotations were made. Every single trip was screened for potentially critical situations. These were annotated using a predefined coding scheme. In addition, trip length, trip duration and particularly speed were analyzed using data from the wheel sensors. Finally, all data types were synchronized and merged into a database. For the analysis, the mean values of each study group (conventional bicycle, pedelec, s-pedelec) were calculated and compared using appropriate statistical significance tests. In other words, we investigated whether differences between the three groups were due to variance within each group or due to differences between the bicycle types in the real world. We consider differences between the bicycle groups to be statistically significant if they can be generalized to the bicycle population as a whole with a probability of at least 95%.

Travel behavior

During the four-week observation period, the participants made an average of 50 trips on their bike, covering an average total distance of 192.5 km. They used their bike for every fifth trip. The average trip duration was about 17 minutes. There is no statistically significant difference between the three different bicycle types. The trip lengths of s-pedelec users were significantly longer than those of ordinary cyclists and pedelec users (7.2 km per trip for s-pedelec users, 3.5 km per trip for ordinary cyclists and 4.5 km per trip for pedelec users).

All participants used the road most frequently (61.4% of km ridden), followed by the cycling infrastructure (15.9% of km ridden) and footpaths (9.5%). Contrary to current legislation, s-pedelec users also use the cycling infrastructure (13.7% of their km ridden), particularly off-road shared-use paths (9.8% of their km driven). All three groups used footpaths on which cyclists were not permitted (7.4% of km ridden), with ordinary cyclists doing this most often (9.7%).

The participants used their bikes most often for work-related trips (30.0% of all trips), followed by leisure/sport (19.3%), shopping (16.5%) and in connection with services (13.2%). S-pedelec users used their bike more often for work-related journeys than the other two groups (53.6% as opposed to 30.0% for all participants). With increasing age, participants used their bikes more for leisure and less to get to work.

Participants were asked to indicate an alternative means of transport for their bike trips. For 18.4% of all trips there was no alternative means of transport. For the remaining trips there were differences between pedelec and s-pedelec users, on the one hand, and conventional cyclists, on the other. Pedelec and s-pedelec users most often stated that the car was the alternative means of transport, whereas conventional cyclists stated most often that public transport was the alternative.

To summarize the results regarding travel behavior, there are only a few differences between conventional cyclists and pedelec and s-pedelec users. First, s-pedelec users travel longer distances and go on more work-related trips than the other two groups. Second, pedelec and s-pedelec users tend to regard the car as the alternative means of transport, unlike conventional cyclists, who tend to regard public transport as the alternative.

Speed

One research question was whether and how the potentially higher speeds of electric bicycles would be used in reality. We measured two kinds of speed: i) journey speed, which is the average speed for the entire journey, including stops at red lights, junctions, etc., and ii) cycling speed, which is the average speed while the bicycle is actually moving. In general, the journey speed is lower than the cycling speed. In this study the journey speed was on average 1.4 km/h lower than the cycling speed in all three groups.

Table 3 displays the average journey and cycling speed for each bicycle type and age group. The results show that s-pedelec users cycled fastest, followed by pedelec users then conventional cyclists. Participants younger than 40 years of age cycled fastest, followed by those aged 41 to 64 and finally those aged 65 and older. The indices a, b and c for the group average values indicate if there is a statistically significant difference and which groups differ. For group values with the same indices there is no statistically significant difference. Thus, the results for the age groups have to be interpreted as follows. The difference in speed between participants younger than 40 and participants from 41 to 64 years old is not statistically significant and can be considered to be random variation. However, both groups cycled significantly faster than participants aged 65 or older. That applies to both journey speed and cycling speed. As far as the differences between bicycle types are concerned, there are statistically significant differences between all three bicycle groups in terms of both journey speed and cycling speed. The influence of age is accounted for. For s-pedelec users there is only a group average available for the age group from 41 to 64. Only in this age group was there a large

Table 3:
Average speed by bicycle type and age group
(n = sample size, M = mean, SD = standard deviation)

