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Do electric bicycles cause an increased injury risk compared to conventional bicycles? The potential impact of data visualisations and corresponding conclusions

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ABSTRACT

The increasing number of bicycle crashes leading to injuries in the Netherlands is frequently related (e.g., in the media) to increased use of the electric bicycle. For this reason, policy makers face the challenge of selecting and implementing the most promising countermeasures including those focused on electric bicycles. It may be questioned, however, to what extent the electric bicycle itself is a (direct) cause of crashes leading to injuries or whether other factors are important for explaining the increased number of bicycle injury crashes. On the basis of an abbreviated list of criteria by Elvik (2011), this paper illustrates the potential influence of factor inclusions, analysis selections, and data presentations on the general impression about crash causation with the electric bicycle as an example. The aim is to provide a 'best practice guide' by taking into account (1) a theoretical explanation of causal mechanisms, (2) control for confounders, and (3) a statistical association of sufficient strength and consistency in the expected direction. We conclude that an apparent increased risk of electric bicycles may be explained by factors such as age, exposure, health factors, and gender of the cyclist. A relatively simple analysis, by comparing fatality numbers of conventional and electric bicycles, showed that including or excluding these factors may lead to vastly different interpretations of fatality causes and the relative risk of electric bicycles compared to conventional bicycles.

1. Introduction

The most recent number of bicycle crashes in the Netherlands is alarming with the highest number of cyclist fatalities in 2022 since 1996 (Statistics Netherlands, 2023a) and an increase in the number of seriously injured bicyclists over recent decades (Aarts, et al., 2022; de Groot-Mesken, Duivenvoorden, & Goldenbeld, 2015). Each year, upon publication, these numbers lead to a renewed discussion about how cycling safety should be improved and to what extent the increasing use of electric bicycles plays a role in the rising numbers of cyclist injuries and fatalities. Policy makers face the challenge of taking targeted measures to increase cycling safety, while also aiming to stimulate cycling as an attractive means of transport because of its positive effects on health, independent mobility, and the environment (Oja et al., 2011; APPM, Tour de Force, 2022).

Since its introduction, the electric bicycle (also known as e-bike, e-bicycle, or pedelec) has not only enabled people to cycle with less required physical effort (Theurel, Theurel, & Lepers, 2012), but people can also retain cycling as a mode of transport for a longer time than on a conventional bicycle (Castro, et al., 2019). As a consequence, bicycle use in older people has increased substantially as well, but this also led to an increase in exposure to their elevated likelihood of a traffic crash and, unfortunately, an increase in injuries due to bicycle crashes (see e.g., Krul, Valkenberg, Asscherman, Stam, & Klein Wolt, 2022; Statistics Netherlands, 2023b). Given the goal of encouraging cycling, however, policies should not aim at reducing the amount that people cycle, but at reducing the number of crashes or injuries per distance travelled (i.e., risk). This has raised the question to what extent electric bicycles cause vehicle-specific crashes and injuries, as compared to conventional bicycles, and whether such crashes occur more frequently and/or lead to

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more severe injuries compared to crashes with conventional bicycles.

It is important to realize that the main message people receive about the risks of cycling can greatly influence their perception and, therefore, the public opinion about these risks. For policy makers, such perceptions may influence their choices for policies and solutions (Burstein, 2003): in this case countermeasures to increase cycling safety. There are many ways to present data, and the way that is chosen may direct policy makers in their belief of what causes exist and must be addressed. Also, an incorrect image may, amongst others, lead to an ineffective deployment of (already limited) resources. The main aim of this paper, therefore, is to illustrate the potential influence of factor inclusions, analysis selections, and data presentations on the general impression about crash causation, with the electric bicycle as an example, in the form of a 'best practice' guide.

The most suitable research design to infer cause and effect is by performing a first measurement, introducing an intervention in one group and not in another, followed by a second measurement afterwards (i.e., a before-after study with a control group). As has also been concluded for other road safety issues, such as the impact of traffic education (see e.g., Twisk, 2014), we assume that before-after studies with a control group are too small to include enough crashes for drawing statistically valid conclusions. Indeed, even though there may be relatively many observations of crashes, most of the times there are many more possible factors that contribute to the cause of a crash. If each of these factors are taken into account, this greatly reduces the possibilities for detecting a meaningful effect (i.e., statistical power) resulting in a larger required sample size to perform reliable analyses. Therefore, researchers fall back on cross-sectional research by studying factors from an observed sample within a fixed time period (e.g., one year). Such designs have the disadvantage that users of (in this case) electric and other bicycles are not randomly assigned to their type of bicycle, but have bought either type of bicycle for their own motivation (i.e., based on consumer preference). People who choose to buy an electric bicycle may differ on numerous characteristics such as, for example, the physical ability to balance their bicycle and reach a certain speed. These characteristics may influence their risk of a bicycle crash or injury independent of bicycle type: such potentially influencing factors are known as confounds and can greatly influence the relationship between bicycle type and crash risk in crash studies. In crash studies, a confounding factor may influence both the dependent variable –crashes or injuries– and the main independent variable –bicycle type– leading to a spurious association, i.e., a risk difference between bicycle types.

1.1. *Criteria for assessing causality in Cross-sectional crash studies*

A cross-sectional study has inherent weaknesses in answering the question of whether a relationship is causal. To facilitate the discussion about causality in the absence of more appropriate research designs, Elvik (2011) has formulated nine criteria for assessing whether a relationship found in a cross-sectional study may be causal (see appendix A for all nine criteria). In this paper, we have summarised these criteria into three main criteria for the assessment of causality in cross-sectional studies (see Table 1.). This abbreviated list contains criteria regarding the theoretical underpinning with which a study should start, the control for potential confounding factors within the study, and the statistical association that forms the output of the study (see Table 1.).

In Chapter 2, the possible theoretical explanation of causal mechanisms is addressed and in Chapter 3, we illustrate potential spurious associations using Dutch data by Statistics Netherlands (2023a). In Chapter 4, the importance of identifying a statistical association of sufficient strength and consistency in the expected direction is discussed and in Chapter 5, we draw tentative conclusions on relative risk differences and advise on the study design of future studies on electric bicycles.

Table 1
Criteria for interpreting causality for cross-sectional crash studies (adapted from Elvik, 2011).

Criterion	Operational definition
Theoretical explanation of causal mechanisms	Findings should be supported by well-established laws of physics or laws of human perception and information processing. Preferably such knowledge enables to formulate hypotheses about the direction of the expected association.
Control for confounders	The identification of potentially confounding variables; existence of an effect attributed to treatment after potentially confounding variables have been controlled for; completeness of the control for confounding variables.
Statistical association of sufficient strength and consistency in the expected direction	A statistically significant and substantial change in crashes or injuries associated with bicycle type. Also, consistency in direction and size of the effect attributed to bicycle type across subsets of the data, for instance more falls while mounting or dismounting in case there is a theoretical explanation regarding these crash types.

2. Theoretical explanation of causal mechanisms

One of the first questions of any study about the risks of electric bicycles should be which factors may cause their users to be more at risk than users of conventional bicycles. For this reason, this section discusses several theoretical explanations of causal mechanisms for crash patterns that are mentioned in the literature and/or have been tested empirically.

