# E-bikers’ braking behavior: Results from a naturalistic cycling study

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**ABSTRACT**

**Objective**: The number of e-bike users has increased significantly over the past few years and with it the associated safety concerns. Because e-bikes are faster than conventional bicycles and more prone to be in conflict with road users, e-bikers may need to perform avoidance manoeuvres more frequently. Braking is the most common avoidance manoeuvre, but is also a complex and critical task in emergency situations, since cyclists must reduce speed quickly without losing balance. The aim of this study is to understand the braking strategies of e-bikers in real-world traffic environments and to assess their road safety implications. This paper investigates 1) how cyclists on e-bikes use front and rear brakes during routine cycling, and 2) whether this behaviour changes during unexpected conflicts with other road users.
**Methods**: Naturalistic data were collected from six regular bicycle riders who each rode e-bikes during a period of two weeks, for a total of 32.5 hours of data. Braking events were identified and characterized through a combined analysis of brake pressure at each wheel, velocity, and longitudinal acceleration. Furthermore, the braking patterns obtained during unexpected events were compared with braking patterns during routine cycling.
**Results**: In the majority of braking events during routine cycling, cyclists used only one brake at a time, favouring one of the two brakes according to a personal pre-established pattern. However, the favoured brake varied among cyclists: 66% favoured the rear brake and 16% the front brake. Only 16% of the cyclists showed no clear preference, variously using rear brake, front brake, or combined braking (both brakes at the same time), suggesting that the selection of which brake to use depended on the characteristics of the specific scenario experienced by the cyclist rather than on a personal preference. In unexpected conflicts, generally requiring a larger deceleration, combined braking became more prevalent for most of the cyclists; still, when combined braking was not applied, cyclists continued to use the favoured brake of routine cycling. Kinematic analysis revealed that, when larger decelerations were required, cyclists more frequently used combined braking instead of single braking.
**Conclusions**: The results provide new insights into the behaviour of cyclists on e-bikes and may provide support in the development of safety measures including guidelines and best practices for the optimal brake use. The results may also inform the design of braking systems intended to reduce the complexity of the braking operation.

**Keywords**: electric bicycle, pedelec, braking performance, cycling safety, naturalistic data, traffic conflict, rider behaviour.

## INTRODUCTION

The number of users of e-bikes has grown rapidly in the past few years in Europe, the United States and China (CONEBI 2017; Fishman and Cherry 2016). E-bikes, also known as pedelecs, are bicycles with pedal assistance via an auxiliary electric motor. In larger cities, e-bikes represent a space-saving and energy efficient alternative to cars. Furthermore, e-biking has been shown to be beneficial for physical fitness in middle-aged adults (de Geus et al. 2013). As a result, e-bike use is supported by some governments through national incentive schemes (European Cyclists' Federation 2016). If the growth in the e-bike segment continues, e-bikes may become a mode of active transportation with a significant impact in the road traffic. E-bikes allow higher speeds than conventional pedal bicycles, facilitate longer commuting distances, and require less physical effort. This makes e-bikes more suited for sharing infrastructure with motorized vehicles and more accessible to a greater range of user profiles (including elderly riders) than conventional bicycles. Consequently, e-bikers may be exposed to more complex traffic situations (Reynolds et al. 2009) and may be more susceptible to the reduced perceptual capacity and stability coming with ageing (Boele-Vos et al. 2017; Kovácsová et al. 2016). The operational speed increase seen in e-biking (Huertas-Leyva et al. 2018; Schleinitz et al. 2015) may also have severe implications for road safety (Dozza 2013) due to the difficulty other road users have in perceiving the actual speed of e-bikes (Petzoldt et al. 2017), and because of the rise in traffic conflicts with other road users (Huertas-Leyva et al. 2018). Consequently, cyclists on e-bikes need to perform avoidance manoeuvres more frequently than those riding conventional pedal bicycles (Dozza and Bianchi Piccinini 2014).