	Bicycle			Pedelec			S-pedelec			Total		
	n	*M*	*SD*	*n*	*M*	*SD*	*n*	*M*	*SD*	*n*	*M*	*SD*
Average journey speed (km/h)												
≤ 40 years	8	14.9	3.5	16	18.7	5.3	3	-	-	27	**18.0** [a]	4.5
41 - 64 years	9	14.4	2.2	14	16.1	4.4	6	23.6	2.4	29	**17.1** [a]	4.8
≥ 65 years	11	12.7	2.8	19	13.6	1.7	1	-	-	31	**13.2** [b]	2.9
Total	28	**13.9** [a]	2.9	49	**16.0** [a]	4.5	10	**21.8** [b]	4.8			
Average cycling speed (km/h)												
≤ 40 years	8	16.6	3.4	16	20.4	5.0	3	-	-	27	**19.6** [a]	4.8
41 - 64 years	9	15.8	2.3	14	17.5	4.0	6	25.1	3.7	29	**18.5** [a]	4.8
≥ 65 years	11	13.9	2.6	19	14.8	1.9	1	-	-	31	**14.4** [b]	2.2
Total	28	**15.3** [a]	2.9	49	**17.4** [b]	4.4	10	**23.2** [c]	4.9			
Data source: wheel sensor data for the entire observation period												

enough sample. However, the average speed for the whole group of s-pedelec users was calculated based on all s-pedelec users.

We also analyzed the distribution of the cycling speed (Figure 3). Overall, the overall cycling speed ranged from 10.1 km/h to 31.9 km/h. The variations in speed were greater for pedelec and s-pedelec users than for conventional cyclists. We also calculated the speeds exceeded by 85% and 15% of the participants. These speeds characterize the lower and upper ranges of the speed distribution. At the lower end of the speed distribution, 85% of conventional cyclists cycled faster than 12.3 km/h, 85% of pedelec users faster than 13.5 km/h and 85% of s-pedelec users faster than 18.3 km/h. At the upper part of the speed distribution, 15% of conventional cyclists cycled faster than 18.1 km/h, 15% of pedelec users faster than 22.3 km/h and 15% of s-pedelec users faster than 27.9 km/h.

To summarize, the results were as expected for speed. S-pedelec users cycled fastest, followed by pedelec users and then conventional cyclists. In addition, the variation in speed was greater for pedelec and s-pedelec users than for conventional cyclists. However, there was less difference in speed between pedelec users and conventional cyclists. Pedelec users evi-

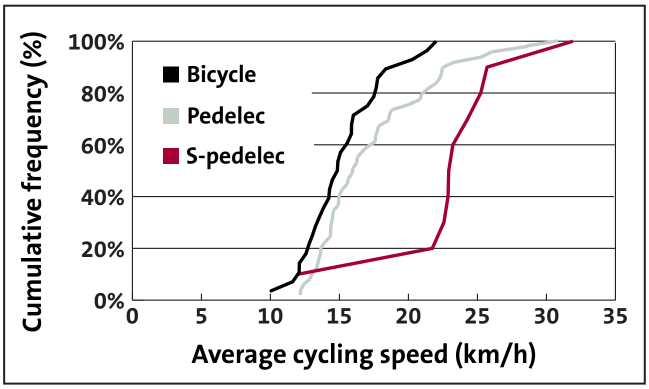

Figure 3:
Average cycling speed distribution by bicycle type (wheel sensor data for the entire observation period)

dently use the motor assistance primarily for convenience and to cycle as fast as cyclists but with less effort.

Traffic Safety

At the time of the observation period there was no reliable accident data available. We therefore used the number and type of critical incidents for the purpose of assessing safety. The videos were screened and annotated using a predefined coding scheme by specially trained observers. A traffic situation is regarded as critical if the participant or another road user is most likely to lose control of the vehicle. We differentiate between five types of critical incidents:

1. Conflict with a fall: This is a conflict between the cyclist and another road user or an object, resulting in a fall (with and without collision).
2. Conflict without a fall but with a reaction: The cyclist or another road user needs to brake or take evasive action to resolve a traffic conflict or avoid a collision.
3. Conflict without a fall or a reaction: This is a conflict in which the cyclist does not execute a maneuver (e. g. another vehicle overtakes too close).
4. Fall: The cyclist falls without the involvement of anyone else.
5. Near fall: The cyclist avoids falling but only with difficulty (without the involvement of anyone else).

