

Energy Recapture through Deceleration – Regenerative Braking in Electric Vehicles from a User Perspective

Peter Cocron*, Franziska Bühler, Thomas Franke, Isabel Neumann, Benno Dielmann and

Josef F. Krems

Department of Psychology, Chemnitz University of Technology, 09107 Chemnitz, Germany

We report results from a 1-year field study (N=80) on user interactions with regenerative braking in electric vehicles (EVs). Designed to recapture energy in vehicles with electric powertrains, regenerative braking has an important influence on both, the task of driving and energy consumption. Results from user assessments and data from onboard data loggers indicate that most drivers quickly learned to interact with the system, which was triggered via accelerator. Further, conventional braking manoeuvres decreased significantly as the majority of deceleration episodes could only be executed through regenerative braking. Still, some drivers reported difficulties when adapting to the system. These difficulties could be addressed by offering different levels of regeneration so the intensity of the deceleration could be individually modified. In general, the system is trusted and regarded as a valuable tool for prolonging range.

Keywords: electric vehicles, regenerative braking, skill acquisition, trust, acceptance

Statement of relevance

Regenerative braking in electric vehicles has direct implications for the driving task. We found that drivers quickly learn to use and accept a system, which is triggered via accelerator. For those reporting difficulties in the interaction, it appears reasonable to integrate options to customize or switch off the system.

*Corresponding author: peter.cocron@psychologie.tu-chemnitz.de

"This is an Accepted Manuscript of an article published by Taylor & Francis Group in Ergonomics on 14/06/2013, available online: <http://dx.doi.org/10.1080/00140139.2013.803160>"

Citation: Cocron, P., Bühler, F., Franke, T., Neumann, I., Dielmann, B., & Krems, J. F. (2013). Energy recapture through deceleration – regenerative braking in electric vehicles from a user perspective. *Ergonomics*, 56(8), 1203-1215. [dx.doi:10.1080/00140139.2013.803160](http://dx.doi.org/10.1080/00140139.2013.803160)

1. Introduction

In the debate about decreasing CO₂ emissions, hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs) and fully electric vehicles (EVs) are regarded as promising solutions for a more sustainable transportation system. Such technological innovations also have an impact on the driving task and require effective interfaces (Haslam and Waterson, 2013). Commercially available full HEVs can achieve an improvement in fuel efficiency of 60% or more compared to similar conventional internal combustion engine (ICE) vehicles. Most of the energy saved by HEVs originates from the use of a regenerative braking system (Romm and Frank 2006).

Originally developed for energy recapture in rail traffic, regenerative braking is now integrated in most vehicles with electric propulsion systems. A regenerative braking system converts kinetic energy into electric energy during deceleration manoeuvres. The energy that is usually wasted during braking manoeuvres can be recaptured and stored for later use (Cikanek and Bailey 2002).

The major research objective of our paper is to examine the impact of regenerative braking on the driver. We assume that the regenerative braking system serves as energy saving system, to which the drivers have to adapt, irrespective of which particular regeneration strategy is implemented in the vehicle. In our research we apply the Power Law of Practice (Newell and Rosenbloom 1981) to investigate (1) how long it takes EV drivers to learn to utilize accelerator triggered regenerative braking during deceleration. Furthermore, we assess the driver perspective of such a function at first on a (2) general level and relate these findings to (3) trust and (4) acceptance in order to give (5) recommendations on the future layout of such systems. As part of several international field trials on EVs (Vilimek, Keinath, and Schwalm 2012) these issues were addressed in a German 1-year field study

Citation: Cocron, P., Bühler, F., Franke, T., Neumann, I., Dielmann, B., & Krems, J. F. (2013). Energy recapture through deceleration – regenerative braking in electric vehicles from a user perspective. *Ergonomics*, 56(8), 1203-1215. [dx.doi:10.1080/00140139.2013.803160](https://doi.org/10.1080/00140139.2013.803160)

(Cocron et al. 2011, Franke et al. 2012) with a total of 80 drivers who each drove an EV for six months.