Although braking is the most commonly used avoidance manoeuvre (Johnson et al. 2010), it is a complex task in emergency situations, since the cyclist must reduce speed quickly while maintaining stability despite the narrow contact patch of the tires. On e-bikes, braking becomes even more important than on conventional bicycles. In fact, braking at a higher operational speed requires a higher deceleration than braking at a lower operational speed to achieve the same stopping distance. Poor braking performance, due to weak application of the brakes or single rear braking, may be insufficient to avoid a collision, while over-braking due to panic (e.g. applying front brake too hard) frequently leads to pitching over the handlebar (Swedish Transport Administration 2014) or to wheel lock-up with the bicycle sliding and the rider falling. Despite the importance of braking for cycling safety and the popularity of e-bikes, very few authors have studied braking behaviour on bicycles: Parkin and Rotheram (2010) studied the influence of road gradient on braking deceleration, Lie and Sung (2010) investigated the relationship between brake force distribution and maximum deceleration, while Beck (2009) and Wilson (2004) demonstrated the stopping superiority of the front brake over the rear brake. Other studies have investigated braking assistance systems such as haptic-based braking assistance for road bicycles (Corno et al. 2017), and an anti-lock braking prototype for bicycles (Enisz et al. 2014; Maier et al. 2016). Related research for powered two-wheelers, which share similar stability constraints as single-track vehicles, studied riding dynamics and stability during braking manoeuvres (Cossalter et al. 2004) and braking patterns with naturalistic data (Baldanzini et al. 2016). The lack of studies regarding cyclist braking behaviour indicates the need for research in real traffic conditions in order to gain full understanding of the actual performance of the e-bikers during evasive manoeuvres. This knowledge would help to define interventions to increase the safety of e-bikers and understand the different safety implications for e-cycling versus conventional cycling.

The aim of this study is to understand the braking strategies of e-bikers in real-world traffic and to assess their road safety implications. This paper analyses cyclists' behaviour using naturalistic data to investigate 1) how cyclists on e-bikes use front and rear brakes during routine cycling and 2) whether this behaviour changes during unexpected conflicts with other road users. Furthermore, the study investigates the kinematics of e-bikes during braking, to understand the extent to which deceleration and velocity depend on the different uses of the brakes and the braking conditions (i.e. planned/proactive vs unexpected/reactive).

## METHOD

### Naturalistic Cycling Data

This study used a subset of the naturalistic data collected using e-bikes in Gothenburg during the E-bikeSAFE project (Dozza et al. 2016). Data consisted of recordings of the cycling activities on e-bikes of six regular bicycle riders (Table 1) during a period of two weeks each, for a total of 32.5 hours. Data was collected between August and November 2013 using three instrumented e-bikes of the same model.

### Bicycle Instrumentation

The e-bikes were equipped with front and rear rim brakes actuated by two hand levers located on the right and left sides of the handlebar, respectively. Each e-bike was equipped with two Flexiforce resistive force sensors on the brake pads (one per wheel), a GPS, two inertial measurement units (on the frame and handlebar) and one forward-facing video camera (Figure 1). E-bike equipment consisted of a motor (250 W) to support pedaling when speed not exceeding 25 km/h, a control unit, two brake switches, a throttle (active up to 6 km/h in accordance with European regulations), and a battery. Data was collected at 100 Hz, except for the GPS (10 Hz) and camera (30 fps).

### Braking Usage

**Identification of braking events**: Braking events were identified through combined analysis of brake pressure (front and rear wheel), velocity and longitudinal acceleration. The beginning of each braking event was defined as the time at which the e-bikers activated at least one of the two brakes for a minimum duration of 0.4 s. Braking ended when the cyclist released the brake(s) or when the longitudinal acceleration became positive again. The braking events excluded the phase after braking when the rider could perform a swerve manoeuvre without braking. When two successive braking events were detected in a time interval less than 1.5 s, the events were merged and considered as one. Events in which the e-bike had an initial velocity lower than 7 km/h were considered not relevant and were excluded. Through this identification process, 1566 braking events from the six riders were selected. The smallest and largest sets of individual rider's data consisted of 172 and 335 braking events, respectively. Figure 2 shows an example of the data collected during braking events.

