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The safety of electrically assisted bicycles compared to classic bicycles

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ABSTRACT

Use of electrically assisted bicycles with a maximum speed of 25 km/h is rapidly increasing. This growth has been particularly rapid in the Netherlands, yet very little research has been conducted to assess the road safety implications. This case–control study compares the likelihood of crashes for which treatment at an emergency department is needed and injury consequences for electric bicycles to classic bicycles in the Netherlands among users of 16 years and older. Data were gathered through a survey of victims treated at emergency departments. Additionally, a survey of cyclists without any known crash experience, drawn from a panel of the Dutch population acted as a control sample. Logistic regression analysis is used to compare the risk of crashes with electric and classical bicycles requiring treatment at an emergency department. Among the victims treated at an emergency department we compared those being hospitalized to those being send home after the treatment at the emergency department to compare the injury consequences between electric and classical bicycle victims. The results suggest that, after controlling for age, gender and amount of bicycle use, electric bicycle users are more likely to be involved in a crash that requires treatment at an emergency department due to a crash. Crashes with electric bicycles are about equally severe as crashes with classic bicycles. We advise further research to develop policies to minimize the risk and maximize the health benefits for users of electric bicycles.

1. Introduction

Governments are encouraging cycling because of the significant environmental, climate, congestion and public health benefits of cycling (Heinen et al., 2010) and such benefits have also been reported for electric bicycles (Gojanovic et al., 2011; Ji et al., 2012). Electrically assisted bicycles (EB) are increasingly popular (Kühn, 2012), as illustrated for the Netherlands in Fig. 1. The significant health burden among cyclists due to road crashes (European Commission, 2010) raises the question of how safe EBs are compared to other bicycles, here denoted as classic bicycles (CBs). There is a need for a deeper understanding of the implications of this emerging vehicle type to develop suitable policies, also for road safety (Rose, 2012). Therefore, this paper compares the crash likelihood and injury consequences of crashes with EBs and CBs among users of 16 years and older. According to European legislation, the electrically assisted bicycle is a bicycle with pedal assistance of which the output is progressively reduced and finally cut off as the bicycle reaches a speed of 25 km/h (Kühn, 2012).

Research on e-bikes has focused on explanations for the growing use (Weinert et al., 2007), the physical effort required to ride an EB (Theurel et al., 2012), and health effects (Gojanovic et al., 2011; Ji et al., 2012). Safety research has focused on (aberrant) riding behavior (Wu et al., 2012; Yao and Wu, 2012; Bai et al., 2013) and injury patters among EB users (Du et al., 2013), but comparisons with CBs to judge how road safety will be affected are rare. Exceptions are a study by Van Boggelen et al. (2013) in the gray literature, suggesting a higher crash likelihood among EB users, and a scientific study by Hu et al. (2014) who found EB crashes to be more severe than CB crashes.

This paper sets out to examine two research questions. Firstly, does crash likelihood differ between those riding EBs and CBs? Secondly, are there any differences in crash severity between EB and CB users? Risk differences between EBs and CBs may result from characteristics of the bicycles, their users (and interaction with other traffic) and how well the road is adapted to users' needs. These are explored in Section 1.1 and 1.2. The study is focused on the overall risk and severity of crashes and not on specific crash types.

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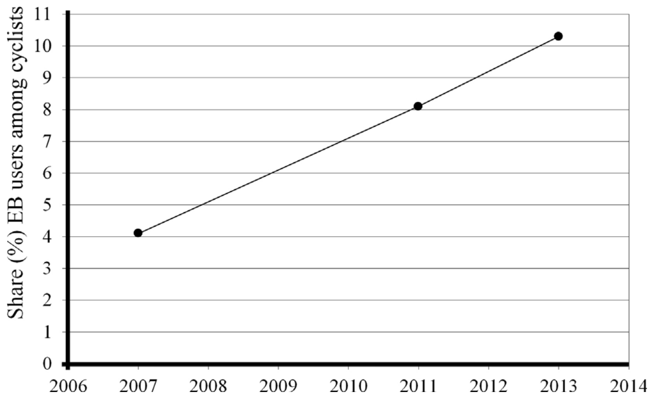

Fig. 1. Development of the share of EB users among cyclist above 16 years of age. Sources: Hendriksen et al. (2008), Duijm et al. (2012), TNS NIPO (2014).