2. Background

2.1 Regenerative Braking

Particularly in heavy stop-and-go traffic, regenerative braking is regarded as a valuable means to improve a vehicle's energy efficiency. Aside from differences in technical layout, drivers seem to have considerable influence on the vehicle's energy efficiency. Romm and Frank (2006) argue that aggressive driving or inefficient use of regenerative braking in HEVs can lead to a more than 30% decrease in fuel efficiency. Different driving strategies appear to have a much bigger impact on efficiency in electric powertrain vehicles than in ICE vehicles.

The technical implementation of regenerative braking in EVs varies considerably. Energy regeneration from deceleration is either triggered via accelerator pedal, brake pedal or both pedals. The amount of deceleration caused by energy regeneration differs substantially between vehicle types. Thus, deceleration may resemble ICE engine braking or even braking manoeuvres. Eberl et al. (2012) studied the intensities of regenerative braking and found that test drivers evaluated an EV with a stronger deceleration in the regeneration phase as more directly controllable than EV concepts with less deceleration.

Comparing an accelerator triggered system with regeneration via brake pedal in a simulator Schmitz et al. (2012) reported that drivers used the hydraulic brake less when regeneration braking was triggered via accelerator. Drivers generally preferred the accelerator triggered system and rated it as more suitable for efficient driving.

In recent studies on user experiences with EVs, regenerative braking was addressed as part of the driving experience (Everett et al. 2010). Results of a field study from the US

Citation: Cocron, P., Bühler, F., Franke, T., Neumann, I., Dielmann, B., & Krems, J. F. (2013). Energy recapture through deceleration – regenerative braking in electric vehicles from a user perspective. *Ergonomics*, 56(8), 1203-1215. [dx.doi:10.1080/00140139.2013.803160](https://doi.org/10.1080/00140139.2013.803160)

(Turrentine et al. 2011) indicated that participants had learned to appreciate a system, which was integrated in the accelerator pedal. The participants who drove a converted MINI Cooper (MINI E) appreciated the fact that they could accelerate and decelerate mostly using the accelerator pedal. Moreover, some drivers reported they tested how far they could drive without applying the brake pedal.

Walsh et al. (2010) reported on track tests with six drivers representing the most- and least-efficient drivers of a greater sample. During deceleration on a high speed track, the most aggressive driver achieved only 15% of regenerative energy capture efficiency compared to 93% regained by the most efficient driver, who used no friction braking during deceleration. As the most efficient driver was an expert in eco-driving, the potential for driver training was thus evident. Walsh et al. (2010) argued that in order to increase the range of EVs, driving styles might have to be modified.

Existing user studies on EVs highlight two important aspects. First, drivers seem to appreciate such a function and second, there is considerable variance in how drivers use the system to regain energy. Moreover, different regenerative braking strategies have already been discussed by the drivers (Solberg 2007; Berman 2011). Against this background we investigated how long it took drivers to familiarise themselves with such a function and how they evaluated regenerative braking.

2.2 Skill Acquisition

Newell and Rosenbloom (1981) developed a theory that stated why certain learning phenomena can be best described by a power law. The authors called it the Power Law of Practice and showed that in various areas there exists a quantifiable relation between the time to fulfil a certain task and the number of practice trials. As the number of trials increases, the

Citation: Cocron, P., Bühler, F., Franke, T., Neumann, I., Dielmann, B., & Krems, J. F. (2013). Energy recapture through deceleration – regenerative braking in electric vehicles from a user perspective. *Ergonomics*, 56(8), 1203-1215. [dx.doi:10.1080/00140139.2013.803160](https://doi.org/10.1080/00140139.2013.803160)

time necessary to complete the task decreases, though at a declining rate. The Power Law has been applied to data from many areas of research, such as perceptual motor skills, perception, problem solving and motor behaviour (for an overview see Lacroix and Cousineau 2006).