**Characterization of braking events**: To extract the relevant information on rider braking behaviour, braking events were characterized according to the rider's use of the rear and front brakes plus two parameters related to the braking distance: velocity prior to brake activation ($Velocity_{INI}$) and *Deceleration* (Table 2). As is typical with naturalistic data, not all events were captured with a complete data set. Data selected that passed our quality check corresponds to 81% of the events from a first selection.

Braking events were further classified as *unexpected* when the manoeuvre was a reaction to avoid a conflict, in contrast to a planned braking to pro-actively regulate speed during routine cycling. A comprehensive description of the definition of the selected subsample of unexpected events (51 cases) by video analysis can be found in Huertas-Leyva et al. (2018). The remainder of the identified braking events (1515 cases) were considered as braking events during *routine* cycling. Each of the unexpected braking events was further coded as to *threat type*.

### Statistical Analyses

The braking behaviour of riders was characterized qualitatively to determine the frequencies of the three different types of braking in both *routine* and *unexpected* braking events. Odds ratio (OR) test with 95% confidence intervals (CI) was used to determine the effect of the type of braking scenario (*routine*/*unexpected*) on the use of both brakes at once (combined braking), and to determine the effect of the *threat type* on the selection of combined braking in contrast to single braking (only rear and only front brake merged) during unexpected braking events. The effect was considered significant when 1.0 fell outside the 95% CI.

To account for possible differences in *Deceleration* and $Velocity_{INI}$ between the type of brake action ($Type_{braking}$) selected by the e-bikers, ANOVAs were performed with $Type_{braking}$ as a fixed factor with test for interaction between $Type_{braking}$ and *Subject*. Taking into account that the number of samples was not balanced across riders, linear mixed models were also defined, treating *Subject* as a random effect. To meet the requirements for normality and homogeneity of variance for ANOVA, a square root transformation was applied to *Deceleration* before the test. Significance levels for all tests was set to $\alpha = 0.05$.

## RESULTS

### Analysis of Braking Usage

The distribution of the type of braking action (routine vs. unexpected), by rider, is showed in Table 3, where participants are grouped by their pre-established braking pattern (*Rear/Front/Mix*) and sorted according to the prevalence of the favoured brake in routine cycling (from higher to lower). In most braking events during routine cycling, e-bikers used one brake at a time, and typically favoured one of the two brakes according to a personal pre-established pattern; cyclists exhibited braking strategies with discrepancies in the favoured brake among them, though (4/6 favoured rear brake and 1/6 front brake). Only one e-biker (1/6) variously used rear brake, front brake, or combined braking without a pre-established brake preference (*Mix* in Table 3), suggesting a predominant selection of the brake usage based on the characteristics of the specific scenario rather than personal preference. Within the subset of unexpected braking events, the general pattern changed. The odds ratio analysis revealed that, overall, during an unexpected braking event, the probability of performing combined braking increased, with an OR [95% CI] of 7.98 [3.10, 20.47]. With braking cases and riders pooled, the average prevalence of combined braking use per e-biker was 11.7% for routine braking and 43.5% for the subsample of unexpected braking events. From this subsample, two of six riders still used single braking as their most prevalent braking strategy, selecting the same brake as that preferred for routine braking events (rear brake for both participants).

The *threat types* identified in the unexpected braking events were heterogeneous for each rider sample. Overall, car, pedestrians and cyclists represented approximately 90% of all the threats in the sample of unexpected braking events. No effect of the *threat type* on the selection of the combined braking was found in the OR [95% CI]: cars 2.76 [0.79-9.61]; pedestrian 2.33 [0.52-10.40]; cyclists 0.29 [0.06-1.39]. The sample containing the remaining threat categories was insufficient for statistical analysis.

**Kinematics of Braking Events**

**Routine cycling (planned):** Analysis of the routine braking events (Table 4) revealed that, on average, when e-bikers used combined braking instead of single braking, e-bikers performed higher decelerations (1.84 $m/s^2$; $p<0.001$) and were circulating faster (22.7km/h; $p=.003$). No differences were found between front versus rear single brake use ($p = 0.162$) with average deceleration in both cases under 1 $m/s^2$. The analysis of variance found a significant interaction between $Type_{braking}$ and *Subject* for dependent variables *Deceleration* ($p = 0.025$) and $Velocity_{INI}$ ($p < 0.001$). Results from the linear mixed model to counteract the unbalanced design were dismissed since no significance in slope or intercept of the random variable subject was found. Additionally, Figures A1 to A4, from online supplement, show the cumulative frequency distribution curves and frequency of braking usage for different levels of *Deceleration* and $Velocity_{INI}$ for the three types of braking.

