Transportation Research Interdisciplinary Perspectives 20 (2023) 100831

Contents lists available at ScienceDirect

Transportation Research Interdisciplinary Perspectives

journal homepage: www.sciencedirect.com/journal/transportation-research-interdisciplinary-perspectives

Compliance to eco-riding recommendations on an E-scooter: Effects on energy consumption and user acceptance

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A R T I C L E I N F O

Keywords:
Electric powered two-wheeler
Human factors
Simulator
Eco-riding assistance
Eco-driving

A B S T R A C T

Eco-riding assistance systems on electrified powered two-wheelers aim at decreasing energy consumption. However, the efficiency of such systems depends on the riders' behavior. Therefore, the present paper evaluates an eco-riding assistance system giving recommendations for regenerative braking, coasting, and sailing regarding compliance, transfer effects, energy consumption, and acceptance.

$N = 31$ participants had to complete a test course including highway, rural roads, and urban riding in a purpose-built E-scooter simulator. A between-subjects study design with three groups was chosen to determine possible effects: (1) *Control condition* without any assistance; (2) *Basic condition* with recommendations triggered by vehicle- or map-based data; (3) *Comprehensive condition* with recommendations based on vehicle-, map-, and Vehicle-to-everything (V2X)-based data. Due to the multitude of sensors, the comprehensive condition received more recommendations than the basic condition. The riders of the basic and comprehensive condition received no recommendations on the last section of the test course to assess possible transfer effects.

Riders with assistance ride slower and sail more often than the control group. This is valid also for sections without riding recommendations. Overall, the riders with assistance have a lower energy consumption on sections with coasting recommendations (Basic condition: 18.2 % less energy consumption; Comprehensive condition: 12.8 %) and on sections without any eco-riding assistance (Basic condition: 9.5 %; Comprehensive condition: 8.2 %). The frequency of recommendations has no effect on the efficiency as the basic condition and the comprehensive condition show comparable riding behavior and do not differ regarding energy consumption. Finally, all the participants rate all three recommendation types as positive.

Altogether, the results endorse the benefit of eco-riding assistance for electrified powered two-wheelers concerning energy efficiency and provide indications for the design of such systems.

Introduction

Due to climate change the parties of the United Nations adopted the Paris Agreement (UNFCCC, 2015) which demands that global warming is limited to 1.5 degrees Celsius compared to pre-industrial levels. Therefore, the reduction of greenhouse gases is one of the most important challenges ahead. In 2018, the traffic and transportation sector accounted for 14.3 % of greenhouse gas emissions worldwide (Lamb et al., 2021). This number has been increasing over the last 30 years. In industrialized countries the contribution of the traffic and transportation sector is even higher, e.g., in Austria roughly 30 % (Umweltbundesamt, 2017) or in the USA 29 % (United States EPA, 2021). The majority of emissions caused by traffic and transportation stems from traffic on the road (Lamb et al., 2021). Therefore, the stakeholders in the mobility sector are looking for possibilities to reduce greenhouse gases in this domain.

As driving a vehicle with internal combustion engine (ICE) produces local emissions through burning fossil fuels, it is important to decrease

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https://doi.org/10.1016/j.trip.2023.100831
Received 21 October 2022; Received in revised form 10 March 2023; Accepted 29 April 2023
Available online 18 May 2023
2590-1982/

fuel consumption. Driver behavior is one crucial factor which affects fuel consumption substantially which was shown already in the 1970s (Evans, 1979). Speed is one of the most important factors for fuel consumption: For example, a naturalistic driving study showed that the driving velocity affects fuel consumption up to 30 % (LeBlanc et al., 2010). Dorrer (2004) estimates that efficient driving strategies could reduce fuel consumption by 26 % to 58 % depending on road type. Huang et al. (2021) compared novice drivers and experienced drivers when absolving a test route in Hong Kong. They demonstrated that the mean fuel consumption rate of novice drivers was slightly (2 %) higher than that of experienced drivers. The authors explain the better efficiency of experienced drivers with a different usage of the gas pedal. Barkenbus (2010) summarizes fuel-efficient driving behavior (so-called eco-driving) with the following aspects: moderate acceleration, early gear-shifting, anticipative driving, maintaining an even driving pace, driving at or below the speed limit, and eliminating excessive idling.

A strategy to assist eco-driving is the development of eco-driving support systems (Sanguinetti et al., 2020). These systems provide drivers with feedback on their driving behavior. Usually, the feedback is given via a visual display in the vehicle. Currently, a high variety of eco-driving support systems exist on the market: An overview by Sanguinetti et al. (2017) includes feedback specifically targeting accelerating, cruising, and/or decelerating, feedback reflecting fuel economy, and feedback comparing current with average efficiency. Several studies have proven the benefit of eco-driving support systems: According to a literature review by Kurani et al. (2015), the benefit ranges between no fuel savings to over 50 %. Additionally, several studies demonstrate the driver acceptance of eco-driving support systems (Radlmayr et al., 2015; Staubach et al., 2014; Vaezipour et al., 2018).

While vehicles with ICE burn fossil fuels, electric vehicles (EVs) use an electric motor for propulsion. Therefore, they can contribute to reduce greenhouse gas emissions if they replace internal combustion engines in traffic – especially when the electricity is produced from renewable energy sources (Mersky et al., 2016). Compared to vehicles with ICE, EVs have the special feature to regain energy – and by this to enlarge their range – via regenerative braking: The vehicle is decelerated and a portion of the kinetic energy is stored by a short-term storage system. The energy is held until it is required again to accelerate the vehicle (Clegg, 1996).

The penetration of EVs on the markets is in a sharp increase (IEA, 2021). In contrast, the development of electrified powered two-wheelers (E-PTWs) does not run according to the trends in car evolution. This is surprising as the options to save greenhouse gases and energy are enhanced with E-PTWs compared to electrified cars. Especially in situations with one occupant in a vehicle a powered two-wheeler is a more sustainable solution. Several observations show that the occupancy rate in Europe lies between 1.2 and 1.7 occupants per car on average (Adra et al., 2004). Regarding this, the occupancy rate depends on the purpose of the trip as especially commuting trips are low occupied. Several studies show that potential users have positive attitudes towards electrified powered two-wheelers (Habich-Sobiegalla et al., 2018; Jayasingh et al., 2021). According to an empirical study with $N = 404$ potential consumers in Spain, driving range, monetary incentives, and technical reliability are the most important predictors of purchase intention (Higueras-Castillo et al., 2021).

The EMotion project (Electric mobility in L-category vehicles for all generations; https://www.emotion-project.at) seeks to develop new lightweight electrical vehicles. The project aim is to close the gap between electric mopeds and motorcycles to enable possibilities for environmentally friendly and cost attractive commuting (Will et al., 2021). For this purpose, two scooter prototypes are developed in the project which are especially designed for younger and elderly generations and fit into the categories L1e-B (4 kW) and L3e-A1 (8 kW). The vehicles reach driving ranges of up to 100 km and should induce car drivers to switch to scooters for their daily commutes (see Fig. 1).

Comparable to vehicles with ICE, the driving efficiency of an EV depends on the driving behavior. The British Department of Transportation (2017) published tips for efficient driving of EVs: Among other tips, they recommend to drive foresighted, to reduce unnecessary acceleration and braking, to avoid harsh braking, to use regenerative braking, and to use an efficient speed range (i.e., not full speed). Similarly, Helmbrecht et al. (2013) sum up that the most successful strategies for efficient driving with EVs are avoiding unnecessary acceleration and unnecessary high final velocity, long decelerations with the vehicle's gained momentum without propulsion instead of braking, and slow and smooth accelerations. The authors demonstrate that experienced users of an EV can reduce energy consumption by more than 25 % through efficient driving behavior.