In the driving context, focusing on the operation of in-vehicle information systems, Jahn, Krems, and Gelau (2009) fitted the Power Law to training data to compare ease of learning in different systems. Although the power function provided robust results irrespective of the methods used (Newell and Rosenbloom 1981, as quoted in Ritter and Schooler 2001), its applicability to learning data has been questioned mainly with regards to averaging performance scores across participants (Brown and Heathcote 2003). In the current study, we still apply the Power Law as we want to illustrate learning experiences reported subjectively by the drivers. For the assessment of the learning process in regenerative braking, we adapt the general equation of the Power Law according to Lacroix and Coisineau (2006),

$$BP = a + bN^{-c}$$

where *BP* is performance in a specific braking parameter at a certain individual level of experience *N* (km), *a* is the asymptotic value of the braking parameter, *b* is the amplitude at the beginning of learning and *c* is the learning rate. The asymptote *a* is deliberately included in the equation as the performance in regenerative braking is studied over a longer period of time, so it can be assumed that participants reach a plateau in performance. In the section on skill acquisition we examine subjective and objective learning data and apply the Power Law of Practice to describe the exact learning duration from data logger data.

2.3 Acceptance and Trust

In addition to the assessment of the learning process, we examine how actual drivers evaluate regenerative braking. Strengths and drawbacks of such a new system need to be identified at

Citation: Cocron, P., Bühler, F., Franke, T., Neumann, I., Dielmann, B., & Krems, J. F. (2013). Energy recapture through deceleration – regenerative braking in electric vehicles from a user perspective. *Ergonomics*, 56(8), 1203-1215. [dx.doi:10.1080/00140139.2013.803160](https://doi.org/10.1080/00140139.2013.803160)

an early stage to allow for potential adjustments of the system layout. Van der Laan, Heino, and de Waard (1997) proposed a simple method to assess the acceptance of advanced transport telematics. They postulate two dimensions, usefulness and satisfaction, which are measured by nine rating-scale items. As the method is easy to use and quite economical, the scale has been used in numerous studies on human machine interaction in traffic (e.g. Comte 2000).

In several studies on the human interaction with new in-vehicle systems, researchers (e.g. Rudin-Brown and Parker 2004, Kazi et al. 2007) emphasized also trust as a factor, which is crucial for examining new systems. As regenerative braking automates elements of the deceleration process, findings on human trust in automation should serve as an additional basis for the evaluation of the system. To assess operator's trust in cruise control (CC) Cahour and Forzy (2009) proposed a scale integrating trust and related notions based on past research on trust by Muir (1994). Cahour and Forzy (2009) argue that whenever new technology is integrated in the human-machine interaction (HMI), human activity somehow undergoes change. Particularly, if human task elements are transferred to machines, the corresponding loss of control can be compensated for by trust. Muir and Moray (1996) stated that trust in automation heavily depends on the operator's belief that the system can fulfil a task as accurately as the operator. The more the operators trusted a system, the more they tended to use it. If operators distrusted the system, they were more likely to reject it and execute the task by hand. According to the adapted definition of trust by Rajaonah, Anceaux, and Vienne (2006), in decision-making situations, users choose whether or not they will delegate functions to automated systems. In the current study we interrogate if this is also the case for delegating the deceleration to regenerative braking.

