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

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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 enter to 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, our 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 [1]. Sales figures in Germany [2] and other European nations are growing, and are expected to continue to grow [3]. In China, e-bike sales figures reached 10 million per year already in 2005 [4]. 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 [5]. It appears that the e-bike is often a substitute for public transport [6] or a car [7]. 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 [8], [9]. It has been found that even elder citizens that gave up cycling previously are getting back onto the road on e-bikes [10]. 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 [11] show that the rate of crashes that involve e-bikes has risen continuously in recent years. 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 [12]. 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 [10]. Our own research [13] shows 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 [14], [15].

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 [16]. 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. [17] let participants drive in a simulation 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 (ca. 48.3 km/h) or 60 mi/h (ca. 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 [18], 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 faster appears to be relatively stable, and has been found also for pedestrian crossing decisions [19]–[21].

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 [22] or the observing drivers' gender [17], [18]. One central factor is drivers' age. A common finding is that younger drivers tend to accept smaller gaps than older motorists [17], [18]. 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 [18]. 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" [23].

Unfortunately, most previous studies focused solely on situations in which a decision to cross in front of a motorised vehicle was required. The vehicle approach speeds investigated were usually 40 km/h or higher. One exception is Te Velde et al.'s [24] 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. In addition, we manipulated the road gradient and the observers' perspective. Gradient appeared to be an interesting factor as speeds that can be achieved with an e-bike would appear atypical especially when cycling uphill. 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 [25]. A side view might provide sufficient eccentricity, whereas a frontal view would certainly not. Finally, to account for the widely reported age effects, we investigated two different age groups. (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 ca. 16 000 km (younger group) and ca. 13 500 km (older group), respectively.

2.2 Experimental conditions (see Table 1 for an overview)

We used two different bicycles in our 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 our specific 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 our definition, the right of way), which resulted somewhat more in a side view of the oncoming cyclist (Figure 2, right).

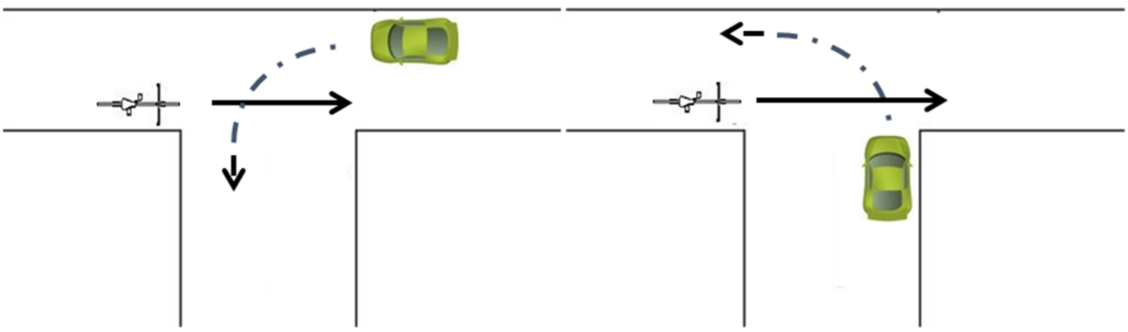

Figure 2. Experimental setup for frontal view (left) and side view (right) of the approaching bicycle (participant seated in vehicle).

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 our 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. Our 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.

Table 1. Overview of factors and factor levels.

age	bicycle type	road gradient	observer's perspective	speed
30-45 65 +	conventional bike e-bike	0% 3.75%	front view side view	15 km/h 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 to ensure that participants would be able to perceive the approaching bicycle correctly (none of our participants showed substantial vision impairments). 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 setup allowed us to link the participants' response to the position and speed of the approaching bicycle.

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 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, the order of the approaching bicycle type and its speed were balanced as well. 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.

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. 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 our 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. As we had no specific hypotheses with regard to potential 3-5-way interactions between factors, we did not go beyond 2-way interactions in our analysis. An overview of the ANOVA and corresponding effect sizes, including main effects and 2-way 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, ca. 2.5%) that were smaller than the critical gap size of 3.4 s.

