Cite as: Schleinitz, K., Petzoldt, T., Franke-Bartholdt, L., Krems, J.F., & Gehlert, T. (2017). The German Naturalistic Cycling Study – Comparing cycling speed of riders of different e-bikes and conventional bicycles. *Safety Science, 92*, 290-297. dx.doi.org/10.1016/j.ssci.2015.07.027

The German Naturalistic Cycling Study - Comparing cycling speed of riders of different e-bikes and conventional bicycles

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ABSTRACT

In recent years, the number of electric bicycles on European, American and especially Chinese roads has increased substantially. Today, 11% of all bicycles sold in Germany are e-bikes. Given their potential to reach higher maximum speeds, concerns have been raised about a possible increase in crash risk associated with e-bike use. However, as of now, it is unclear if and how often the potentially higher speed is actually reached in everyday cycling. As part of the German Naturalistic Cycling study we measured and compared the speed of three bicycle types (conventional bicycles, pedelecs (pedalling supported up to 25 km/h), S-pedelecs (pedalling supported up to 45 km/h)) under naturalistic conditions. Ninety participants, divided in three age groups, took part in our study. Participants used their own bikes or e-bikes. The bicycles were equipped with a data acquisition system, which included sensors to record speed and distance, as well as two cameras. Data was collected over a period of four weeks for each participant. Nearly 17,000 kilometres of cycling were recorded in total. The statistical analysis revealed significant differences in mean speed between all three bicycle types. Pedelec riders were, on average, 2 km/h faster than cyclists. S-pedelec speed was even 9 km/h higher. A similar pattern was also found when analysing free flow conditions and uphill or downhill cycling separately. The highest speed was measured on carriageways and bicycle infrastructure, regardless of bicycle type. Participants aged over 65 years rode significantly slower than younger participants. Data on acceleration from standstill largely confirm the differences between bicycle types and age groups. The results show that electric bicycles indeed reach higher speeds than conventional bicycles regularly. Although it is unclear if this also leads to an increase in crash risk, it can be assumed that the consequences of a crash might be, on average, more severe.

Keywords: e-bikes, speed, acceleration, infrastructure types, Naturalistic Cycling Study.

1 INTRODUCTION

In recent years, the distribution of electric bicycles (e-bikes) has increased continuously. Especially in China, the number of e-bikes has risen substantially (Bundesministerium für Verkehr Innovation und Technologie, 2013). A similar trend can be observed in the US and in Europe (Rose, 2012). In Germany, about 1.6 million electric bicycles are currently on the road (Zweirad-Industrie-Verband, 2014), and it is expected, that this number will increase even further (Jellinek et al., 2013). As a result of this development, questions have been raised regarding a potentially increased crash risk for e-bikes. One central concern that has been voiced repeatedly is the fact that these e-bikes can reach a higher speed than conventional bicycles, which might lead to a variety of problems (Bai et al., 2013; Jellinek et al., 2013; Skorna et al., 2010). Scaramuzza and Clausen (2010) estimated an increase of severe injuries of about 150%, and an increase of even 350% for fatalities, if the overall cycling mean speed would increase by 6 km/h as a result of the growing distribution of e-bikes.

Data on the speed of conventional bicycles have been inconsistent. Two US studies found comparable mean speeds of 18 km/h (Dill and Gliebe, 2008) and 16 km/h (Thompson et al., 1997). Other investigations from Europe have reported mean speeds between 12 km/h and 14 km/h for conventional cyclists (Dozza and Werneke, 2014; Menghini et al., 2009). Up until now, only few studies have investigated the average speed of e-bikes. Results from China (Cherry and He, 2009; Lin et al., 2007) suggest that e-bikes are considerably faster than conventional bicycles. Mean speeds were found to be 7 km/h (Lin et al., 2007) and 5 km/h (Cherry and He, 2009) higher, respectively. For users of a US bike share programme higher travel speeds were found for e-bikes (13 km/h) in comparison to bicycles (11 km/h) on carriageways, whereas e-bike speed was lower on shared use facilities (Langford et al., 2015). For Europe, a Swiss study (Paefgen and Michahelles, 2010) reported an e-bike mean speed of about 19 km/h, however lacked comparable data for conventional bicycles. An observational study in Germany recorded a mean speed of nearly 17 km/h for e-bikes (Alrutz, 2013, 2012), which was two to three km/h higher than for conventional bicycles.

Unfortunately, the term e-bike has been applied to a very broad range of vehicles, with a high variance in the support they provide, and subsequently with profound differences in the potential maximum speed. In China, some scooters with only rudimentary pedals are considered e-bikes (Cherry and Cervero, 2007). Such vehicles would hardly be called e-bikes by European standards. But also in Europe, different categories of electric bicycles exist. In Germany, we distinguish between so called pedelecs, which support pedalling up to 25 km/h (250W), and S-pedelecs, which support up to 45 km/h (500W) (Zweirad-Industrie-Verband, 2012). Similar categorisations (often with consequences for licensing, insurance etc.) exist in most European countries (Jellinek et al., 2013). It is obvious that comparisons of operating speed between different studies from different countries all over the world, with different traffic environments, different cyclist populations, and different bicycle categories are problematic.

Adding to this problem is the fact that the cited studies use a variety of different methodologies, each with their individual shortcomings and restrictions. Many investigations covered only a limited range of infrastructure types, as they either used a stationary (Jellinek et al., 2013; Lin et al., 2007; Thompson et al., 1997) or “floating vehicle” (Cherry and He, 2009) approach. This might result in a considerable bias in the data (limited infrastructure and traffic environment, bias in the observed cyclist populations, trip purposes etc.), and can limit the generalisability of the findings. Such observations also hamper the assessment of the influence of a variety of variables, as age, gender and even bicycle type have to be judged by an observer and cannot be directly collected (Jellinek et al., 2013; Lin et al., 2007). Other issues include limitations in subject samples or the lack of proper control groups (Paefgen and Michahelles, 2010).