Overall, there were 202 critical incidents during the four-week observation period. There were two falls without the involvement of anyone else and one fall as a result of a conflict with a car turning left. The car driver involved violated the right of way of the pedelec user while turning. The falls without the involvement of anyone else were due to a wet or slippery road surface. The most common incidents were conflicts without falls but with a reaction of the cyclist to resolve the conflict. There were no statistically significant differences between conventional cyclists, pedelec and s-pedelec users or between the three different age groups in terms of the number of critical incidents in which they were involved. The same applies to the number of critical situations relative to kilometers cycled. Thus, despite their higher average speed, s-pedelec users were not involved in critical incidents more often than conventional cyclists or pedelec users.

To describe the critical incidents in more detail, we used the German accident type classification that is also used in the official accident statistics [6]. The accident type describes the traffic conflict. This is a phase in the traffic situation in which, due to improper action or other causes, the further course of events can no longer be controlled. Unlike the kind of accident, the accident type does not describe the actual collision but indicates how the conflict came about before a possible collision. The accident type is therefore also suitable for describing critical incidents that may or may not result in an accident [6]. Another advantage is that it is commonly used in accident research and statistics. Thus, it also allows comparisons to be made with these sources. Figure 4 shows the frequency of critical incident types for conventional cyclists, pedelec and s-pedelec users. For all three groups, the most frequent conflicts were between road users in longitudinal traffic followed by conflicts involving a road user turning into or crossing a road. In the great majority of cases, these were caused by oncoming vehicles using the participant's lane (e. g. for overtaking) or failure to give way to the participant by a motorized vehicle. The least common critical incident type in all three groups was where no other road user was involved.

