

Cite as: Petzoldt, T., Schleinitz, K., Krems, J.F., & Gehlert, T. (2017). Drivers' gap acceptance in front of approaching bicycles – Effects of bicycle speed and bicycle type. *Safety Science*, 92, 283-289.
dx.doi.org/10.1016/j.ssci.2015.07.021

Drivers' gap acceptance in front of approaching bicycles – Effects of bicycle speed and bicycle type

Tibor Petzoldt¹, Katja Schleinitz¹, Josef F. Krems¹ & Tina Gehlert²

¹Technische Universität Chemnitz, 09107 Chemnitz, Germany

²German Insurers Accident Research (UDV), Wilhelmstr. 43/43 G, 10117 Berlin, Germany

E-mail: tibor.petzoldt@psychologie.tu-chemnitz.de

Tel: +49 (0) 371 / 531 36519; Fax: +49 (0) 371 / 531 836519

This is the "Accepted Author Manuscript (AAM)" of a work submitted to Elsevier (Safety Science). It includes author-incorporated changes suggested through the processes of submission, peer review and editor-author communications. It does not include other publisher value-added contributions such as copy-editing, formatting, technical enhancements and pagination. The published journal article is available at <http://dx.doi.org/10.1016/j.ssci.2015.07.021>.

ABSTRACT

The growing popularity of electric bicycles gives rise to a variety of road safety questions. One of the issues is e-bikes' potential to achieve a higher speed compared to conventional bicycles. Especially for road users that are unfamiliar with that type of bicycle, underestimations of speed might be suspected which could lead drivers to accept unsafe gaps (e.g. for turning manoeuvres) in front of approaching e-bikes. But also higher speed as such might prove problematic, as previous studies have shown repeatedly that drivers tend to choose smaller time gaps in front of vehicles approaching at higher speed. Forty-two drivers (two age groups) were recruited to investigate their gap acceptance behaviour on a test track. Participants were seated in a car, waiting to enter traffic, which would have required crossing a lane on which a cyclist approached. Cyclists approached at speeds between 15 and 35 km/h and rode either a conventional bicycle or an e-bike. Participants were instructed to press a foot pedal to indicate the last moment at which they would be willing to enter traffic in front of the bicyclist. Results show that with increasing cyclist speed, accepted time gaps became significantly shorter. At the same time, participants appeared to select shorter time gaps when the approaching bicycle was an electric one, even though the two different bicycle types could not be distinguished from the participants' position. Although we found only few accepted gap sizes that would have been especially risky, the findings indicate that the effect of bicycle speed has to be considered when discussing the consequences of an increased e-bike prevalence for road safety.

Keywords: road safety, e-bike, time to arrival.

1 INTRODUCTION

Electric bicycles have seen a steep rise in popularity in the last decade (Rose, 2012). Sales figures in Germany (Zweirad-Industrie-Verband, 2013) and other European nations are growing, and are expected to continue to grow (Zweirad-Industrie-Verband, 2011). In China, e-bike sales figures reached 10 million per year already in 2005 (Weinert et al., 2007). In general, this development is welcomed, as cycling, also on e-bikes, is considered a healthy, environmentally friendly mode of transport. Previous studies also indicate that a lot of e-bike users do not necessarily use it as a substitute for a conventional bike, as it has been reported that the length of trips made with an e-bike was considerably longer (Cherry and Cervero, 2007). It appears that the e-bike is often a substitute for public transport (An et al., 2013) or a car (Popovich et al., 2014). In addition, a lot of elderly cyclists that would otherwise not be able to ride a conventional bike because of their physical condition can continue to cycle (Dill and Rose, 2012; Parker, 2006). It has been found that even elder citizens that gave up cycling previously are getting back onto the road on e-bikes (Alrutz, 2013). In terms of promoting healthy and environmentally friendly mobility, the trend towards e-bikes might be embraced unequivocally.

However, as more and more e-bikes are on the road today, road safety concerns have been voiced. Chinese accident statistics (Feng et al., 2010) show that the rate of crashes that involve e-bikes has risen continuously in recent years (however, it has to be acknowledged that the Chinese definition of e-bike is much wider than the European one). Data from Switzerland, where e-bikes are listed as a separate category of road user in the accident statistics since 2011, point in a similar direction (Achermann Stuermer et al., 2013). Especially worrisome is the fact that accident severity appears to be higher than for conventional bicycles.

In this context, one aspect that has been questioned is how other road users cope with the fact that there now is something on the road that looks like a normal bicycle, however accelerates much faster, and reaches quite different speed levels than a conventional bicycle. In a German survey of e-bike riders, one of the potentially hazardous situations that the cyclists considered relevant was the underestimation of their speed by a motorised vehicle (Alrutz, 2013). Schleinitz et al. (2014) showed that e-bikes reach higher mean speeds, and also travel for longer proportions of their trips at speeds beyond 20, 25 and 30 km/h. Similar results have been reported by others (Cherry and He, 2009; Hacke, 2013).