An often-mentioned argument for a potential decrease in safety of cyclists on an electric bicycle (the vehicle) are higher speeds compared to those on a conventional bicycle because of the added motor support. In part, this is justifiable, because many studies indeed have shown that cyclists on an electric bicycle ride at a 1 to 4 km/h higher speed compared to a conventional bicycle (see e.g., Dozza, Piccinini, & Werneke, 2016; Flügel et al., 2019; Huertas-Leyva, Dozza, & Baldanzini, 2018; Schleinitz, Petzoldt, Franke-Bartholdt, Krems, & Gehlert, 2017; Twisk, Stelling, Van Gent, De Groot, & Vlakveld, 2021; Jenkins et al., 2022) and the relationship between (increasing) speed and crash rate is well-established (see e.g., Aarts and Van Schagen, 2006). According to Flügel et al. (2019), the largest speed differences between conventional and electric bicycles occur on uphill road sections, but also free-flow circumstances are related to pronounced speed differences (Schleinitz, Petzoldt, Franke-Bartholdt, Krems, & Gehlert, 2017). In the Netherlands, a relatively flat country, Nationwide Data Collection (NDC) found the free-flow speed for electric bicycles to be 3 km/h higher than for classic bicycles and 4 km/h lower than for racing and mountain bicycles (Rijksoverheid, 2022).

An increased speed of electric bicycles may be related to an increase in safety–critical interactions with other road users, which could lead to a higher risk of a collision (Dozza, Piccinini, & Werneke, 2016; Huertas-Leyva, Dozza, & Baldanzini, 2018; Petzoldt, Schleinitz, Heilmann, & Gehlert, 2017b). If the speed of the electric bicycle itself is the decisive factor, one might expect that a large part of collisions with other road users consists of rear-end collisions (because of increased speed differences with other road users and/or more overtaking manoeuvres) or more severe injuries after frontal collisions. While there is empirical research on the effect on fatality risk or injury severity of the speed with which vehicles hit cyclists and pedestrians in collisions (see e.g., Nie, Li, and Yang, 2015), we found no similar empirical research on the effect of cyclists' speeds. In addition, the majority of multi-vehicle (MV) bicycle crashes in the Netherlands result in a side-impact collision (i.e., approximately 69 % and 71 % for conventional or electric bicycles, respectively, in 2018–2021; SWOV, 2023b). A possible explanation for this is that the (higher) speed of an electric bicycle is underestimated by another road user, resulting in errors in choosing crossing safe gaps (Petzoldt, Schleinitz, Gehlert, & Krems, 2017a). It could therefore be questioned whether the electric bicycle is the decisive factor in the cause of such collisions, or the (behaviour of the) other road user. However, even if this explanation holds, one would expect that electric bicycles are more often involved in side-impact collisions than conventional bicycles, which was also not the case in the Netherlands. Given the above, it remains difficult to argue that an increase in conflicts, potentially leading to a collision, occurs purely due to a speed increase of about 3 km/h.

A second explanation that is frequently mentioned is that the additional weight of an electric bicycle elevates the risk of falling, for example while mounting or dismounting the electric bicycle (Popovich, et al., 2014; Van Cauwenberg, De Bourdeaudhuij, Clarys, De Geus, & Deforche, 2019). It may be questioned, however, whether the additional weight of an electric bicycle's motor and batteries (approximately 7 kg; Bosch eBike Systems, n.d.) is large enough to increase this risk because the total amount of added weight is relatively small compared to the weight of a cyclist's body (an average Dutch person weighs 78 kg; Statistics Netherlands, 2023c). In an experiment, Twisk et al. (2017) did find participants to take more time to achieve the speed of 6 km/h on an electric bicycle than on a conventional bicycle, which may reduce their balance at these low speeds. However, it took them less time to achieve a speed of 10 km/h at which a bicycle is almost self-stable (Kooiman, Meijaard, Papadopoulos, Ruina, & Schwab, 2011). It is also difficult to formulate a hypothesis based on this study because the association depends on the speed range and because manufacturers nowadays also sell electric bicycles with a start assistant up to 6 km/h (see e.g., Kalkhoff, n.d.; Van Raam, n.d.). These are new developments of which the market penetration is not clear yet, but likely to be very low. Furthermore, after correcting for age, there seems to be no difference in the number of crashes while mounting or dismounting between conventional or electric bicycles (Valkenberg, Nijman, Schepers, Panneman, & Klein Wolt, 2017; Schepers, Klein Wolt, & Fishman, 2018).

It has been suggested that front wheel drive is related to more difficulties with handling, heavier steering, and/or an increased chance of skidding compared to other motor locations (Contò & Bianchi, 2022; Kristek, Peršić, Premec, & Vražić, 2022), which could contribute to increased crash risk leading to injuries. With some (front wheel) motors, for example, the engine reacts with a short delay when the rider starts pedalling more rapidly, which may feel unnatural. To what extent riding an electric bicycle is safe and comfortable (e.g., resembles handling a conventional bicycle) depends on the quality of the bicycle's cadence sensors, torque sensors, the implemented control methods for the motor, and/or how the motor and battery placement contribute to the bicycle's weight distribution (Contò & Bianchi, 2022). If cyclists experience differences with riding a conventional bicycle, they may be able to get used to this and adapt their cycling behaviour. With the limited research in this area, it is difficult to base a hypothesis on these technical characteristics. Furthermore, mid-drive motors are considered the safest because their centre of gravity is closest to that of the rider, resulting in the most balanced weight distribution compared to front or rear wheel motors (Contò & Bianchi, 2022). The fact that electric bicycles equipped with mid-drive motors have the largest and rising market share (over two-thirds of Dutch sales in 2018; Stella Bicycles, n.d.) makes the hypothesis that difficulties with handling an electric bicycle causes an increased crash risk, compared to conventional bicycles, even more difficult to substantiate. Indeed, because mid-drive electric bicycles most closely resemble the weight distribution of conventional bicycles, and more advanced (torque) sensors and motor control methods become available that resemble handling a conventional bicycle, any potential effect of handling difficulties on the total number of electric bicycle crashes should diminish as well.

3. Control for confounding factors

A number of factors has been suggested as potential confounders for the relationship between bicycle type and the risk of (severe) injuries or fatalities due to crashes. People may use an electric bicycle differently than a conventional bicycle, or the electric bicycle may attract other (potentially novel) users to cycling than the conventional bicycle. In particular exposure may confound the relationship as users of electric bicycles tend to cycle more often and longer distances (e.g., Bourne, et al., 2020; Fyhri & Sundfør, 2020). Therefore, this paper uses simple risk figures with risk defined as number of bicycle fatalities per exposure (see Rumar, 1999). If electric bicycle users have the same number of fatalities per distance travelled, then electric bicycle users have more fatalities overall. Since their introduction, electric bicycles have attracted specific user groups such as older people (see e.g., Van Cauwenberg et al., 2019). For this reason, age may also confound the relationship as older cyclists tend to be more vulnerable and susceptible to injuries if they are involved in a crash, irrespective whether using a conventional or an electric bicycle (Swov, 2015). Finally, because users select their vehicle themselves, electric bicycle users may differ in other respects such as gender and health as well. Account for confounding factors such as gender is performed by breaking down the risk figure (bicycle fatalities per exposure) into subgroups, for example, a separate risk figure for men and women.

3.1. Illustrating the influence of confounding factors

To illustrate the influence of confounding factors on the interpretation of recent bicycle crash data from the Netherlands, the numbers of bicycle fatalities were analysed. Given the combination of three data sources (see paragraph 3.1.1.), it is highly likely that Statistics Netherlands reliably determines the numbers of road fatalities in the Netherlands. Furthermore, the general public opinion and traffic safety policies are greatly influenced by these (yearly published) statistics and, therefore, were selected as the most relevant cases.