In order to enhance the scooter's efficiency, the EMotion scooters will be equipped with an innovative eco-riding support system which provides recommendations concerning the rider's behavior. Up to now, eco-riding support systems for E-PTWs are still unknown in literature and not available on the market. Therefore, eco-riding support system concepts from other EVs and vehicles with ICE, such as passenger cars and trucks, were considered and transferred to the E-PTWs.

The present study aims at answering the question (1) whether the riders use the recommendations at all in terms of changing their riding behavior according to the system suggestions. For this purpose, parameters for compliance with the recommendations are developed and analyzed. Furthermore, the study investigates (2) whether the riders can transfer the recommended behavior to comparable traffic situations without any system support. As recommendations would typically be based on sensor data, it is determined how much sensor input is necessary: (3) Is V2X technology essential or is a reduced setup based on on-board sensors and map-based data sufficient? A major aim of the study is the system's effect on energy consumption. Finally, it is assessed (4) how riders evaluate such an eco-riding support system and if they want this system in their own vehicle.

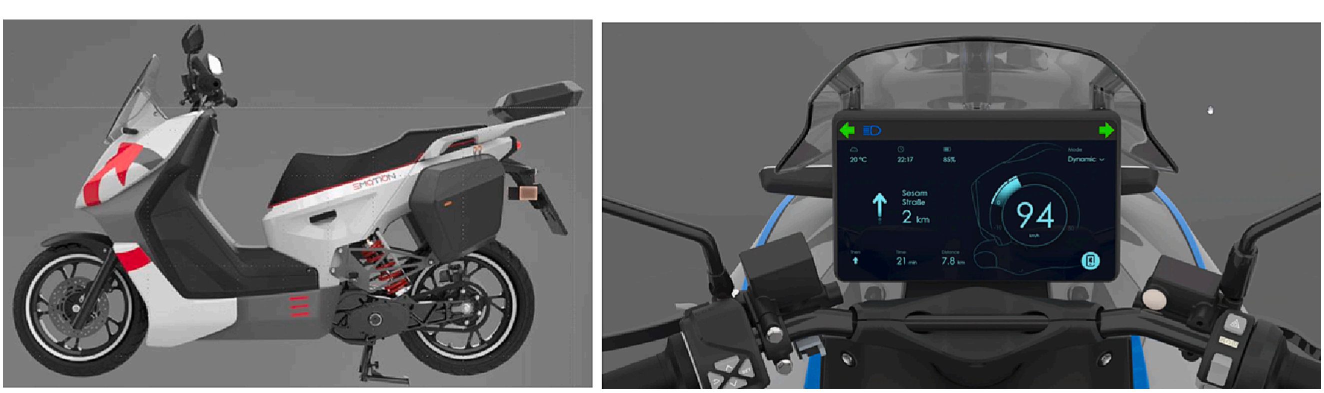

Fig. 1. Sketch of the 8 kW EMotion scooter prototype and its cockpit (© KTM Technologies GmbH, 2022).

As the scooters of the EMotion project are in technical development, the study is conducted using an electric scooter riding simulator. Besides availability, the riding simulator has the advantage that it allows to answer the research questions in a controlled and tailor-made setting. The simulator was purpose-built to match the geometry, ergonomics, and the expected riding behavior of the 8 kW EMotion electric scooter.

Methods

Eco-riding support system

The eco-riding support system presented three types of riding recommendations on the display:

- *Recuperate*: Via recuperation (also known as regenerative braking), the rider decelerates the scooter and energy is gained. The rider has to turn the throttle twist grip in riding direction to recuperate. Recuperation is displayed by a generic green flash icon (see Fig. 2 top left).
- *Sail*: Via sailing, the electric motor is decoupled and only road inclination, air drag, or roll resistance influence the velocity. The rider has to lose the throttle twist grip to the neutral position in order to sail. Sailing is displayed by a blue sailboat icon (see Fig. 2 top middle).
- *Coasting*: Via coasting, the vehicle is moving with constant speed avoiding energy inefficient maximum speed of the vehicle (here: recommendation between 87 km/h and 93 km/h instead of 100 km/h). On even surface, the rider has to maintain the throttle twist grip in a constant position. Coasting is displayed by a generic yellow equal-like icon (see Fig. 2 top right).

After the recommended behavior is shown, the icon fades and a circling boundary in the matching color pops up as feedback (see Fig. 2 lower row). The feedback is displayed as long as the rider shows the desired riding behavior.

The eco-riding support system considers various sources of information to determine the appropriate recommendation type. Two variants were implemented with different capabilities:

- The *Basic* variant considers on-board sensors (e.g., velocity) and map-based data (e.g., speed limits or stop signs).
- The *Comprehensive* variant considers information provided in the Basic variant plus vehicle-2-X based data (e.g., traffic light status or behavior of surrounding traffic).

As the comprehensive system considers more sources of information it is able to react on more situations and to emit a higher number of recommendations. There was no further difference between the two variants other than the number of recommendations shown. The state-of-charge (SOC) in percent battery capacity is continuously displayed in the instrument cluster, therefore allowing the participants to observe the SOC changes over time.

Simulator description

The study was conducted on the electric scooter riding simulator at WIVW (see Fig. 3) with the driving simulation software SILAB® version 7.0. The mockup represents the real scooter ergonomics in terms of handlebar, rider seat and foot rest position. All realistic controls, such as front and rear brake as well as throttle twist grip with regenerative braking capability (rotating in opposing direction as for acceleration) are implemented. The mockup is slightly passively rotatable along the longitudinal axis. This rider-induced roll angle gets measured and is used as input for the vehicle dynamics model in addition to the steering angle. The steering torque is provided as force-feedback with up to 30 Nm. Three 55-inch displays provide a 180 degrees horizontal field of view. Two 5.5-inch OLED displays simulate visual information in the mirrors. An 8-inch color LED touchscreen with a resolution of 800 × 480 pixels serves as dashboard. Sound is provided by a 5.1 surround sound system.

The electric drive train, engine map as well as energy consumption map and battery model data were implemented in the virtual vehicle to match the 8 kW electric scooter behavior as it is designed within the scope of the EMotion project. The scooter has a maximum speed of approx. 100 km/h.

Test course

The test course had a total length of 26 km and consisted of four main parts (see Fig. 4):