The aim of this study was the investigation of speed (including acceleration) of electric bicycles in comparison to conventional bicycles. In order to avoid the described methodological issues, the naturalistic cycling methodology appeared to be most appropriate. In naturalistic observations, cameras and sensors are used to record the road users' usual behaviour to obtain data that is not contaminated by the influence of experimental manipulation. With motorised vehicles, *Naturalistic Driving Studies* (NDS) have been conducted for more than 20 years now (Dingus et al., 2006; Kessler et al., 2012; Lee et al., 2004). Only recently has the NDS approach been applied for the investigation of cyclist behaviour (so called *Naturalistic Cycling Studies*, NCS). Most NCS were interested in the identification of safety critical situations when riding a conventional bicycle (Dozza and Werneke, 2014; Johnson et al., 2010), while others focused on mobility behaviour or rider distraction (Gustafsson and Archer, 2013; Knowles et al., 2012). So far, no NCS has been conducted that addressed the speed differences between different bicycle types. Our study investigated the speed and acceleration of conventional bicycles, pedelecs and S-pedelecs without restrictions, taking into consideration aspects such as infrastructure, road gradient and riders' age.

2 METHOD

2.1 Participants

Participants were recruited through newspaper ads or flyers in cycling shops. The applicants filled in a recruitment questionnaire, which included questions on their socio-demographic status and technical data of their bicycle, with special focus on the bicycle type (conventional bicycle, pedelec, S-pedelec). Applicants were selected for participation based on criteria such as bicycle type, frequency of usage and age. As we were especially interested in e-bikes, we tried to recruit as many e-bike riders as possible. However, since S-pedelecs are still rather rare (Preißner et al., 2013; Zweirad-Industrie-Verband, 2013), there were relatively few applicants for this group. At the same time, we had a substantial number of candidates for the pedelec category. Those candidates were, on average, older riders, which is in line with the reported age structure of the overall pedelec rider population in Germany (Alrutz, 2013; Preißner et al., 2013). To ensure comparability of our different user groups, we selected users of conventional bicycles for participation matching the age of the pedelec riders. 90 cyclists took part, however data of five participants had to be excluded from analysis as the data sets were incomplete. 85 datasets (32 female, 53 male), divided in three age groups (see Table 1 for an overview), remained for analysis[1]. Gender was not equally distributed across the different bicycle types. Our S-pedelec riders were all male, whereas in the other two groups, distribution was more (although not fully) even (bicycle: 11 female, 17 male, pedelec: 21 female, 27 male). As participants were supposed to use their own bicycles for the study, we saw a wide range of different bicycle types. The majority of our participants' conventional bicycles were so called city bikes, with also a few mountain bikes. Only two pedelec riders owned a mountain bike style pedelec, the rest were all city bikes. All S-pedelec riders used trekking or city bikes. Nearly 60% of the e-bike riders reported to use a regular bicycle in addition to their e-bike. All participants received €100 for their participation.

Table 1: Overview of demographic data (*N* = 85).

	Cyclist			*Pedelec rider*			*S-pedelec rider*		
Age groups	*N*	*M age*	*SD age*	*N*	*M age*	*SD age*	*N*	*M age*	*SD age*
≤ 40 years	*8*	*30.8*	*7.1*	*15*	*33.3*	*6.6*	*3*	*25.0*	*9.5*
41 - 64 years	*9*	*52.4*	*8.5*	*14*	*54.1*	*7.2*	*6*	*43.2*	*1.7*
≥ 65 years	*11*	*69.5*	*3.2*	*19*	*70.4*	*3.2*	*-*	*-*	*-*
Total	***28***	***51.5***	***17.2***	***48***	***53.5***	***16.8***	***9***	***37.1***	***10.3***

[1] Due to the use of stricter criteria for the inclusion of datasets, the subject sample differs slightly from the published research report (Schleinitz et al., 2014). Consequently, values in descriptive statistics differ as well. However, the overall findings based on inferential statistics are identical.

2.2 Data Acquisition System (DAS)

Trained technicians installed and uninstalled a data acquisition system (DAS) on the participants' own bicycles. A speed sensor was installed on the front wheel to record speed and distance data (data rate 2 Hz). Two cameras (Type ACME FlyCamOne eco V2), placed in a small box, were mounted on the handlebar. One camera captured the forward scenery and the other the face of the cyclist. The videos were recorded at 30 frames per second with a resolution of 720x480 pixels (VGA). All data was stored on two SD-memory cards, one for video (32 GB) and one for speed data (4 GB). Participants started and stopped recording with a flip switch.

2.3 Procedure

The study was conducted in and around Chemnitz (Germany) from July to November 2012. Exposure to different weather conditions did not differ between the three bicycle types, as we made sure that during the whole period of data acquisition, the same proportion of conventional bicycles, pedelecs and S-pedelecs was instrumented. For each participant, data was recorded over a period of four weeks. Weather conditions varied from hot and sunny in summer to cold and icy in October. An individual appointment for the installation of the DAS was arranged with each participant. In order to check their level of cycling ability, the technician conducted a short cycling skill test with the participants. None of the participants showed any specific deficits. During the course of the observation period, participants were instructed to use their bicycles as they would do normally. They were supposed to record every single trip they made, regardless of trip purpose, trip duration, time of day or other factors. Necessary maintenance procedures like DAS repairs and exchange of storage media were carried out by our technicians. At the end of the observation period, another individual appointment was made for dismounting the DAS.

2.4 Data preparation

Sensor data

Data of the wheel sensors were collected for each trip to obtain data for speed and covered distance. Data of non-trip recordings (e.g. DAS still activated while the bike was already parked) were excluded from the analysis. To calculate operating speed, we followed the common procedure in removing all standstill situations (speed = 0 km/h) from the dataset (Cherry, 2007; Dill and Gliebe, 2008; Lin et al., 2007).

To analyse the cyclists' acceleration, we decided to look into situations in which the cyclist started from standstill. Due to the relatively low data rate (2Hz), reporting acceleration in m/s² appeared inappropriate. Instead, we described the development of speed immediately after a standstill situation, without the calculation of an actual acceleration metric. We analysed a window of 15s after a bike started moving again. Only situations in which a speed of a least 5 km/h inside that window was reached were included in the analysis. If this was not the case, it had to be assumed that no normal acceleration had occurred (e.g. the bike was pushed).

Video data

To investigate the influence of different infrastructure characteristics on cyclists' speed, video material was annotated for each trip continuously for one week that was chosen randomly. The categories of infrastructure were based on definitions in German road traffic regulations (StVO, see Table 2). We also annotated free flow situations (no other road user in front of cyclist, no curves or other obstacles) and instances of clearly downhill and uphill riding.