It has been found previously that vehicle approach speed influences drivers' gap acceptance behaviour. Already in 1977, turning manoeuvres at a T-junction were observed in order to gain insight into the effect of speed on gap acceptance (Cooper et al., 1977). The analysis showed an effect of speed (which varied between 27.5 mi/h and 42.5 mi/h – i.e. 44.2 km/h and 76.5 km/h) on the size of accepted time gaps, with smaller gaps being accepted with increasing speed. Alexander et al. (2002) let participants drive in a driving simulator and required them to complete right turn manoeuvres (be aware that this study is from the UK, i.e. the situation equals a left turn manoeuvre in most other countries). Participants were instructed to stop at the intersection, and make a turn across a lane with oncoming traffic when they considered it safe to do so. The oncoming cars approached at either 30 mi/h (approximately 48.3 km/h) or 60 mi/h (approximately 96.6 km/h). The results showed that drivers tended to accept gaps that were on average 2 s smaller when the approaching vehicle was travelling faster. Similar results have been reported from another driving simulator study (Yan et al., 2007), in which participants were required to turn left (in a right hand driving environment) into the traffic stream. Here, the accepted gaps at the higher speed level were about 1.6 s smaller than the ones accepted at lower speed. The tendency to accept smaller gaps when the approaching vehicle is

Cite as: Petzoldt, T., Schleinitz, K., Krems, J.F., & Gehlert, T. (2017). Drivers' gap acceptance in front of approaching bicycles – Effects of bicycle speed and bicycle type. *Safety Science*, 92, 283-289. [dx.doi.org/10.1016/j.ssci.2015.07.021](https://doi.org/10.1016/j.ssci.2015.07.021)

faster appears to be relatively stable, and has been found also for pedestrian crossing decisions (Lobjois and Cavallo, 2007; Oxley et al., 2005; Petzoldt, 2014).

In addition to vehicle approach speed, a number of other aspects have been reported to influence the size of the accepted gaps, such as the type of the oncoming vehicle (Bottom and Ashworth, 1978) or the observing drivers' gender (Alexander et al., 2002; Yan et al., 2007). One central factor is drivers' age. A common finding is that younger drivers tend to accept smaller gaps than older motorists (Alexander et al., 2002; Yan et al., 2007). Interestingly, the effect of speed is often more pronounced in older drivers, i.e. the size of the accepted gaps differs much more between different speed levels (Yan et al., 2007). One potential explanation that has been provided for this interaction between age and approach speed is that older drivers appear to "overestimate at lower speeds and underestimate at higher speeds" (Scialfa et al., 1991).

Most of the effects described above are a direct reflection of effects found for time to collision (TTC) / time to arrival (TTA) judgments. The estimation of the time it takes an object to arrive at a certain predefined position is often argued to underlie road users' decisions and behaviour (e.g., Rock and Harris, 2006; Stewart et al., 1993). Probably the most prominent theoretical assumption on how such an estimation is made is the so called tau-hypothesis (Lee, 1976). Following this hypothesis, the perception of TTC is direct and does not require additional processing of, e.g., object size or distance. However, since "tau-theory has become one of the best researched topics in perceptual psychology" (Hecht and Savelsbergh, 2004; p. 1), it has become clear that there is more to TTC estimation than just the observation of optical expansion.

One of the most replicated findings is that there is a positive correlation between object approach speed and participants' TTC estimates (e.g., Hancock and Manser, 1997; Manser and Hancock, 1996; Oberfeld and Hecht, 2008; Schiff et al., 1992; Schiff and Oldak, 1990). The ex-

Cite as: Petzoldt, T., Schleinitz, K., Krems, J.F., & Gehlert, T. (2017). Drivers' gap acceptance in front of approaching bicycles – Effects of bicycle speed and bicycle type. *Safety Science*, 92, 283-289. [dx.doi.org/10.1016/j.ssci.2015.07.021](https://doi.org/10.1016/j.ssci.2015.07.021)

planation provided for this effect is that, to some degree, observers rely on physical distance to make estimates of TTC, a phenomenon that has been described as distance bias (Law et al., 1993). Petzoldt (2014) was able to show that the effect of approach speed on the gap size accepted by pedestrians can be explained mainly with this effect.

Age effects have been found for judgments of TTC, too. Usually, it is reported that older observers are less accurate than younger ones in estimating TTC. What this phrasing of the findings fails to acknowledge is that in most cases, this lower accuracy is actually a systematic bias towards lower estimates, i.e. older observers show a strong tendency to underestimate TTC (Hancock and Manser, 1997; Petzoldt, 2014; Schiff et al., 1992). This, at least partially, can serve as an explanation for the differences in accepted gap size between different age groups.

Unfortunately, (applied) TTC studies and gap acceptance studies alike mostly focused solely on situations in which judgments or decisions in relation to motorised vehicles were required. The vehicle approach speeds investigated were usually 40 km/h or higher. One exception is Te Velde et al.'s (2005) study of pedestrian crossing behaviour when confronted with an oncoming bicycle (however, with a maximum speed of just 6.5 km/h). If the effect of speed on accepted gap size can also be found at speed levels that are typical for bicycles is, at this stage, unclear. Also, the differences between the investigated speed levels were often rather high, leaving open the question of whether rather subtle differences in speed, as they would be expected between conventional bicycles and e-bikes, would be perceived and acted upon.

Aim of the experiment presented in this paper was to investigate what gap sizes drivers choose when confronted with an oncoming cyclist. The experiment was conducted on a test track, where participants seated in a car were supposed to indicate their minimum acceptable gap when asked to turn in front of an approaching bicycle.

Of primary interest was the effect of the cyclist's speed on the accepted gaps, and whether it matters if the approaching vehicle is a conventional bicycle or an e-bike. Based on the reported findings, we hypothesised that a higher approach speed would result in smaller accepted time gaps. The inclusion of bicycle type was of explorative character. Given that vehicle-related differences in gap acceptance have usually been linked only to vehicle size, we did not expect to find differences between conventional bicycles and e-bikes.