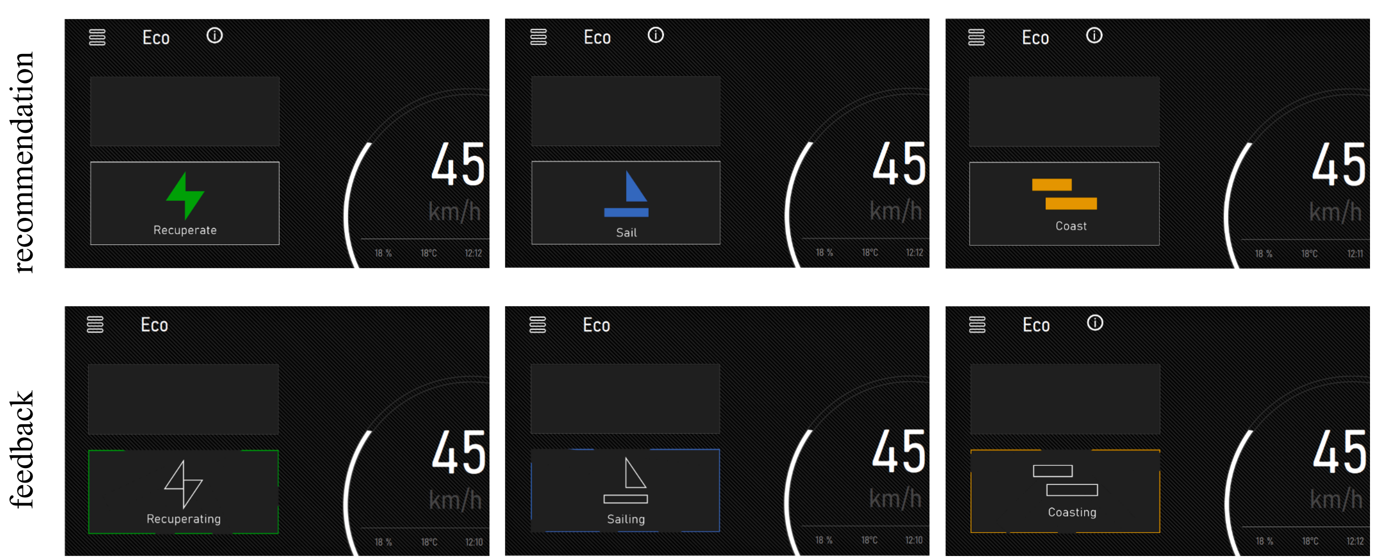

Fig. 2. Implemented icons for riding recommendations and according feedback if the recommended behavior is shown: recuperation (on the left), sailing (center), coasting (on the right).

Fig. 3. Electric scooter riding simulator at WIVW.

Fig. 4. Screenshots of highway section (on the left), rural road (center), and urban section (on the right).

1. Highway section (length 8 km) with coasting recommendations on 6.3 km and four deceleration situations due to congestion and speed limits.
2. Rural road (length 10 km) with six deceleration situations due to red traffic lights, slow traffic ahead and speed limits.
3. Urban section (length 6 km) with 13 deceleration situations due to red traffic lights, a narrow zone, surrounding traffic, stop signs and speed limits.
4. Rural road (length 2 km) with two deceleration situations due to speed limits.

The experimental groups experienced the coasting recommendation on the highway section in the same way. However, the number of sailing and regenerative braking recommendations differed: While the riders of the basic condition received 10 recommendations, the comprehensive group participants got 23 recommendations. At the end of the test course a short rural road section without any recommendations was implemented to investigate transfer effects of the coasting recommendation.

Measured variables

The simulation software SILAB® records all rider input parameters (e.g., throttle twist grip position, brake lever positions) and data of the simulated vehicle (e.g., velocity, longitudinal acceleration) with a frequency of 60 Hz. Subjective data were mainly gathered in the final inquiry after the simulator ride. For the two experimental groups, it contained different questions on the overall rating of the eco-riding support system, on its acceptance, the human–machine interface, and the interaction with the system. Furthermore, the participants ranked their experienced usefulness of the three riding recommendations recuperate, sail, and coast. Answers to the different statements on the eco-riding support system were given on a 7-point Likert scale ranging from 1 = “does not apply at all” to 7 = “fully applies“.

Procedure

The participants were welcomed and filled out the informed consent with all relevant information about the study as well as the data privacy statement in the beginning. After that, two short rides to re-familiarize with the simulator handling and to get to know the eco-riding support system followed. The instruction in the subsequent test ride aimed at provoking a naturalistic and realistic motivation for efficient riding. This is important to draw conclusions from potential energy consumption differences between control and experimental groups. The riders were not forced to follow the recommendations. All riders – regardless of the experimental condition - were told that the remaining battery capacity at the end of the trip will be transferred to additional expense allowance (e.g., 10 % battery capacity left transfers to 5 € in addition). This reward system was not meant to replicate the money the participants would have been saving in reality. It was meant to create a serious motivation for all participants to ride energy efficiently by using this gamification approach. Studies evaluating efficient behavior in other domains (e.g., smart home) used comparable methods (e.g., Paetz et al., 2012).

At the same time, all participants were told to arrive at their destination in time (<30 min), because they have an appointment there. The additional expense allowance would be withdrawn if they arrive late. This should avoid efficient, but unnatural behavior, such as riding 50 km/h on a highway. The appointment closed with a final inquiry. For ethical reasons, all riders received their additional reward at the end of the study and regardless of their performance.

Panel description

A total of $N = 31$ riders participated in the study while eight of the riders were female. All participants completed a sophisticated simulator training prior to participating in any study. Age as well as riding experience varied significantly between the participants (see Table 1). The participants hold a valid A1 (light motorcycle) or A (motorcycle) driver's license and were all recruited by WIVW. They received an expense allowance for their participation. There were no professional riders or test riders in the sample. While n = 11 riders formed the control group, the Basic condition and the Comprehensive condition consisted of n = 10 participants each.

Data analysis

Applied parameters

Compliance with coasting recommendations and possible transfer effects are determined through the percentage of time in which the participant rode within the range of the recommended coasting velocity. The analysis regarding compliance is conducted for the highway section with a length of 6.3 km as the riders were allowed to ride faster than the recommended velocity in this segment. The check for transfer effects was conducted on a rural road segment with a length of 1 km without any recommendations at the end of the test track.

Compliance with regenerative braking and sailing recommendations and transfer effects is assessed by means of the extent of velocity reduction for each possibility to decelerate. In general, three options exist to reduce the velocity of the E-PTW: (1) braking via using the mechanical brakes at the handlebar; (2) sailing via releasing the throttle twist grip to a neutral position so that the E-PTW rolls and is e.g., decelerated by the rolling resistance; (3) regenerative braking via throttle twist grip.

The extent of velocity reduction is calculated by the accumulation of all decelerations per option. Fig. 5 shows the example of a deceleration situation due to a red traffic light. The rider approaches the traffic light keeping velocity stable by means of sailing and accelerating. After a short and a longer regenerative braking episode the rider accelerates slightly again and stops at the traffic light by sailing and mechanical braking. The analysis shows that the rider decelerated 22.5 km/h in total via recuperating, 5.2 km/h via sailing, and 16.5 km/h via mechanical braking in the whole situation. Compliance with regenerative braking and sailing recommendations is characterized by a high number of decelerations through regenerative braking and sailing and minimum to none decelerations through mechanical braking.

The analysis of compliance with regenerative braking and sailing recommendations is conducted for all 28 segments in which the riders of the comprehensive condition received recommendations. Possible transfer effects were determined by analysis of all other road segments without any recommendations.

In the results section this parameter is used to compare the three conditions. In a first step it is necessary to test if the three conditions differ regarding their total velocity decrease. If the groups differ and one group decelerates more than the other groups, the probability for, e.g., more regenerative braking is also higher. The three groups are comparable concerning their cumulated velocity decrease ($F(2,28) < 1$; see Table 4). Therefore, the parameter can be used for the analyses without limitations.

In total, the participants slowdown 1129.4 km/h on average in the 28 test situations. It is important to point out that the absolute value of 1129.4 km/h has little meaning only. Rather, the comparison of the cumulated velocity decrease per deceleration option is significant.

Efficiency effects of the recommendations are analyzed via the energy consumption. The consumption is defined as the difference between energy losses via acceleration and gains via regenerative braking: If the energy consumption is negative the losses outweigh the gains (e.g., while accelerating) and the state of charge decreases; if the energy consumption is positive the gains outweigh the losses (e.g., while regenerative braking) and the state of charge increases.