3.1.1. Databases and definitions

Before presenting the results of the analyses, several sources and definitions are clarified. First, data concerning traffic fatalities as reported by the Dutch national statistics agency (Statistics Netherlands, 2023a) were analysed from 2018 to 2021, supplemented with limited (preliminary) data from 2022. This database contains the number of traffic fatalities for each year, split by age, gender, and bicycle type. The data are derived from the Dutch traffic crash registration police reports, court records, and reports by medical examiners and is, thanks to the combination of the three sources, considered the database with the highest accuracy regarding traffic fatalities available in the Netherlands. A traffic fatality is defined as a *"road user who dies as a result of a suddenly occurring incident on a public road on Dutch territory which is related to traffic, in which at least one moving vehicle was involved"* (Statistics Netherlands, 2023d). Furthermore, Statistics Netherlands (2023d) defines electric bicycles as *"bicycles powered by an electric motor"*. The Dutch law states that electric bicycles may only offer pedalling support up to 25 km/h with a maximum power rating of 250 Watts (Rijksoverheid, n.d.), therefore also including electric cargo bicycles with these specifications. Speed pedelecs are not included in this category: these are classified as mopeds. Conventional bicycles include all types of bicycles without an electric motor, also including mountain bikes and racing bicycles.

Even though the data on traffic fatalities of Statistics Netherlands (2023a) is the most complete and accurate for all traffic deaths, it is important to note that the type of bicycle was automatically registered as a *conventional* bicycle in case it was *unknown* to the person or agency who completed the registration whether or not the involved bicycle was an electric bicycle (Statistics Netherlands, 2023a). This could mean that the number of fatalities with an electric bicycle is underreported and, therefore, concerns a lower limit.

Data regarding specific characteristics of Dutch cyclists were derived from the Dutch national travel survey ODiN. ODiN is a continuous national travel survey in which the past four years approximately 60.000 Dutch inhabitants (Min: 53.000 and Max: 67.000 in 2019 and 2021, respectively; Statistics Netherlands, 2023e) filled in an activity-based travel diary of all trips made on one day in that year. Each participant in the NTS is drawn from the Municipal Basic Administration and weighed accordingly to form a representative sample of the Dutch population. For our analyses, data regarding bicycle ownership and exposure (kilometres travelled) were derived from ODiN.

3.2. Bicycle fatalities in the Netherlands

The analysed data concerning bicycle fatalities in the Netherlands are displayed in Fig. 1, separated for each year, ranging from 2018 to 2022. Additionally, in appendix B the absolute numbers are displayed, also including car occupants who died in traffic. The number of bicycle fatalities per year has surpassed the number of car occupants fatalities in the last three years (Statistics Netherlands, 2023a). This indicates the trend and relevance of the current traffic safety problem for cyclists in the Netherlands.

When analysing conventional and electric bicycle types separately, it becomes apparent that the number of fatalities with conventional bicycles fluctuated between 192 in 2022 and 127 in 2021, while the number of electric bicycle fatalities has increased consistently from 57 in 2018 to 99 in 2022 (see appendix B). Approximately one third of all bicycle fatalities since 2019 concern electric bicycles, with the highest percentage occurring in 2021 (39 %).

3.2.1. Exposure factor 1: Cyclist population (bicycle owners)

Even though the absolute numbers are very important, they provide limited insight into the true fatality risk of the two bicycle types. As there are many more people who own a conventional bicycle than an electric bicycle (Statistics Netherlands/ODiN + k, 2022), Fig. 2 shows the number of bicycle fatalities per million owners of conventional or electric bicycles in the Netherlands. Based on this first but fairly limited correction, it becomes clear that a much larger share of electric bicycle riders fatally crashed as compared to the share of conventional bicycle riders.

3.2.2. Exposure factor 2: Use

Even though the number of bicycle fatalities per million bicycle owners provides more insight in the likelihood of fatalities per type of bicycle, this calculation method is very limited with regard to fatality risk. For example, cyclists who hardly ever (or never) use their bicycle are included with the same weight as people who cycle on a daily basis. Furthermore, it is unknown to what extent people own one or more (types of) bicycles. For this reason, it is much more appropriate to base analyses about the causes of risks on factors that are theoretically related to these fatalities (Elvik, 2011). For this reason, actual *use* of a vehicle seems a much more suitable exposure measure to determine risk than mere *possession* of a vehicle, because using a bicycle to travel through traffic actually exposes the rider to traffic and the risks that follow (Hakkert & Braimaister, 2002). For example, an important road safety question that we would like to be able to answer using risk figures is whether the number of fatalities changes when people use an electric bicycle instead of a classic bicycle to make the same trips. The term *bicycle use*, however, can be defined in different ways (see e.g., Vanparijs, Int Panis, Meeusen, & de Geus, 2015):

1. Number of bicycle trips (cycling frequency). A cyclist who makes *more trips* (of similar length) on the bicycle is *more frequently* exposed to the risks associated with participating in traffic. However, cyclists do not all make trips of similar length, therefore, even if this variable provides basic information about risk exposure, it does not control for trip lengths. This is important especially for users of electric bicycles, as studies have shown that electric bicycle riders not only complete more, but also longer journeys than cyclists with a conventional bicycle (Fyhri & Fearnley, 2015; Kroesen, 2017; Fyhri & Sundfør, 2020; Schepers, Klein Wolt, Helbich, & Fishman, 2020a; Bourne, et al., 2020). Using only cycling frequency as the exposure measure might therefore result in biased conclusions if we were to answer the question of whether the number of fatalities changes when people use an electric bicycle instead of a conventional bicycle.
2. Amount of time spent on the bicycle (cycling time). Cyclists who spend *more time* on a bicycle should also, in theory, be exposed to traffic risks for *longer* periods of time. However, a long-lasting trip might also be the result of other factors, such as a low riding speed or delays because of other reasons (e.g., busy traffic, waiting for other road users, traffic lights, etc.).

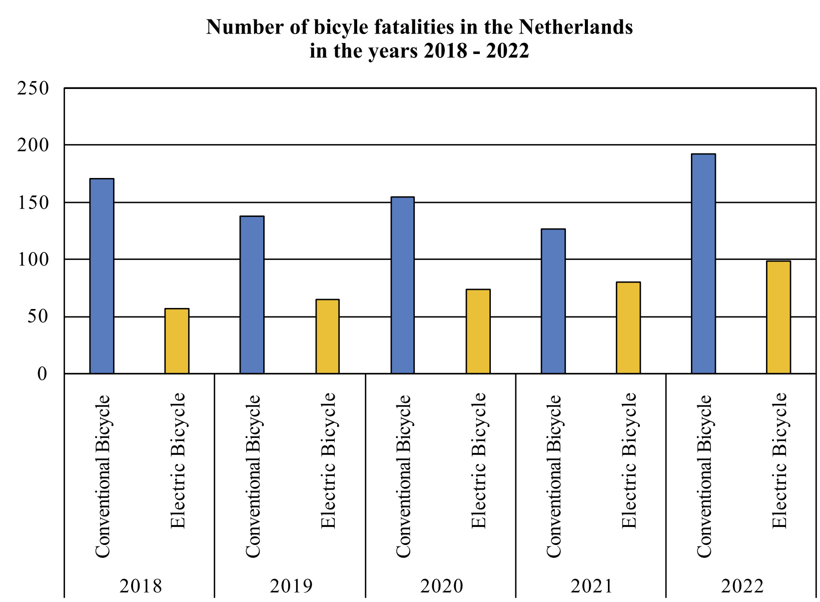

Fig. 1. Number of bicycle fatalities in the Netherlands in the years 2018–2022. Source: Statistics Netherlands (2023a).