The overall annotation procedure was based on Klauer, Perez and McClafferty (Klauer et al., 2011). All annotators received a special training. Discrepancies found by the senior annotators in spot checks were discussed and resolved in team meetings. In total, 1,023 videos with a duration of about 263 hours were annotated. The video annotations were synchronised with the sensor data in our database, so that the cyclists' speed could be linked to the infrastructure characteristics.

Table 2: Overview of the annotated categories of infrastructure.

Type of infrastructure	*Description/Examples*
Carriageway	*Part of a road used by cars etc.*
Bicycle infrastructure	*Bicycle lane, bike path*
Pavement	*Footpath along the sides of a road*
Pedestrian precinct	*Pedestrian-only use, some or all automobile traffic prohibited*
Unpaved	*Forest path, field path*
Miscellaneous	*All other types of infrastructures i.e. parking facility, small path between buildings, path in allotment*

3 RESULTS

In order to assess the relationship between the different bicycle types and cycling speed without the confounding influence of age (and since we were not able to recruit older participants in the S-pedelec group, resulting in an empty cell in our design), we conducted analyses of covariance (ANCOVA) with participants' age as covariate. It has to be acknowledged that the ANCOVA regression slopes were not homogeneous in several cases. Therefore, we conducted additional ANOVAs, in which we included the age group as a factor (see Table 1), and omitted the S-pedelec group as a level of the factor bicycle type. All reported post-hoc pairwise comparisons were corrected for multiple comparisons (Bonferroni correction).

3.1 Dataset overview

Overall, we recorded 4,327 trips with a total distance of 16,873 kilometres during the four weeks of data collection. On average, each participant cycled about 198.5 km during the study. Although the S-pedelec riders appeared to have cycled longer total distances than the other two groups, an ANCOVA revealed no significant differences between the bicycle types, F (2, 81) = 2.87, p = .062, η^2_p = 0.07, (see Table 3). Age had also no significant influence on the distance cycled, F (1, 81) = 2.73, p = .103, η^2_p = 0.03. It has to be noted that, for all bicycle types (especially the S-pedelecs), the range in total distance travelled is considerable. For mean trip length, the ANCOVA revealed a significant difference between the bicycle types, F (2, 81) = 5.91, p = .004, η^2_p = 0.13, whereas no effect for age was found, F (1, 81) = 0.41, p = .523, η^2_p = 0.01. Trips on S-pedelecs (M = 7.3 km, SD = 4.4 km) were significantly longer compared to trips completed with pedelecs (M = 4.7 km, SD = 2.9 km, p = .035) and conventional bicycles (M = 3.5 km, SD = 2.5 km, p = .003). Pecelec and bicycle trip length did not differ significantly from each other (p = .350).

Table 3: Mean total distance travelled in km per bicycle type and age group (N = 85).

	Bicycle (N = 28)				*Pedelec (N = 48)*				*S-pedelec (N = 9)*			
Age group	*M*	*SD*	*Min*	*Max*	*M*	*SD*	*Min*	*Max*	*M*	*SD*	*Min*	*Max*
≤ 40 years	*149.1*	*69.7*	*64.5*	*291.1*	*166.7*	*114.0*	*53.1*	*471.8*	*135.1*	*45.5*	*89.6*	*180.6*
41 - 64 years	*210.9*	*113.3*	*42.8*	*411.0*	*193.4*	*110.7*	*65.9*	*446.3*	*345.5*	*288.0*	*148.8*	*922.8*
≥ 65 years	*198.3*	*131.4*	*30.2*	*425.8*	*206.1*	*61.5*	*111.9*	*324.2*	-	-	-	-
Total	***188.3***	***110.1***	***30.2***	***425.8***	***190.1***	***94.8***	***53.1***	***471.8***	***275.4***	***251.8***	***89.6***	***922.8***

3.2 Speed

Mean speed, free flow conditions and road gradient

Figure 1 displays the distribution of trip mean speed. In general, S-pedelec riders completed more trips with higher mean speed than the other two groups. The analysis of mean speed (see Table 4) strengthened this impression. S-pedelecs travelled at ca. 24.5 km/h on average, pedelecs at 17.4 km/h, and conventional bicycles only at 15.3 km/h. An ANCOVA revealed a significant effect of bicycle type, F (2, 81) = 15.33, p < .001, η^2_p = 0.28. Pairwise comparisons showed that all bicycle types differed significantly from each other ($p \leq .019$). Participants' age had a significant influence on operating speed as well, F (1, 81) = 27.92, p < .001, η^2_p = 0.26.

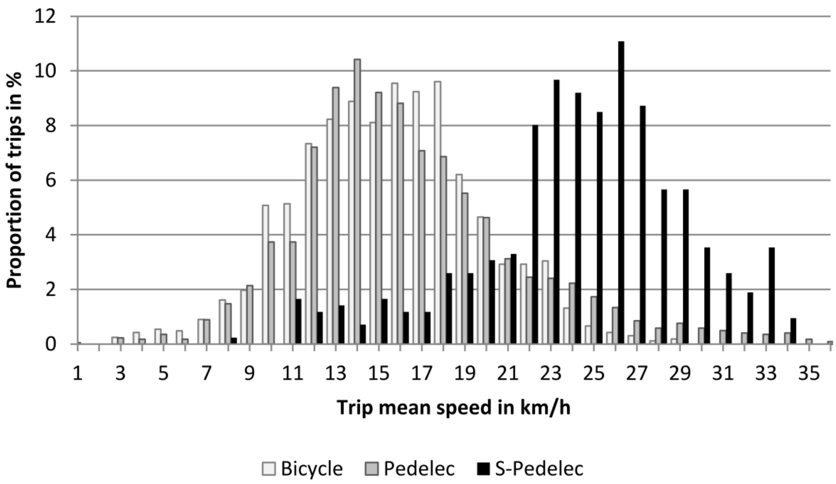

Figure 1: Proportion of trips made at different speeds (1 km/h steps) per bicycle type (N = 85).

Table 4: Mean speed per trip in km/h for different bicycle types and age groups (*N* = 85).