In addition, we manipulated the road gradient and the observers' perspective. Gradient appeared to be an interesting factor as the use of an e-bike allows its user to achieve speed levels when riding uphill which, with a conventional bicycle, are usually only achieved on flat sections of road. As common sense suggests, and data from Schleinitz et al. (2014) show, cyclists are slower when riding uphill compared to their average cycling speed. If drivers use this knowledge for their gap acceptance decisions, they should be more willing to turn in front of a bicycle that is approaching uphill, i.e., we should expect smaller accepted gaps under this condition.

With regard to the observers' perspective, we assumed that a side view might allow for a somewhat better estimate of the approaching cyclists speed. It has been suggested that a certain degree of eccentricity when observing an oncoming object would lead to better judgments of its approach (Schiff and Oldak, 1990). A side view might provide sufficient eccentricity, whereas a frontal view would certainly not. However, it was not clear what effect such a better judgment of approach would have on gap acceptance, so we did not formulate a specific hypothesis.

Finally, to account for the widely reported age effects, we investigated two different age groups. We expected younger drivers to accept smaller gaps than older ones. (Table 1 gives an overview of the different factors and factor levels of the experiment.)

2 METHOD

2.1 Participants

Forty-two participants in two age groups (30-45 years, 65 years and older) took part in the experiment. The younger group (13 male, 8 female) had a mean age of 34.0 years (SD = 4.4), the older participants (18 male, 3 female) were, on average, 71.1 years (SD = 5.0) old. All participants had a driver's license. Their reported annual mileage was approximately 16 000 km (younger group) and approximately 13 500 km (older group), respectively.

2.2 Experimental conditions (see Table 1 for an overview)

We used two different bicycles in the study, a conventional bike and an e-bike (see Figure 1). The electric bicycle provided pedalling support up to 45 km/h. Rear-view mirror and license plate (both required for fast e-bikes in Germany) were removed to make the e-bike look like an ordinary bicycle. The conventional bicycle was chosen to resemble the looks of the e-bike as closely as possible, so that there were no obvious differences in design that could be spotted from a distance. Both bicycles had a small cycling computer installed to display the current speed.



Figure 1. Conventional bicycle (left) and e-bike (right) used in the experiment.

To manipulate road gradient, we conducted the experiment on two different “tracks”. One track had practically no gradient at all, so bicycles were approaching on a more or less flat section of road. The other track had a grade of 3.75 %, resulting in a slight uphill climb for the cyclists.

Two different situations in which the car would have crossed the path of the approaching bicycle were implemented (Figure 2), resulting in two different perspectives for the observer. In the first situation, the car was supposed to turn left in front of a bicycle approaching from the opposite direction, so the driver had a frontal view of the cyclist (Figure 2, left). A left turn manoeuvre was also the basis for the second situation, however, here, the bicycle was approaching from the left (and had, per instruction, the right of way), which resulted somewhat more in a side view of the oncoming cyclist (Figure 2, right).

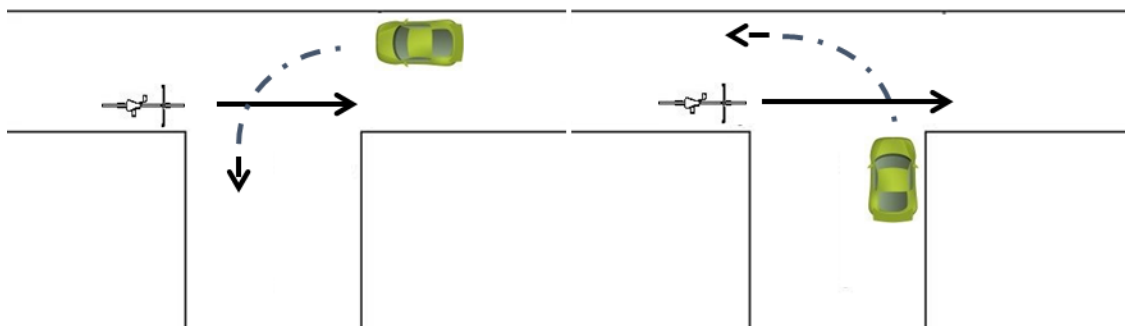


Figure 2. Experimental setup for frontal view (left) and side view (right) of the approaching bicycle (participant seated in vehicle).

We selected four different speed levels. Speeds of 15, 20 and 25 km/h were used for both bicycle types. In addition, a 35 km/h condition was realised with the e-bike (within the experimental setup, this speed could not be achieved with the conventional bicycle). The bicycles were ridden by student assistants that we trained previously, so they would be able to reach and hold the required speed. The cyclists used the display of the cycling computer to observe

their own speed. If a deviation of more than 1 km/h (as displayed) in the crucial phase of the approach occurred, the trial was aborted and repeated.

With the exception of the 35 km/h condition, all within-factor levels were fully crossed. This resulted in a total of 28 different combinations (2x2x3 with the conventional bike plus 2x2x4 with the e-bike). Both age groups were confronted with all 28 combinations.

Table 1. Overview of factors and factor levels.

age	bicycle type	road gradient	observer's perspective	speed
30-45	conventional bike	0%	front view	15 km/h
65 +	e-bike	3.75%	side view	20 km/h
				25 km/h
				35 km/h (e-bike only)

2.3 Procedure

Before the actual experiment began, we conducted a vision test (Snellen eye chart) to ensure that participants would be able to perceive the approaching bicycle correctly. None of the participants showed substantial vision impairments, with 39 out of 42 having a visual acuity of 100% or above for at least one eye (the remaining three had a minimum of 67% visual acuity). This was followed by the collection of demographic data. Then, the actual experiment began.