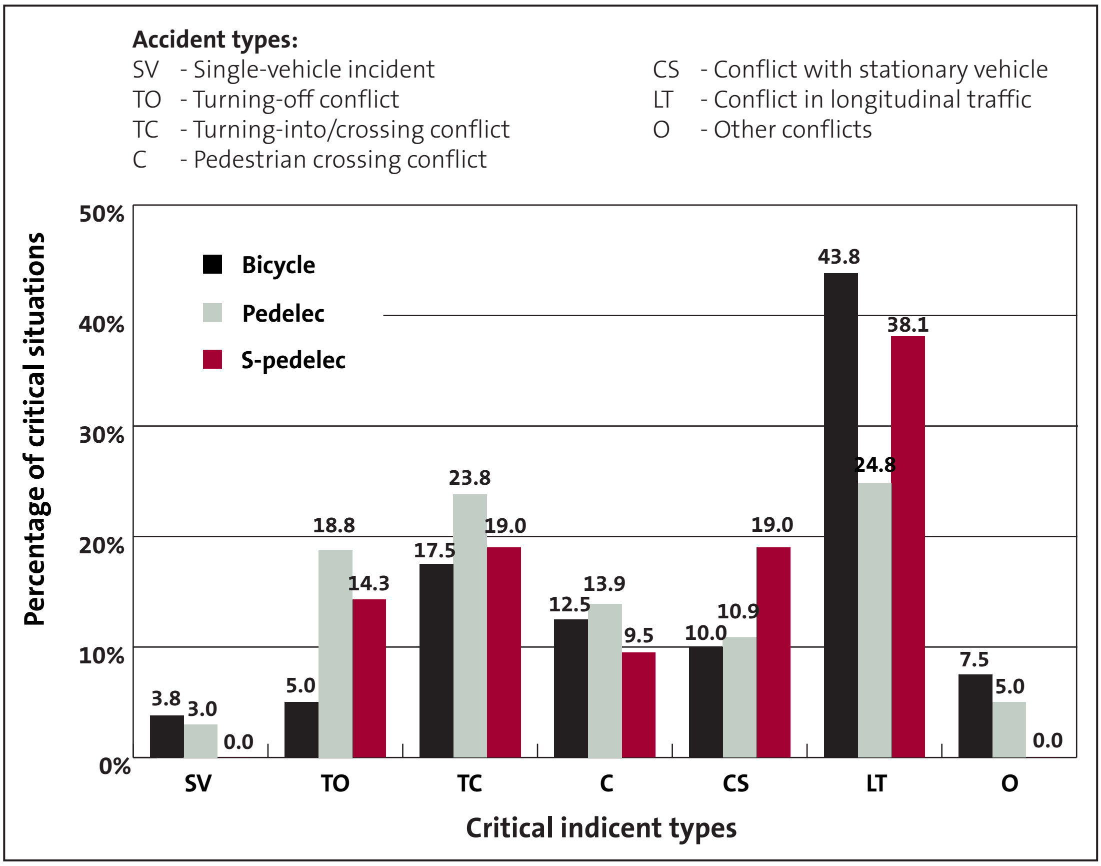

Figure 4:
Frequency of critical incident types by bicycle type (video data for the entire observation period)

Looking at the two main types of critical incidents for pedelec users in more detail, we found that the most common type were turning-into and crossing conflicts in which the participants may or may not have the right of way (see 321 in Figure 5). For s-pedelec users and conventional cyclists, the most common conflicts occurred with oncoming vehicles in longitudinal traffic (see 681 in Figure 5).

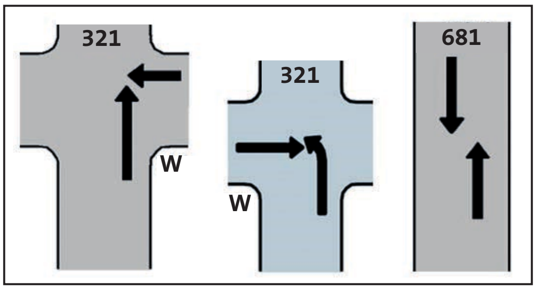

Figure 5:
Critical incident types 321 and 681 according to the German accident type classification [6] (W = no right of way)

The other road users involved in the critical incidents were most often car drivers, followed by pedestrians and other cyclists or e-bike users. There were also critical incidents involving multiple participants in all three groups, for example a pedestrian walking a dog.

The distribution of the critical incidents across the different types of infrastructure for all three groups (conventional cyclists, pedelec users and s-pedelec users) corresponds to what you would expect given the distances cycled on each infrastructure type. Critical incidents occurred most often on the roads, followed, in the case of conventional cyclists and s-pedelec users, by off-road shared-use paths and, in the case of pedelec users, by roadside shared-use paths. Most critical incidents occurred while the cyclists were using the infrastructure in compliance with the traffic regulations. There were only a few critical incidents in which the participants were using the footpath instead of the road.

In summary, the number and type of critical incidents that occurred were similar for conventional cyclists, pedelec users and s-pedelec users. The conflicts in which pedelec and s-pedelec users became involved were very much the same as those involving conventional cyclists [7].

To assess traffic safety, we also investigated the rule violations of pedelec users and cyclists over the entire observation period. The following behavior was observed:

- Cycling in the wrong direction
- Cycling on footpaths on which cycling was not permitted
- Failure to use the mandatory infrastructure

The participants cycled 88.8% of the total distance traveled in the right direction and using the correct infrastructure. This percentage was lower for s-pedelec users than for conventional cyclists and pedelec users (88.8% for cyclists, 90.8% for pedelec users and 80.4% for s-pedelec users). Cycling in the wrong direction was rare. The participants cycled only 1.2% of the total distance traveled on the road or cycling infrastructure in the wrong direction. Cycling on footpaths on which cycling was not permitted occurred significantly more often. Where participants used such a footpath, the road was available as an alternative for two-thirds of the distance. For one-third of the distance there was no alternative available. This happened in residential areas, for example, or where the road was closed due to roadworks.