**Unexpected scenarios:** The braking deceleration in unexpected braking events differed from routine cycling braking events. As predicted, since unexpected conflicts typically require reducing speed in a restricted time, the deceleration increased in unexpected compared to routine cycling for all three types of braking strategy (front only, rear only or combined). However, as in routine braking, the mean *Deceleration* using either brake alone during unexpected braking events was significantly lower than for combined braking ($p < 0.001$; Table 4). Initial velocity proved not to be a determinant of braking strategy during unexpected braking ($p = 0.258$). The analysis of variance showed an interaction between $Type_{braking}$ and *Subject* for dependent variables *Deceleration* ($p = 0.006$) and not for $Velocity_{INI}$ ($p = 0.596$).

## DISCUSSION

The aim of this study was to investigate the braking strategies used by riders on e-bikes to better understand the related safety implications of this new mode of transportation. Using naturalistic data, we analysed the braking strategies during *routine* cycling (pro-active braking) and during *unexpected* conflicts with other road users (re-active braking) to unveil potential different patterns. Different braking strategies were identified in terms of the patterns of front and rear brake application and the related kinematics. The results provide valuable information on the braking behaviour of e-bikers in real world traffic environments which may support cycling safety actions.

We found that in most of the braking events during *routine* cycling, e-bikers used only one brake at a time (single braking), and that most of the riders (5 of 6) consistently favoured one of the two brakes as a pre-established personal pattern. The favoured brake was most often the rear (4 of 6). From analysis of the kinematics of the types of braking usage in *routine* cycling, it was found that when combined braking was applied, instead of single braking, e-bikers achieved decelerations that, on average, were approximately double those of single brake use. Analysis of frequency of braking patterns showed a significantly higher incidence of combined brake use for *unexpected* events compared to *routine* cycling events. This finding is coherent with the fact that emergency manoeuvres require high decelerations within a short time period. However, in many cases the e-bikers persisted in using their single preferred brake as in *routine* cycling; despite achieving lower decelerations than with combined braking (averages below 1.60 $m/s^2$ for both front and rear single braking vs. 2.40 $m/s^2$ with combined braking). This may represent an important finding in the understanding of the braking behaviour during unexpected braking events and the influence of the braking habits established during *routine* cycling on the effectiveness of emergency manoeuvres.

The deceleration values reported here are consistent with those from the previous controlled experiment of Taylor (1993) which measured deceleration at the onset of a yellow traffic light (average 2.29 $m/s^2$; 15th-percentile 1.28 $m/s^2$). Our deceleration values for both *unexpected* and *routine* braking events are in the same range as those from the Dutch design manual for cycle traffic (CROW 2006), which associates a deceleration of 1.5 $m/s^2$ with comfortable braking and 2.6 $m/s^2$ with emergency stop. However, the deceleration values found here were far from the maximum deceleration defined by the pitch-over threshold (Beck 2009; Wilson 2004), ranging from 5.4 to 7.0 $m/s^2$. The brake decelerations we observed during *unexpected* braking suggest that the predominance of single brake use (usually the rear) represents a common deficiency amongst riders in terms of braking effectiveness in emergency scenarios. Previous studies demonstrated the risk of loss of stability through lateral sliding of the rear wheel during hard braking using the rear alone (Klug et al. 2017), and the advantages of combined braking together with the higher braking capability of the front brake over the rear brake (Beck 2009; Wilson 2004). Optimum braking is generally achieved by applying enough force to both rear and front brakes to reduce speed quickly, while avoiding the common tendency in a stressful situation of locking up the front wheel or risking pitch-over from over-braking the front wheel (Klug et al. 2017; Maier, Pfeiffer, Scharpf et al. 2016). The complexity of the braking manoeuvre in single track vehicles is due to the variations in load distribution between front and rear wheels during the braking process, which means that the optimum distribution of braking force front-rear also varies throughout this interval (Cossalter et al. 2004). In addition, differences in road surface characteristics (e.g. dry asphalt vs. wet, smooth vs. cobblestoned) modify braking capabilities and thus, the braking force distribution required for an optimum manoeuvre. All this makes hard to riders to have an accurate picture of the more suitable way of braking. In fact, our results indicated that cyclists do not universally adopt one generic pattern linked to the proper way of braking.