Participants were seated in a real car to observe the approaching cyclists from a driver's perspective. A foot pedal was installed that should be pressed to indicate a turning/crossing decision. A camera was positioned outside the vehicle to record the cyclist's approach. In front of the camera, a small LED was installed that lit up when the foot pedal was depressed. This set-up allowed us to link the participants' response to the position and speed of the approaching bicycle.

Cite as: Petzoldt, T., Schleinitz, K., Krems, J.F., & Gehlert, T. (2017). Drivers' gap acceptance in front of approaching bicycles – Effects of bicycle speed and bicycle type. *Safety Science*, 92, 283-289.
dx.doi.org/10.1016/j.ssci.2015.07.021

Once seated, participants received the necessary instructions. At the beginning of each trial, they were supposed to hold their head in a position that did not allow them to look outside the car when the cyclist's approach started. When the cyclist reached a distance of about 100 m from the car, the experimenter gave a signal that it was now allowed to observe the cyclist approaching. Participants then depressed the foot pedal when they considered the cyclist to be in a distance that would be their minimum acceptable gap to still cross in front of the cyclist. They were instructed to choose a gap which they felt would still be comfortable and safe in a "normal" drive, i.e. not being in a hurry, but also not being exceptionally relaxed. Participants completed two practice trials before data acquisition started.

As the manipulation of road gradient (0% vs. 3.75%) and observer's perspective (front view vs. side view) required different setups on the test track, we had four different experimental blocks that were balanced across all participants. Inside these blocks, e-bike and conventional bike approach alternated (we had two student assistants, dressed identically, one on each bike, who took turns at the task to speed up the process and prevent fatigue). The order of the different speed levels was randomized (see Table 2 for an example of how the experimental blocks were arranged). After the experimental trials were completed, participants were debriefed and received their monetary compensation of €25. In total, the complete experiment took about 90 min.

Table 2. Example of experimental block arrangement.

Trial Number	Block 1 0% / front view	Block 2 3.75% / front view	Block 3 3.75% / side view	Block 4 0% / side view
1	e-bike / 25 km/h	e-bike / 15 km/h	e-bike / 35 km/h	e-bike / 15 km/h
2	bike / 15 km/h	bike / 20 km/h	bike / 15 km/h	bike / 15 km/h
3	e-bike / 35 km/h	e-bike / 25 km/h	e-bike / 20 km/h	e-bike / 25 km/h
4	bike / 20 km/h	bike / 15 km/h	bike / 25 km/h	bike / 20 km/h
5	e-bike / 15 km/h	e-bike / 35 km/h	e-bike / 15 km/h	e-bike / 20 km/h
6	bike / 25 km/h	bike / 25 km/h	bike / 20 km/h	bike / 25 km/h
7	e-bike / 20 km/h	e-bike / 20 km/h	e-bike / 25 km/h	e-bike / 35 km/h

To have a certain benchmark of how long it would have taken to actually cross/turn in front of the cyclist, we asked two individuals to complete the crossing/turning manoeuvre several times with their personal vehicles. This was done after the experiment, with no other road users present, and no specific instructions (other than to complete a “normal” turning manoeuvre). We measured the time it took from standstill until the vehicle had crossed the lane and was positioned in a 90° angle (i.e. in driving direction) again. We considered the result to be the critical gap size for the implemented scenario. It has to be acknowledged that this procedure was rather unstandardized, and allows only for a coarse estimation of actual crossing/turning time (e.g., reaction times / latencies of driver and vehicle are not included).

3 RESULTS

We analysed the data in a five factorial ANOVA for mixed designs, omitting the 35 km/h condition (which was missing for the conventional bicycles). This condition, however, is still included in the figures for visual comparison. An overview of the ANOVA and corresponding effect sizes, including main effects and interactions, can be found in Table 2.

In Figure 3, the size of the accepted gaps dependent on the approaching cyclist's speed is displayed. As can be clearly seen, participants tended to accept smaller gaps when the approach

speed was higher, which was confirmed through statistical analysis, $F(2, 80) = 68.95$, $p < 0.001$, $\eta^2_p = .63$. Post-hoc comparisons (Bonferroni-corrected for multiple comparisons) showed significant differences between all three analysed speed levels (all $p < .001$). It has to be noted that although the vast majority of accepted gaps would have been safe, we found 29 accepted gaps (out of 1,176, approximately 2.5%) that were smaller than the critical gap size of 3.4 s.

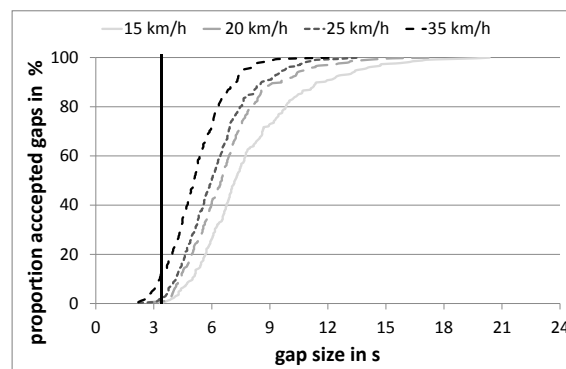


Figure 3. Cumulative proportion of accepted gaps of a certain size for crossing/turning dependent on the cyclist's approach speed. Solid vertical line indicates critical gap size of 3.4 s.