		Bicycle (N = 28)				*Pedelec (N = 48)*				*S-pedelec (N= 9)*			
Age group		*M*	*SD*	*Min*	*Max*	*M*	*SD*	*Min*	*Max*	*M*	*SD*	*Min*	*Max*
Speed	*≤ 40*	*16.6*	*3.4*	*13.1*	*22.0*	*20.5*	*5.2*	*12.9*	*31.0*	*23.4*	*0.9*	*22.6*	*24.3*
	41-64	*15.8*	*2.3*	*12.6*	*20.3*	*17.5*	*4.0*	*12.2*	*25.3*	*25.1*	*3.7*	*21.7*	*31.9*
	≥ 65	*13.9*	*2.6*	*10.1*	*18.4*	*14.8*	*1.9*	*12.2*	*18.6*	-	-	-	-
	Total	***15.3***	***2.3***	***10.1***	***22.0***	***17.4***	***4.4***	***12.2***	***31.0***	***24.5***	***3.1***	***21.7***	***31.9***
Speed free flow	*≤ 40*	*18.0*	*2.9*	*13.9*	*21.4*	*23.6*	*5.9*	*14.5*	*33.1*	*22.1*	*3.5*	*18.7*	*25.7*
	41-64	*17.6*	*3.4*	*13.6*	*25.4*	*18.6*	*4.5*	*13.3*	*28.0*	*26.3*	*4.1*	*22.1*	*33.5*
	≥ 65	*13.6*	*2.8*	*9.7*	*17.9*	*15.6*	*2.5*	*11.3*	*20.5*	-	-	-	-
	Total	***16.1***	***3.6***	***9.7***	***25.4***	***19.0***	***5.5***	***11.3***	***33.1***	***24.9***	***4.2***	***18.7***	***33.5***
Speed uphill	*≤ 40*	*14.5*	*3.1*	*10.8*	*19.6*	*20.4*	*5.1*	*13.9*	*31.8*	*20.7*	*1.9*	*19.4*	*22.8*
	41-64	*13.9*	*4.0*	*9.3*	*23.2*	*16.1*	*3.2*	*9.6*	*22.1*	*22.2*	*4.4*	*16.8*	*28.9*
	≥ 65	*10.9*	*2.1*	*7.6*	*14.0*	*13.5*	*2.2*	*10.6*	*17.3*	-	-	-	-
	Total	***12.9***	***3.4***	***7.6***	***23.2***	***16.4***	***4.6***	***9.6***	***31.8***	***21.7***	***3.7***	***16.8***	***28.9***
Speed down-hill	*≤ 40*	*19.6*	*3.2*	*14.5*	*24.6*	*26.9*	*7.0*	*18.5*	*42.9*	*27.0*	*2.6*	*25.1*	*29.9*
	41-64	*20.6*	*2.3*	*16.8*	*24.5*	*21.2*	*5.6*	*11.4*	*28.7*	*28.3*	*3.1*	*25.7*	*34.4*
	≥ 65	*16.7*	*3.6*	*11.9*	*21.7*	*18.5*	*2.4*	*15.2*	*22.3*	-	-	-	-
	Total	***18.8***	***3.5***	***11.9***	***24.6***	***21.9***	***6.2***	***11.4***	***42.9***	***27.9***	***2.9***	***25.1***	***34.4***

For all bicycle types, the speed under free flow conditions (n = 84, one participant was not recorded riding under free flow conditions) was in general slightly higher than mean speed (Table 4). The ANCOVA showed a significant effect of bicycle type, F (2, 80) = 8.54, p < .001, η^2_p = 0.18, as well as a significant influence of age as covariate, F (1, 80) = 34.77, p < .001, η^2_p = 0.30. Pairwise comparisons showed that riders of conventional bicycles rode significantly slower than the riders of e-bikes (both p ≤ .10). There was no significant difference between pedelec and S-pedelec.

As expected, road gradient had an influence on the cyclists' speed as well (Table 4). When riding downhill, our participants were, on average, 5.8 km/h faster than when cycling uphill, F (1, 81) = 30.90, p < .001, η^2_p = 0.28. We again found significant effects of bicycle type, F (2, 81) = 12.88, p < .001, η^2_p = 0.24 and age, F (1, 81) = 33.09, p < .001, η^2_p = 0.29. The speed of the conventional bicycles differed significantly from the speed of the other two types (both p ≤ .001), whereas there was no difference between pedelec and S-pedelec. There was no significant interaction between bicycle type and road gradient.

Mean distance travelled at higher speed

In addition to the assessment of differences in mean speed, we analysed to what extent our cyclists travelled at a higher speed. For this purpose, the distance covered at speeds above 20 km/h, 25 km/h and 30 km/h was related to the total cycling distance of each group (see Figure 2). As expected, S-pedelec riders covered a much higher proportion of their overall mileage at the higher speed levels. More than 80% of their total cycling distance was completed at a speed of 20 km/h or above, and still 34% with a speed of 30 km/h or higher.

Separate ANCOVAs revealed a significant main effect for bicycle type on each of the three speed levels (an overview of all effects can be found in Table 5). Pairwise comparisons showed significant differences between all three bicycle types for the 20 km/h level (all $p \leq .031$). At 25 km/h and 30 km/h, only the difference between S-pedelecs and the other two bicycle types was significant (all $p < .001$).

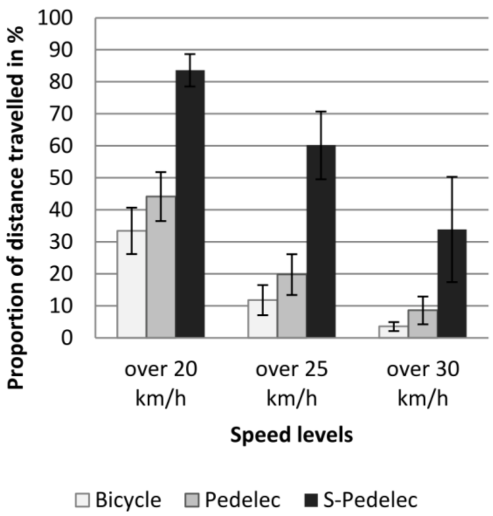

Figure 2: Proportion of distance travelled at speeds above 20 km/h, 25 km/h and 30 km/h per bicycle type (*N* = 85).