1.1. Crash likelihood

1.1.1. Characteristics of the bicycle

The weight of a bicycle may affect safety. For instance, additional weight has to be handled while mounting and dismounting when speed is low and active steering is required to stabilize the bicycle (Kooijman et al., 2011). Falling while mounting or dismounting is a frequent crash type in older cyclists (Schepers and Klein Wolt, 2012). The weight of CBs varies between 16 and 23 kg as compared to between 25 and 32 kg for EBs(Van Boggelen et al., 2013). Another difference between CBs and EBs is how traction forces are transmitted. In CBs, traction needed to accelerate forward is provided by the rider through the rear wheel, whereas, the engine power of a large share of the currently available EBs is transmitted through the front wheel (Van Boggelen et al., 2013). Front wheel traction reduces the normal forces in the front wheel contact area and increases the likelihood of front wheel skidding. Balance and directional control of a moving bicycle is done by lateral displacement of the contact points through steering, which generates lateral forces in the front wheel contact area (Meijaard et al., 2007). Without lateral forces in the front wheel contact area one is unable to balance and cornering becomes even more difficult. Front wheel driven EBs suffer from this problem.

1.1.2. Characteristics of the user

Road user characteristics are a common cause of collisions (Evans, 2004). It is plausible that EB users may exhibit characteristics and behavior that changes their crash likelihood. Compared to CB users, EB users in the Netherlands tend to be older (Van Boggelen et al., 2013) and are therefore more prone to sustain injuries in the case of a crash (Li et al., 2003). This study will therefore control for age and gender. An interesting behavioral characteristic is speed. Speed is a common cause of road traffic collisions (Evans, 2004) and EBs enable riders to travel at higher speeds, potentially contributing to additional crash risk. However, the average cruising speed of EB's has been estimated at only 1 to 3 km/h above the average cruising speed of CB's in the Netherlands (De Waard, 2013; Twisk et al., 2013b; Van Boggelen et al., 2013). Still, for EB riders that lack experience and are averagely older than CB users, the speed may be problematic relative to their skills and capabilities. They may perform overtaking maneuvers that they would not do on CBs.

1.1.3. Road design characteristics

Road design may play a role to the extent that EB users' needs differ from those of CB users. Research has suggested that certain infrastructure characteristics such as the width of bicycle paths need to be adapted to cyclists' speed to allow for safe cycling (Parkin and Rotheram, 2010). However, we assume the differences between EBs and CBs are too small to make a difference in this respect. Note that the Dutch bicycle design manual recommends a design speed of 20 km/h for 'basic' bicycle paths or 30 km/h for main cycle routes (CROW, 2007), i.e., still above the operational speeds of CBs and EBs.

1.2. Injury severity

With the exception of speed, the aforementioned differences between EBs and CBs do not appear to be related to injury severity. Speed is related to injury severity as it increases the energy transferred to victims in the case of a crash. However, research shows substantial increases of injury severity of vulnerable road users above impacts speeds of 30 km/h (Kim, et al., 2007; Rosen and Sander, 2009), i.e., well above the average speed at which EBs and CBs are used. It is therefore difficult to underpin a hypothesis on injury severity. User characteristics such as age are related to injury severity (Kim et al., 2007) and need to be controlled for to conclude whether differences are related due to bicycle type.

2. Methodology

2.1. Data

Two questionnaire studies, commissioned by the Dutch Ministry of Infrastructure and the Environment, were used in this study to gather data on crashes and exposure. The response and distribution between victims and controls and between EB and CB users are shown in Table 1. As the survey of cyclists was conducted among people over 16 years of age, we only included and reported on victims treated at emergency departments (EDs) over 16 years of age (the survey among victims included 12 years of age and older).

