Road safety of electric bicycles

Compact accident research

Unfallforschung der Versicherer
GDV

Content

Preliminary remarks

Electric bicycles are becoming increasingly popular. Sales have been rising continually since 2007. 605,000 electric bicycles were sold in Germany in 2016 alone. Electric bicycles account for 15 percent of all bicycles sold [1], according to the Zweirad-Industrie-Verband (ZIV), the German bicycle industry association.

Table 1 provides an overview of the technical characteristics of different electric bicycles and how they are treated in road traffic regulations. Broadly speaking, there are two different types: throttle-assist e-bikes (which give you power on demand and do not require you to pedal) and pedal-assist e-bikes, where the motors kicks in when you are pedaling (so called pedelecs and S-pedelecs). Pedelecs have a maximum power output of 250 watts and provide pedal assistance up to a speed of 25 km/h. Pedelecs are classified as bicycles in the road traffic regulations and can be used on all cycling facilities. Cycling facilities include, in particular, cycle paths, mandatory cycle lanes, optional protection lanes, cycling roads and any facility with signs indicating it can be used by cyclists. Pedelecs are the most popular type of electric bicycles in Germany. S-pedelecs, on the other hand, have a maximum power output of 500 watts and provide pedal assistance up to a speed of 45 km/h. They are classified as mopeds and may only be ridden by those with a valid driving license or the German test certificate for mopeds, a suitable helmet and a motor insurance sticker. S-pedelec riders are not allowed to use the cycling infrastructure [2].

In this UDV compact accident research report we use the legal classifications just described above to describe different types of e-bike. Electric bicycles with pedal assistance up to a speed of 25 km/h are referred to as pedelecs. Those with pedal assistance up to a speed of 45 km/h are called S-pedelecs. The term electric bicycle is used to cover all pedal-assist e-bikes: both pedelecs and S-pedelecs. Throttle-assist e-bikes which give you power on demand are referred to as e-bikes. They are not inclu-

Table 1: Comparison of the technical characteristics and legal classifications of pedelecs, s-pedelecs and e-bikes

	Pedelec	S-Pedelec	E-Bike
Power output	250 watts	500 watts	4,000 watts**
Assistance up to	25 km/h	45 km/h	Throttle-assist system regardless of pedaling up to 45 km/h
Vehicle type	Bicycle	Moped	Moped
Driving license	No	Yes	Yes
Helmet	Recommended	Mandatory	Mandatory
Insurance	No	Yes	Yes
Use of cycling infrastructure	Yes	No	No
Market share*	98%	2-3%	

* According to the Zweirad-Industrie-Verband (ZIV), the German bicycle industry association [1]
** E-bikes can also be equipped with more powerful motors and have a higher performance. They are then regarded as mopeds.

ded in this research. Elsewhere, however, the term e-bike is very often used to cover both throttle-assist e-bikes and pedal-assist e-bikes (pedelecs and S-pedelecs).

As electric bicycles and pedelecs in particular, become increasingly popular, they present new challenges for road safety. The focus on road safety research is whether and how their potentially higher speeds affect riders' cycling behavior and the risks involved.

In recent years a number of studies on travel behavior and road safety of pedelecs and S-pedelecs have been carried out by and on behalf of the UDV (German Insurers Accident Research):

The study Safety **Aspects of High-Speed Pedelec Electric Bicyles** (2012) analyzed safety-related aspects of S-Pedelecs by means of crash tests and cycling tests [3].

In the **Pedelec Naturalistic Cycling Study** (2014), travel behaviour and cycling behavior of riders of pedelecs, S-pedelecs and conventional bicycles were observed in real traffic and compared over a period of four weeks [4]. The focus was on the distances actually traveled and the speeds reached. In a subsequent study, the data was further analyzed concerning helmet use, red light violations and infrastructure usage [5].

In the study **Einfluss von Radverkehrsaufkommen und Radverkehrsinfrastruktur auf das Unfallgeschehen (2015) (Influence of cycling traffic volume and cycling infrastructure on traffic accidents),** the speed of pedelec riders and cyclists was measured on selected stretches of road [6].

The study **Geschwindigkeitswahrnehmung von einspurigen Fahrzeugen (2015) (Perceptions of the speed of single-track vehicles)** examined in four experiments how other road users (particularly drivers) perceive the speeds of different two-wheelers (particularly electric bicycles) [7].

In a survey entitled **Verkehrsklima in Deutschland 2016 (Traffic climate in Germany in 2016)**, the characteristics of pedelec riders were ascertained and compared with conventional bicyclists and a representative random sample of the total population [8].

In a comprehensive **accident analysis** the UDV compared German accidents recorded by the police involving pedelec riders and cyclists since 2012 (section 4.1) [17].This UDV compact accident research report summarizes the results of these studies and provides an overview of what we currently know about travel behavior and road safety of electric bicycles.

Sociodemographic characteristics of pedelec riders

In 2016 for the first time Pedelec riders (with pedal assistance up to 25 km/h) were included in the survey **Verkehrsklima in Deutschland (Traffic climate in Germany)** [8]. Table 2 shows the sociodemographic characteristics of pedelec riders, conventional bicyclists and a representative random sample of the total population. People who rode a pedelec or bicycle at least one to three times a week were allocated to the pedelec rider and cyclist group, respectively. Those who met this criterion for both bicycles and pedelecs were included in both groups. Around half of the pedelec riders were also included in the cyclist group. But, only 4 percent of cyclists were also included in the pedelec rider group. 93 percent of the cyclists never rode a pedelec, and 3 percent rode a pedelec one to three days a month or less.

The pedelec riders were significantly older than the cyclists or the representative random sample of the total population. 58 percent of the pedelec riders were aged 54 years or older compared to 40 percent in the representative sample of the total population and 37 percent of the cyclist group. Accordingly, a higher percentage of pedelec riders were no longer working compared to the other two groups (38 percent of the pedelec riders compared to 29 percent of the representative sample of the total population and 25 percent of the cyclists). Over two-thirds of the pedelec riders were male (69 percent). In contrast men made up only around half of the representative sample of the total population. Like the people in that representative sample, around half of the pedelec riders used a car (almost) every day. Only around 41 percent of the cyclists used a car daily. Pedelecs are thus particularly popular among older people. This has to be taken into account when calculating the safety risk.

Table 2: Characteristics of the pedelec riders, cyclists and the representative sample of the total population (weighted, pedelec riders: n=48, cyclists: n=572, total population sample: n=2,061)

		Pedelec riders (%)	Cyclists (%)	Total population sample (%)
Gender	**Male**	69.1	55.0	48.8
	Female	30.9	45.0	51.2
Age	**18-24**	13.4	8.9	7.7
	25-34	1.2	13.8	14.6
	35-44	20.8	18.0	16.0
	45-54	6.3	22.6	21.6
	55-64	26.1	13.5	15.7
	65-74	26.1	14.6	15.6
	75 Jahre and over	6.1	8.5	8.8
	Average	54 years	49 years	50 years
Household income (monthly, net)	**Less than 1,500 Euro**	4.2	17.2	19.3
	1,500 to under 2,000 euros	28.2	14.7	13.4
	2,000 to under 2,600 euros	13.9	12.9	12.2
	2,600 to under 3,600 euros	9.1	14.2	14.6
	3,600 euros or more	21.6	17.2	16.1
	Not stated	23.0	23.7	24.5

▶

		Pedelec riders (%)	Cyclists (%)	Total population sample (%)
Employment status	Working	56.6	59.5	55.2
	Working on a casual/occasional basis	0.8	7.7	5.2
	In training/further education	0.0	4.7	2.3
	Not working	38.0	25.4	29.3
	Not stated	4.6	7.4	7.9
Car use	(Almost) daily	49.6	40.6	52.3
	1 to 3 days a week	29.5	30.1	21.2
	1 to 3 days a month	1.4	7.6	5.8
	Never or almost never	0.0	2.6	2.9
	Never or almost never	19.4	19.0	17.8

Travel behavior

In the **Pedelec Naturalistic Cycling Study**, travel behavior and cycling behavior of conventional cyclists and pedelec and S-pedelec riders in real traffic were compared [4]. This study is one of the few in Germany that have taken a comprehensive look at their patterns of mobility and behavior in the saddle.