The energy consumption was calculated for three sections:

- The highway section with a length of 6.3 km to identify effects of coasting recommendations
- The sum of the 28 test segments to identify effects of sailing and regenerative braking recommendations
- All sections without any recommendations to identify transfer effects

Statistical analysis

Data pre-processing was done with MATLAB®. Data analysis was conducted using MATLAB®, Excel® and SPSS®. In a first step, parameters such as percentage of time in a predefined velocity range or energy consumption were calculated within the individual. Then, the individual parameters were aggregated per condition across all participants. Planned comparisons via contrasts were used to answer the research questions concerning compliance with recommendations, transfer effects, and efficiency effects: Contrast 1 tests whether the control group is different to the two experimental groups (basic + comprehensive). Contrast 2 compares the two experimental groups. Alpha has been adjusted according to Bonferroni to account for multiple testing with the same data. Levene's test was used to check for equality of variances. In case of different variances an adjusted procedure was used. In the results section, varying variances are apparent through adjusted degrees of freedom.

Concerning the subjective evaluations, t-tests for independent samples were conducted to compare the two experimental groups. Cohen's d is reported as effect size for the planned comparisons and the t-tests (Field, 2013).

Results

Compliance with the coasting recommendations

The participants of all three groups ride slower than 87 km/h during most of the time on the highway (see Fig. 6). Riders of the experimental groups spend more time in this slow velocity range than the control group. The recommended velocity range between 87 and 93 km/h is used during 23 % (Comprehensive condition) respectively 21 % (Basic condition) of riding time on the highway. In contrast, the control group participants ride within this corridor during 13 % of the time. Due to one control group participant riding in the target range 74 % of the time the groups do not differ statistically. The most distinct difference is observable in the fastest speed range: While the experimental groups rarely travel faster than 93 km/h, the riders of the control group on average ride faster than 93 km/h 25 % of the time. The velocity behaviors of the riders in the Basic and Comprehensive condition are

Table 1
Panel description (N = 31).

	M	*SD*	*MIN*	*MAX*
Age in years	41	19	16	71
Motorcycle mileage during lifetime in km	97 289	146 984	250	700 000
Motorcycle mileage covered during the last 12 months in km	6 774	10 477	150	50 000

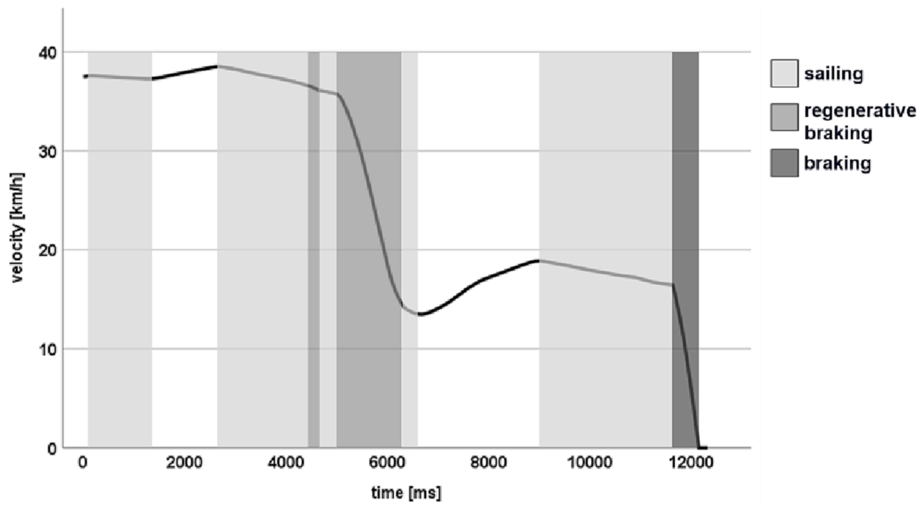

Fig. 5. An example of a deceleration situation (approaching a red traffic light). The line depicts velocity over time. The background color illustrates, if the rider used sailing, regenerative braking, or manual braking.

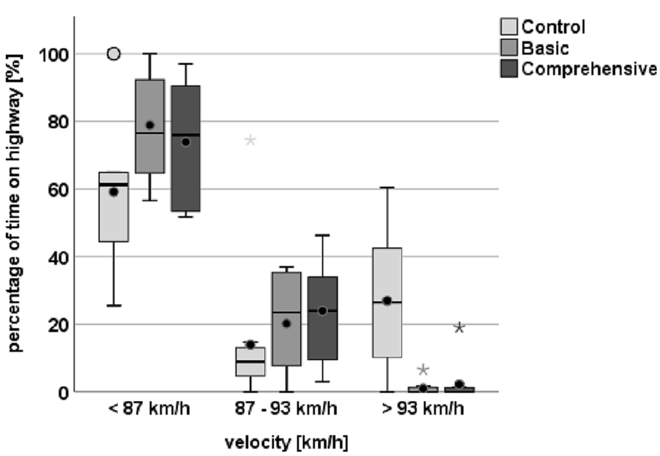

Fig. 6. Percentage of time on the highway for velocity range and condition. Boxplots are shown (line: median; dot: mean value).

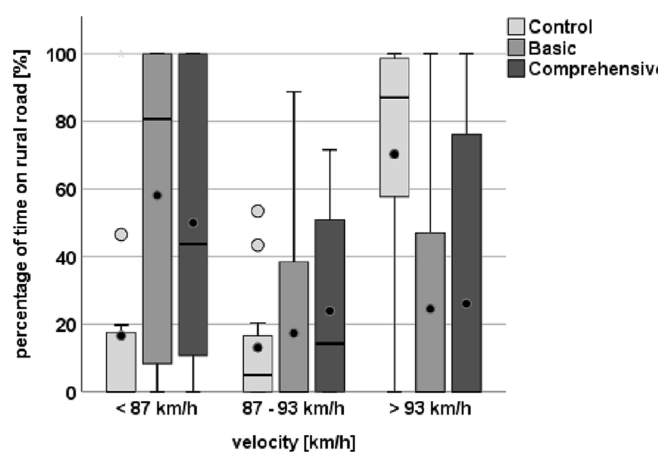

Fig. 7. Percentage of time on the highway for velocity range and condition. Boxplots are shown (line: median; dot: mean value).

comparable for the three velocity ranges. Inferential statistics can be found in Table 2.

Transfer effects of the coasting recommendations

As can be seen from Fig. 7, differences between the groups can be found for the section without any recommendations: Riders of the experimental groups ride more with velocities < 87 km/h, while they ride less with velocities greater than 93 km/h. Concerning the target range between 87 and 93 km/h, however, the percentages are comparable. Furthermore, the Basic and the Comprehensive group do not differ concerning their velocity behavior when traveling on this section. Inferential statistics are summarized in Table 3.

Table 2
Inferential statistics for compliance with the coasting recommendations (Contrast 1: Control vs. Basic + Comprehensive; Contrast 2: Basic vs. Comprehensive). Bold font indicates statistical significance.

Parameter	*t*	*df*	*p*	*Cohen's d*
< 87 km/h				
Contrast 1	**2.32**	**28**	**0.028**	**0.96**
Contrast 2	0.57	28	0.576	0.30
87–93 km/h				
Contrast 1	1.25	28	0.221	0.35
Contrast 2	0.49	28	0.629	0.25
> 93 km/h				
Contrast 1	**4.02**	**10.51**	**0.002**	**2.11**
Contrast 2	0.61	11.10	0.552	0.30

Table 3
Inferential statistics for transfer effects of the coasting recommendations (Contrast 1: Control vs. Basic + Comprehensive; Contrast 2: Basic vs. Comprehensive). Bold font indicates statistical significance.