2.2. Survey of bicycle crash victims treated at EDs

Between July 2011 and June 2012, the Dutch Consumer and Safety Institute carried out a retrospective study among bicycle crash victims treated at EDs (see Appendix 1 for survey questions). Victims' files were retrieved from the Dutch Injury Surveillance System, which records statistics of all people treated for an injury by EDs in 13 Dutch hospitals. Questionnaires were sent to the victims two months after their crash, seeking information about crash characteristics and bicycle use preceding the crash. Some 1993 victims over 16 years of age responded corresponding to a response rate of 46% (Kruijer et al., 2013). Of those victims, 385 (19%) were admitted to hospital after being treated at the ED, enabling analysis of injury consequences. The data was weighted for age and gender, based on the representation in the Injury Surveillance System.

Table 1
Sample size among victims and controls (group letters are included for reference in Section 2).

Bicycle type	Victims treated at EDs (Consumer and Safety Institute)	Cyclists/controls (TNS NIPO)
EB	A. 294	C. 791
CB	B. 1699	D. 517

2.3. Survey of cyclists (controls)

At the end of 2013 TNS NIPO conducted a questionnaire study using their panel. Background characteristics of the 200,000 persons of the panel such as age, gender, and previous response behavior are known. Panel members are asked to participate in up to one survey per month and receive a small reward in return. Members save up points for a self-chosen gift voucher equalling to a payment of around 10 euro per hour of participation. For reasons of efficiency, a pre-selection was done to oversample EB users aiming to achieve as many EB as CB users. The sample contained more EB that CB users due to differences in response rate (91% among EB users; 61% among CB users), possibly because EB users are older and older people are more likely to respond. The dataset contains a weighting factor, based on comparing the response to the panel, to represent age, gender and other demographical characteristics. This corrects for the response rate differences between EB and CB users but under the assumption that other independent variables are not related to the likelihood of responding (Sheikh, 1986).

Using the 2011 periodic regional road safety survey (PRRSS), an additional correction was applied to represent the distribution between EB and CB users around the time the survey among crash victims was carried out, i.e., from the second half of 2011 up to the first half of 2012. The PRRSS is conducted every two years for general monitoring of road safety and traffic behavior (see Duijm et al., 2012 for more information about the 2011 PRRSS). In the 2011 PRSS, 706 or 8.1% of the 8756 cyclists who responded indicated they used an EB at the end of 2011. The weighting factor in the TNS NIPO data set for cyclists has been adapted to represent this distribution.

3. Analysis method

Binary logistic regression was used in this case–control study to compare groups. This type of regression predicts a binary response from a set of variables, e.g., to compare cases to controls, crash types or levels of injury severity (Peduzzi et al., 1996; Vandenbulcke-Plasschaert, 2012). The following comparisons are made in this study:

1. Victims treated at an ED versus non-victims ('controls') in order to compare crash likelihood (groups A and B versus groups C and D in Table 1).
2. Victims who were admitted to hospital versus victims who were sent home after the ED treatment to compare injury severity.

The two logistic regression analyses yield Odds Ratio's (ORs) for the independent variables that are regressed on the dichotomous outcome variable and that can easily be related to the two research questions. Age gender, and bicycle use are added as control variables to all analyses as they are related to the likelihood and consequences of bicycle crashes (Kim et al., 2007; Ormel et al., 2008; Twisk et al., 2013a). Additional control variables in the second analysis are speed and whether the victim indicated health condition to have played a role in the crash. Examples of physical complaints are being tired or dizzy or suffering from low vision. These variables were only available for crash victims and could therefore not be added to the analysis on crash risk. The questions that respondents have answered for these variables are included in Appendix 1. Instances of missing values for one of the variables are excluded from the analyses. These are included in the tables as the category 'unknown'.

4. Results

We included some characteristics of crashes with EBs and CBs in Table 2. Generally, the differences are small but in the expected direction. Crashes with EBs are more often single-bicycle crashes while (dis)mounting and occur more often in curves and while overtaking. However, the numbers are too low to report true statistical significance.

Section 4.1 and 4.2 describe the results of the logistic regression analyses. Descriptive statistics are included in the tables by cross tabulation of the independent and dependent variables, e.g., column counts and percentages for victims and non-victims for the first analysis.

Table 2
Characteristics of crashes with CBs and EBs.