The daily cycling behavior of a total of 90 participants was recorded over a period of four weeks with the help of wheel sensors, video cameras and GPS trackers. Figure 1 shows on the left the front view of the camera and on the right a pedelec equipped with the different instruments. Attitudes towards conventional bicycles and electric bicycles and subjective perceptions of cycling behavior were surveyed by means of questionnaires.

Average group values (cyclists, pedelec riders and S-pedelec riders) were calculated for relevant variables (e.g. speed, distance, attitudes, etc.). Where differences be-tween the groups were found, it was determined whether these were statistically significant. That means, it was examined if the differences could be attributed to random variations within the participant group. If the probability of a random variation is 5 percent or lower, the differences between the groups are regarded as a statistically significant result. That means, with a proba-

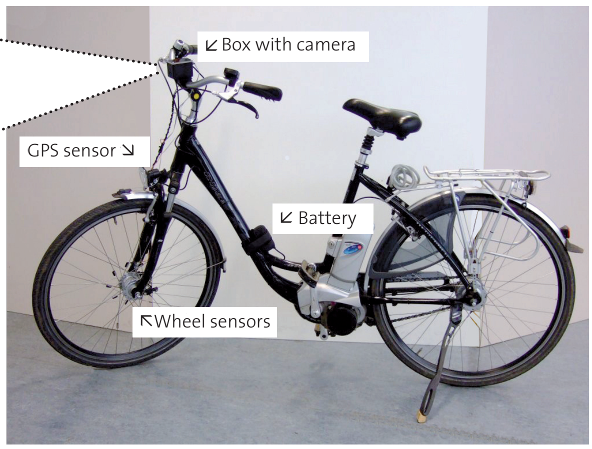


Figure 1: Front view through the camera on the left, pedelec with measurement instruments on the right

bility of 95 percent (or higher) there is a genuine difference between the groups of participants (cyclists, pedelec riders and S-pedelec riders). In addition, observations were described and trends reported if, for example, the sample size was too small to permit significance tests.

Travel behavior results

Duration/number of trips: The participants made an average of 50 trips in four weeks. The average trip duration was 17 minutes. There was no difference in the number of trips or in the trip duration between pedelec riders and cyclists. S-pedelec riders made significantly longer trips (7.1 km) than pedelec riders (4.7 km) and cyclists (3.5 km).

Infrastructure used: All participants most frequently used the road (61.4 percent of the kilometers ridden, N=16,986 km). This was followed by cycling facilities (15.9 percent) and sidewalks (9.5 percent). All of the participants stated that they also used sidewalks on which bicycles are not allowed (section 4.2.3). Although S-Pedelec riders are not allowed to use cycling facilities by law, they stated that they do so.

Trip purpose: The most common trip purpose was to get to and from work (30 percent of trips, N=4,348). Pedelecs were used more often than conventional bicycles or S-pedelecs for recreational or sport-related purposes. S-pedelecs were used more often than conventional bicycles and pedelecs for getting to and from work. These reflect the different average age and work situations of pedelec and S-pedelec riders. In this study pedelec riders were on average also older than S-pedelec riders (53 compared to 42), and a higher share was no longer working. Thus leisure mobility was more common among pedelec riders, while the journey to work was more relevant for S-pedelec riders.

Alternative means of transport: Cyclists stated most often public transport as their alternative means of transport, whereas pedelec and S-pedelec riders most often stated the car. That is similar to the results of Traffic climate survey (see Table 2).

In summary, there were no significant differences between cyclists and pedelec riders in terms of their mobility. S-pedelec riders, on the other hand, made longer trips and more often used their vehicle for the journey to and from work.

Speed

In the **Pedelec Naturalistic Cycling Study** and the study **Einfluss von Radverkehrsaufkommen und Radverkehrsinfrastruktur auf das Unfallgeschehen (Influence of cycling traffic volume and cycling infrastructure on traffic accidents**), the real speeds traveled in road traffic were measured [4, 6]. In the study **Geschwindigkeitswahrnehmung von einspurigen Fahrzeugen (Perceptions of the speed of single-track vehicles)**, car drivers were asked to estimate the speed of two-wheelers in a number of experiments [7].

Speeds in real traffic

In both studies different types of average speeds were measured. This section describes only the results for driving speed (i.e. the speeds without idle times at traffic signals, intersections, etc.). Average speed can be measured over certain distances, as it was, for example, in the **Pedelec Naturalistic Cycling Study** [4], or locally at road cross-sections, as, for example, in the study **Einfluss von Radverkehrsaufkommen und Radverkehrsinfrastruktur auf das Unfallgeschehen (Influence of cycling traffic volume and cycling infrastructure on traffic accidents)** [6].

It should be noted that speeds measured locally at a cross-section are always higher than speeds measured along a stretch of road [9].

Figure 2 shows the speed profiles for cyclists, pedelec riders and S-pedelec riders from the **Pedelec Naturalistic Cycling Study.** On the x-axis the average speed is shown. The y-axis shows the cumulative percentage of participants reaching the corresponding average speed. The gray line shows the speed profile for cyclists, the pink line for pedelec riders and the red line for S-pedelec riders. The two broken gray lines indicate the upper and lower sections of the speed distribution. The section within these two broken gray lines shows the speed exceeded by 15 percent of riders and not reached by 85 percent of riders. The figure shows:

- S-pedelec riders have the highest average speed (23.2 km/h), followed by pedelec riders (17.4 km/h) and cyclists (15.3 km/h). All differences are statistically significant.

- The average speed of the slowest of all participants is 10.1 km/h, and that of the fastest is 31.9 km/h.

- The fastest 15 percent of cyclists ride at an average speed of at least 18.1 km/h, while for pedelec riders it is 22.3 km/h and for S-pedelec riders 27.9 km/h.

- The slowest 15 percent of cyclists ride at an average speed no faster than 12.3 km/h, pedelec riders no faster than 13.5 km/h and S-pedelec riders no faster than 18.3 km/h.