Parameter	*t*	*df*	*p*	*Cohen's d*
< 87 km/h				
Contrast 1	**2.74**	**26.205**	**0.011**	**1.10**
Contrast 2	0.41	17.644	0.687	0.18
87–93 km/h				
Contrast 1	0.78	28	0.443	0.18
Contrast 2	0.57	28	0.576	0.23
> 93 km/h				
Contrast 1	**2.93**	**28**	**0.007**	**1.13**
Contrast 2	0.09	28	0.933	0.04

Compliance with the sailing and regenerative braking recommendations

With a mean reduction between 796 and 849 km/h, regenerative braking is the most used deceleration type and does not differ between the groups (see Fig. 8). Sailing is used for an absolute decrease of 214 to 303 km/h on average. The riders of the control group use sailing to a lesser extent than the riders of the groups with recommendations. In contrast, the experimental groups use mechanical braking less than the control group. Regarding recuperating, sailing, and mechanical braking both experimental groups do not differ. The according inferential statistics can be found in Table 5.

Transfer effects of the sailing and regenerative braking recommendations

Also, on sections without any sailing and recuperating recommendations the deceleration behavior is similar to sections with such recommendations (see Fig. 9): While the amount of regenerative braking is equal, the control group riders use the mechanical brakes more and use the sailing function less than the experimental groups. In contrast, both experimental groups are comparable regarding regenerative braking, sailing, and braking. Table 6 displays the results from the inferential analyses.

Efficiency effects of the recommendations

The control group riders consume more energy on the highway compared to the riders with coasting recommendations (see Fig. 10). The difference is 18.2 % for the Basic condition and 12.8 % for the Comprehensive condition. Similarly, on sections without any recommendations the consumptions of the Basic group (9.5 %) and the Comprehensive group (8.2 %) are lower than those of the control group. In contrast, the results of the three conditions do not differ when riding on the sections with sailing and recuperating recommendations: The three groups gain energy in a comparable amount.

Neither on the sections with coasting, with sailing and regenerative braking, nor on sections without any recommendations the Basic and Comprehensive condition differ regarding energy consumption.

The inferential statistics are displayed in Table 7.

User acceptance

In general, the participants of the two experimental groups evaluate the riding recommendations as positive in the final inquiry (see Fig. 11): On average, the riders state that they tried to comply with the recommendations and agree that they saved energy due to the displayed recommendations. All participants confirm that they could transfer the

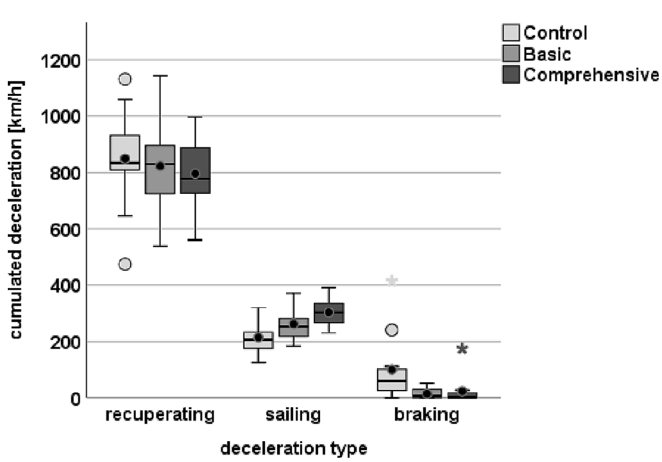

Fig. 8. Cumulated velocity reduction for deceleration type and condition. Boxplots are shown (line: median; dot: mean value).

Table 4
Mean and standard deviation of cumulated velocity decrease for the three groups and the total sample.

Condition	*M*	*SD*
Control	1 163.2	137.3
Basic	1 099.0	152.6
Comprehensive	1 122.6	78.3
Total	1 129.4	125.9

Table 5
Inferential statistics for compliance with the sailing and regenerative braking recommendations as well as mechanical braking (Contrast 1: Control vs. Basic + Comprehensive; Contrast 2: Basic vs. Comprehensive). Bold font indicates statistical significance.

Parameter		*t*	*df*	*p*	*Cohen's d*
recuperating					
	Contrast 1	0.66	28	0.515	0.16
	Contrast 2	0.37	28	0.715	0.18
sailing					
	Contrast 1	**3.24**	**28**	**0.003**	**0.84**
	Contrast 2	1.63	28	0.114	0.78
braking					
	Contrast 1	**2.66**	**28**	**0.013**	**1.06**
	Contrast 2	0.24	28	0.805	0.25

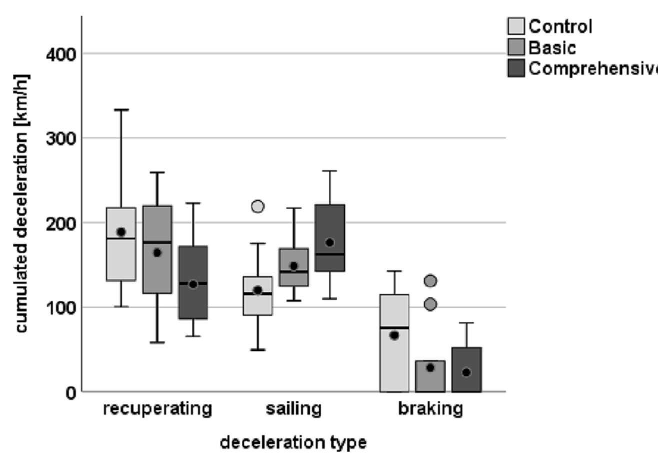

Fig. 9. Cumulated velocity reduction for deceleration type and condition. Boxplots are shown (line: median; dot: mean value).

Table 6
Inferential statistics for transfer effects of the sailing and regenerative braking recommendations as well as mechanical braking (Contrast 1: Control vs. Basic + Comprehensive; Contrast 2: Basic vs. Comprehensive). Bold font indicates statistical significance.

Parameter		*t*	*df*	*p*	*Cohen's d*
recuperating					
	Contrast 1	1.86	28	0.074	0.39
	Contrast 2	1.35	28	0.187	0.66
sailing					
	Contrast 1	**2.58**	**28**	**0.015**	**0.79**
	Contrast 2	1.41	28	0.169	0.14
braking					
	Contrast 1	**2.31**	**28**	**0.028**	**0.65**
	Contrast 2	0.27	28	0.790	0.68

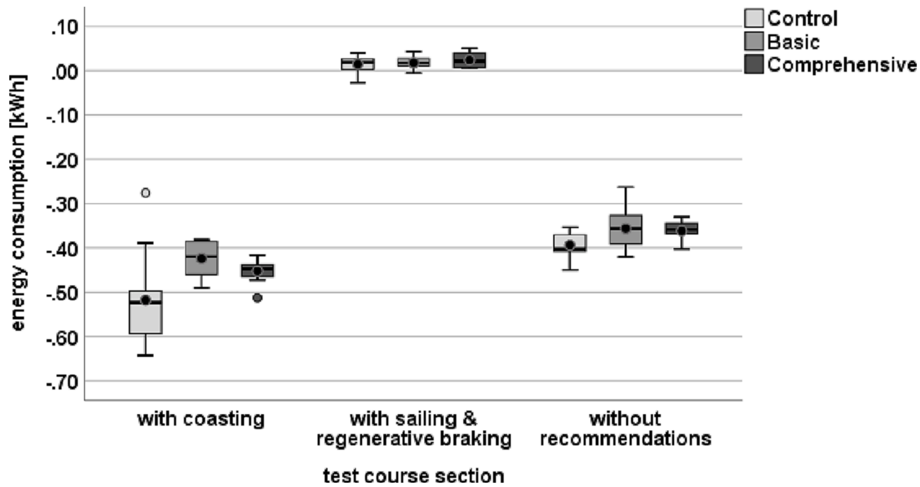

Fig. 10. Energy consumption for test course section and condition. Boxplots are shown (line: median; dot: mean value).