Independent variables	Bicycle type		Bicycle type[a]	
	CB	EB	CB (%)	EB (%)
Crash types				
Multiple vehicle crash	566	76	33	26
Single-bicycle, (dis)mounting	132	49	8	17
Other single-bicycle crashes	1001	169	59	57
Road situation				
Straight road	792	123	47	42
Curve	312	70	18	24
Intersection or roundabout	368	70	22	24
Different situation	227	31	13	11
Crash occurred while overtaking				
No	1637	288	96	98
Yes	62	6	4	2
Total	1699	294	100	100

[a] Column percentages excluding unknown.

Table 3
Association between bicycle type and involvement in crashes for which treatment at an ED is needed.

Independent variables	Treated at an ED		Treated at an ED[a]		B	S.E.	OR (95% CI)	*P*
	No	Yes	No (%)	Yes (%)				
Type of bicycle								
CB	1202	1699	92	85	0		1	
EB	106	294	8	15	0.65	0.13	1.92 (1.48–2.48)	<0.001
Gender								
Male	623	1061	48	53	0		1	
Female	685	932	52	47	−0.39	0.08	0.68 (0.59–0.79)	<0.001
Age								
16–49 years	754	1094	58	55	0		1	
50–64 years	353	467	27	23	−0.18	0.09	0.83 (0.70–0.99)	0.04
>65 years	201	432	15	22	0.15	0.11	1.16 (0.94–1.43)	0.17
Bicycle use per week								
Less than 1 day	287	195	22	10	0		1	
1–2 days	274	355	21	18	0.60	0.12	1.83 (1.43–2.33)	<0.001
3–4 days	258	451	20	23	0.90	0.12	2.45 (1.92–3.12)	<0.001
4–7 days	489	946	37	49	1.07	0.11	2.92 (2.35–3.62)	<0.001
Unknown	0	46						
Total	1308	1993	100	100				

[a] Column percentages excluding unknown.

Table 4
Association between bicycle type and injury severity (hospitalization required after an ED treatment).

Independent variables	Admitted to hospital		Admitted to hospital[a]		B	S.E.	OR (95% CI)	*P*
	No	Yes	No (%)	Yes (%)				
Type of bicycle								
CB	1390	309	86	80	0		1	
EB	218	76	14	20	0.14	0.17	1.15 (0.82–1.62)	0.42
Gender								
Male	868	193	54	50	0		1	
Female	740	192	46	50	0.15	0.13	1.16 (0.90–1.50)	0.25
Age								
16–49 years	924	169	57	44	0		1	
50–64 years	374	93	23	24	0.30	0.15	1.35 (1.01–1.82)	0.04
>65 years	310	122	19	32	0.84	0.16	2.32 (1.68–3.19)	<0.001
Bicycle use per week								
Less than 1 day	167	28	11	7	0		1	
1–2 days	292	64	19	17	0.14	0.25	1.15 (0.70–1.88)	0.59
3–4 days	349	102	22	27	0.34	0.24	1.41 (0.88–2.25)	0.15
4–7 days	759	187	48	49	0.38	0.22	1.46 (0.94–2.27)	0.09
Unknown	41	4						
Role of health condition in crash								
None	1365	314	86	83	0		1	
Physical condition played a role	222	65	14	17	0.38	0.16	1.46 (1.07–2.01)	0.02
Unknown	21	6						
Speed								
15–25 km/h	471	117	30	31			1	
Up to 5 km/h	623	147	39	38	−0.05	0.19	0.95 (0.66–1.37)	0.79
5–15 km/h	172	55	11	14	0.02	0.17	1.02 (0.73–1.44)	0.89
>25 km/h	324	63	20	16	0.66	0.22	1.94 (1.27–2.97)	<0.01
Unknown	18	3						
Total	1608	385	100	100				

[a] Column percentages excluding unknown.

4.1. Involvement in crashes requiring ED treatment against bicycle type

Table 3 presents the outcomes for the comparison between victims treated at EDs and controls. The significant OR of 1.92 for EBs suggests that, after controlling for gender, age and the amount of bicycle use, EB users are more at risk of having a crash for which treatment at an ED is needed than CB users. Other significant results are a lower crash likelihood for females compared to males and a higher crash likelihood for frequent cyclists compared to those who cycle less than one day per week. Note that the latter is expected as frequent cyclists are more exposed to risk.