The reasons for the high frequency of single brake use during unexpected events cannot be clearly determined from the data. Based on the findings, the following three hypotheses may guide future investigations to understand the rationale of emergency braking behaviours and develop measures to promote more effective, and thus safer braking habits:

1) preference for single brake use is linked to a conscious decision, based on a personal evaluation of the unexpected event as low risk;

2) single brake use is an automatic response when lack of time disallows overcoming a pre-established pattern to consciously perform combined braking;

3) single brake use stems from a lack of confidence in performing a hard deceleration due to the fear of loss of control/stability.

The suggested further work requires to investigate with interviews the motivations of e-bikers for the use of their predominant braking pattern (e.g. stability concerns, braking effectiveness, awareness of front wheel lock danger, previous experience with bicycles) and to confirm a positive relationship between routine braking and emergency braking patterns (e.g. measuring time to collision and identifying the cases with the highest risk level). The results of this study improve understanding of the braking behaviours and capabilities of riders on e-bikes. In light of these results, we highlight the need for interventions aimed to ensure safe use of e-bikes. Specifically, our results suggest that combined braking use should be encouraged for e-bikers as a preventive measure to become an automatic anticipatory response in unexpected events that may turn into critical. Another strategy which minimizes perception-response time, thus providing more time to stop, is the use of the 'covered position' (maintaining one or more fingers on a brake lever) whenever circulating in dense traffic, as is suggested also for motorcyclists (Thom et al. 1985).

In addition to the provision of braking strategy guidelines and training for e-bikers, design and development of safety assistance systems for e-bikes may promote improved confidence and performance in e-bikers when braking. A key issue in design for optimizing the braking parameters of a bicycle is the location of the center of mass of the frame (Lie and Sung 2010). The US Consumer Product Safety Commission (part 1512.5), requires that manufacturers of conventional bicycles supply hand brakes with a braking effectiveness of approximately 4.9 $m/s^2$. Brakes with similar capabilities are required by the European standard for electric bicycles EN 15194:2017 (4.25 $m/s^2$ for mountain bike using front brake only). These deceleration values are not far from the pitch-over threshold found in literature. Consequently, there is a low margin for possible improvement in the performance of braking systems. A pitch-over sequence is primarily dependent on the interaction between center of mass location of the bicycle-rider unit and deceleration rate (Moorhead 2015). The bicycle-rider unit has a high center of gravity in relation to its wheelbase (Taylor 1993), the lower and more rearward the bicycle-rider center of mass, the higher the decelerations that may be achieved before the rider is thrown over the handlebars during braking. Since e-bikes are heavier than conventional bicycles (because of battery, motor and sensors), the deceleration threshold could be increased with a design that places the battery and the motor in a position that is lower and more rearward (Niska and Wenäll 2018). As another approach, design of embedded systems to maximize stopping capacity based on longitudinal wheel slip or loading would be more easily implemented on an e-bike than on a conventional bike. Adoption of an anti-lock braking system to avoid locking the wheels and pitch-over, as proposed by Enisz et al. (2014) and Maier et al. (2016) in their prototypes, or implementation of systems like integrated braking systems, to automatically redistribute the brake force between the front and rear wheels, may offer effective solutions for decreasing stopping distance without compromising stability.

Some limitations of this study should also be considered. The data used was from a relatively small sample of commuters of whom most had no previous experience riding e-bikes. Thus, the possible influences of age, gender or experience riding e-bikes could not be assessed. The naturalistic study was conducted in a Swedish city and any possible correlations between the results and the particular infrastructure, weather conditions or cultural context or habits (e.g. high presence of coaster brakes in children's bicycles) were not accounted for. For unexpected braking events, a larger sample would be required to assess the effect of demographics or type of scenario on the braking strategies. We suggest further studies using larger samples of riders including cyclists with different motivations, different types of e-bike, different brake technology (e.g. disc brakes) and different cultural infrastructural contexts to improve understanding of emergency braking behaviour on e-bikes.