Table 5: Summary of all ANCOVA results for the three higher speed levels (*N* = 85).

		F	p	η^2_p
over 20 km/h	*Bicycle type*	*13.06*	***<.001***	*0.24*
	Age group	*42.02*	***<.001***	*0.34*
over 25 km/h	*Bicycle type*	*19.78*	***<.001***	*0.32*
	Age group	*31.66*	***<.001***	*0.28*
over 30 km/h	*Bicycle type*	*13.48*	***<.001***	*0.25*
	Age group	*9.46*	***.003***	*0.11*

Speed on different types of infrastructure

Table 6 displays the mean operating speed and the total distance cycled on each of our annotated types of infrastructure. The analysis is only reported at a descriptive level, as cell sizes vary considerably. Also, there is a wide variation in how often and how long each individual cyclist travelled on a specific infrastructure category, so participants' contributions to the cells' mean values are highly variable. Because of that, we decided to abstain from inferential statistics for this analysis.

S-pedelec riders cycled fastest on all types of infrastructure. The highest speed was measured when participants were travelling on the carriageway or bicycle infrastructure. Only for these two infrastructure types, we found a difference between conventional bicycles and pedelecs, whereas for all other categories, the mean speed were more or less equal. For all bicycle types, the speed recorded on the pavement and in pedestrian precincts was relatively high, although in Germany it is not legal to cycle on such infrastructure (with few exceptions). Also conspicuous was the high speed of S-pedelecs on bicycle infrastructure, especially when compared to the other two bicycle types. The use of S-pedelecs on bicycle infrastructure is illegal, yet our participants covered 18% of their total mileage there.

Table 6: Mean speed per trip in km/h on different types of infrastructure per bicycle type (N = 85).

Infrastructure	*Bicycle*				*Pedelec*				*S-pedelec*			
type	*N*	*M*	*SD*	*Σ km*	*N*	*M*	*SD*	*Σ km*	*N*	*M*	*SD*	*Σ km*
Carriageway	*28*	*16.4*	*2.7*	*640.8*	*48*	*18.8*	*4.4*	*1,387.7*	*9*	*25.6*	*2.8*	*331.9*
Bicycle infrastructure	*27*	*16.7*	*4.0*	*204.1*	*42*	*18.4*	*4.7*	*328.1*	*6*	*23.6*	*2.3*	*60.3*
Pavement	*28*	*13.3*	*3.0*	*126.6*	*48*	*13.9*	*4.8*	*201.0*	*7*	*17.6*	*3.2*	*22.5*
Pedestrian precinct	*17*	*12.7*	*4.0*	*17.8*	*15*	*11.1*	*2.8*	*15.3*	*2*[*]	*19.8*	*2.9*	*1.5*
Unpaved	*15*	*13.7*	*4.7*	*120.1*	*31*	*14.5*	*5.0*	*189.0*	*5*	*16.4*	*3.1*	*11.8*
Miscellaneous	*27*	*9.9*	*2.2*	*44.1*	*48*	*9.4*	*3.3*	*56.1*	*9*	*14.2*	*1.6*	*11.1*

[*]Note: Only few instances of cycling in pedestrian precincts were recorded for S-pedelec riders.

Influence of age on speed

To analyse the effect of age in more detail, ANOVAs that included the age group (see

Table 1) as a factor were calculated only for conventional bicycles and pedelecs. For mean speed, the analysis showed a significant main effect of the factor age group (n = 76), F (2, 70) = 9.02, p < .001, η^2_p = 0.21 (Figure 3, top left). Pairwise comparisons showed a significant difference between our older and younger group (p < .001). ANOVAs analysing speed under free flow conditions (n = 75, Figure 3, top right), and speed dependent on road gradient (n = 76, Figure 3, bottom) also showed this age effect, F (2, 69) = 14.18, p < .001, η^2_p = 0.29 and F (2, 70) = 13.53, p < .001, η^2_p = 0.28. Pairwise comparisons again showed in both cases that the older group differed significantly from the younger one (both p < .001), but also from the 41-64 year olds (p ≤ .014). We found no significant interactions between age group and any other variable for any of the ANOVAs.

A similar pattern was also found for the mean total distance travelled at a higher speed level (see Table 7). Again, the ANOVAs confirm the effect of age group (all p ≤ .006; η^2_p = 0.13 - 0.24).

Post-hoc comparisons showed that older participants differed significantly from the younger participants (all $p \leq .006$) in all three speed levels. At the 20 km/h level, there was also a difference between the older participants and the 41 to 64 years group ($p = .006$).