Figure 4 displays the accepted gap size for the different speed levels depending on the four factors bicycle type, road gradient, observer's perspective and observer's age. A clear effect was found for the comparison of the two bicycle types (Figure 4, top left). The size of the accepted gaps was consistently about 0.5 s smaller when participants were approached by an electric bicycle as compared to a conventional bicycle, $F(1, 40) = 18.41$, $p < 0.001$, $\eta^2_p = .32$.

Likewise, the road's gradient had an influence on the size of the accepted gaps (Figure 4, top right). When the approaching cyclist was riding uphill, accepted gaps were again about 0.5 s smaller than when there was no grade, $F(1, 40) = 12.21$, $p = 0.001$, $\eta^2_p = .24$. The observers' perspective (Figure 4, bottom left) did not appear to affect accepted gap size, $F(1, 40) = 0.61$, $p = 0.438$, $\eta^2_p = .02$.

From the inspection of the mean values, it appears that participants' age played a role in the size of accepted gaps as well, with differences of up to 1.0 s between the two age groups for certain speed levels (Figure 4, bottom right). However, the ANOVA showed no main effect of age group, $F(1, 40) = 1.02$, $p = 0.319$, $\eta^2_p = .03$. It has to be acknowledged that an effect size of about $\eta^2_p = .1$ would have been required to find a significant difference between the two age groups (with a statistical power of .8).

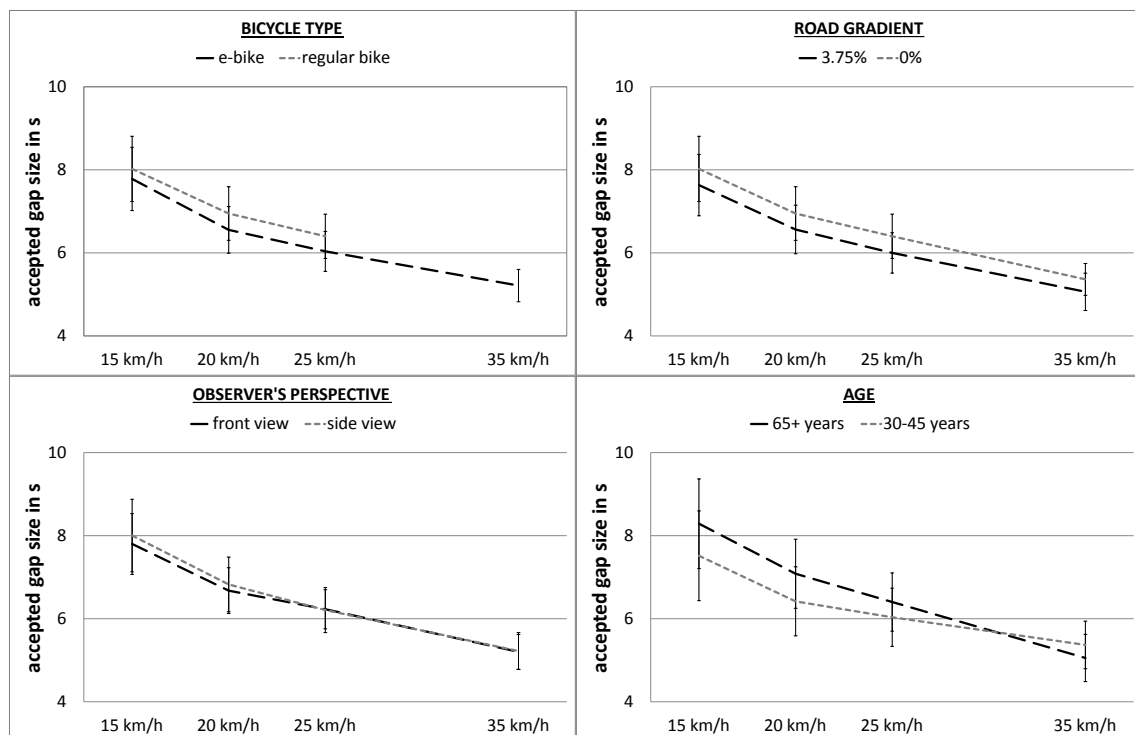


Figure 4. Accepted gap size for the different speed levels dependent on bicycle type (top left), road gradient (top right), observer's perspective (bottom left) and observer's age (bottom right). Error bars represent 95% confidence intervals.

As Table 3 shows, there was also an interaction between bicycle type and age group. The inspection of the data suggests that the main effect of bicycle type is mainly driven by the response of older participants, who chose an average gap of 7.0 s (SD = 2.1) in front of an approaching e-bike, and a gap of 7.6 s (SD = 2.4) in front of a conventional bicycle. There was no such difference for the younger group, which chose gaps of 6.6 s (SD = 1.6) and 6.7 s (SD = 1.5),

respectively. In contrast, there was no interaction between speed and any of the other factors.

The ANOVA also uncovered a three-way interaction between speed, gradient and age group.

As Figure 5 shows, the effect of road gradient increased with increasing speed for the younger participants, whereas it slightly decreased for the older group.

Table 3. Summary of ANOVA results for the accepted gap size. Significant effects in boldface.