**ACKNOWLEDGMENTS**

This work was partially supported by the 7th Framework Program of the European Commission within the Marie Curie Innovative Training Network (MOTOrcycle Rider Integrated SafeTy, grant agreement n. 608092) and Trafikverket (Skyltfonden – BikeModel). Vinnova and Trafikverket sponsored the collection of the naturalistic data used in this study. This study was performed at SAFER, the Vehicle and Traffic Safety Center at Chalmers.

**REFERENCES**

Baldanzini, N., Huertas-Leyva, P., Savino, G., & Pierini, M. (2016). Rider Behavioral Patterns in Braking Manoeuvres. Transportation Research Procedia, 14, 4374–4383. doi.org/10.1016/j.trpro.2016.05.359

Beck, R. F. (2009). Mountain bicycle acceleration and braking factors. Accident Reconstruction Journal, 19(4), 49–56.

Boele-Vos, M. J., Commandeur, J. J. F., & Twisk, D. A. M. (2017). Effect of physical effort on mental workload of cyclists in real traffic in relation to age and use of pedelecs. Accident Analysis and Prevention, 105, 84–94. doi.org/10.1016/j.aap.2016.11.025

Confederation of the European, & Bicycle Industry (CONEBI). (2017). European Bicycle Market 2017 Edition—Industry & Market Profile (2016 Statistics). Brussels. Retrieved from https://www.raivereniging.nl/ecm/?id=workspace://SpacesStore/072e2902-93de-4eb5-99dd-25227982fcaa

Corno, M., D'Avico, L., Panzani, G., & Savaresi, S. M. (2017). A haptic-based, safety-oriented, braking assistance system for road bicycles. IEEE Intelligent Vehicles Symposium, Proceedings, (Iv), 1189–1194. doi.org/10.1109/IVS.2017.7995874

Cossalter, V., Lot, R., & Maggio, F. (2004). On the braking behavior of motorcycles. SAE Paper 2004-32, 18(1). doi.org/10.4271/2004-32-0018

CROW. (2006). Design manual for cycle traffic. The Netherlands.

Dozza, M. (2013). What is the Relation between Bicycle Dynamics and Safety in the Real World ? In Proceeding of the Bicycle and Motorcycle Dynamics Conference, Nov 10-13, Narashino, Japan.

Dozza M., Bianchi Piccinini, G. F., (2014). "Do cyclists on e-bikes behave differently than cyclists on traditional bi-cycles?". In Proceedings of the 3rd International Cycling Safety Conference, Gothenburg, Sweden. Nov. 18-19.

Dozza, M., Bianchi Piccinini, G. F., & Werneke, J. (2016). Using naturalistic data to assess e-cyclist behavior. Transportation Research Part F: Traffic Psychology and Behaviour, 41, 217–226. doi.org/10.1016/j.trf.2015.04.003

Enisz, K., Szalay, I., Nagy, K., Kohlrusz, G., Fodor, D., & Jakab, R. (2014). Development of a bicycle anti-lock braking system prototype. International Journal of Automotive Engineering and Technologies, 3(3), 111–118. doi.org/10.18245/ijaet.38209

European Cyclists' Federation. (2016). Electromobility for all. Financial incentives for e-cycling. Brussels.

Fishman, E., & Cherry, C. (2016). E-bikes in the Mainstream: Reviewing a Decade of Research. Transport Reviews, 36(1), 72–91. doi.org/10.1080/01441647.2015.1069907

de Geus, B., Kempenaers, F., Lataire, P., & Meeusen, R. (2013). Influence of electrically assisted cycling on physiological parameters in untrained subjects. European Journal of Sport Science, 13(3), 290–294. doi.org/10.1080/17461391.2011.606845

Huertas-Leyva, P., Dozza, M., & Baldanzini, N. (2018). Investigating cycling kinematics and braking maneuvers in the real world: e-bikes make cyclists move faster, brake harder, and experience new conflicts. Transportation Research Part F: Traffic Psychology and Behaviour, 54, 211–222. doi.org/10.1016/j.trf.2018.02.008

Johnson, M., Charlton, J., Oxley, J., and Newstead, S. 2010. “Naturalistic Cycling Study: Identifying Risk Factors for on-Road Commuter Cyclists.” Annals of advances in automotive medicine / Annual Scientific Conference. Association for the Advancement of Automotive Medicine. Scientific Conference 54: 275–83.