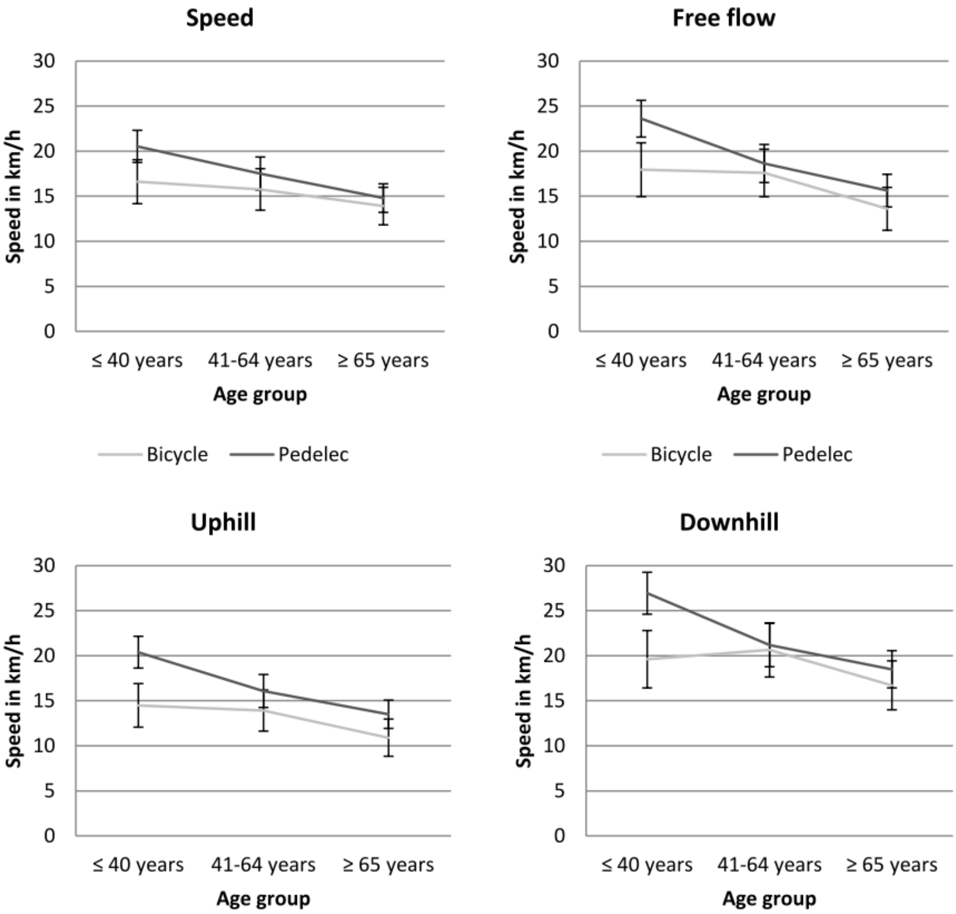

Figure 3: Overall mean speed (top left), speed under free flow conditions (top right) and speed dependent on road gradient (bottom) per bicycle type (conventional bicycle and pedelec only) and age group (n = 76).

Table 7: Proportion of total distance travelled at high speed levels for bicycle types and age groups (n = 76).

		Bicycle (N = 28)		Pedelec (N = 48)		Total (N = 76)	
		M	*SD*	*M*	*SD*	*M*	*SD*
Proportion over 20 km/h in %	*≤ 40 years*	*41.5*	*22.1*	*63.1*	*24.1*	*55.6*	*25.2*
	41-64 years	*36.0*	*16.2*	*48.9*	*25.3*	*43.9*	*22.7*
	≥ 65 years	*13.6*	*16.4*	*25.8*	*15.0*	*25.7*	*15.3*
	Total	***33.5***	***18.7***	***44.2***	***26.3***	***40.2***	***24.3***
Proportion over 25 km/h in %	*≤ 40 years*	*17.3*	*17.9*	*36.6*	*26.4*	*29.8*	*25.2*
	41-64 years	*12.1*	*11.0*	*19.6*	*19.8*	*16.7*	*17.0*
	≥ 65 years	*7.6*	*5.9*	*6.7*	*4.2*	*7.1*	*4.8*
	Total	***11.8***	***12.1***	***19.8***	***22.0***	***16.9***	***19.2***
Proportion over 30 km/h in %	*≤ 40 years*	*5.0*	*5.1*	*19.6*	*22.6*	*14.5*	*19.6*
	41-64 years	*3.5*	*3.5*	*6.0*	*6.7*	*5.0*	*5.7*
	≥ 65 years	*2.6*	*2.0*	*1.9*	*1.5*	*2.1*	*1.7*
	Total	***3.6***	***3.6***	***8.6***	***15.0***	***6.7***	***12.3***

3.3 Acceleration

In Figure 4 (left), acceleration from standstill is illustrated for the three bicycle types (N = 85). It is clearly visible that S-pedelec riders accelerated much stronger than the other two groups. After 2.5 s, they were, on average, more than 2 km/h faster than conventional bicycles and pedelecs, after 5 s, the difference was nearly 5 km/h. In contrast, there appears to be no difference between conventional bicycles and pedelecs. It has to be acknowledged that, as we have shown previously, speed and age are confounded. Since the S-pedelec sample was, on average, younger than the other samples, the actual effect of bicycle type might be smaller than the graph suggests.

Figure 4 (right) displays the relationship between age group and acceleration (similar to the analysis of the effect of age on speed, only conventional bicycles and pedelecs are included, *n* = 76). As the results on operating speed would have suggested, the three different age groups also differed in terms of acceleration. The youngest group reached certain speed levels much earlier than the other two. There also seems to be a difference, however less pronounced, between the two other groups, with the oldest cyclists having accelerated the weakest.

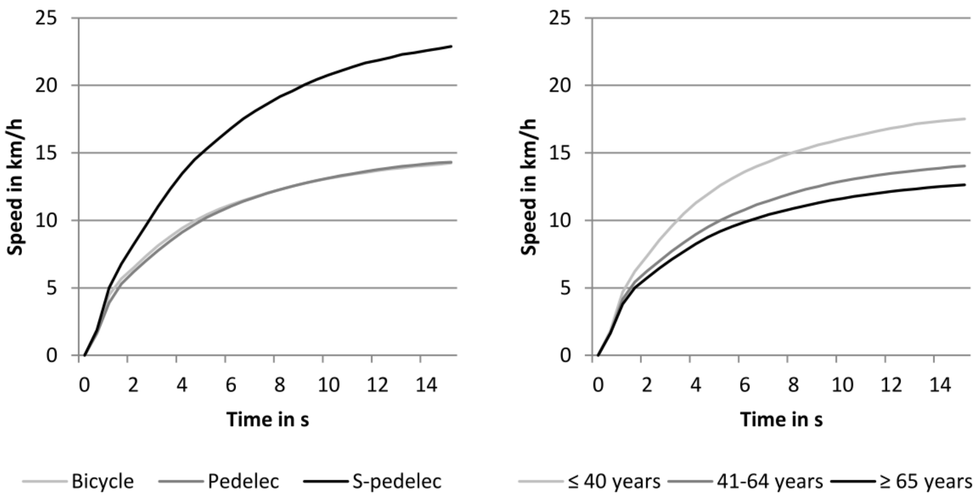

Figure 4: Acceleration per bicycle type (left, *N* = 85) and age group (right, conventional bicycle and pedelec only, *n* = 76).