Citation: Cocron, P., Bühler, F., Franke, T., Neumann, I., Dielmann, B., & Krems, J. F. (2013). Energy recapture through deceleration – regenerative braking in electric vehicles from a user perspective. *Ergonomics*, 56(8), 1203-1215. [dx.doi:10.1080/00140139.2013.803160](https://doi.org/10.1080/00140139.2013.803160)

3. Study Objectives

Based on existing literature on driver interaction with new in-vehicle technology, we identified (1) skill acquisition, (2) general user evaluation, (3) trust and (4) acceptance as appropriate means to derive (5) recommendations for future regeneration layouts from the user perspective. Regarding (1) skill acquisition we investigated how fast drivers learn to utilize such a function applying the Power Law of Practice (Newell and Rosenbloom 1981). Analogical to research on in-vehicle information systems (Jahn, Krems, and Gelau 2009), we examined in particular how long it took EV novices to substitute conventional braking manoeuvres with regenerative braking. With respect to (2) general user evaluation, we investigated strengths and weaknesses of an accelerator triggered regenerative braking using a qualitative approach. The qualitative findings were the basis to further investigate (3) trust and (4) acceptance of regenerative braking in more detail. Related to (3) trust, we expected according to Kazi et al. (2007) that trust rises at first and then remains constant. Additionally, based on Muir and Moray (1996), we assumed a positive relation between trust and the actual usage of regenerative braking. Based on Comte (2000), we hypothesised that (4) driver's acceptance undergoes a change after interacting with the system. Additionally, we expected a positive relation to trust and based on Jamson (2006) a positive relation to actual behaviour. The findings obtained in the four areas are then used to (5) make suggestions for improving the system's layout based on the driver's perspective. Addressing these objectives appeared to be necessary to decide how regenerative braking should be implemented in EVs from a human factors perspective. The need to investigate long term effects of regenerative braking usage was also emphasized by Schmitz et al. (2012).

Citation: Cocron, P., Bühler, F., Franke, T., Neumann, I., Dielmann, B., & Krems, J. F. (2013). Energy recapture through deceleration – regenerative braking in electric vehicles from a user perspective. *Ergonomics*, 56(8), 1203-1215. [dx.doi:10.1080/00140139.2013.803160](https://doi.org/10.1080/00140139.2013.803160)

4. Framework of the 1-Year Field Study

4.1 Structure

In our article we report results from two 6-month periods of a 1-year field study on EV usage. Both study periods were nested within a larger German field study on acceptance and suitability for daily use of EVs. In each study period, drivers were interviewed three times: when receiving the vehicle (T0), after 3 months (T1) and when returning the cars after 6 months (T2). A wide range of methods was applied to assess various aspects of the user experience in the context of electro-mobility study (Cocron et al. 2011, Franke et al. 2012). A qualitative approach was chosen predominantly in Study Period 1 to understand how drivers learn to interact with regenerative braking and how they evaluate the system. In Study Period 2 quantitative methods assessing, for instance, trust were used to quantify the results of Study Period 1. Unless specified otherwise, approval was assessed using a 6-point Likert scale ranging from 1 (*completely disagree*) to 6 (*completely agree*).

4.2 Test Vehicle

The test vehicle in both study periods was a standard MINI Cooper, converted to a battery-powered vehicle with a lithium ion battery pack. The MINI E was a two-seater, which was powered by a 150-KW electric engine and reached a top speed of 152 km/h. The regenerative braking system was implemented in the accelerator pedal. As soon as the driver released the pedal, the vehicle decelerated rapidly.

4.3 Data Loggers

In Study Period 1 and 2, driving data such as acceleration and speed were continuously recorded via onboard data loggers in all vehicles. Marked keys were distributed among the participants so logger data could be unambiguously assigned to each participant. Regarding

Citation: Cocron, P., Bühler, F., Franke, T., Neumann, I., Dielmann, B., & Krems, J. F. (2013). Energy recapture through deceleration – regenerative braking in electric vehicles from a user perspective. *Ergonomics*, 56(8), 1203-1215. [dx.doi:10.1080/00140139.2013.803160](https://doi.org/10.1080/00140139.2013.803160)

the learning curve of the usage of regenerative braking, two braking parameters were taken into account. The sampling rate of the data was 1 km. A braking manoeuvre is defined as using the brake pedal to decelerate. The first braking parameter B_{man} represents the number of braking manoeuvres per 100 km. The second braking parameter B_{prop} stands for the proportion of braking manoeuvres in total deceleration time.