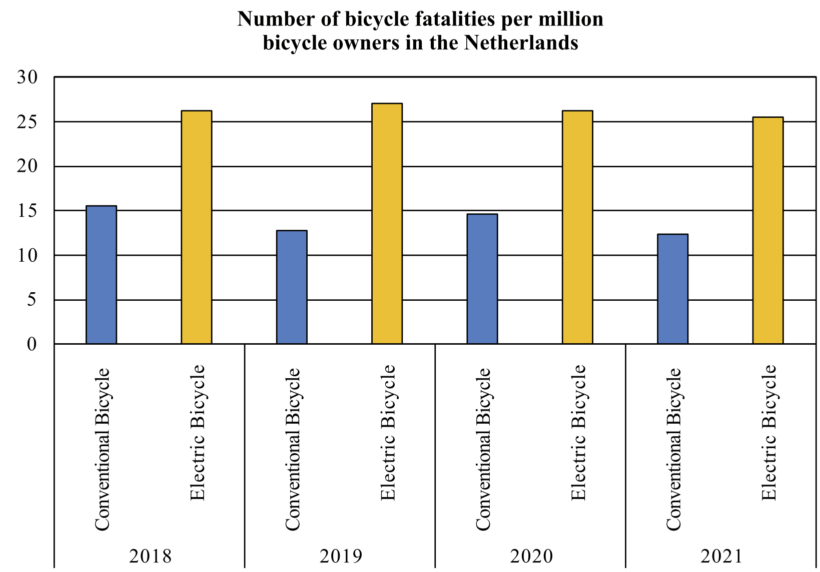

Fig. 2. Number of bicycle fatalities per million bicycle owners in the Netherlands. Sources: Statistics Netherlands (2023a); Statistics Netherlands/ODiN + k (2022).

3. Amount of distance cycled (cycled kilometres). The last discussed exposure measure is cycled distance. Even though this variable is also not *the* perfect indicator for exposure, 'each kilometre travelled' does control for the number of trips cycled (for example, 10 trips of 1 km are assumed to result in a similar risk exposure as 1 trip of 10 km). Also traffic delays are taken out of the calculation (e.g., standing still while waiting to cross a road does not add to the distance cycled). Taken together, this suggests that cycled distance is the most comparable exposition measure to answer the question of whether the same trips would be safer on one type of bicycle as on another. Limitations of this exposure measure still exist, however, because the amount of risk also fluctuates based on factors such as the location (e.g., rural vs. urban environments) or the time of day (Elvik, 2011) and, therefore, distance should ideally be broken down by place and time. In Fig. 3, the application of this variable is illustrated by calculating the number of bicycle fatalities per billion kilometres cycled on a conventional or an electric bicycle in the Netherlands for multiple years.

After dividing the number of bicycle fatalities per year by the number of kilometres travelled for both types of bicycles, it becomes apparent that in all the displayed years, there were more fatalities per (billion) kilometres for electric bicycle users than for conventional bicycle users (see Fig. 3). In other words: the risk of a fatal crash is higher on an electric bicycle, even though the risk difference between conventional and electric bicycles turns out the be smaller when correcting for cycled distance compared to when correcting for the number of bicycle owners.

3.2.3. *Confounding factor: Age*

Not only in the Netherlands, but also in many other countries, research has shown that the group of users of an electric bicycle consists of significantly older people than users of a conventional bicycle (see e.

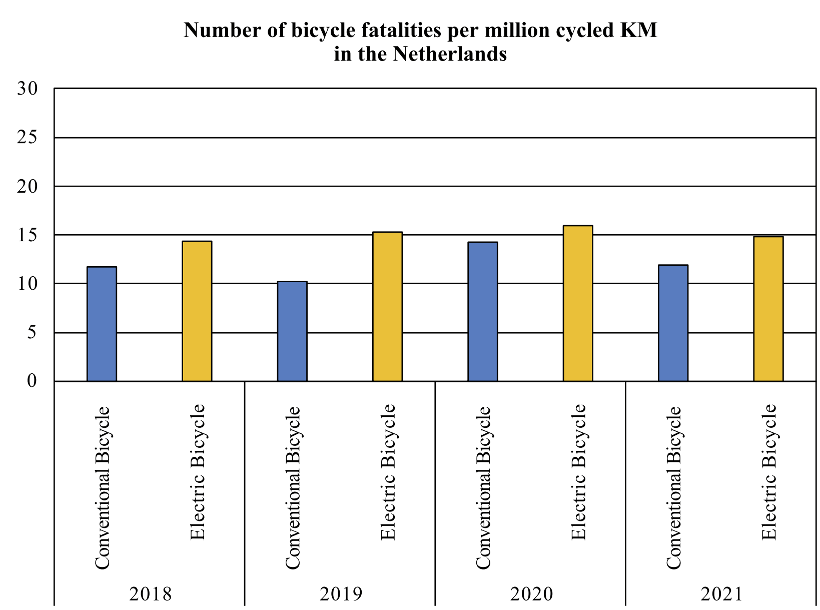

Fig. 3. Number of bicycle fatalities per billion cycled kilometres in the Netherlands from the years 2018, 2019, 2020, and 2021. Sources: Statistics Netherland (2023a); Statistics Netherlands/ODiN + k (2022).

g., Schepers, Klein Wolt, Helbich, & Fishman, 2020a; Krul, Valkenberg, Asscherman, Stam, & Klein Wolt, 2022). Specifically for (Dutch) cyclists aged 60 years or older, approximately half of all the travelled kilometres by bicycle were made on an electric bicycle, increasing further with increasing age (see Fig. 4). In comparison, the large majority of kilometres in the age group up until 50 years of age were made on conventional bicycles.

Evidence shows that cycling performance and traffic safety in general are related to ageing (see e.g., Swov, 2015; SWOV, 2023a; Schepers, Weijermars, Boele, Dijkstra, & Bos, 2020b; Williams & Carsten, 1989). The effects of *ageing*, however, should be interpreted as an umbrella term for the effects of physical and cognitive changes, that occur in a human being while growing older, on the ability to cycle (or drive, walk) safely in traffic. *Physical factors* such as fitness, agility, strength, balance, resilience, recovery capacity, illness, and sensory capacities all influence cycling behaviour, crash risk, and injury severity (Schepers et al., 2020b). This is also the case for *mental factors* like knowledge, experience, and cognitive abilities (e.g., attention, memory, reaction speed). Lastly, compensation strategies are also important: (older) cyclists may for example avoid darkness or crowdedness by changing their cycling routes or (departure) times (e.g., compensation at the strategic level; Schepers et al., 2020b).

As displayed in Fig. 5, the number of bicycle fatalities in older people is relatively high, both for conventional and electric bicycle riders. For cyclists with a conventional bicycle, the number of fatalities in the age groups 70–80 years or 80+ years was nearly the same, or even more, than for the group of conventional cyclists aged between 0 and 50 years. The largest difference in bicycle fatality numbers between conventional and electric bicycles occurred in the age group 0–50 (see Fig. 5). In the age groups of 50 years and older, the difference in fatalities between conventional and electric bicycle riders seems to decrease with increasing age. Based on these numbers, the assumption of age being an important factor in bicycle fatalities seems justifiable. For this reason, Fig. 6 shows the number of bicycle fatalities per bicycle type and age group, divided by the total amount of cycled kilometres (exposure) for each category. Based on the data visualised in Fig. 6, the conclusions regarding the elevated risk of the electric bicycle based on the analyses in Fig. 2 and Fig. 3 seem to be different. After correcting for age and exposure of the cyclists, the outcomes suggest the risk of fatal crashes with an electric bicycle is *lower* than the risk of fatal crashes with a conventional bicycle for the age groups older than 50 years (see Fig. 6). In other words: older people riding an electric bicycle might even have a lower risk for a fatal crash on an electric bicycle than on a conventional bicycle.