Participants aged 65 years and older ride significantly slower compared to younger participants. That applies to both cyclists and pedelec riders. Their average speed is lower than the average speed of their vehicle group:

- 13.9 km/h for cyclists of 65 years or older compared to 15.3 km/h for all cyclists
- 14.8 km/h for pedelec riders of 65 years or older compared to 17.4 km/h for all pedelec riders

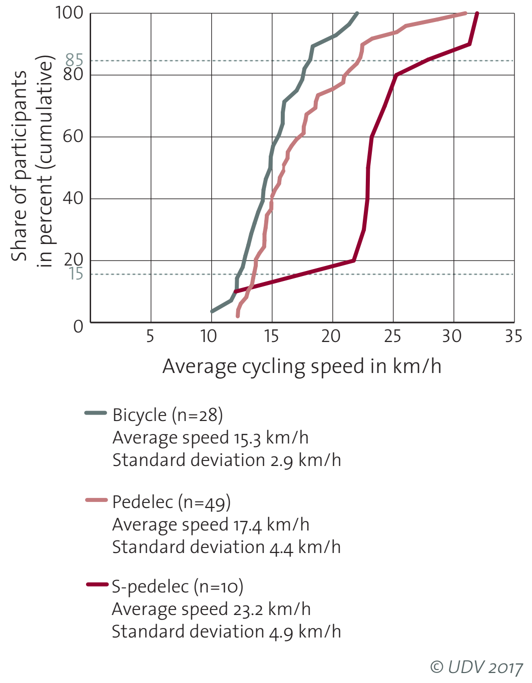


Figure 2: Speed by type of two-wheeler (wheel sensor data per trip; data acquisition period of four weeks)

However, also in the 65+ age group pedelec riders ride faster than cyclists. Due to the small sample size, it was not possible to differentiate between S-pedelec riders by age group.

In the study **Einfluss von Radverkehrsaufkommen und Radverkehrsinfrastruktur auf das Unfallgeschehen (Influence of cycling traffic volume and cycling infrastructure on traffic accidents)**, the speeds of cyclists and pedelec riders were measured locally (i.e. at a cross-section of a road). Therefore, the average speeds are around 1 to 2 km/h higher than those in the **Pedelec Naturalistic Cycling Study**. There are methodological reasons for this. When speed is measured locally, a higher share of faster cyclists is recorded than in continuous speed measurement. As a result, the average speeds are generally 2 km/h higher than in continuous speed measurement. Taken these differences into account these the speeds of the pedelec riders in the two studies are comparable. As in the **Pedelec Naturalistic Cycling Study**, the average speeds of the cyclists and pedelec riders hardly differ in the Study on the influence of cycling traffic volume and cycling infrastructure on traffic accidents. The difference between pedelec riders and cyclists was somewhat great-er in cyclists who were obviously older than 65.

In summary, the speed measurements of both studies [4, 6] show that pedelec riders do cycle faster in real traffic than cyclists. However, the difference is not as great as expected. Pedelec riders appear to use motor assistance primarily to attain similar speeds to cyclists, only with less effort. Nevertheless, older pedelec riders also cycle faster than older cyclists. It is noteworthy that the speeds of pedelec riders vary more strongly than those of cyclists. A smaller percentage of them also take advantage of the higher speed range of pedelecs. S-pedelec riders, on the other hand, are clearly faster than pedelec riders and cyclists. They regularly reach speeds outside the usual speed range of cyclists.

Speeds as perceived by other road users

It is not only the actual speed that is important for road safety; the perception of speed by other road users is also important. Since there is hardly any visible difference between electric bicycles and conventional bicycles, it might be that other road users underestimate the speeds of pedelecs and S-pedelecs. Therefore, four experiments were carried out to study car drivers' estimation of the speeds of two-wheelers, particularly electric bicycles [7].

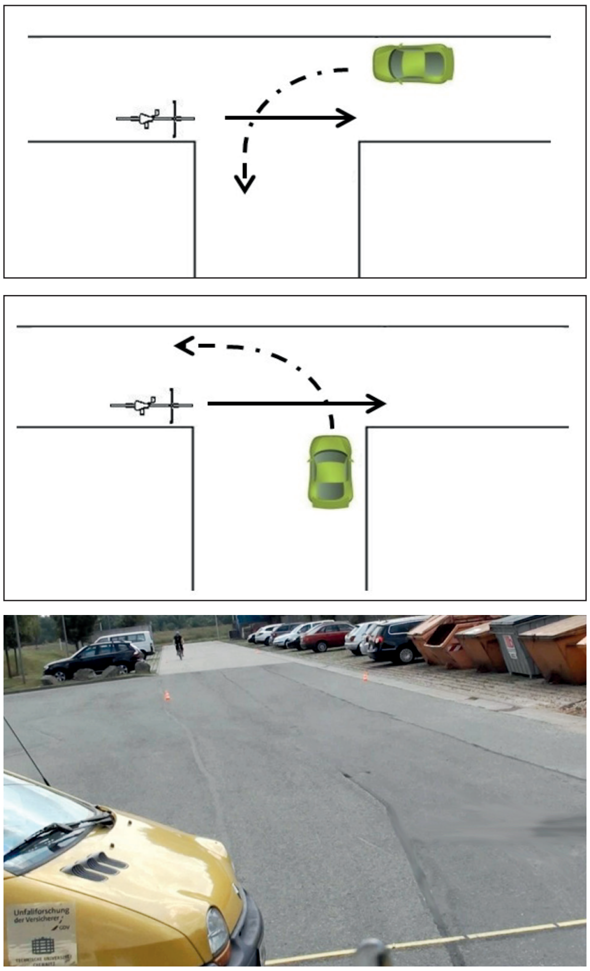
Figure 3: Still frame from the video for the estimation of the time to arrival (TTA) from the viewpoint of the participants

The estimation of speed forms the basis of many everyday decisions in traffic (e.g. before a turning maneuver or crossing a road). Most people are able to do this well enough. However, it is very difficult for people to explic-itly estimate and specify speeds. These explicit estimations are usually inaccurate. Therefore, in this study the participant's speed estimations were collected as follows:

- The estimated time required by a two-wheeler to reach a particular point (**estimated time to arrival TTA**)
- The decision to turn off the road in front of an approaching two-wheeler (**gap acceptance**) [7, 10]

For the estimated time to arrival (TTA), the participants were shown videos of two-wheelers approaching in oncoming traffic (figure 3, see previous page). Defined sections of the video were then blanked out. The participants had to press a button when they thought the two-wheeler rider would reach the white line.

Driver's gap acceptance was investigated by seating the participants in a modified car. Two-wheeler riders approached them, and the participants had to decide when they would only just turn off in front of them (figure 4). Both a frontal view and a side view of the two-wheeler rider were investigated (a frontal view for turning into a road and a side view for turning off).



42 to 46 active drivers took part in the experiments. For the two wheelers a conventional bicycle, a moped and an electric bicycle were used. The electric bicycle was an S-pedelec in order to reach speeds of up to 45 km/h. Its insurance sticker was removed, and a model was selected that looked no different from a standard pedelec. Therefore, the results in the speed range up to 25 km/h are also valid for pedelecs.

Estimated time to arrival (TTA)

TTA in general: The participants generally underestimate the time required by the two-wheeler riders to reach a particular point. In other words, they thought the two-wheeler riders would arrive sooner than they actually did. That applies to all types of two-wheeler. It is assumed that they unconsciously include a time buffer to be on the safe side.

TTA by speed: At higher speeds (in this case 35 km/h), a significantly longer time to arrival is estimated than for speeds of 25 km/h. In other words, at the higher speed two-wheelers are perceived to arrive later than at lower speed. This finding also applies to all types of two-wheeler. Thus the time buffer that drivers may be including unconsciously is shorter at higher speeds.