4.2. Injury consequences against bicycle type

Table 4 presents the outcomes for the comparison between victims who were admitted to hospital and victims who were sent home after the ED treatment. The non-significant OR of 1.15 for EB users compared to CB users shows that victims using EBs are about equally often hospitalized than victims using CBs. Other significant results are an increased likelihood of hospitalization for older victims and victims with physical complaints. Cyclists reporting higher speeds above 25 km/h prior to their crash are more likely to be hospitalized compared to those reporting lower speeds.

5. Discussion

This study was one of the first to compare the crash likelihood and injury consequences of EBs to CBs. The results show that, after controlling for age, gender and amount of bicycle use, EBs users are more likely to be involved in a crash that requires treatment at ED. Among victims treated at an ED, EB users are equally likely to be admitted to hospital as CB users.

The only study known to the authors that compared the crash likelihood and injury consequences between EBs and CBs was by Van Boggelen et al. (2013). They found a 30% greater crash risk among EB users for which ED treatment is needed per kilometer cycled. Contrary to the current study, Van Boggelen et al. (2013) did not control for demographic characteristics such as age and gender. However, the results are broadly consistent.

Hu et al. (2014) compared the severity of crashes with EBs to CBs in Hefei, China and found EB crashes to be most severe. Compared to the current study, they found a much greater and significant difference. This can be explained by the speed differential. While cruising speed in the Netherlands differs 1–3 km/h between EBs and CBs (De Waard, 2013; Twisk et al., 2013b, Van Boggelen et al., 2013), it amounts to 7 km/h in China (Lin et al., 2008). It was already known that speeds of motorised vehicles play a role in cycling safety (Kim et al., 2007) and these outcomes suggest that cycling speed plays a role as well. We may have found injury severity to differ more between EB and CB crash victims had the speed difference between them been greater in the Netherlands.

We have suggested a number of factors that may contribute to risk differences between EB and CB users such as the higher mass of EBs compared to CBs that may interfere with (dis)mounting, engine power being transmitted to the front wheel in a large share of EB types which could contribute to skidding while cornering, and riding speed in relation to user capabilities. Although our descriptive crash statistics showed some findings in accordance with these suggestions such as more crashes with EBs our crash numbers are too low to allow for significance testing. Therefore, we cannot yet adequately explain the difference in crash likelihood that we found.

To develop measures to maximize the health benefits and minimize the risk of EB use, more research is needed. This could be crash research with a larger sample size and additional medical information such as injury severity score, injured body part, and length of hospitalization. Research could also be experimental, for instance related to safe cornering and how engine power is transmitted. New buyers of EBs may also benefit from training. More generally, it is likely that EB users benefit from a variety of measures that have also been proven effective for CB users such as safer infrastructure.

5.1. Generalizability

To what degree are the results of this study transferable to other countries? Cycling safety in the Netherlands is at a much higher level than other European countries (see e.g., Pucher and Buehler, 2008), but this applies to both EBs and CBs. Where differences in operation speeds between EBs and CBs are as small as in the Netherlands, the outcomes may be in the same range. Electric bicycle speed is dependent on legislation which differs between countries (for an overview, see Rose, 2012). Similarly, this studies' outcomes cannot be transferred to the new type of e-bike now being introduced in Europe, the so-called 'high speed e-bike' with an engine power cut off at 45 km/h (see e.g., Kühn, 2012).

5.2. Limitations

This study did not include less severe crashes for which no treatment was needed or for which treatment by a general practitioner was sufficient. We are therefore unable to draw conclusions about the likelihood of crashes in general. However, the advantage of our focus on more severe crashes is that it aligns well with the national targets that are mostly focused on severe crashes.

Our sample may have been too small to detect significant differences between crash types making it difficult to draw firm conclusions about which factors may or may not contribute to the difference in crash risk. We recommend increasing the sample size as we did find some differences in the expected direction which may have been insignificant due to our low sample of EB victims.