	<i>F</i>	<i>p</i>	η^2_p
speed	68.95	<.001	.63
bicycle type	18.41	<.001	.32
gradient	12.21	.001	.23
perspective	0.61	.438	.02
age group	1.02	.319	.03
speed x bicycle type	0.57	.570	.01
speed x gradient	0.49	.616	.01
speed x perspective	0.71	.495	.02
speed x age group	1.03	.316	.03
bicycle type x gradient	2.34	.142	.05
bicycle type x perspective	2.30	.138	.05
bicycle type x age group	12.76	.001	.24
gradient x perspective	0.26	.610	.01
gradient x age group	2.72	.107	.06
perspective x age group	2.99	.092	.07
speed x bicycle type x gradient	0.10	.907	<.01
speed x bicycle type x perspective	0.18	.835	<.01
speed x bicycle type x age group	0.34	.709	.01
speed x gradient x perspective	0.11	.894	<.01
speed x gradient x age group	6.77	.002	.14
speed x perspective x age group	2.97	.057	.07
bicycle type x gradient x perspective	<0.01	.957	<.01
bicycle type x gradient x age group	0.19	.663	<.01
bicycle type x perspective x age group	0.09	.762	<.01
gradient x perspective x age group	0.23	.635	.01
speed x bicycle type x gradient x perspective	0.03	.974	<.01
speed x bicycle type x gradient x age group	1.42	.247	.03
speed x bicycle type x perspective x age group	0.81	.451	.02
bicycle type x gradient x perspective x age group	1.00	.324	.02
speed x bicycle type x gradient x perspective x age group	1.80	.171	.04

Cite as: Petzoldt, T., Schleinitz, K., Krems, J.F., & Gehlert, T. (2017). Drivers' gap acceptance in front of approaching bicycles – Effects of bicycle speed and bicycle type. *Safety Science*, 92, 283-289. [dx.doi.org/10.1016/j.ssci.2015.07.021](https://doi.org/10.1016/j.ssci.2015.07.021)

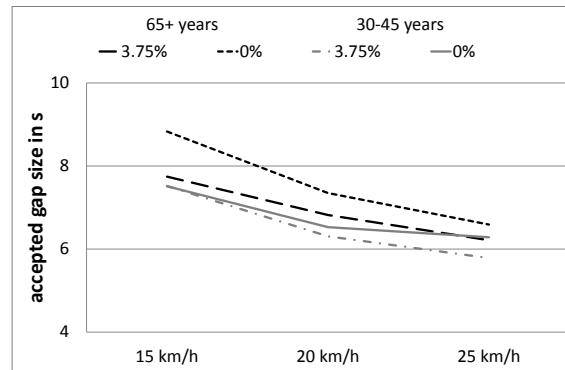


Figure 5. Three-way interaction between age group, road gradient and speed. (35 km/h condition and error bars omitted in this graph to increase legibility)

4 DISCUSSION

Aim of the experiment was to investigate the influence of approach speed and bicycle type on drivers' gap acceptance. We found a clear effect of approach speed on the size of accepted gaps. The faster the oncoming bicycle was, the smaller were the gaps the participants selected for crossing/turning in front of the cyclist. Interestingly, the type of bicycle had an effect on accepted gap size as well. Selected gaps in front of oncoming e-bikes were significantly smaller compared to the gaps chosen when a conventional bicycle approached. This effect occurred although participants had no prior knowledge about the fact that different bikes were used (a few participants reported afterwards to have noticed the difference between the bicycles once they had passed their position, but also confirmed that they were unable to tell them apart in the approach situation).

One possible explanation for this effect is the potential difference in posture and pedalling frequency when using an e-bike compared to a conventional bicycle. As the pedalling support of an e-bike allows the rider to achieve higher speeds with less effort, pedalling frequency can be suspected to be, on average, lower than with a conventional bicycle. At the same time, the lower effort might also be reflected in the cyclists overall position and posture on the bicycle.

This, as a whole, might convey the impression of a comparatively slow approach. The finding that the effect of bicycle type was especially strong in older participants confirms previous studies which reported that older drivers have problems in properly assessing the time it takes for an oncoming vehicle to arrive (Scialfa et al., 1991). If indeed the ability to judge an objects' approach is compromised, it appears reasonable to rely, consciously or not, on heuristics and prior knowledge, such as experience with a cyclist's usual look when he is riding at a certain speed. Unfortunately, the use of heuristics does not necessarily lead to good decisions, as has been demonstrated for example for (bicycle) overtaking situations (Walker, 2007).

Heuristics can also be suspected to have caused the effect of road gradient. To expect (again, consciously or not) that a bicycle approaching uphill is comparatively slow is, to some degree, reasonable. Other assumptions (e.g. it is easier to decelerate for the climbing cyclist) might add to this impression, resulting in smaller gaps accepted in front of oncoming cyclists that are riding uphill. However, we found no interaction between road gradient and speed. It appears that the effect is independent of whether the actual approach speed would be common (i.e. low) or uncommon (i.e. high) for the climbing scenario.

Worrisome is the finding that some participants accepted gaps that were smaller than the critical time gap. Although it has to be acknowledged that the chosen definition of the critical gap was rather simple, the specific shortcomings of the approach (neglect of response latencies, no consideration of safety margins) suggest that the 2.5% unsafe gaps might be an underestimation. Even when the indication to accept a gap and actual crossing/turning behaviour have been found to be not exactly congruent (te Velde et al., 2005), the fact that unsafe gaps are considered for crossing/turning is problematic. Coupled with the result that smaller gaps are chosen when the cyclists' approach speed is higher and when the oncoming bicycle is an e-bike, it can be suspected that electric bicycles are at increased risk of being involved in a safety critical situation.