Table 7
Inferential statistics for efficiency effects (Contrast 1: Control vs. Basic + Comprehensive; Contrast 2: Basic vs. Comprehensive). Bold font indicates statistical significance.

Parameter	*t*	*df*	*p*	*Cohen's d*
with coasting				
Contrast 1	**2.40**	**11.200**	**0.035**	**1.33**
Contrast 2	1.78	15.495	0.094	0.82
with sailing & regenerative braking				
Contrast 1	0.92	28	0.364	0.16
Contrast 2	0.82	28	0.422	0.39
without recommendations				
Contrast 1	**2.68**	**28**	**0.012**	**1.18**
Contrast 2	0.34	28	0.733	0.15

recommendations to situations without recommendations. Almost all riders would like to have these kind of riding recommendations in their own E-PTW. These results are valid for both experimental groups as their judgments are comparable. Table 8 provides all inferential statistics.

According to $n = 13$ of the $N = 20$ riders (65 %), regenerative braking is the most useful recommendation, because they rate it as the best option to gain energy ($n = 10$) and because it appears most frequently ($n = 5$). 4 riders (20 %) evaluate sailing as the most useful recommendation and argue that it is the best option to save energy ($n = 3$) and that it supports anticipative riding ($n = 1$). 3 riders (15 %) consider coasting as the most helpful recommendation as it is a reminder to ride slower and it appears most frequently. Concerning the second and third rank the ratings are rather clear: More than half of the sample rates sailing recommendations as second useful and coasting recommendations as third useful (see Table 9).

$N = 7$ riders (35 %) state that they would use the recommendations in their E-PTW in daily usage. In contrast, $n = 10$ participants (50 %) would use the riding recommendations especially when being unexperienced in riding an E-PTW. $N = 2$ riders (10 %) would use the recommendations during long trips in order to reduce range anxiety (i.e., anxiety in response to the limited range of an EV; Franke et al., 2012; Noel et al., 2019) and one rider (5 %) would use the system only sometimes. There was no rider who never would use the

Table 8
Inferential statistics of the comparison between Basic and Comprehensive condition for subjective evaluations.

Item	*t*	*df*	*p*	*Cohen's d*
I tried to comply with the recommendations	1.04	18	0.311	0.30
I saved energy due to the display	0.78	18	0.446	0.25
I could transfer the recommendations on situations without recommendations	0.65	18	0.591	0.35
I would like to have riding recommendations in my E-PTW	0.66	18	0.518	0.47

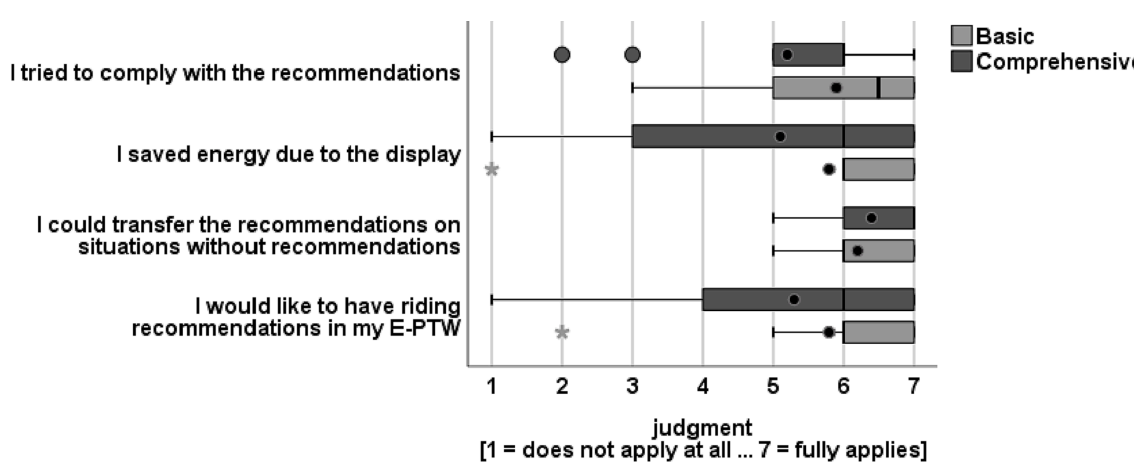

Fig. 11. Participant judgment for item and condition. Boxplots are shown (line: median; dot: mean value).

Table 9
Frequency of participants' rankings concerning the subjectively perceived usefulness of the recommendations.

Recommendation	*rank 1*	*rank 2*	*rank 3*
Coasting	3	5	12
Regenerative braking	13	4	3
Sailing	4	11	5

recommendation in an E-PTW.

Discussion

This experiment examined the effects of three different eco-riding recommendations on compliance and efficiency in a scooter riding simulator. Furthermore, transfer effects and subjective evaluations of the system were considered.

Compliance, energy consumption, and acceptance

Based on the obtained data, the coasting recommendations had an effect on riding behavior: The participants with system travelled mostly slower and, in contrast to the riders without recommendations, hardly ever faster than the recommended velocity. However, they use the suggested speed range of 87 – 93 km/h less frequently than velocities slower than 87 km/h. This indicates that the participants use the coasting recommendations more as a speed limiter warning than an advice to keep the suggested velocity constantly. The riders transfer this learnt riding behavior also to situations without any coasting recommendations. As a result, the participants with coasting recommendations consume less energy than the group without system on the relevant test course section. Compared to the control group, the gains of the coasting recommendations lie between 18.2 % for the Basic condition and 12.8 % for the Comprehensive condition. These benefits are in the range of gains with eco-driving support systems known from the literature (Kurani et al., 2015). Compared to the other recommendation types, the coasting suggestion seems to have the most positive impact on energy consumption and, therefore, on driving range. As driving range is essential to improve user acceptance (Higueras-Castillo et al., 2021) and to prevent range anxiety (Franke et al., 2012), it is advisable that future eco-riding assistances contain a coasting recommendation – no matter whether the rider will use it as a speed limiter warning or as a recommendation to keep a suggested velocity.

It should be mentioned that in this study, the coasting recommendation was designed to avoid riding with the vehicle's top speed, which brings the electric engine in a rather inefficient energy consumption state. Due to the 8 kW electric scooter and a top speed of approx. 100 km/h, the recommendation was given to stay about 10 km/h below the technically possible top speed. It can be assumed that the general logic of that recommendation would also work for other types of electric scooters, e.g., with a lower top speed as long as it recommends a velocity resp. torque request range that allows the electric motor to work energy efficiently. Yet, further research might be necessary to understand the influence of the recommended absolute velocity or the road type. For instance, the compliance might change if the coasting recommendation suggests a velocity of 20 km/h for a 30 km/h top-speed electric scooter that is most commonly driven in a crowded urban area among other vehicles floating at 30 km/h. Regardless of that measurable benefit, the participants rate coasting as the least useful recommendation. In order to increase the acceptance of such a system it might be useful to implement information campaigns, tutorials, or advices in the vehicle's manual. They could be helpful to make the rider aware that, typically, an electric motor can work way more efficiently if it is operated somewhat below maximum power output without significantly decreasing speed or increasing travel time.

Regenerative braking is the main deceleration technique across all three groups. This phenomenon is comparable to other studies examining driving behavior in EVs (e.g., Helmbrecht et al., 2014). Consequently, no effects for the regenerative braking recommendation were observable. As soon as riders have learnt that almost all necessary decelerations in regular traffic can be conducted via regenerative braking instead of mechanical braking any recommendations for this behavior seem to have no additional benefit. However, not all participants of the control group have internalized this behavior as some riders use the mechanical brakes still rather frequently. It could be helpful to support these riders via other strategies: In the automotive sector, haptic feedback via an active gas pedal was successful at reducing fuel or energy consumption (e.g., Azzi et al., 2011; Larsson and Ericsson, 2009). This concept could be transferred to an E-PTW: A haptic movement of the throttle twist grip in regenerative braking direction as soon as the rider uses the mechanical brakes could remind her/him of the regenerative braking function. Further research has to prove if such solutions would be beneficial. Finally, the riders rate the regenerative braking recommendation as the most useful one. This result underlines the subjective importance of regenerative braking for the participants.