It is important, however, that the calculations shown in Fig. 6 are interpreted with caution, firstly because of the limited range of available age group data. In particular the first age group, aged between 0 and 50 years, has a much larger age range than the other age groups. With this classification, it is not possible to investigate age effects within the group of cyclists younger than 50 years. For example, it is unknown whether the age of the bicycle fatalities is evenly distributed within this group, or that one specific age group (e.g., adolescents) is overrepresented. The same applies for the 80+ years group, even though the sample size of this group is much smaller not only in the general population, but also in the cycling population. Furthermore, the set boundary for age classification can severely impact the fatality risk values of those groups. As an illustration, Fig. 7 shows the calculated risk values for the same groups of cyclists (though for conventional or electric bicycles separately), but each group is divided based on different age values. This illustration shows that different group divisions or cut-off points may underestimate the risks of specific age groups. Indeed, even though an age effect may still be found, it could lead to an underestimation of the actual risk values of, in this case, people with higher ages (see Fig. 7). At the same time, the risk values of the 80+ group should also be interpreted with caution because of the relatively limited sample size (both in the population as in the national travel survey, for example) compared to the other age groups.

3.2.4. Confounding factor: Gender

Another factor that has been reported to influence the crash risks of cyclists is gender (e.g., Schepers et al., 2020a; Fyhri et al., 2019). As depicted in Fig. 8, the majority of bicycle fatalities were male, and the majority of male bicycle fatalities was with a conventional bicycle (Statistics Netherlands, 2023a). After calculating the relative risk per billion cycled kilometres (see Fig. 9), the risk of a bicycle fatality seems higher on an electric bicycle, both for males and females. The overall risk of a bicycle fatality is higher for males regardless of bicycle type, while the magnitude of the risk increase of the electric bicycle is similar for both males and females. Based on these data, one may conclude again that the overall fatality risk of an electric bicycle is higher compared to a conventional bicycle, both for males and females.

3.2.5. The factors age, gender, and exposure combined

The last calculation presented in this paper concerns the three aforementioned factors combined: the number of bicycle fatalities in the Netherlands per age group, gender, and divided by exposure (see Fig. 10). Based on this calculation, it can be concluded that after correction for age and gender, the increased risk of the electric bicycle disappears. The risk of females is mostly lower compared to males in all age groups, even though the risk of older women on an electric bicycle is more comparable to men, but still lower. The risk of a bicycle fatality increases similarly with age, both for conventional and electric bicycles. In the highest age groups, however, the risk of a bicycle fatality again seems higher for conventional bicycles than for electric bicycles.

Apart from the earlier mentioned limitation in the available range of the age groups, it is important to also re-emphasize the potential underreporting of fatalities with an electric bicycle (see section 3.1.1.). This could indicate that the calculated risk for electric bicycles may be a

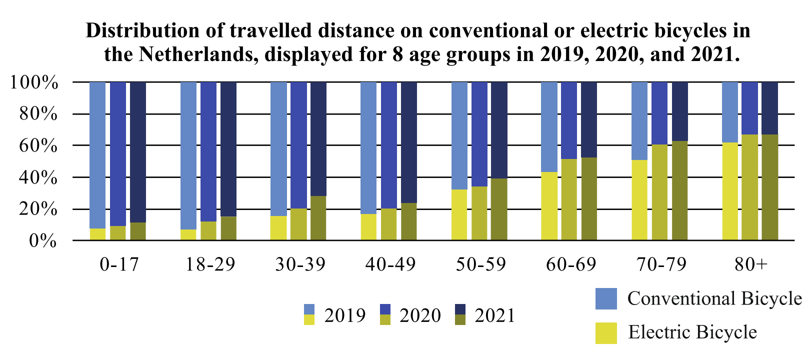

Fig. 4. Distribution of travelled distance on conventional or electric bicycles in the Netherlands, displayed for eight age groups in 2019, 2020, and 2021. Source: Statistics Netherlands/ODiN + k (2022).

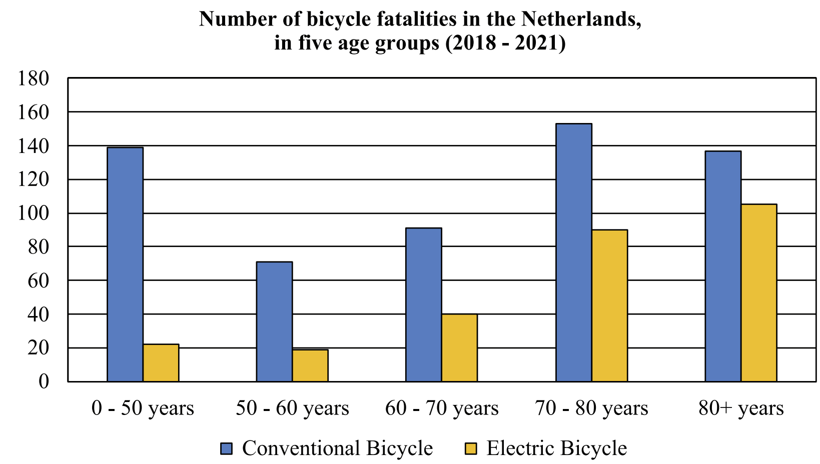

Fig. 5. Number of bicycle fatalities in the Netherlands in five age groups (2018–2021). Source: Statistics Netherlands (2023a).

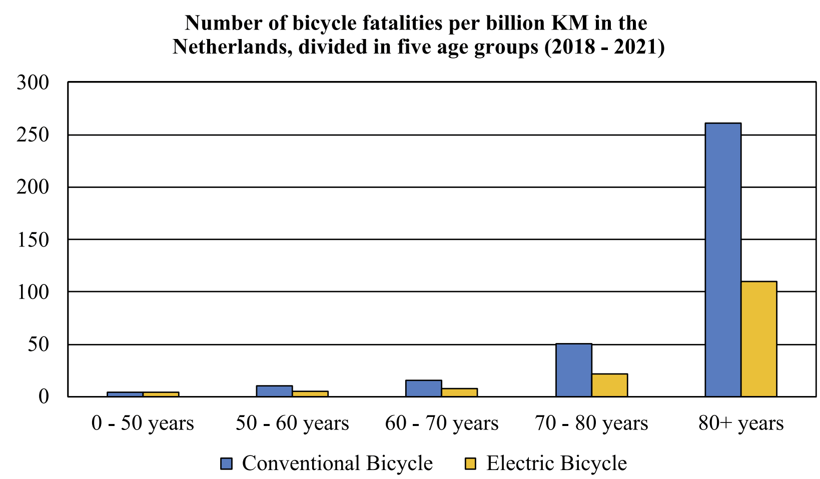

Fig. 6. Number of bicycle fatalities per billion KM in the Netherlands, divided in five age groups (2018–2021). Sources: Statistics Netherlands (2023a); Statistics Netherlands/ODiN + k (2022).

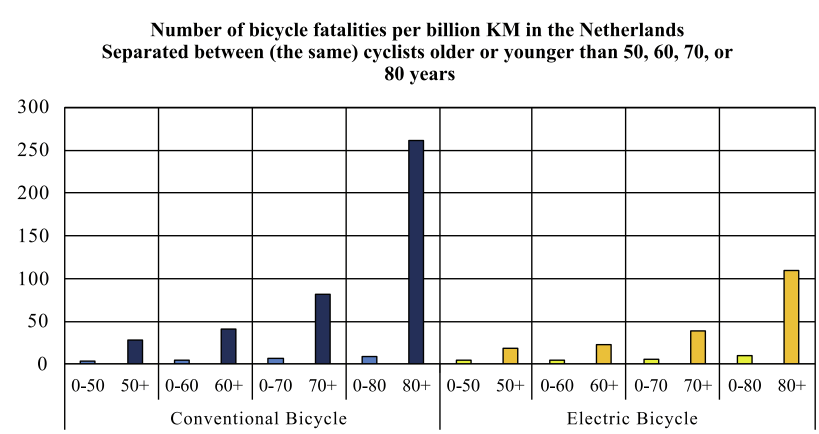

Fig. 7. Number of bicycle fatalities per billion KM in the Netherlands, separated between cyclists older or younger than 50, 60, 70, or 80 years. Sources: Statistics Netherlands (2023a); Statistics Netherlands/ODiN + k (2022).