Where cycling infrastructure was available, it was used in most cases (91.1% of the distance over which there was mandatory cycling infrastructure). Off-road shared-use paths were always used, where available. Participants deviated most often from roadside shared-use paths, followed by marked cycle lanes on the road. In summary, it can be said that cyclists and pedelec users most often violate the regulations when the infrastructure available does not suit their needs.

Summary

The growing number of electric bicycles, together with their higher maximum speed, raises concerns about traffic safety, in particular the risk of crashes and accidents. German Insurers Accident Research (UDV) and Chemnitz University of Technology therefore carried out a large-scale naturalistic cycling study to investigate the travel behavior, speed and road safety of users of electric bicycles in Germany. The main results were as follows:

- Pedelecs are currently used mainly by older people.
- Conventional bicycles and pedelecs are used to a similar extent and for similar purposes. S-pedelec users use their vehicles more often for the journey to and from work than the other two groups.
- The average journey and cycling speeds of s-pedelec users are significantly higher than those of pedelec users and conventional cyclists. The average speed of pedelec users is also significantly faster than that of cyclists. However, it seems they use the motor assistance primarily for convenience in order to reach similar speeds with less effort.

- The cycling speeds of s-pedelec and pedelec users vary more than those of conventional cyclists.
- There are no differences in the number of critical incidents between the three vehicle types. Even the higher average speed of s-pedelec users does not lead to more critical incidents.
- The most frequent types of critical incidents for all three vehicle types were conflicts between road users in longitudinal traffic and turning-into/crossing conflicts. As would be expected from the numbers of other road users using the infrastructure, most conflicts were with cars, followed by pedestrians and other cyclists or pedelec users. Typically, conflicts with cars occurred when drivers violated the participant's right of way, maneuvered their cars out of parking spaces, turned off or executed a U-turn. Conflicts with pedestrians, other cyclists or pedelec users typically occurred when they crossed the participant's lane, were moving along in the same direction or coming towards the participant. In summary, the conflicts of s-pedelec and pedelec users are very similar to those of conventional cyclists.

Conclusions

The comparison of conventional bicycles, on one hand, with pedelecs and s-pedelecs, on the other hand, shows that the latter are not less safe than bicycles or associated with different risks. The potentially higher speeds of pedelecs are used mainly by s-pedelec users. Pedelec users use the motor assistance primarily for convenience.

It therefore seems justifiable to legally classify pedelecs as bicycles and s-pedelecs as mopeds. Because of their higher average speed, s-pedelecs should continue to be restricted to using the roads rather than the cycling infrastructure. Their users should be obliged to have a vehicle registration and to wear a helmet. It is certainly possible that, although s-pedelec users are involved in similar numbers of accidents to pedelec users and cyclists, their injuries are more serious due to their higher speeds. This is suggested by initial results from Switzerland.

The greater variation in speed among pedelec and s-pedelec users as opposed to cyclists, combined with the increasing growth in their numbers, represents a challenge in terms of the sizing of the cycling infrastructure, which should be based on the ERA 2010 guidelines [8] and allow safe overtaking among cyclists. Since a few s-pedelec users are still using the cycling infrastructure, there is a need for more information to be provided on their rights and obligations.

Concluding remark

This study represents a current snapshot of the use of electric bicycles in a German city that is suitable for that purpose. The results were obtained in the context of the current legal framework, the market shares of electric bicycles and the characteristics of the different groups of users. A change to these variables could result in a different assessment of the safety of motor-assisted cycling. Future trends affecting pedelecs and s-pedelecs should therefore be monitored carefully.

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German Insurers Association

Wilhelmstraße 43 / 43G, 10117 Berlin
PO Box 08 02 64, 10002 Berlin

Phone: + 49 (0) 30 2020 - 5000, Fax: + 49 (0) 30 2020 - 6000
Internet: www.gdv.de, www.udv.de