Klug, S., Moia, A., Verhagen, A., Görges, D., & Savaresi, S. M. (2017). Effectiveness of Actuating on Rectilinear Bicycle Braking Dynamics. IFAC-PapersOnLine, 50(1), 972–979. doi.org/10.1016/j.ifacol.2017.08.173

Kovácsová, N., de Winter, J. C. F., Schwab, A. L., Christoph, M., Twisk, D. A. M., & Hagenzieker, M. P. (2016). Riding performance on a conventional bicycle and a pedelec in low speed exercises: Objective and subjective evaluation of middle-aged and older persons. Transportation Research Part F: Traffic Psychology and Behaviour, 42(October), 28–43. doi.org/10.1016/j.trf.2016.06.018

Lie, D., & Sung, C. K. (2010). Synchronous brake analysis for a bicycle. Mechanism and Machine Theory, 45(4), 543–554. doi.org/10.1016/j.mechmachtheory.2009.11.006

Maier, O., Pfeiffer, M., Scharpf, S., & Wrede, J. (2016). Conditions for nose-over and front wheel lockup of electric bicycles. In MECATRONICS 2016 / 17th International Conference on Research and Education in Mechatronics, REM 2016 (pp. 219–224). doi.org/10.1109/MECATRONICS.2016.7547145

Maier, O., Pfeiffer, M., & Wrede, J. (2016). Development of a Braking Dynamics Assistance System for Electric Bicycles: Design, Implementation, and Evaluation of Road Tests. IEEE/ASME Transactions on Mechatronics, 21(3), 1671–1679. doi.org/10.1109/TMECH.2015.2505186

Moorhead, A. (2015). The effect of bicycle geometry, rider posture and rider anthropometrics on pitch-over dynamics.

Niska, A, and Wenäll, J. 2018. “Simulated Single-Bicycle Crashes in the VTI Crash Safety Laboratory.” In Proceedings, 7th International Cycling Safety Conference, ICSC2018, Barcelona, Spain.

Parkin, J., & Rotheram, J. (2010). Design speeds and acceleration characteristics of bicycle traffic for use in planning, design and appraisal. Transport Policy, 17(5), 335–341. doi.org/10.1016/j.tranpol.2010.03.001

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

Reynolds, C. C. O., Harris, M. A., Teschke, K., Cripton, P. A., & Winters, M. (2009). The impact of transportation infrastructure on bicycling injuries and crashes: A review of the literature. Environmental Health: A Global Access Science Source, 8(1). doi.org/10.1186/1476-069X-8-47

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

Swedish Transport Administration (STA). (2014). Safer cycling – a common strategy for the period 2014-2020.

Taylor, D. (1993). Analysis of Traffic Signal Clearance Interval Requirements for Bicycle-Automobile Mixed Traffic. Transportation Research Record: Journal of the Transportation Research Board, (1405), 13–20.

Thom, D. R., Arao, H. G., & Hancock, P. A. (1985). Hand Position and Motorcycle Front Brake Response Time. In SAGE (Ed.), Proceedings of the Human Factors Society - 29th Annual Meeting. Los Angeles: SAGE Publications (pp. 278–281). Los Angeles, CA: SAGE Publications.

Wilson, D. G. (2004). Bicycling Science. Third edition (Mit Press).