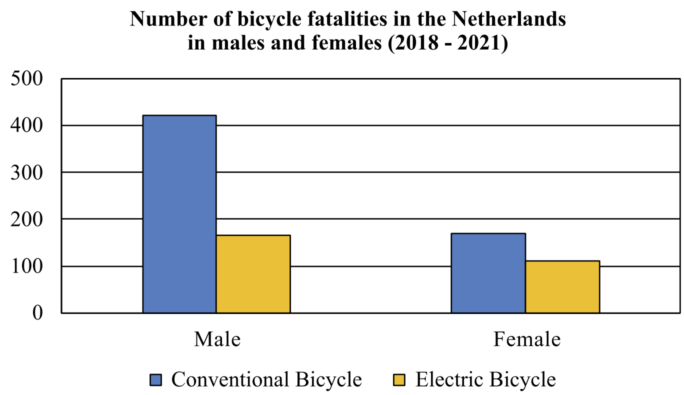

Fig. 8. Number of bicycle fatalities in the Netherlands in males and females (2018–2021). Source: Statistics Netherlands (2023a).

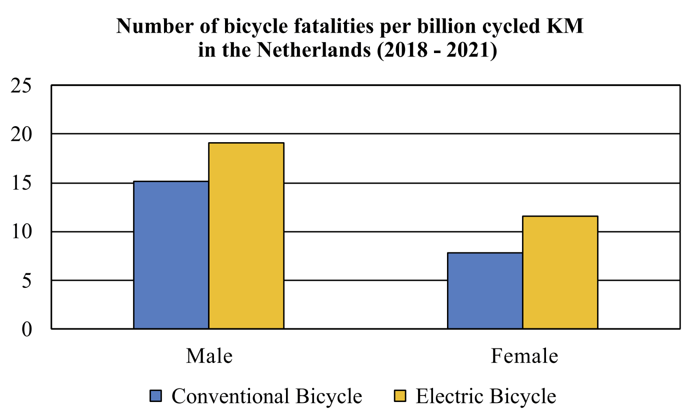

Fig. 9. Number of bicycle fatalities per billion cycled KM in the Netherlands (2018–2021). Sources: Statistics Netherlands (2023a); Statistics Netherlands/ODiN + k (2022).

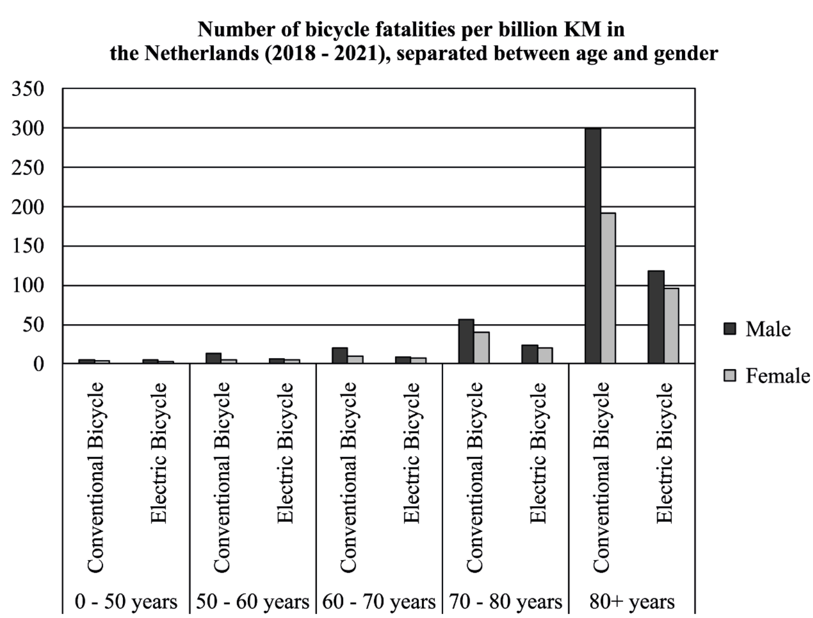

Fig. 10. Number of conventional and electric bicycle fatalities per billion kilometres in the Netherlands (2018–2021), separated between age and gender. Source: Statistics Netherlands (2023a), Statistics Netherlands/ODiN + k (2022).

lower limit, and it could be possible that the number of involved electric bicycles is higher, and therefore the risk as well. In other words: the exact risk ratio between cyclists with a conventional or an electric bicycle cannot be determined based on these data. However, even with this limitation, this analysis does tentatively show that the risk on an electric bicycle is *not necessarily higher* than the risk on a conventional bicycle, and that the differences in crash risk between conventional and electric bicycle users are not solely dependent on the (vehicle) characteristics of the electric bicycle, but also largely on (a combination of) user characteristics such as age, gender, and exposure.

All in all, these limitations do not prevent illustrating that conclusions about crash causation can change considerably after including different types of exposure measures and/or corrections for confounding factors. This illustration should therefore point (similar) analyses into the right direction, while remaining cautious with deriving conclusions.

4. Statistical association of sufficient strength and consistency in the expected direction

The last aspect of inferring causality concerns identifying a statistical association of sufficient strength and consistency in the expected direction (Elvik, 2011). Given that the final analysis displayed in Fig. 10, which included all three of the confounders, did not provide a difference in the expected direction, it is not possible to determine to what extent that association is sufficiently strong and consistent. Therefore, several examples from the international literature are discussed in this section. For reasons of consistency we would ideally rely on studies on fatal bicycle crashes. As well-conducted studies on fatal bicycle crashes with a comparison between conventional bicycles and electric bicycles are lacking, we discuss this topic using studies on non-fatal bicycle crashes.

One factor that could be used to illustrate this aspect is also related to age. For example, Gaster and Gehlert (2022a; 2022b) found that, after correction for exposure, the risk of a crash was only higher on an electric bicycle for cyclists in the age categories 18–24, 25–34, and 80+, but not for people in other age categories. The authors explained this inconsistency by inferring that the younger age groups may be overconfident and reach much higher speeds with the offered pedal support, while physical and mental decline of older cyclists may lead to difficulties with handling an electric bicycle (Gaster & Gehlert, 2022a; 2022b).

Another factor is the apparent inconsistency between studies in the found effects of gender on bicycle crash risk. For example, Fyhri et al. (2019) concluded that women in general, regardless of age, have a higher risk on electric bicycles as compared to conventional bicycles. Schepers et al. (2020a), however, concluded that only older women have a higher risk of a bicycle crash with an electric bicycle. Furthermore, Hertach et al. (2018) found that being male was a risk factor for a crash with an electric bicycle, while being female was related to severe injuries after an electric bicycle crash.

Finding a seemingly selective effect, particularly without a clear a-priori hypothesis, makes it less likely that the effect occurred because of the defined factor (in this case: gender and bicycle type), but more likely that another confounding factor is more influential and not (yet) controlled for. For example, an effect of gender on crash risk could, in theory, be explained by differences in bicycle designs. Traditionally, there are specific bicycle designs for men and women and the most pronounced difference between these designs is a so-called 'step-through' frame on a ladies-bicycle. It is unlikely, however, that this difference explains an increased crash risk for (older) women because a 'ladies-bicycle' should make it easier to mount or dismount (i.e., it is not necessary to move one leg over the frame of the bicycle). Fyhri et al. (2019) mentioned another possible explanation. They state that electric bicycles tapped into a relatively new market of cyclists, and that these new cyclists were largely women. In other words: the factor 'gender' could be confounded by the factor 'novel user', and inexperience with a vehicle and/or traffic is a well-known risk factor for crashes (Fyhri et al., 2019).