TTA by type of two-wheeler: Moreover, the participants estimated a significantly earlier time of arrival for a moped traveling at the same speed as an e-bike or conventional bicycle. The e-bike was thus perceived to be traveling more slowly than the moped when they were in fact moving at the same speed.

Figure 4: Turning-in and turning-off scenarios for gap selection (above); implementation of the turning-off scenario (below)

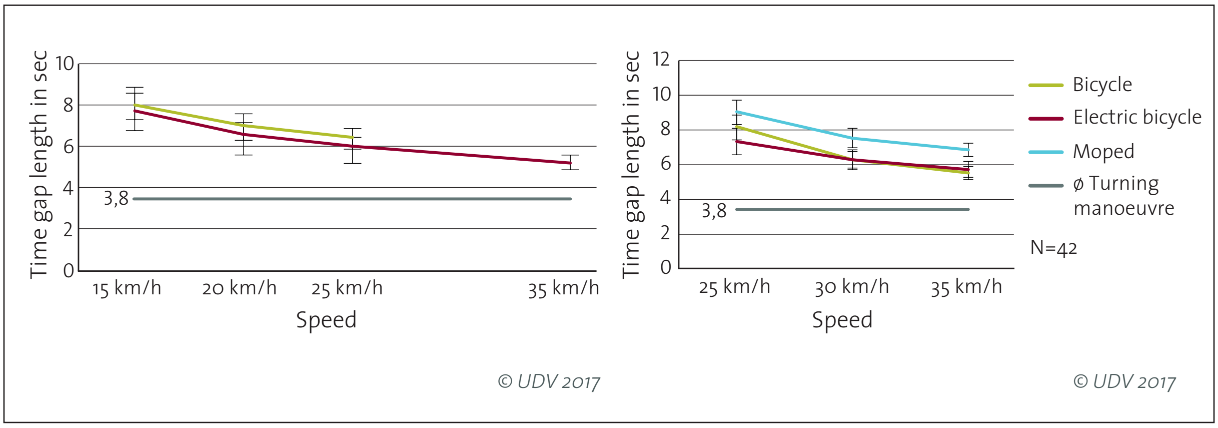


Figure 5: Time gap for turning off in front of two-wheeler riders by speed and type of two-wheeler

Decision about when to turn (gap acceptance)

Figure 5 shows the selected time gap in seconds (y-axis) depending on speed (x-axis) for different approaching two-wheelers. The straight gray line shows the time for an average turning maneuver in the selected scenario. To get this value repeated turning maneuvers were carried out in advance.

Time gap by speed: The time gaps are longer at lower speeds than at higher speeds. Thus the participants executed their turning maneuver significantly closer to approaching two-wheelers at higher speeds than to two-wheelers at lower speeds, regardless of the type of two-wheeler involved. Therefore, turning is riskier.

Time gap by type of two-wheeler: Smaller gaps were selected in front of an electric bicycle compared to a conventional bicycle traveling at the same speed, especially at a speed of 25 km/h (figure 5, right), a realistic speed for pedelecs and S-pedelecs in real traffic (section 3.1). This is remarkable because the electric bicycle and the conventional bicycle looked the same as far as the participants could tell. Traveling at the same speed, significantly smaller gaps were accepted in front of the electric bicycle and the conventional bicycle compared to the moped (figure 5, right).

However, most participants selected time gaps that were longer than an average turning maneuver (figure 5, gray line). In other words, there were generally no critical turning situations for the two-wheeler riders.

Pedal frequency

Hypothesis: The previous results suggest that the participants may use other indicators to estimate speed apart from actual speed or two-wheeler type. For example, at the same speed S-pedelecs and pedelecs allow more relaxed pedaling than bicycles, thanks to their electric pedal assistance. That could have an effect on how people ride and on their posture. Other road users could also use the rider's movements to estimate the speed. To test this assumption in a further experiment the link between pedal frequency as an indicator of relaxed cycling and the estimated time to arrival was investigated.

Result: Traveling at the same speed a rider cycling with low pedal frequency is expected to arrive later (and is thus estimated as traveling more slowly) than one cycling with a high pedal frequency. There is no difference between different types of two-wheeler. Riders who pedal more slowly are perceived to be traveling more slowly, even if they are actually traveling just as fast as those who are pedaling more quickly.

In summary, the different experiments show that higher speeds and cycling with a low pedal frequency are associated with later estimated arrival times and the selection of shorter time gaps for turning maneuvers. Since electric bicycles allow faster, more relaxed cycling, it might be that other road users underestimate their speed and select shorter time gaps for turning maneuvers before oncoming electric bicycles compared to oncoming conventional bicycles.

Road safety

In order to assess the road safety of pedelecs, first a **comprehensive accident analysis** was carried out for pedelec accidents reported to the police since 2012. Second, **cycling behavior** of pedelec riders was analyzed using data from the **Pedelec Naturalistic Cycling Study** [4,5]. Third, in crash tests the possible **consequences of accidents involv-ing S-pedelec riders** were investigated [3].

Accident analysis

In Germany only recently representative police accident data became available which distinguishes between cyclists and pedelec. Since 2014 the Germany Federal Statistical Office (Destatis) records pedelec accidents nationwide. The accident data available so far shows [16]:

- In 2016 a total of 3,982 pedelec riders were involved in an accident. 61 of them were killed, 1,158 were seriously injured, and 3,095 suffered minor injuries. The number of pedelec riders involved in accidents rose by 25 percent compared with the previous year (2015: 2,992). However, the number of pedelecs sold rose by only 13 percent in the same period [1].

- Older riders have a higher share of accidents compared to other age groups. In 2015 in the age group 65 years and above there were 9 riders per 100,000 people involved in an accident, but only one rider in the age group 25 to 35 years and only two in the age group 35 to 45 years [11].

The UDV used the police accident data for a detailed analysis of pedelec accident characteristics. In some German federal states, the police have been recording accidents involving pedelecs separately since 2012. There was data available from Baden-Württemberg, Brandenburg, Saxony, Hamburg, Saxony-Anhalt, Hesse, Thuringia, Bremen and Münster (North Rhine-Westphalia). Since there is no representative travel behavior data to calculate accidents risks (e.g. per kilometer driven), the pedelec accidents were analyzed and compared to bicycle accidents. In order to get the comparison sample of bicycle accidents the time period of analysis was determined for each federal state separately. That is because data acquisition of pedelec accidents started at different times in different federal states, so the periods cannot be compared between the federal states. The final sample consists of 2,458 pedelec accidents and 82,209 bicycle accidents from 2012 to 2015.

Results:

Age distribution: The percentage of older riders involved in accidents with pedelecs was significantly higher than for bicycle accidents. 67 percent of the pedelec riders in accidents were at least 55 years old (cyclists: 26 percent), nearly half (47 percent) were over 65 (cyclists: 14 percent), and 21 percent were older than 74 (cyclists: 6 percent).

That corresponds to the age distribution described by Destatis [11]. It reflects the age distribution in the current main user group. It is mostly older people who ride pedelecs [8].

Accident consequences: Figure 6 shows the share of casualties by injury severity for pedelec riders and cyclists. The accident consequences for pedelec riders were more serious than for cyclists across all age groups. When pedelec riders had an accident, they were seriously injured or killed more often than cyclists (29 percent for pedelec accidents vs. 17 percent for bicycle accidents).