Cite as: Petzoldt, T., Schleinitz, K., Krems, J.F., & Gehlert, T. (2017). Drivers' gap acceptance in front of approaching bicycles – Effects of bicycle speed and bicycle type. *Safety Science*, 92, 283-289. [dx.doi.org/10.1016/j.ssci.2015.07.021](https://doi.org/10.1016/j.ssci.2015.07.021)

Unfortunately, there is no obvious intervention that can help increase the size of accepted gaps in front of e-bikes in an instant. When following the assumption that heuristics play a role in gap acceptance, and that such heuristics might be responsible for the smaller accepted gaps in front of e-bikes, the conclusion must be to help road users develop new heuristics that also consider the e-bike and its behaviour. With increased exposure, one might assume that learning processes will lead road users to a different understanding of the speed of “bicycle-shaped vehicles”, i.e. increased speed levels might become part of the mental model that is used for the crossing decision heuristic. However, it might be more effective to try establish e-bikes as a separate category of vehicle, distinct from conventional bicycles, e.g., by introducing visual features that help observers differentiate between the two vehicle types. Again, however, one should not expect such an intervention to yield effects immediately. Perceptual heuristics do usually not employ deliberate thought processes (“it looks different than a normal bike, I should be careful”), but are rather implicit rules (Hecht, 1996), learned through repeated practice. So, even when the e-bike is designed clearly distinct from conventional bicycles, road users will need time to experience and learn that the “thing not quite looking like a bicycle” does indeed not behave like a bicycle. But of course, this learning process can and should be supported by any means available.

5 Acknowledgments

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

REFERENCES

Achermann Stuermer, Y., Allenbach, R., Ewert, U., Scaramuzza, G., Niemann, S., Hayoz, R., Daehler-Sturny, C., 2013. SINUS-Report 2013 - Sicherheitsniveau und Unfallgeschehen im Strassenverkehr 2012. SINUS-REPORT.

Cite as: Petzoldt, T., Schleinitz, K., Krems, J.F., & Gehlert, T. (2017). Drivers' gap acceptance in front of approaching bicycles – Effects of bicycle speed and bicycle type. *Safety Science*, 92, 283-289. [dx.doi.org/10.1016/j.ssci.2015.07.021](https://doi.org/10.1016/j.ssci.2015.07.021)

Alexander, J., Barham, P., Black, I., 2002. Factors influencing the probability of an incident at a junction: Results from an interactive driving simulator. *Accident Analysis & Prevention* 34, 779–792. doi:10.1016/S0001-4575(01)00078-1

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

An, K., Chen, X., Xin, F., Lin, B., Wei, L., 2013. Travel characteristics of e-bike users: Survey and analysis in Shanghai. *Procedia - Social and Behavioral Sciences* 96, 1828–1838. doi:10.1016/j.sbspro.2013.08.208

Bottom, C.G., Ashworth, R., 1978. Factors affecting the variability of driver gap-acceptance behaviour. *Ergonomics* 21, 721–734. doi:10.1080/00140137808931774

Cherry, C.R., Cervero, R., 2007. Use characteristics and mode choice behavior of electric bike users in China. *Transport 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*.

Cooper, D.F., Storr, P.A., Wennell, J., 1977. Traffic studies at T-junctions. 4. The effect of speed on gap acceptance and conflict rate. *Traffic Engineering & Control* 18.

Dill, J., Rose, G., 2012. Electric bikes and transportation policy: Insights from early adopters. *Transportation Research Record* 2314, 1–6. doi:10.3141/2314-01

Feng, Z., Raghuvanshi, R.P., Xu, Z., Huang, D., Zhang, C., Jin, T., 2010. Electric-bicycle-related injury: A rising traffic injury burden in China. *Injury prevention* 16, 417–9. doi:10.1136/ip.2009.024646

Hacke, U., 2013. Potenzielle Einflüsse von Pedelecs auf die Verkehrssicherheit.

Hancock, P.A., Manser, M.P., 1997. Time-to-contact: more than tau alone. *Ecological Psychology* 9, 265–297. doi:10.1207/s15326969eco0904_2

Cite as: Petzoldt, T., Schleinitz, K., Krems, J.F., & Gehlert, T. (2017). Drivers' gap acceptance in front of approaching bicycles – Effects of bicycle speed and bicycle type. *Safety Science*, 92, 283-289. [dx.doi.org/10.1016/j.ssci.2015.07.021](https://doi.org/10.1016/j.ssci.2015.07.021)

Hecht, H., 1996. Heuristics and invariants in dynamic event perception: Immunized concepts or nonstatements? *Psychonomic Bulletin & Review* 3, 61–70. doi:10.3758/BF03210741

Hecht, H., Savelsbergh, G.J.P., 2004. Theories of time-to-contact judgment, in: Hecht, H., Savelsbergh, G.J.P. (Eds.), *Time-to-Contact*. Elsevier B.V., pp. 1–11.

Law, D.J., Pellegrino, J.W., Mitchell, S.R., Fischer, S.C., McDonald, T.P., Hunt, E.B., 1993. Perceptual and cognitive factors governing performance in comparative arrival-time judgments. *Journal of Experimental Psychology: Human Perception and Performance* 19, 1183–1199. doi:10.1037/0096-1523.19.6.1183

Lee, D.N., 1976. A theory of visual control of braking based on information about time-to-collision. *Perception* 5, 437–459.