5. Conclusions and suggestions

Analysing the causes of bicycle crashes is important because the numbers of bicycle injury crashes and fatalities are high and have increased over the last years both nationally and internationally (see e.g., Statistics Netherlands, 2023a; Schepers et al., 2020a; Krul et al., 2022; Gaster & Gehlert, 2022a; Scaramuzza et al., 2015). A considerable part of these crashes occurred with electric bicycles, of which the share in the total number of bicycle crashes is also increasing (Statistics Netherlands, 2023a; Gaster & Gehlert, 2022a; Fyhri et al., 2019). For this reason, the electric bicycle may be held accountable for the rising numbers. Indeed, some (preliminary) analyses may point out that the risk of a bicycle crash is higher on an electric bicycle compared to a conventional bicycle, which could indicate that safety policies should be aimed at electric bicycles specifically. However, on the basis of a summarised list of criteria by Elvik (2011), we showed that the user groups and the corresponding usage patterns of conventional and electric bicycle users are considerably different and may be just as, or even more, decisive for the increased fatality risk, than bicycle type alone.

5.1. Lessons learned

Statistics about bicycle usage in recent years show that the majority of cycled kilometres in the Netherlands of people aged over 60 years were made on an electric bicycle, while this share was much lower for cyclists younger than 50 years (Statistics Netherlands/ODiN + k, 2022). In accordance, multiple studies show that the mean age of victims of bicycle crashes with an electric bicycle is higher than the mean age of crashed cyclists with a conventional bicycle. Older age is known to be related to (age-related) physical and cognitive decline: factors which influence cycling performance, physical fragility, crash risk, and injury severity (Schepers et al., 2020b). In addition, electric bicycles are also used to travel further distances than conventional bicycles (Bourne, et al., 2020; Fyhri & Sundfør, 2020).

With regard to bicycle fatalities with conventional or electric bicycles in the Netherlands over the time period from 2018 to 2021, relatively simple analyses show that after correcting for exposure and gender, the general risk of a bicycle fatality seems higher on an electric bicycle compared to a conventional bicycle. If the factor age is added to these calculations, however, the results turn out differently and reveal age as the most decisive factor for the increased fatality risk. Strictly taken, this basic analysis even seems to reveal that older cyclists with an electric bicycle have a lower risk of a fatal crash compared to a conventional bicycle. Limitations in data registration, however, do not allow drawing such firm conclusions because the number of electric bicycles in the equation should be interpreted as a lower boundary. This analysis does show, however, that it is unlikely that the increased number of bicycle fatalities is caused by the electric bicycle as a vehicle alone.

Our findings are to a large extent in line with results from Germany by Gaster and Gehlert (2022a). They also found that in bicycle crashes leading to severe or fatal injuries, after correcting for exposure and age, the risks of conventional and electric bicycles were comparable or even higher for conventional bicycles in the age groups older than 35 years. They also acknowledge the limitations with regard to underreporting and/or misclassification of electric bicycle victims, and highlight the necessity to combine official crash registration reports with questionnaire studies among bicycle crash victims. Such studies allow the type of bicycle to be determined with greater certainty. Unfortunately, few of those studies correct for exposure in distance travelled, age, and gender. Many (preliminary) analyses reported in scientific literature indicate an increased likelihood of a crash with an electric bicycle, but the addition of more (reliable) and theoretically relevant control variables (i.e., age, exposure, health factors) mostly leads to less pronounced or diminished effects with regard to an increased risk of the electric bicycle (e.g., Fyhri et al., 2019; Schepers et al., 2020a; Gaster & Gehlert, 2022a; 2022b).

5.2. Future recommendations

This paper illustrates how the inclusion of an exposure measure and other confounding factors has a large impact on the conclusions of a comparison of the safety of an electric bicycle and conventional bicycle. For example, using the same figures on traffic fatalities, the electric bicycle would be related to substantially more deaths per cyclist (bicycle user), slightly more deaths per distance travelled if all groups are combined in one risk figure, and substantially fewer deaths per distance travelled within separate age groups. Given the absence of opportunities to experimentally investigate causality of the safety impact of bicycle type, it is highly recommended that, for best practice, theoretically sound exposure measures and confounders are involved in the analyses and that the found effects are clear and consistent across groups. Specifically, this means that we recommend to at least correct for age, distance travelled, and gender to draw conclusions on the risks of both conventional and electric bicycle types.

These results could point policy makers into a more nuanced direction with regard to safety measures for the electric bicycle. Indeed, based on our findings, it is possible to substantiate the theory that the increased injury crash risk of electric bicycles may, to a large extent, be caused by a group of novel users as compared to users of conventional bicycles. Electric bicycles attract and allow older, more fragile people, who already have an increased risk for severe injury after a crash, to cycle more and/or longer than they could on a conventional bicycle, at the cost of exposing themselves more or longer to the risks of a traffic crash. After controlling for this confounder, a statistical association in the expected direction becomes visible between increasing age and bicycle fatality risk, pointing towards the importance of age and exposure for explaining the fatality risk of electric bicycles. Taking these factors into account may lead to more effective countermeasures, for example by focussing on factors that help prevent crashes for all cyclists, such as infrastructural measures.

5.3. Limitations

It is important to note that any study has its limitations, and the analyses showed and discussed in the current paper are no exception. We wrote this paper with the main intention of illustrating the potential consequences of choices made during data analysis and presentation and provide ‘best practice’ guidelines. This very goal, however, also required us to make choices with regard to presentation, inclusion of data, and performed analyses. For this reason, and also because of the limitations belonging to the presented data, these analyses were kept relatively simple and should therefore be interpreted with some caution. Furthermore, even though the applied criteria should lead to more reliable inferences about causality, absolute causality cannot be determined without some form of experimental control. For this reason, any inference about causality based on cross-sectional data will remain indicative (Elvik, 2011), but nevertheless should allow policy makers to make more nuanced choices about countermeasures and policy to reduce risks and traffic victims altogether.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Appendix

Appendix A. Operational criteria of causality for observational road safety evaluation studies (Source: Elvik, 2011)

Criterion of causality	Theoretical definition	Operational definition
1. Statistical association	There should be a statistical association between cause and effect	A statistically significant change in variables measuring safety associated with safety treatment
2. Strength of association	A strong association is more likely to be causal than a weak association	Treatment effect stated in terms of effect size compared to effect sizes for other variables present in the data
3. Consistency of association	A consistent association is more likely to be causal than an inconsistent association	The consistency in direction and size of effect attributed to safety treatment across subsets of the data or different model specifications, assessed by means of a consistency score
4. Clear causal direction	It should be clear which of two variables is the cause and which is the effect	The temporal order between variables; a priori considerations; reversal of effect when treatment is removed
5. Control for confounders	The association between cause and effect should exist when confounding variables are controlled for	The identification of potentially confounding variables; existence of an effect attributed to treatment after potentially confounding variables have been controlled for; completeness of the control for confounding variables
6. Causal mechanism	The mechanism generating an effect should be identified and measured	Changes in target risk factors influenced by a road safety treatment and changes in risk factors representing behavioural adaptation to the treatment
7. Theoretical explanation	A plausible theoretical explanation of the findings of a study should be given	Findings should not contradict well-established laws of physics or laws of human perception and information processing
8. Dose-response pattern	Treatments administered in large doses should have larger effects than treatments administered in small doses	Treatments that are intense or have large effects on target risk factors should be associated with larger changes in safety than less intense treatments or treatments with small effects on target risk factors
9. Specificity of effect	Effects of a cause operating only in a certain clearly defined group should only be found within that group	An effect of safety treatments targeted at clearly defined groups should only be found in those groups and not in other groups

Appendix B. Numbers of bicycle fatalities and car occupants fatalities in the Netherlands for the years 2018–2022.