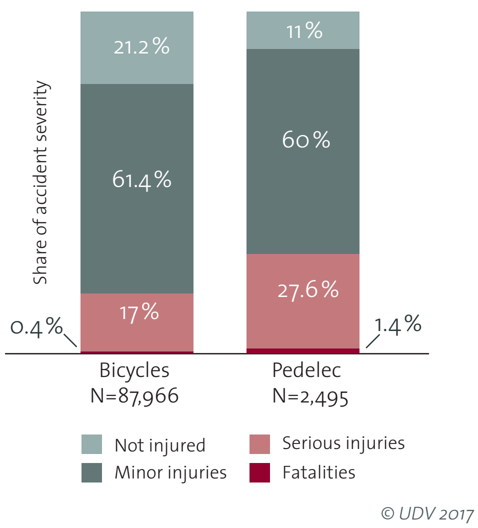


Figure 6: Percentages of uninjured, injured and killed pedelec riders and cyclists

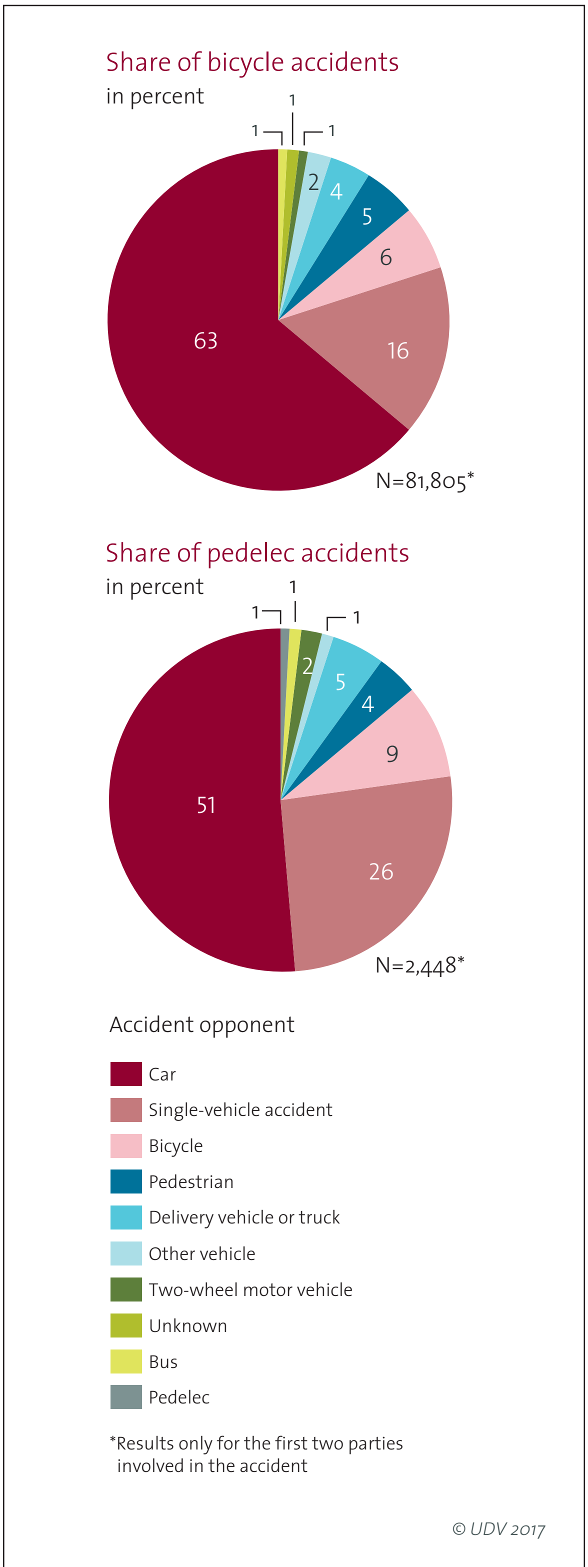
Locality: Accidents involving bicycles and pedelecs happened predominantly in built-up areas. However, the percentage of accidents occurring outside built-up areas was almost twice as high for pedelecs (16 percent) as for bicycles (9 percent). Older pedelec riders (65 years and older) had more accidents outside built-up areas than younger pedelec riders. The reason may be that pedelec riders (and older riders, in particular) cycle more often on roads outside built-up area. The results on travel behavior show that they use their pedelec more often for leisure mobility (see section 2) which also includes cycling trips in the countryside.

Accident types: There was a higher share of accidents where the rider lost control of the vehicle for pedelec accidents than for bicycle accidents (39 percent for pedelec accidents compared to 24 percent for bicycle accidents). The vast majority of these so called driving accidents were single-vehicle accidents (85 percent for cyclists and 91 percent for pedelec riders). Inappropriate speed was involved in around one out of three of these accidents. Thus, it seems that there are more cycling errors when people use a pedelecs compared to a bicycle. That can be inappropriate speed but also other handling problems. But it is also possible that single-vehicle accidents involving pedelecs are more often reported. It is known that a high number of accidents involving bicycles are not reported to the police. For pedelecs accidents that could be different, e.g. because they are more severe and therefore more often reported to the police.

Accident opponents: Figure 7 compares the accident opponents of pedelec and bicycle accidents. The percentage of single-vehicle accidents was significantly higher than for pedelec accidents than for bicycle accidents (26 percent compared to 16 percent). Moreover, in pedelec accidents there were more often other cyclists involved than in bicycle accidents.

Gender distribution: There was no difference between pedelec and bicycle accidents in terms of gender distribution. The percentage of men involved in both bicycle and pedelec accidents was higher than that for women (men 60 percent).

Accident causes: The causes of an accident are recorded by the police officer on-site based on standardized categories [12]. This includes accident causes related to the person (e.g. alcohol, speeding, disregard right of way), related to road conditions (e.g. icy road) and related to the vehicle (e.g. brakes, lights). Most often there was the category of "other errors made by the person in control of



the vehicle" (38 percent for cyclists, 46 percent for pedelec riders). These are falls, for example. Inappropriate speed was specified in 21 percent of pedelec accidents, which is higher than for bicycle accidents (17 percent). It appears that pedelec riders lost control of their vehicle more often than cyclists, or at least had problems selecting the appropriate speed in a given situation. It is also striking that pedelec riders over 65 were more often involved in accidents caused by inappropriate speed than cyclists in the same age group. It is possible that older pedelec riders attain speeds with pedal assistance that they would not on a conventional bicycle and but that they are not able to control it.

Terrain: There were a higher percentage of accidents on slopes for pedelecs than for bicycles. This corresponds to the higher share of accidents for pedelecs where the riders lose control over the vehicle.

Pedelec accidents differ from bicycle accidents in important aspects. The higher percentage of older people can be explained by the overrepresentation of older people in the current user group. The greater accident severity of pedelec riders compared to cyclists indicates that the pedelec itself can be problematic. That applies to all age groups, but to older pedelec riders in particular. Surpringly, older pedelec riders are also involved in accidents resulting from inappropriate speed, a cause of accident cause that is usually associated with younger people. It may be that the electric pedal assistance leads older riders to adopt a riding style that is that not match to their capabilities and would not be possible without pedal assistance. Inappropriate speed in that respect could also be at low speeds.