4 DISCUSSION AND CONCLUSION

Aim of this study was to investigate the speed and acceleration of electric and conventional bicycles under naturalistic conditions. We differentiated between electric bicycles that provide support up to 45 km/h (so called S-pedelecs) and 25 km/h (pedelecs). The results showed a very clear pattern. S-pedelecs travelled at a higher mean speed overall and under various specified conditions. They completed a much higher number of their trips at high mean speeds (Figure 1), just as they completed a much larger portion of their total travelling distance at higher speeds (Figure 2). In addition, they appeared to accelerate stronger than conventional bicycles and pedelecs. Furthermore, as speed limits of 30 km/h might impact especially on the behaviour of faster cyclists (i.e. S-pedelec riders), the potential mean speed might be even higher under different conditions. We also found significant differences in multiple measures between pedelecs and conventional bicycles, although less pronounced. Somewhat surprising was the absence of a difference between pedelecs and conventional bicycles with regard to their acceleration behaviour. This might interpreted as an indication that, when accelerating from standstill, the pedelec riders used the assistance that the motor provided mainly to reach their desired speed easier, not earlier. In general, however, the results support findings from previous studies, which compared conventional bicycles to either a form of S-pedelec (Cherry and He, 2009) or pedelec (Jellinek et al., 2013; Onnen-Weber et al., 2012). It appears that, at least to some degree, cyclists use the support that e-bikes provide to ride faster.

A similar pattern emerged when we looked into the effect that different types of infrastructure might have on cycling speed. The S-pedelec riders cycled fastest on each type of infrastructure. In contrast, pedelec and conventional bicycle speed differed only on the carriageway and cycling infrastructure. This suggests that the potential of pedelecs can be exploited especially under free flow conditions, which are hardly found on infrastructure other than carriageway or bike path. It has to be acknowledged that we found a substantial amount of illegal infrastructure use in our dataset. Despite the fact that S-pedelecs are not allowed to use bike paths in Germany, our S-pedelec riders still used them to a considerable degree, and at a much higher speed. As a result, a previously uncommon variation in speed is introduced to the cycling infrastructure, which certainly increases the potential for conflicts. The use of infrastructure usually reserved for pedestrians appears to be another problem. However, mean speed on the pavement and pedestrian precincts at least suggest that cyclists adapt and slow down.

As anticipated (Jellinek et al., 2013; Lin et al., 2007), cyclists' age had a significant influence on their speed. When analysed in separate groups, participants 65 years and older were slowest overall, and travelled the shortest distances at higher speeds, whereas participants 40 years or younger produced the highest mean speed and the largest proportion of riding at higher speeds. Pedelec riders in the oldest group were, on average, slower than the riders of conventional bicycles in the two other age groups. It appears that the concern that older pedelec riders might be cycling at a speed beyond their control is mostly unfounded. Of course, individual cases and situations in which control is lost due to excessive speed might still occur, but so they do for younger cyclists.

We have to acknowledge that the uneven distribution of gender in the different groups of bicycle users might have had a confounding effect on the measured mean speed. Previous observations have found a higher speed for male cyclists compared to female riders (Lin et al., 2007). However, current S-pedelec riders are predominantly male, so the bias in our sample accurately reflects the current user population. In addition, the potential of a self selection bias due to the recruitment of volunteers cannot be denied. Especially for the older participants, it might be suspected that especially healthy and fit riders might be overrepresented. Consequently, mean speed, especially of older riders, might have been slightly overestimated when compared to the complete cyclist population.

The question of whether their overall higher speed makes e-bike riders more accident prone remains yet to be answered. Chinese statistics suggest that the number of e-bike related injuries and fatalities increased in recent years, whereas the number decreased for overall road traffic and conventional bicycles (Feng et al., 2010; Zhang et al., 2013). However, it is unclear if the underlying cause is indeed a higher crash rate of e-bikes, or rather a higher crash severity. Siman-Tov, Jaffe and Peleg (2012) hypothesised that cycling speed might be related to a higher likelihood of specific types of injury. Based on Nilsson's power model that relates speed to road accidents, it can be assumed that a higher speed results in a higher crash risk as well as injury severity (Aarts and van Schagen, 2006; Elvik et al., 2004). Even if the actual cycling mean speed changed only moderately, a higher rate of injuries and fatalities would have to be expected. Especially for S-pedelecs, this aspect needs to be considered when discussing about road regulations.

The actual road safety impact of e-bikes and their potential to reach higher speeds can, at this stage, be only predicted in very broad terms. Given the difference in the user populations (which is not reflected in our matched participant sample), it is not unreasonable to assume that currently, e-bikes do not cause any change in cycling mean speed at all. However, there is some evidence that the acceptance of e-bikes is growing also among younger cyclists (Jellinek et al., 2013). It has even been suggested that the e-bike is going from being a "rehabilitation vehicle" to a trendy accessory (Touring Club Schweiz, 2014). In which way this will change two wheeled traffic and road safety in the middle and long term is a matter of speculation. For the time being, it appears that the regulations in place (treat pedelecs like conventional bicycles, S-pedelecs like small motorbikes) are appropriate. It only seems that, especially for S-pedelecs, there is the need for a stronger enforcement of these regulations.

5 ACKNOWLEDGMENTS

The research presented in this paper was funded by German Insurers Accident Research (UDV).

6 REFERENCES

Aarts, L., van Schagen, I., 2006. Driving speed and the risk of road crashes: A review. Accid. Anal. Prev. 38, 215–224. doi:10.1016/j.aap.2005.07.004

Alrutz, D., 2012. Pedelecs im Alltag Was bedeutet der Boom für die (inter-) kommunale Planung ? PGV – Wegweisend für den Radverkehr.

Alrutz, D., 2013. Anforderungen von Pedelecs an die kommunale Radverkehrsinfrastruktur PGV – Wegweisend für den Radverkehr Themenübersicht Rasante Entwicklung der Verkaufszahlen.

Bai, L., Liu, P., Chen, Y., Zhang, X., Wang, W., 2013. Comparative analysis of the safety effects of electric bikes at signalized intersections. Transp. Res. Part D Transp. Environ. 20, 48–54. doi:10.1016/j.trd.2013.02.001

Bundesministerium für Verkehr Innovation und Technologie, 2013. Radverkehr in Zahlen. Wien.

Cherry, C.R., 2007. Electric two-wheelers in China: Analysis of environmental, safety, and mobility impacts. Production. University of California, Berkeley, USA.

Cherry, C.R., Cervero, R., 2007. Use characteristics and mode choice behavior of electric bike users in China. Transp. Policy 14, 247–257. doi:10.1016/j.tranpol.2007.02.005

Cherry, C.R., He, M., 2009. Alternative methods of measuring operating speed of electric and traditional bikes in China-Implications for travel demand models, in: Proceedings of the Eastern Asia Society for Transportation Studies.