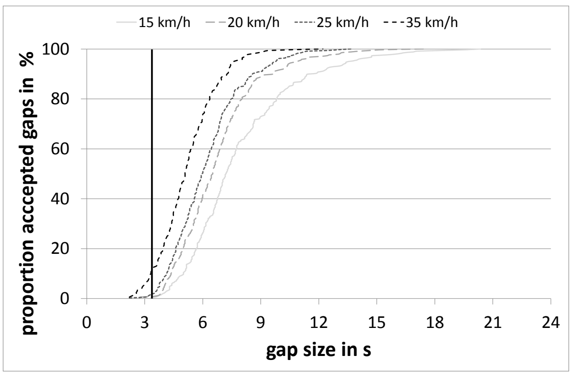

Figure 3. Cumulative proportion of accepted gaps of a certain size for crossing/turning dependent on the cyclist's approach speed. Solid vertical line indicates critical gap size of 3.4 s.

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 then 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, however, 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).

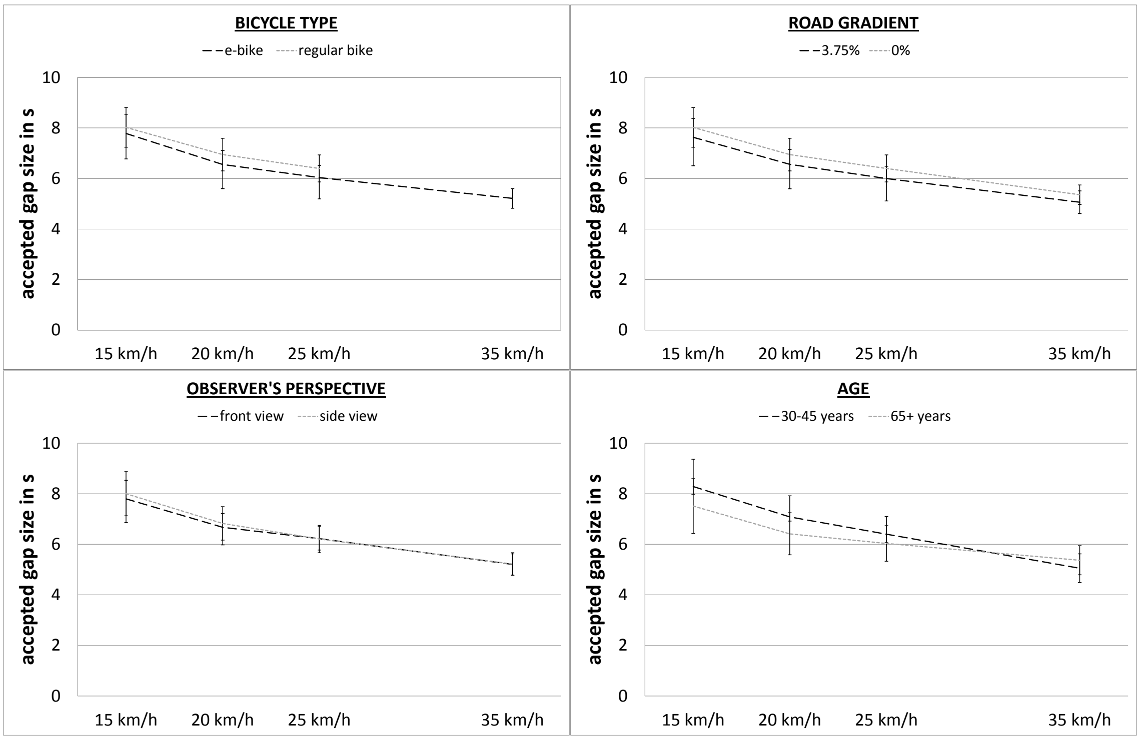

Figure 4. Accepted gap size for the different speed levels dependent on bicycle type (top left), road gradient (top right), observer's perspective (bottom left) and observer's age (bottom right).

As Table 2 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, was no interaction between speed and any of the other factors.

Table 2. Summary of ANOVA results for the accepted gap size. Significant effects in boldface.

	F	p	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

4 DISCUSSION

Aim of our 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 our 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 cyclists confirms previous studies which reported that older drivers have problems in properly assessing the time it takes for an oncoming vehicle to arrive [23]. 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 [26].

Heuristics can also be suspected to have caused the effect of road gradient. As common sense suggests and data from our own research [13] shows, cyclists are slower when riding uphill compared to their average cycling speed. 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 our participants accepted gaps that were smaller than our critical time gap. Although it has to be acknowledged that our definition of the critical gap was rather simple, the specific shortcomings of our 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 behavior have been found to be not exactly congruent [24], 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.

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