Figure 7: Percentages of different types of road users involved in bicycle and pedelec accidents compared

Cycling Behavior of electric bicycle riders

Cycling behavior was also observed and analyzed in the **Pedelec Naturalistic Cycling Study.** Of particular interest were safety-related behaviors such as helmet use, red light violations and unlawful use of the infrastructure. Due to the small sample size (a total of 90 participants) the absolute values need to be interpreted with care. Instead, most relevant are the relative differences between conventional bicycles, on the one hand, and pedelecs and S-pedelecs, on the other. [5].

Helmet use

During the four-week observation period, a camera directed at the rider's face, recorded whether a helmet was worn during the trip (see figure 2). 85 participants were included in the analysis (28 cyclists, 48 pedelec riders and 9 S-pedelec riders). 76 percent of all participants said they wear a helmet occasionally or often. Around half of the cyclists and S-pedelec riders and around 37 percent of the pedelec riders said they occasionally wear a helmet. Around 15 percent of the cyclists, 46 percent of the pedelec riders and a third of the S-pedelec riders said they wear a helmet on almost every trip. 35 percent of the cyclists, 20 percent of the pedelec riders and 11 percent of the S-pedelec riders said they never wear a helmet. This is a rather frequent helmet use compared to the representative observations in traffic carried out by the German Highway Research Institute (BASt) in 2015. There only 20 percent of the 41- to 60-year-old cyclists wore a helmet. This rate for was even lower 17- to 41-year-olds [13]. Since the participants of the **Pedelec Naturalistic Cycling Study** took part voluntarily, it may be that they are particularly safety conscious and therefore wear a helmet more often than the average people.

It was also investigated what characteristics are associated with helmet use at the trip level. A helmet was worn on 58 percent of all trips (N=3,711 trips; all types of two-wheeler).

Type of two-wheeler: A helmet was worn on 66 percent of the pedelec trips compared to 42 percent of the bicycle trip). A helmet was worn on only 89 percent of the trips with an S-pedelec, although a helmet is mandatory for S-pedelecs according to the German Road Traffic Regulations (StVO).

Journey length: A helmet was more often worn on longer journeys (>3 km) than shorter journeys (<3 km). That applies to all types of two-wheeler. Figure 8 shows the percentages of trips on which a helmet was worn by journey length (under or over 3 kilometers) and type of two-wheeler. For example, a helmet was worn on 74 percent of pedelec trips longer than 3 kilometers. On the other hand, a helmet was worn on only 59 percent of pedelec trips of less than 3 kilometers.

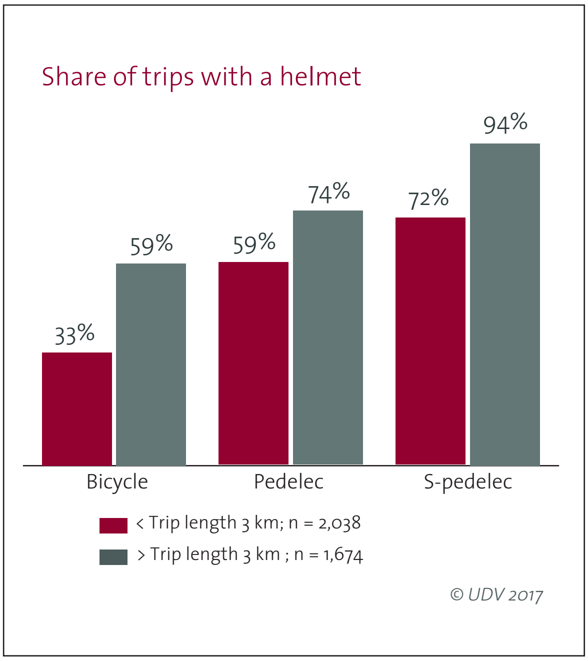


Figure 8: Percentages of trips with a helmet by trip length and two-wheeler type

Speed: Trips with a helmet tend to have a higher average speed than trips without a helmet. Figure 9 shows the average speed of all trips with and without a helmet by two-wheeler type and age group. The differences are no-table for S-pedelec riders and the age group of 41 to 64 years. An average speed of 19.4 km/h was reached on S-pedelec trips without a helmet compared to 25 km/h with a helmet.

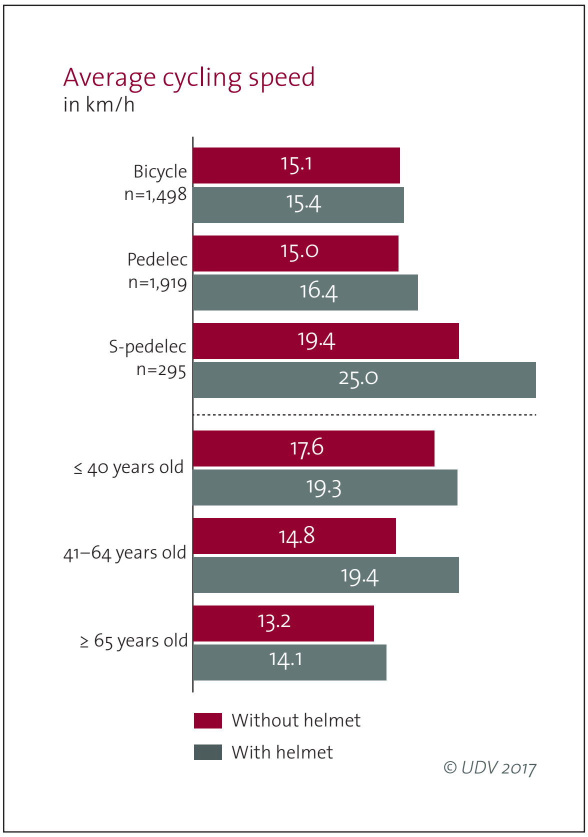


Figure 9: Average speed in km/h for trips with and without a helmet by two-' wheeler type and age

Risk compensation: A higher speed for trips with a helmet suggests that cyclists and electric bicycle riders with a helmet ride faster and possibly also take more risks (so called risk compensation). To investigate this, a regression analysis was conducted with the actual speed as outcome variable and trip characteristics (trip length, helmet use) as predictor. Risk compensation is more likely if helmet use turns out to be a good predictor of the actual speed ridden. S-pedelecs were not included in the analysis, since wearing a helmet is mandatory for them. Therefore the motivation to wear a helmet might be different compared to pedelec riders or cyclists. The results show that helmet use does not predict the actual speed. Obviously wearing a helmet does not tempt people to ride more risky. Instead, the trip length is a very good predictor of speed. People rode at higher speeds on longer journeys. Since people also tend to wear a helmet on longer journeys, it seems much more plausible that other trip characteristics influence both helmet use and speed. These might be, for example, the trip purpose or the infrastructure used.

Red light violations

In the **Pedelec Naturalistic Cycling Study**, red light violations were recorded by means of a camera filming in the direction of travel. The data of 88 participants was included in the analysis (31 cyclists, 47 pedelec riders and 10 S-pedelec riders). During the four-week observation period, a total of 7,969 traffic light situations were recorded in which the participants should have stopped. In 17 percent of these situations (n=1,335), the participants ran a red light, and in a further 5 percent they avoided the red light by changing to a different part of the infrastructure. This rate was comparable for cyclists and both groups of electric bicycle riders. Electric bicycle riders ran a red light just as often as cyclists. Participants over the age of 65 ran a red light significantly less often than younger participants. That applies to both cyclists and electric bicycle riders.