We advise additional questions about background characteristics of victims and controls and bicycle characteristics to be included in future research. In the analysis on injury severity, we included the role of health condition in the crash. By definition, this is not available for non-victims as they were not involved in a crash. However, instead of asking about the role of physical complaints in the crash, we advise to ask about the number of physical complaints irrespective of crash involvement. This information is available for both controls and cases. Also, weight and height could be included for both victims and non-victims to estimate their BMI. This allows additional control for differences between EB and CB users, thereby strengthening the underpinning that resulting risk differences are due to vehicle characteristics. For EBs we would like to know if these are front or rear wheel powered to identify a possible loss of balance and directional control problem.

This study may suffer from problems of self-reporting such as inaccurate recall of crash circumstances and responding in socially desirable ways (Heiman, 1999). This may especially apply to the comparison of crash types and characteristics, but probably less to the analysis on crash risk that includes only bicycle type and demographic characteristics that are specific and less prone to recall bias. Nevertheless, future research using other approaches than questionnaire research may improve the validity of the findings, for instance experimental research.

6. Conclusions

This study compared crash risk and injury consequences between users of EBs to users of CBs. The following conclusions were drawn:

- Use of electric bicycles is associated with an increased risk to be treated at an emergency department due to a crash.
- Among victims treated at an ED, EB users are about equally likely to be admitted to hospital as CB users.

The present study only looked at the risks for individual users. The overall impact of EBs on road safety are complex (Schepers et al., 2014) and require more research. However, there is some evidence that EBs may lead to a modal shift from driving (Hendriksen et al., 2008; Johnson and Rose, 2013). This means that not only the risk for the user differs before and after the shift but also that the risk to which other road users are exposed changes. For instance, should a driver switch to an EB, their individual risk is likely to increase (per kilometer). However, the risk (per kilometer) for other road users decreases, partly due to the so called 'Safety in Numbers' effect as well as the risk that was previously caused by the car (Elvik, 2009; Schepers and Heinen, 2013).

Several other aspects need to be included in future research to draw conclusions about the health effects of EBs in general. It depends on the amount of physical exercise (see e.g. Theurel et al., 2012) compared to riding a CB, but also on which activities are replaced by use of EBs. EB trips may replace car trips and thereby also reduce air pollution. As many EBs trips are recreational tours, they may also replace other recreational activities (Hendriksen et al., 2008). Together these changes affect the amount of physical exercise, exposure to road safety risks and air pollution that all contribute to health effects (De Hartog et al., 2010). The outcomes of research on broader effects may support policy decisions affecting the attractiveness of the EB, e.g. taxes on EBs.

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Appendix 1.

Questions in the survey for victims and controls

This appendix describes questions used for the study described in this paper that were asked to victims by the Dutch Consumer and Safety Institute and to controls (non-victims) by TNS NIPO. Note that age and gender were already known from the Dutch Injury Surveillance System for victims and from the panel database for controls by TNS NIPO. Whether the victim was admitted to hospital was also retrieved from the Dutch Injury Surveillance System. The Dutch Injury Surveillance System also contains crash types.

Bicycle type

-Victims: at what kind of bicycle did you cycle when the crash occurred: EB/another type of bicycle.

-Controls: do you use an EB: yes/no?

Amount of bicycle use

How many days per week do you use a bicycle?

- ☐ less than 1 day
- ☐ 1 – 2 days
- ☐ 3 – 4 days
- ☐ 4 – 7 days

Health condition (victims)

Did the crash occur due to your own physical condition?

- ☐ no
- ☐ yes, namely (check off the primary cause):
  - ☐ I was tired
  - ☐ I was dizzy
  - ☐ I was ill
  - ☐ I suffer from low vision
  - ☐ I suffer from impaired hearing
  - ☐ I suffer from balance problems
  - ☐ I have problems with motor coordination
  - ☐ else: …

Road situation (victims)

Where did the crash occur?

- ☐ a straight section
- ☐ a bend
- ☐ an intersection
- ☐ a roundabout
- ☐ else: …

Maneuver and crash type (victims)

What did you do when the crash occurred (you may check off multiple responses)?

- ☐ …
- ☐ mounting
- ☐ dismounting
- ☐ I was overtaking another road user
- ☐ …

Speed (victims)

At what speed were you cycling when the crash occurred?

- ☐ I was standing still
- ☐ slowly (under 5 km/h)
- ☐ normal (5-15 km/h)
- ☐ fast (16-25 km/h)
- ☐ racing speed (above 25 km/h)

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