Lobjois, R., Cavallo, V., 2007. Age-related differences in street-crossing decisions: The effects of vehicle speed and time constraints on gap selection in an estimation task. *Accident Analysis & Prevention* 39, 934–943. doi:10.1016/j.aap.2006.12.013

Manser, M.P., Hancock, P.A., 1996. Influence of approach angle on estimates of time-to-contact. *Ecological Psychology* 8, 71–99. doi:10.1207/s15326969eco0801_4

Oberfeld, D., Hecht, H., 2008. Effects of a Moving Distractor Object on Time-to-Contact Judgments. *Journal of Experimental Psychology: Human Perception and Performance* 34, 605–623. doi:10.1037/0096-1523.34.3.605

Oxley, J., Ihsen, E., Fildes, B.N., Charlton, J.L., Day, R.H., 2005. Crossing roads safely: An experimental study of age differences in gap selection by pedestrians. *Accident Analysis & Prevention* 37, 962–971. doi:10.1016/j.aap.2005.04.017

Parker, A., 2006. Electric power-assisted bicycles reduce oil dependence, and enhance the mobility of the elderly, in: *Proceedings of the 29th Australasian Transport Research Forum (ATRF)*. Gold Coast, Australia.

Petzoldt, T., 2014. On the relationship between pedestrian gap acceptance and time to arrival estimates. *Accident Analysis & Prevention* 72, 127–133. doi:10.1016/j.aap.2014.06.019

Cite as: Petzoldt, T., Schleinitz, K., Krems, J.F., & Gehlert, T. (2017). Drivers' gap acceptance in front of approaching bicycles – Effects of bicycle speed and bicycle type. *Safety Science*, 92, 283-289. [dx.doi.org/10.1016/j.ssci.2015.07.021](https://doi.org/10.1016/j.ssci.2015.07.021)

Popovich, N., Gordon, E., Shao, Z., Xing, Y., Wang, Y., Handy, S., 2014. Experiences of electric bicycle users in the Sacramento, California area. *Travel Behaviour and Society* 1, 37–44. [doi:10.1016/j.tbs.2013.10.006](https://doi.org/10.1016/j.tbs.2013.10.006)

Rock, P.B., Harris, M.G., 2006. τ as a potential control variable for visually guided braking. *Journal of Experimental Psychology: Human Perception and Performance* 32, 251–267. [doi:10.1037/0096-1523.32.2.251](https://doi.org/10.1037/0096-1523.32.2.251)

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

Schiff, W., Oldak, R., 1990. Accuracy of judging time to arrival: effects of modality, trajectory, and gender. *Journal of Experimental Psychology. Human Perception and Performance* 16, 303–316.

Schiff, W., Oldak, R., Shah, V., 1992. Aging persons' estimates of vehicular motion. *Psychology and Aging* 7, 518–525. [doi:10.1037/0882-7974.7.4.518](https://doi.org/10.1037/0882-7974.7.4.518)

Schleinitz, K., Petzoldt, T., Franke-Bartholdt, L., Krems, J.F., Gehlert, T., 2014. The German Naturalistic Cycling Study - Comparing cycling speed of different e-bikes and conventional bicycles, in: *Proceedings of the 3rd International Cycling Safety Conference, ICSC2014*. Gothenburg, Sweden.

Scialfa, C.T., Guzy, L.T., Leibowitz, H.W., Garvey, P.M., Tyrrell, R.A., 1991. Age differences in estimating vehicle velocity. *Psychology and Aging* 6, 60–66. [doi:10.1037/0882-7974.6.1.60](https://doi.org/10.1037/0882-7974.6.1.60)

Stewart, D., Cudworth, C.J., Lishman, J.R., 1993. Misperception of time-to-collision by drivers in pedestrian accidents. *Perception* 22, 1227 – 1244. [doi:10.1068/p221227](https://doi.org/10.1068/p221227)

Te Velde, A.F., van der Kamp, J., Barela, J.A., Savelsbergh, G.J.P., 2005. Visual timing and adaptive behavior in a road-crossing simulation study. *Accident Analysis and Prevention* 37, 399–406. [doi:10.1016/j.aap.2004.12.002](https://doi.org/10.1016/j.aap.2004.12.002)

Cite as: Petzoldt, T., Schleinitz, K., Krems, J.F., & Gehlert, T. (2017). Drivers' gap acceptance in front of approaching bicycles – Effects of bicycle speed and bicycle type. *Safety Science*, 92, 283-289. [dx.doi.org/10.1016/j.ssci.2015.07.021](https://doi.org/10.1016/j.ssci.2015.07.021)

Walker, I., 2007. Drivers overtaking bicyclists: objective data on the effects of riding position, helmet use, vehicle type and apparent gender. *Accident Analysis and Prevention* 39, 417–425. doi:10.1016/j.aap.2006.08.010

Weinert, J.X., Ma, C., Yang, X., Cherry, C.R., 2007. Electric two-wheelers in China: Effect on travel behavior, mode shift, and user safety perceptions in a medium-sized city. *Transportation Research Record* 2038, 62–68. doi:10.3141/2038-08

Yan, X., Radwan, E., Guo, D., 2007. Effects of major-road vehicle speed and driver age and gender on left-turn gap acceptance. *Accident Analysis and Prevention* 39, 843–852. doi:10.1016/j.aap.2006.12.006

Zweirad-Industrie-Verband, 2013. Zahlen – Daten – Fakten zum Fahrradmarkt in Deutschland.

Zweirad-Industrie-Verband, 2011. Zahlen – Daten – Fakten zum Fahrradmarkt in Deutschland.