The characteristics of the red light violations are described in detail below. Since there were no differences between cyclists and electric bicycle riders, both groups were analyzed together. The following behaviors are thus characteristic of both electric bicycle riders and cyclists.

Behavior: A red light was most often run without any reaction such as braking or stopping (70 percent of red light violations). In around a fifth of the situations, the participants initially stopped at the red light and then crossed it after checking the traffic situation.

Traffic situation: The majority of red light violations occurred when turning off to the right (56 percent of red light violations, compared to 14 percent for turning off to the left and 15 percent for going straight ahead).

Infrastructure: A red light was most often run on cycling lanes (26 percent of red light violations) followed by red light violations on the sidewalk (21 percent of red light violations) and on separate cycle paths and sidewalks along the road (18 percent of red light violations).

Intersection situations: Red light violations were most often observed when approaching a T-junction (38 percent of all red light violations; figure 10). In 58 percent of these red light violations, the participants then turned right, in 27 percent of the cases they turned left, and in 15 percent of them they went straight ahead. A junction like this is rather simple. It may be that two-wheeler riders feel particularly safe here and believe that they can observe the traffic well enough to cross safely even when they are not allowed to.

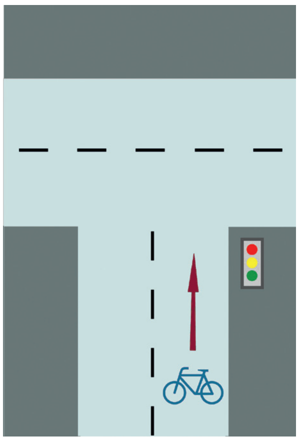


Figure 10: Approaching a T-junction

Avoidance of a red light: In addition to the 17 percent of traffic light situations in which the red light was run, the red light was avoided in a further 5 percent of traffic light situations on average (cylists 6 percent, pedelec riders 5 percent, S-Pedelec riders 3 percents). In these cases, the two-wheeler rider changed the infrastructure and avoided the red light by moving onto the sidewalk, for example. Men and younger participants avoided red lights more often.

Infrastructure use

During the four-week observation period of the Pedelec Naturalistic Cycling Study, cameras filming in the direction of travel recorded participants' use of the infrastructure [5]. The videos where coded. Unlawful use of the infrastructure and cycling against the direction of traffic was recorded and analyzed. In case of unlawful use of the infrastructure the analysis focused on use of the sidewalk where the road should have been used. This was the most common case.

Unlawful use of the sidewalk

Frequency: 81 out of 90 participants (90 percent) used at least once the sidewalk where the road should have been used according to the German Road Traffic Regulations (StVO). 7 percent of the total number of kilometers ridden (approx. 1,200 km) were ridden on the sidewalk where the road should have been used (bicycles: 9 percent; pedelecs: 7 percent; S-pedelecs: 3 percent).

Changing infrastructure: Infrastructure was usually changed in longitudinal traffic. Before and afterwards participants usually generally rode on the road. A lower curb was often used for changing, more often for changing onto the sidewalk than leaving it. Using the sidewalk where the road should have been used often resulted from changes in the infrastructure itself (e.g. cycling on a sidewalk where cycling was allowed and continuing even when a sign appeared that it no longer was). Participants often remained on the sidewalk until there was an appropriate opportunity to leave it (e.g. a drop kerb). There were also a number of situations in which they switched to the sidewalk in order to avoid a red light. They switched back to the correct infrastructure most often in order to turn off the road or at the beginning of a cycling facility.

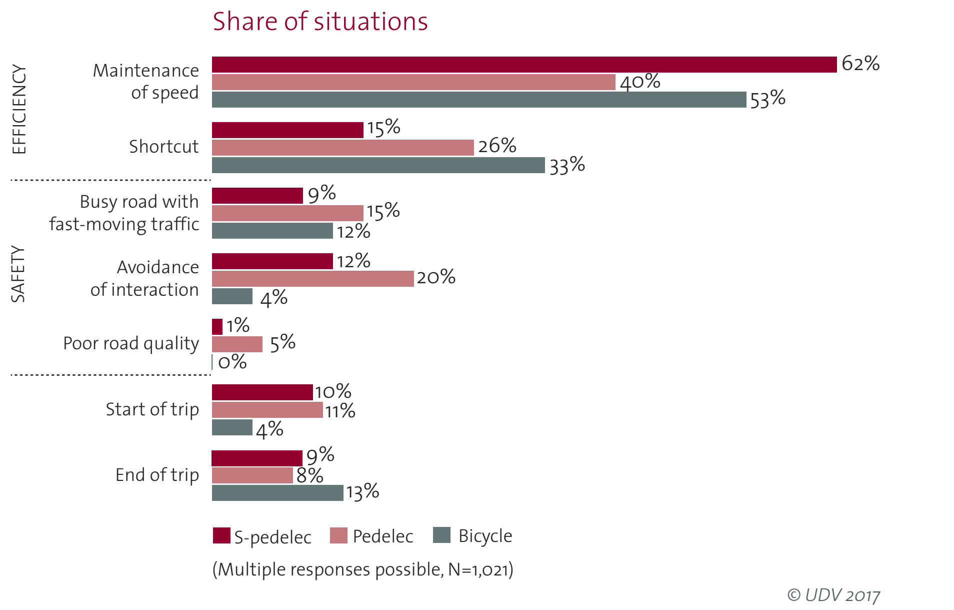


Figure 11: Percentage of situations of unlawful use of the sidewalk by motive and two-wheeler type

Motives: Efficiency appears to be the most important motive for using the sidewalk (figure 11). The sidewalk was mainly used to maintain speed or shorten the journey. This holds true for all participants but applies especially to S-pedelec riders. For example, they used the sidewalk instead of the road in around one third of the situations (33 percent) in order to take a short cut. That may be because S-pedelec riders used their S-pedelec most often for the journey to and from work and mentioned time pressure more often than pedelec riders and cyclists. Cyclists were most often trying to maintain their speed (in 63 percent of cases). That seems plausible since for cyclists it requires additional effort to regain their original speed compared electric bicycle riders.

Riding against the direction of travel

Frequency: Traveling against the direction of travel on the road or cycle paths was rare. On average the participants only spent 1 percent of the kilometers they trav-eled on the road or on cycling facilities proceeding against the direction of travel [4]. Half of the participants cycled at least once against the direction of travel (on the road or a cycling facility, n=181).

Changing infrastructure: Participants rode most often against the direction of travel in longitudinal traffic, on a separate sidewalk or cycle path parallel to the road or on the road itself. They often changed from the road to a separate cycle path and sidewalk parallel to the road and then proceeded against the direction of travel. They changed most often back to the correct direction of travel when turning into a street or when there was an appropriate possibility (e.g. where there was a gap in the central crash barrier).

Motive: Cycling against the direction of travel occurred most often where the cycling facilities where in bad condi-tion. In 22 percent of the situations, there was no cycling facility at all, and in a further 22 percent of the situations the cycling facility was not accessible (because of a central crash barrier, for example). Short cuts (32 percent) and the possibility of maintaining speed (25 percent) were further motives (multiple answers were possible).