Dill, J., Gliebe, J., 2008. Understanding and measuring bicycling behavior: a focus on travle time and route choice. Portland.

Dingus, T.A., Klauer, S.G., Neale, V.L., Petersen, A., Lee, S.E., Sudweeks, J., Perez, M.A., Hankey, J., Ramsey, D., Gupta, S., Bucher, C., Doerzaph, Z.R., Jermeland, J., Knipling, R.R., 2006. The 100-Car naturalistic driving study phase II – Results of the 100-Car field experiment DOT HS 810 593. Blacksburg, Virginia.

Dozza, M., Werneke, J., 2014. Introducing naturalistic cycling data: What factors influence bicyclists' safety in the real world? Transp. Res. Part F Traffic Psychol. Behav. 24, 83–91. doi:10.1016/j.trf.2014.04.001

Elvik, R., Christensen, P., Amundsen, A., 2004. Speed and road accidents.

Feng, Z., Raghuwanshi, R.P., Xu, Z., Huang, D., Zhang, C., Jin, T., 2010. Electric-bicycle-related injury: a rising traffic injury burden in China. Inj. Prev. J. Int. Soc. Child Adolesc. Inj. Prev. 16, 417–419. doi:10.1136/ip.2009.024646

Gustafsson, L., Archer, J., 2013. A naturalistic study of commuter cyclists in the greater Stockholm area. Accid. Anal. Prev. 58, 286–298. doi:10.1016/j.aap.2012.06.004

Jellinek, R., Hildebrandt, B., Pfaffenbichler, P., Lemmerer, H., 2013. MERKUR - Auswirkungen der Entwicklung des Marktes für E-Fahrräder auf Risiken, Konflikte und Unfälle auf Radinfrastrukturen. Wien.

Johnson, M., Charlton, J., Oxley, J., Newstead, S., 2010. Naturalistic cycling study: Identifying risk factors for on-road commuter cyclists. Ann. Adv. Automot. Med. / Annu. Sci. Conf. 54, 275–283.

Kessler, C., Etemad, A., Alessandretti, G., Heinig, K., Selpi, Brouwer, R., Cserpinszky, A., Hagleitner, W., Benmimoun, M., 2012. European Large - Scale Field Operational Tests on In - Vehicle System- Final Report. Aachen.

Klauer, S.G., Perez, M., McClafferty, J., 2011. Naturalistic driving studies and data coding and analysis techniques, in: Porter, B.E. (Ed.), Handbook of Traffic Psychology. Academic Press, San Diego, pp. 73–85. doi:10.1016/B978-0-12-381984-0.10006-2

Knowles, D., Aigner-Breuss, E., Strohmayer, F., Orlet, P., 2012. Naturalistic Cycling. Ablenkung beim Radfahren. Wien.

Langford, B.C., Chen, J., Cherry, C.R., 2015. Risky riding: Naturalistic methods comparing safety behavior from conventional bicycle riders and electric bike riders. Accid. Anal. Prev. 82, 220–226. doi:10.1016/j.aap.2015.05.016

Lee, S.E., Olsen, E.C.B., Wierwille, W.W., 2004. A Comprehensive Examination of Naturalistic Lane-Changes. Washington D.C.

Lin, S., He, M., Tan, Y., He, M., 2007. Comparison study on operating speeds of electric-bicycle and bicycle: Experience from field investigation in Kunming. Transp. Res. Rec. J. Transp. Res. Board 2048, 52–59.

Menghini, G., Carrasco, N., Schüssler, N., Axhausen, K.W., 2009. Route choice of cyclists in Zurich: Arbeitsberichte Verkehrs- und Raumplan. 544.

Onnen-Weber, U., Schramek, M., Butz, H., 2012. Schweriner Versuch. Wismar.

Paefgen, J., Michahelles, F., 2010. Inferring usage characteristics of electric bicycles from position information, in: Proceedings of the 3rd International Workshop on Location and the Web - LocWeb '10. ACM Press, New York, New York, USA, pp. 1–4. doi:10.1145/1899662.1899667

Preißner, C.L., Kemming, H., Wittkowsky, D., Bülow, S., Stark, A., 2013. Einstellungsorientierte Akzeptanzanalyse zur Elektromobilität im Fahrradverkehr. Dortmund.

Rose, G., 2012. E-bikes and urban transportation: emerging issues and unresolved questions. Transportation (Amst). 39, 81–96. doi:10.1007/s11116-011-9328-y

Scaramuzza, G., Clausen, N., 2010. Elektrofahrräder (E-Bikes). Bern.

Schleinitz, K., Franke-Bartholdt, L., Petzoldt, T., Schwanitz, S., Kühn, M., Gehlert, T., 2014. Pedelec-Naturalistic Cycling Study. Berlin.

Siman-Tov, M., Jaffe, D.H., Peleg, K., 2012. Bicycle injuries: a matter of mechanism and age. Accid. Anal. Prev. 44, 135–139. doi:10.1016/j.aap.2010.10.006

Skorna, A.C.H., Treutlein, D., Westmoreland, S., Loock, C.-M., Paefgen, J.F., von Watzdorf, S., Ackermann, L., Bereuter, A., 2010. Baloise Group - Sicherheitsstudie 2010 Gefahren und Risikofaktoren beim Fahrradfahren in Deutschland.

Thompson, D.C., Rebolledo, V., Thompson, R.S., Kaufman, A., Rivara, F.P., 1997. Bike speed measurements in a recreational population: validity of self reported speed. Inj. Prev. 3, 43–5.

Touring Club Schweiz, 2014. Elektrozweiräder im Systemvergleich. Emmen.

Zhang, X., Cui, M., Gu, Y., Stallones, L., Xiang, H., 2013. Trends in Electric Bike-Related Injury in China, 2004-2010. Asia. Pac. J. Public Health 1–8. doi:10.1177/1010539513496840

Zweirad-Industrie-Verband, 2012. Beschreibung der Fahrradtypen. Bad Soden a. Ts.

Zweirad-Industrie-Verband, 2013. Anteil Pedelec45 [WWW Document].

Zweirad-Industrie-Verband, 2014. Jahresbericht. Bad Soden a. Ts.