Participants with eco-riding support system sail more often than the control group to decelerate the scooter. The frequency of sailing recommendations does not affect this riding behavior. This indicates that the recommendations are used as a reminder to reduce velocity in an efficient way via sailing. Therefore, a high frequency and an exact location of the advices seem not to be necessary in a future eco-riding support system. This could facilitate the implementation of sailing recommendations in a real scooter: If an E-PTW lacks certain vehicle sensors to calculate the appropriate point in time to trigger the recommendation it might be sufficient to display general riding suggestions from time to time (e.g., after having started the scooter). Additional research is required to confirm such a conclusion.

The participants rate all three recommendation types as positive. This finding is consistent with studies showing high acceptance of similar eco-driving support systems in vehicles with ICE, which recommend gear-shifting and acceleration/deceleration behavior (Kotte et al., 2016; Radlmayr et al., 2015; Staubach et al., 2014). According to the participants, recommendations are particularly useful when being unexperienced in riding the E-PTW. This suggestion is supported by research findings showing that novice drivers drive less efficient than experienced drivers (Huang et al., 2021). Consequently, it might be desirable for some riders to deactivate recommendations after gaining sufficient riding experience. Therefore, it is suggested to implement an option for the user to personalize the eco-riding support system (Brouwer et al., 2015; Fors et al., 2015) and to adjust the system functionality.

Methodological issues

From a methodological point of view, it should be stated that the chosen instruction and reward system might have influenced riders' behavior. This means that without the potential reward for energy efficient riding, participants might have had higher energy consumption. As the absolute amount of energy was not in the focus in this simulator study, this methodological decision should not have a negative impact. The motivation to use the reward system was to create constant and comparable conditions across all the groups. It seemed important to motivate all participants – regardless of their experimental condition – to ride energy efficiently. If both experimental groups would have received an explanation on the eco-riding support system, while the control group would just have been told to arrive at a certain destination, the comparison between would not have been fair. The control group would have been less sensitive to the relevance of efficient riding. This would have biased the results in a direction that a positive effect of the eco-riding support system would have been easier to detect. Yet, by giving every participant the same instruction and the same extra reward, the observed difference in energy consumption should really be attributable to the eco-riding support system and not only the riders' motivation. Other studies could investigate the effect of an eco-riding support system under more natural conditions in order to understand the acceptance and compliance based on riders' pure initial motivation to ride energy efficiently.

Conclusion

With positive effects on energy consumption and high user acceptance, the results of this study sustain the idea of eco-riding support systems in general. Furthermore, they raise a variety of further research questions for upcoming studies. Several former studies concerning eco-driving support systems found novelty effects, i.e. a negative relationship between length of exposure to feedback and effect size (Sanguinetti et al., 2020). In the previous experiment the participants used the eco-driving system in a test run with 30 min length only. Therefore, it has to be clarified in further studies with longer system usage if a novelty effect also applies for the proven recommendations.

Furthermore, design and functionality of the system recommendations have to be evaluated more in detail. If the system emits recommendations prior to each deceleration situation the frequency of messages could get rather high. Possible non-intended consequences like rider distraction or annoyance have to be prevented in order to ensure efficiency effects of the system. Yet, the results indicate that a higher frequency of recommendations does not provoke higher efficiency as there were no significant differences between the Basic and the Comprehensive condition. This should facilitate a trigger algorithm design that avoids distraction and annoyance due to frequently shown recommendations.

Studies investigating traffic light assistants (Muehlbacher et al., 2014) demonstrated that the surrounding traffic could influence the drivers' compliance to recommendations regarding a slower velocity: When driving with subsequent traffic, the participants follow the system's recommendations to a lesser extent compared to driving without subsequent traffic. This could also apply for the coasting recommendations when riders are worrying about hindering following faster road users. Future research has to determine the role of surrounding traffic for the compliance to coasting recommendations and therefore the system's effectiveness.

Finally, eco-riding support systems are not the only option to improve efficient riding behavior. Several projects demonstrate the positive effect of eco-driving trainings regarding fuel consumption, e.g., for car drivers (Scott et al., 2012), bus drivers (Savković et al., 2019), or professional taxi drivers (Yao et al., 2019). Probably, rider trainings encompassing efficiency could be an alternative to eco-riding support systems – especially for riders who own an older type of E-PTW which is not equipped with any assistances.

Despite the open questions raised by the results of this study, it has been identified that riding recommendations are an effective way to support the rider in order to consume less energy when travelling with an E-PTW. Hence, they are one element in the major challenge to reduce greenhouse gas emissions.

CRediT authorship contribution statement

Dominik Muehlbacher: Conceptualization, Methodology, Investigation, Formal analysis, Writing – original draft, Writing – review & editing, Visualization, Validation. **Sebastian Will:** Conceptualization, Methodology, Investigation, Formal analysis, Writing – original draft, Writing – review & editing, Visualization, Validation. **Nora Merkel:** Data curation, Formal analysis, Visualization, Writing – review & editing. **Nicole Perterer:** Conceptualization, Project administration, Writing – review & editing. **Sara Mlakar:** Conceptualization, Writing – review & editing. **Michael Haller:** Conceptualization, Writing – review & editing. **Martin Perterer:** Conceptualization, Project administration, Writing – review & editing.

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

The data that has been used is confidential.

Acknowledgements

The authors would like to express their deep gratitude to all colleagues, EMotion consortium members, and to all participants that were involved in the research process.

Funding

This study was conducted within the project EMotion (Electric mobility in L-category vehicles for all generations). This project is supported with funds from the Austrian Climate and Energy Fund and implemented in line with the "Zero Emission Mobility" programme (GA: 878111). The funding is coordinated by the Österreichische Forschungsförderungsgesellschaft (FFG).

The study has been approved by WIVW's group in charge for ethical assessment. The strict ethical guideline as defined in the standard operating procedures has been followed.