Road safety

Accident consequences for S-pedelecs

In the study entitled Safety **Aspects of High-Speed Pedelec Electric Bikes**, collisions of S-pedelecs with a bicycle, a car and a pedestrian were simulated in order to investigate how such accidents occur and what consequence they might have [3]. These simulations represent possible accident scenarios due to increasing number of S-pedelecs on the roads. Instrumented hybrid III dummies were used in the experiments in order to record the forces on the head, neck, chest and pelvis. The threshold values were selected based on ECE 94 and 95 [14]. If the forces that impact the dummy exceeded the threshold there would be most likely serious injuries in a real accident.

Accident scenario: collision between two-wheelers in longitudinal traffic

In the first scenario the S-pedelec (traveling at 44 km/h) overtook the bicycle (22 km/h) with an overlap of 0.2 m (figure 12). They touched each other and fall. The thresholds were exceeded for the head and the neck of the S-pedelec dummy. Also there were high values for the neck and chest of the bicycle dummy. But they did not exceed the threshold.

Figure 12: Collision between a bicycle (v=22 km/h) and an overtaking S-pedelec (v=44 km/h).

Accident scenario: collision with a car door

In the second scenario the S-pedelec crashed into the side of a stationary car at 44 km/h (in the middle of the passenger door) (figure 13). The S-pedelec dummy's head, neck and chest were subject to high forces. The threshold was exceeded for the neck bending moment and chest compression speed.

Figure 13: Collision between a stationary car and an S-pedelec coming from the side (v=44 km/h)

Accident scenario: collision with a pedestrian

In the third scenario an S-pedelec hit a stationary pedestrian in the side at 25 m/h (figure 14). For both dummies the threshold for the head was exceeded.

Figure 14: Collision between an S-pedelec (v=25 km/h) and a pedestrian

Summary

Electric bicycles are becoming increasingly popular. For road safety it is important to know whether and how the potentially higher speeds affect their riders' cycling behavior and the possible accident risks. In recent years a number of studies of travel behavior and road safety of electric bicycles, particularly pedelecs and S-pedelecs, have been carried out by and on behalf of the UDV (German Insurers Accident Research). The results show:

- Pedelecs are mainly ridden for recreational/leisure-related purposes by older users. S-pedelecs are mainly used by younger, working people, for the journey to and from work.

- Pedelec riders cycle faster than conventional cyclists in the respective age group, but the difference is not as great as expected. Pedelec riders appear to use motor assistance primarily to attain similar speeds as cyclists, only with less effort. However, the speeds of pedelec riders vary more than those of conventional cyclists. A smaller percentage of them also take advantage of the higher speed range of pedelecs.

- S-pedelec riders are clearly faster than pedelec riders and cyclists. They regularly reach speeds outside the usual speed range of non-motorized cyclists.

- The perceptions and estimates of the speed of two-wheeler riders are subject to systematic distortions. The time required by two-wheeler riders to arrive at a particular point is generally underestimated, particularly at higher speeds. Accordingly, drivers accept shorter time gaps when turning off in front of two-wheeler riders approaching at higher speeds. They accept shorter time gaps for a turning maneuver in front of an electric bicycle compared to a conventional bicycle traveling at the same speed. Riders with low pedal frequency (indicating relaxed cycling) are per-ceived as arriving later at a given point compared to riders with high pedal frequency at the same speed.

- As the number of pedelecs on the roads rises, so does the number of accidents involving them. A large proportion of these accidents involve older pedelec riders. Most often pedelec riders loose of control over the pedelec and, in the case of older riders, choose an inappropriate speed as well. Pedelec riders have more serious accidents than conventional cyclists in the respective e age group.

- Pedelec riders wear a helmet more often than cyclists. S-pedelec riders very often wear a helmet, but not always. All two-wheeler riders are more likely to wear a helmet over longer distances and at higher speeds. However, there are no indications of any risk compensation here. In other words, people do not appear to cycle faster or take more risks just because they are wearing a helmet.

- Cyclists as well as riders of pedelecs and S-pedelecs do not always comply with the traffic rules. Most often they run red lights or use parts of the infrastructure that they are not allowed to. The main reasons seem to be in order to save time and to proceed more efficiently. However, deficient or non-existent cycling facilities also encourage rule violations.

Conclusion

Pedelec riders have a higher average speed than conventional cyclists, but within similar ranges. S-pedelecs are considerably faster and regularly reach speeds outside the range of conventional bicycles.

Traffic Behavior

Pedelecs are mainly ridden by older people. At the same time, the percentage of older people involved in pedelec accidents is rising. Older pedelec riders are involved in accidents resulting from inappropriate speed, a cause of accident that is usually associated with younger people. It may be that the electric pedal assistance leads them to adopt a riding style that does not match their capabilities and would not be possible without pedal assistance. Therefore, they may be at risk, a group that was not regarded as a large risk group for bicycle accidents so far.

We conclude that special training is necessary to cycle safely with a pedelec. This holds especially true, but is not limited, to elderly cyclists. Ideally such training raises awareness for the differences in bicycle dynamics between pedelec and bicycle and practices cycling / braking on higher speeds, uphill and downhill. For their own safety we recommend wearing a helmet for all cyclists.

Cyclists and riders of pedelecs and S-pedelecs regularly violate the traffic rules in order proceed faster or to compensate for inadequate cycling facility. By doing this, they endanger both themselves and other road users. Consequently, it is important to make cyclists aware of their obligations as well as their rights in traffic. At the same time, cycling facilities need to be maintained such as to allow them to proceed on their way quickly and safely.

S-pedelec riders do not always use the roads rather than cycling facilities or wear a helmet as they are supposed to do by law. However, currently there are no suitable helmets for them. Therefore, at the moment potential and actual S-pedelec should be better informed about the legal requirements for S-pedelecs.

Cycling infrastructure

The greater variation in the speeds of pedelec riders compared to cyclists, together with the increase in their numbers, represents a challenge for the cycling infrastructure, especially it's dimensioning. The cycling infrastructure should allow for safe overtaking of wo-wheeler riders among themselves in line with the "Recommendations for cycle paths and lanes" (ERA) [15]. The ERA provides guidance to build and maintain safe cycling infrastructure. According to recent UDV simulations these recommendations should be applied rigorously to ensure a safe cycling infrastructure also in the near future. That means, already today no more cycling infrastructure with only the minimum dimensions should be planned [6].

Equipment and technology

Helmets are mandatory for S-pedelec riders. However, neither bicycle helmets nor motorcycle helmets in accordance with ECE-R22 appear to be suitable. It is therefore necessary to develop special helmets for S-pedelecs. The current efforts being made by the two-wheeler industry should be intensified.

Other road users may misperceive the speed of electric bicycles which could be a problem for road safety. Therefore, it would be desirable if S-pedelecs and pedelecs looked more different from conventional bicycles by means of their design or lighting patterns.

Due to the significantly higher speeds of S-pedelecs and the severe accident consequences there should be more efforts to develop appropriate safety equipment. Safety systems that have proved successful for motorcycles, such as ABS or combined braking systems, could also be adapted for S-pedelecs.

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Content:
Dr. rer. nat. Tina Gehlert

Design:
pensiero KG, www.pensiero.eu

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Published: 08/2017

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