## TABLES

**Table 1.** Demographics of the Participants

| ID | Age | Gender |
|---|---|---|
| ID1 | 50 | Female |
| ID2 | 50 | Female |
| ID3 | 45 | Female |
| ID4 | 28 | Female |
| ID5 | 35 | Male |
| ID6 | 45 | Male |

**Table 2. Description of parameters used to characterize the braking event**

| Parameter | Description |
|---|---|
| $Type_{braking}$ | Type of braking action: single front braking; single rear braking; combined braking (using both brakes) |
| $Velocity_{INI}$ | Initial velocity prior to braking manoeuvre (km/h) |
| *Deceleration* | Average deceleration during the braking event (m/s²) |
| *Threat type* * | Type of conflict coded by threat type: car; cyclist; heavy vehicle; pedestrian; motorcycle/moped; animal; other |

*variable coded only for *unexpected* braking events

**Table 3. Distribution of use of braking for routine and unexpected scenarios with e-bike (6 subjects). Cells in grey represent the most prevalent type of braking per rider.**

| | Rear Favoured | | | | | | | | Front Favoured | | Mix | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | ID3 | | ID6 | | ID4 | | ID2 | | ID1 | | ID5 | |
| $Type_{Braking}$ | *routine* | *unexp.* | *routine* | *unexp.* | *routine* | *unexp.* | *routine* | *unexp.* | *routine* | *unexp.* | *routine* | *unexp.* |
| Front only | 4% | 15% | 16% | 0% | 18% | 0% | 36% | 25% | *87% | 40% | 31% | 8% |
| Rear only | *90% | 31% | *76% | *100% | *74% | *50% | *50% | *50% | 7% | 20% | 42% | 0% |
| Combined | 5.0% | *54% | 8% | 0% | 8% | *50% | 14% | 25% | 6% | 40% | 27% | *92% |
| Total (N) | 322 | 13 | 302 | 3 | 243 | 8 | 211 | 4 | 278 | 10 | 159 | 13 |

** most prevalent type of braking action (≥ 50%)*

**Table 4.** Kinematics of e-bike for braking events in routine and unexpected scenarios for six e-bikers.

| | ***Deceleration*** **(m/s²) Mean ± sd** | | $Velocity_{INI}$ **(km/h) Mean ± sd** | |
|---|---|---|---|---|
| $Type_{braking}$ | **Routine cycling*** | **Unexpected scenarios*** | **Routine cycling*** | **Unexpected scenarios** |
| Front only | 0.96 ± 0.97 | 1.31 ± 0.70 | 18.9 ± 6.4 | 21.7 ± 6.8 |
| Rear only | 0.85 ± 0.78 | 1.56 ± 0.69 | 19.1 ± 6.4 | 18.7 ± 5.8 |
| Combined | 1.84 ± 1.50 | 2.40 ± 1.64 | 22.7 ± 6.2 | 21.9 ± 5.6 |

** p<.05*

## FIGURES

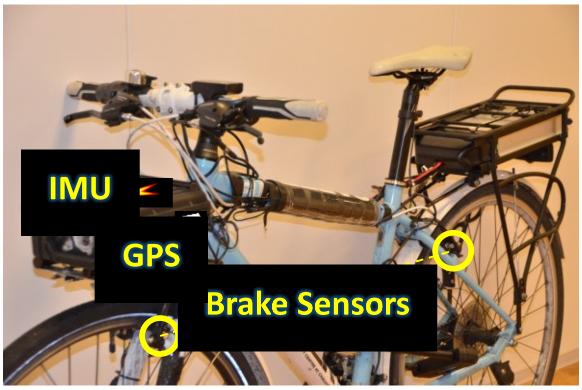


**Figure 1. E-bike instrumentation.**

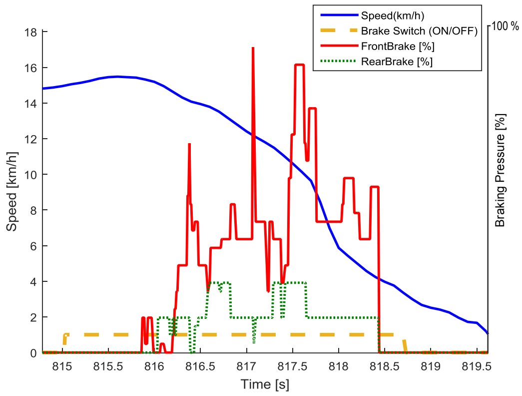


**Figure 2. Example of signals from sensors during a braking event (5 second window).**