Year	No. Bicycle Fatalities			No. Car Occupants Fatalities
	Conventional	Electric	Total	
2018	171 (75 %)	57 (25 %)	228	233

(*continued on next page*)

(*continued*)

Year	No. Bicycle Fatalities			No. Car Occupants Fatalities
	Conventional	Electric	Total	
2019	138 (68 %)	65 (32 %)	203	237
2020	155 (68 %)	74 (32 %)	229	195
2021	127 (61 %)	80 (39 %)	207	175
2022	192 (66 %)	99 (34 %)	291	225
Total	783 (68 %)	375 (32 %)	1158	1065

Source: Statistics Netherlands (2023a).

Appendix C. Numbers of fatalities, owners, distances travelled, and the corresponding risk values for conventional and electric bicycles

Year	Bicycle Type	Fatalities	Owners[1]	Distance Travelled[2]	Fatalities / Owners	Fatalities / Distance Travelled
2018	Conventional	171	11,0	14,56	15,5	11,7
	Electric	57	2,2	3,97	26,2	14,4
2019	Conventional	138	10,8	13,53	12,8	10,2
	Electric	65	2,4	4,24	27,1	15,3
2020	Conventional	155	10,6	10,88	14,6	14,2
	Electric	74	2,8	4,64	26,2	16,0
2021	Conventional	127	10,2	10,68	12,4	11,9
	Electric	80	3,1	5,38	25,5	14,9

1: In million persons.
2: In billion kilometres.
Sources: Statistics Netherlands (2023a); Statistics Netherlands/ODiN + k (2022).

Appendix D. Numbers and percentages of distance travelled split by age group for conventional and electric bicycles

		Distance Travelled[1] / Exposure per year							
		2018		2019		2020		2021	
Age	Bicycle Type	Distance[1]	%[2]	Distance[1]	%[2]	Distance[1]	%[2]	Distance[1]	%[2]
0 – 17 years	Conventional	3,69	96 %	3,44	93 %	2,64	91 %	2,77	89 %
	Electric	0,17	4 %	0,28	7 %	0,27	9 %	0,36	11 %
18 – 29 years	Conventional	2,53	94 %	2,49	93 %	1,94	88 %	1,80	85 %
	Electric	0,15	6 %	0,19	7 %	0,26	12 %	0,32	15 %
30 – 39 years	Conventional	1,65	89 %	1,53	84 %	1,22	80 %	1,15	72 %
	Electric	0,21	11 %	0,29	16 %	0,31	20 %	0,45	28 %
40 – 49 years	Conventional	2,00	86 %	1,76	83 %	1,50	80 %	1,36	76 %
	Electric	0,32	14 %	0,36	17 %	0,38	20 %	0,43	24 %
50 – 59 years	Conventional	1,98	72 %	1,87	68 %	1,54	66 %	1,53	61 %
	Electric	0,75	28 %	0,89	32 %	0,80	34 %	1,00	39 %
60 – 69 years	Conventional	1,75	60 %	1,47	56 %	1,25	48 %	1,22	47 %
	Electric	1,16	40 %	1,14	44 %	1,34	52 %	1,36	53 %
70 – 79 years	Conventional	0,83	45 %	0,84	49 %	0,66	39 %	0,71	37 %
	Electric	1,01	55 %	0,87	51 %	1,01	61 %	1,20	63 %
80+ years	Conventional	0,12	39 %	0,14	38 %	0,13	33 %	0,14	33 %
	Electric	0,19	61 %	0,22	62 %	0,27	67 %	0,27	67 %

1: In billion kilometres.
2: The percentage of the total amount of distance cycled (conventional + electric) for the corresponding year.
Sources: Statistics Netherlands (2023a); Statistics Netherlands/ODiN + k (2022).

Appendix E. Numbers of fatalities, distances travelled, and the corresponding risk values for conventional and electric bicycles, split by age group (2018 – 2021)

Age	Bicycle Type	Fatalities	Distance Travelled[1]	Fatalities / Distance Travelled
0 – 50 years	Conventional	139	33,48	4,2
	Electric	22	4,75	4,6
50 – 60 years	Conventional	71	6,92	10,3
	Electric	19	3,43	5,5
60 – 70 years	Conventional	91	5,69	16,0
	Electric	40	4,99	8,0
70 – 80 years	Conventional	153	3,03	50,4
	Electric	90	4,09	22,0
80+ years	Conventional	137	0,53	260,8
	Electric	105	0,95	110,0

1: In billion kilometres.
Sources: Statistics Netherlands (2023a); Statistics Netherlands/ODiN + k (2022).

Appendix F. Numbers of fatalities, distances travelled, and the corresponding risk values for different age group ranges, split by conventional or electric bicycles (2018 – 2021)

Bicycle Type	Age Range	Fatalities	Distance Travelled[1]	Fatalities / Distance Travelled
Conventional	0 – 50 years	139	33,48	4
	50+ years	452	16,17	28
Electric	0 – 50 years	22	4,75	5
	50+ years	254	13,47	19
Conventional	0 – 60 years	210	40,40	5
	60+ years	381	9,25	41
Electric	0 – 60 years	41	8,19	5
	60+ years	235	10,04	23
Conventional	0 – 70 years	301	46,09	7
	70+ years	290	3,56	81
Electric	0 – 70 years	81	13,18	6
	70+ years	195	5,05	39
Conventional	0 – 80 years	454	49,12	9
	80+ years	137	0,53	261
Electric	0 – 80 years	171	17,27	10
	80+ years	105	0,95	110

1: In billion kilometres.
Sources: Statistics Netherlands (2023a); Statistics Netherlands/ODiN + k (2022).

Appendix G. Numbers of fatalities, distances travelled, and the corresponding risk values for conventional and electric bicycles, split gender (2018 – 2021)

Year	Gender	Bicycle Type	Fatalities	Distance Travelled[1]	Fatalities / Distance Travelled
2021	Male	Conventional	91	6,11	14,9
		Electric	53	2,56	20,7
	Female	Conventional	36	4,57	7,9
		Electric	27	2,82	9,6
2020	Male	Conventional	118	6,19	19,0
		Electric	40	2,26	17,7
	Female	Conventional	37	4,68	7,9
		Electric	34	2,38	14,3
2019	Male	Conventional	90	7,58	11,9
		Electric	37	2,00	18,5
	Female	Conventional	48	5,95	8,1
		Electric	28	2,24	12,5
2018	Male	Conventional	122	7,93	15,4
		Electric	35	1,83	19,2
	Female	Conventional	49	6,64	7,4
		Electric	22	2,14	10,3

1: In billion kilometres.
Sources: Statistics Netherlands (2023a); Statistics Netherlands/ODiN + k (2022).

Appendix H. Numbers of fatalities, distances travelled, and the corresponding risk values for conventional and electric bicycles, split by age group and gender (2018 – 2021)

		Fatalities		Distance Travelled[1]		Fatalities / Distance Travelled	
Age	Bicycle Type	Male	Female	Male	Female	Male	Female
0 – 50 years	Conventional	88	51	17,0	13,8	5,2	3,7
	Electric	14	8	2,5	2,9	5,5	2,7
50 – 60 years	Conventional	54	17	3,9	3,0	13,9	5,6
	Electric	9	10	1,3	2,1	6,7	4,8
60 – 70 years	Conventional	70	21	3,4	2,3	20,4	9,3
	Electric	21	19	2,4	2,6	8,9	7,2
70 – 80 years	Conventional	108	45	1,9	1,1	56,9	39,6
	Electric	50	40	2,1	1,9	23,3	20,5
80+ years	Conventional	101	36	0,3	0,2	299,3	191,7
	Electric	71	34	0,6	0,4	117,9	96,5

1: In billion kilometres.
Sources: Statistics Netherlands (2023a); Statistics Netherlands/ODiN + k (2022).

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