References

Adra, N., Michaux, J.-L., & Andre, M. (2004). *Analysis of the load factor and the empty running rate for road transport* (INRETS-LTE0419 Report).
Azzi, S., Reymond, G., Mérienne, F., Kemeny, A., 2011. Eco-driving performance assessment with in-car visual and haptic feedback assistance. J. Comput. Inf. Sci. Eng. 11 (4).
Barkenbus, J.N., 2010. Eco-driving: An overlooked climate change initiative. Energy Policy 38 (2), 762–769. https://doi.org/10.1016/j.enpol.2009.10.021.
Brouwer, R.F.T., Stuiver, A., Hof, T., Kroon, L., Pauwelussen, J., Holleman, B., 2015. Personalised feedback and eco-driving: An explorative study. Transportation Research Part C: Emerging Technologies 58, 760–771. https://doi.org/10.1016/j.trc.2015.04.027.
Clegg, S. J. (1996). *A Review of Regenerative Braking Systems* (Working Paper 471).
Dorrer, C., 2004. Effizienzbestimmung von Fahrweisen und Fahrerassistenz zur Reduzierung des Kraftstoffverbrauchs unter Nutzung telematischer Informationen. Expert Verlag, Renningen.
Evans, LEONARD, 1979. Driver Behavior Effects on Fuel Consumption in Urban Driving. Human Factors: J. Human Factors Ergonomics Soc. 21 (4), 389–398.
Field, A., 2013. Discovering statistics using IBM SPSS statistics. Sage Publications, London.
Fors, C., Kircher, K., Ahlström, C., 2015. Interface design of eco-driving support systems–Truck drivers' preferences and behavioural compliance. Transp. Res. Part C: Emerg. Technol. 58, 706–720.
Franke, T., Neumann, I., Bühler, F., Cocron, P., Krems, J.F., 2012. Experiencing range in an electric vehicle: Understanding psychological barriers. Appl. Psychol. 61 (3), 368–391.
Habich-Sobiegalla, S., Kostka, G., Anzinger, N., 2018. Electric vehicle purchase intentions of Chinese, Russian and Brazilian citizens: An international comparative study. J. Clean. Prod. 205, 188–200.
Helmbrecht, M., Bengler, K., Vilimek, R., 2013. Strategies for efficient driving with electric vehicles. In: Brandenburg, E., Doria, L., Gross, A., Günzler, T., Smieszek, H. (Eds.), Grundlagen und Anwendungen der Mensch-Maschine-Interaktion: 10. Berliner Werkstatt Mensch-Maschine-Systeme. Universitätsverlag der TU Berlin, Berlin, pp. 83–90.
Helmbrecht, M., Olaverri-Monreal, C., Bengler, K., Vilimek, R., Keinath, A., 2014. How electric vehicles affect driving behavioral patterns. IEEE Intell. Transp. Syst. Mag. 6 (3), 22–32.
Higueras-Castillo, E., Guillén, A., Herrera, L.-J., Liébana-Cabanillas, F., 2021. Adoption of electric vehicles: Which factors are really important? Int. J. Sustain. Transp. 15 (10), 799–813.
Huang, Y., Ng, E.C.Y., Zhou, J.L., Surawski, N.C., Lu, X., Du, B., Forehead, H., Perez, P., Chan, E.F.C., 2021. Impact of drivers on real-driving fuel consumption and emissions performance. Sci. Total Environ. 798 (149297) https://doi.org/10.1016/j.scitotenv.2021.149297.
IEA, 2021. Global electric vehicle stock by region, 2010–2020. Retrieved from. https://www.iea.org/data-and-statistics/charts/global-electric-vehicle-stock-by-region-2010-2020.

Jayasingh, S., Girija, T., Arunkumar, S., 2021. Factors influencing consumers' purchase intention towards electric two-wheelers. Sustainability 13 (22), 12851.

Kotte, J., Josten, J., Zlocki, A., Eckstein, L., 2016. Impact of a visual and haptic driver advice and preview system on a range optimized way of driving in electric vehicles. Transp. Res. Procedia 3, 1071–1079.

Kurani, K. S., Sanguinetti, A., & Park, H. (2015). *"Actual Results May Vary": A Behavioral Review of Eco-Driving for Policy Makers*.

Lamb, W.F., Wiedmann, T., Pongratz, J., Andrew, R., Crippa, M., Olivier, J.G.J., Wiedenhofer, D., Mattioli, G., Khourdajie, A.A., House, J.o., Pachauri, S., Figueroa, M., Saheb, Y., Slade, R., Hubacek, K., Sun, L., Ribeiro, S.K., Khennas, S., de la Rue du Can, S., Chapungu, L., Davis, S.J., Bashmakov, I., Dai, H., Dhakal, S., Tan, X., Geng, Y., Gu, B., Minx, J., 2021. A review of trends and drivers of greenhouse gas emissions by sector from 1990 to 2018. Environ. Res. Lett. 16 (7), 073005.

Larsson, H., Ericsson, E., 2009. The effects of an acceleration advisory tool in vehicles for reduced fuel consumption and emissions. Transp. Res. Part D: Transp. Environ. 14 (2), 141–146.

LeBlanc, D. J., Sivak, M., & Bogard, S. E. (2010). *Using naturalistic driving data to assess variations in fuel efficiency among individual drivers* (UMTRI-2010-34).

Mersky, A.C., Sprei, F., Samaras, C., Qian, Z.S., 2016. Effectiveness of incentives on electric vehicle adoption in Norway. Transportation Research Part D-transport and Environment 46, 56–68.

Muehlbacher, D., Rittger, L., & Maag, C. (2014, 4-5 September). *Real vs Simulated Surrounding Traffic - Does It Matter?* Vortrag auf Proceedings of the Driving Simulation Conference 2014, Paris, France.

Noel, L., Zarazua de Rubens, G., Sovacool, B.K., Kester, J., 2019. Fear and loathing of electric vehicles: The reactionary rhetoric of range anxiety. Energy Res. Soc. Sci. 48, 96–107. https://doi.org/10.1016/j.erss.2018.10.001.

Paetz, A.-G., Kaschub, T., Jochem, P., & Fichtner, W. (2012). *Demand response with smart homes and electric scooters: an experimental study on user acceptance.* Vortrag auf ACEEE Summer Study.

Radlmayr, J., Selzer, T., Arcati, A., Bengler, K., 2015. Haptic gear shifting indication: evaluating acceptance and potential fuel consumption reduction. Procedia Manuf. 3, 2746–2752.

Sanguinetti, A., Park, H., Sikand, S., & Kurani, K. (2017, 2017//). *A Typology of In-Vehicle Eco-Driving Feedback.* Vortrag auf Advances in Human Aspects of Transportation, Cham.

Sanguinetti, A., Queen, E., Yee, C., Akanesuvan, K., 2020. Average impact and important features of onboard eco-driving feedback: A meta-analysis. Transport. Res. F: Traffic Psychol. Behav. 70, 1–14. https://doi.org/10.1016/j.trf.2020.02.010.

Savković, Milicic, M., & Ilic, S. (2019). Effects of Eco-Driving Training: A Pilot Program in Belgrade Public Transport. *Tehnicki vjesnik - Technical Gazette.*

Scott, H., Knowles, M., Morris, A., Kok, D., 2012. The role of a driving simulator in driver training to improve fuel economy. Vortrag.

Staubach, M., Schebitz, N., Köster, F., Kuck, D., 2014. Evaluation of an eco-driving support system. Transport. Res. F: Traffic Psychol. Behav. 27, 11–21.

UK Department of Transportation, 2017. Efficient driving in electric and low-emission vehicles. Retrieved from. https://energysavingtrust.org.uk/sites/default/files/Efficient%20driving%20in%20electric%20and%20low%20emission%20vehicles.pdf.

Umweltbundesamt. (2017). Austria's National Inventory Report 2017. Retrieved from https://www.umweltbundesamt.at/fileadmin/site/publikationen/REP0608.pdf.

UNFCCC. (2015). *Adoption of the Paris Agreement.* (FCCC/CP/2015/10/Add.1).

United States EPA. (2021). Fast Facts. U.S. Transportation Sector Greenhouse Gas Emissions 1990-2019. Retrieved from https://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=P1013NR3.pdf.

Vaezipour, A., Rakotonirainy, A., Haworth, N., Delhomme, P., 2018. A simulator evaluation of in-vehicle human machine interfaces for eco-safe driving. Transp. Res. A Policy Pract. 118, 696–713.

Will, S., Luger-Bazinger, C., Schmitt, M., Zankl, C., 2021. Towards the Future of Sustainable Mobility: Results from a European Survey on (Electric) Powered-Two Wheelers. Sustainability 13 (13), 7151.

Yao, Y., Zhao, X., Ma, J., Liu, C., Rong, J., 2019. Driving Simulator Study: Eco-Driving Training System Based on Individual Characteristics. Transp. Res. Rec. 2673 (8), 463–476. https://doi.org/10.1177/0361198119843260.