5. Study Period 1

5.1 Methods

5.1.1 Sample

During the first 6-month study period in Berlin, a sample of 40 users consisting of 33 male and 7 female participants drove an EV. Participants were an average 48 years old ($SD = 8.9$). Twenty-five percent of users had already driven a fully or partially EV, for example, during a test drive. Nevertheless, none of the participants had previous experience driving the test vehicle, when they received the keys. On average drivers had possessed a driving license for 29 years ($SD = 9.8$). Two participants dropped out during Study Period 1.

5.1.2 Vehicle handover – Think-aloud Task during Test Drive (T_0)

When driving the EV for the first time, users were asked to “think aloud”. The concurrent think-aloud-technique in particular is widely used in qualitative usability testing (e.g. van den Haak, de Jong, and Schellens 2004). As first part of the general evaluation (2) the aim of the qualitative approach was the identification of characteristics of EVs, which novice drivers have to adapt to. For the present study only statements on regenerative braking were analysed in more detail.

Citation: Cocron, P., Bühler, F., Franke, T., Neumann, I., Dielmann, B., & Krems, J. F. (2013). Energy recapture through deceleration – regenerative braking in electric vehicles from a user perspective. *Ergonomics*, 56(8), 1203-1215. [dx.doi:10.1080/00140139.2013.803160](https://doi.org/10.1080/00140139.2013.803160)

5.1.3 Learning to Decelerate with Regenerative Braking

To address the research questions regarding (1) skill acquisition, the learning process was assessed subjectively by the drivers via open interview questions (e.g., “To what extent did you have to adapt to driving the EV?”) and quantitatively via data from onboard data loggers. Although data loggers were installed in all 40 test vehicles, only data from 27 drivers were analyzed, as for 13 drivers it was unclear who was driving the vehicle. We report on the first 500 km of the driving experience in order to focus on the learning phase. The variables B_{man} and B_{prop} , which are described above, are used to assess the learning curve. Regarding the duration of the learning phase, test drivers had to state at T2 how long it took them to adapt to regenerative braking.

5.1.4 General Evaluation of the Regenerative Braking System

After 3 months (T1), drivers were asked via open questions (“How did you experience regenerative braking?”) about their (2) general evaluation of regenerative braking. In addition, the well-established van der Laan Acceptance Scale (Van der Laan, Heino, and de Waard 1997) and three items on system modifications (e.g. “I wish I could switch off regenerative braking if required.”) were administered.

5.2 Results

5.2.1 Vehicle handover – Think-aloud Task during Test Drive (T0)

When drivers referred to the system on a global level, most users (90%) evaluated the system positively. Fifty-one percent of the participants discussed implications of regenerative braking, for instance for the driving task. Drivers expected that the usage of conventional braking would in most cases no longer be necessary, if the vehicle was equipped with

Citation: Cocron, P., Bühler, F., Franke, T., Neumann, I., Dielmann, B., & Krems, J. F. (2013). Energy recapture through deceleration – regenerative braking in electric vehicles from a user perspective. *Ergonomics*, 56(8), 1203-1215. [dx.doi:10.1080/00140139.2013.803160](https://doi.org/10.1080/00140139.2013.803160)

regenerative braking. According to the drivers the system affected the driving especially when approaching traffic lights or roadway curves.

Apart from technical issues, learning to handle the regenerative braking system is one of the main issues drivers talked about during their first interaction with the EV. Almost all drivers (95%) referred to the ease of learning to use the system. However, drivers stated that they would have to adapt to a new kind of driving: accelerating and decelerating with one pedal.

5.2.2 *Learning to Decelerate with Regenerative Braking*

In the final interview at T2 drivers were asked to specify the learning period in retrospective. Framed to hours necessary to adapt, drivers stated that it took them on average less than a day ($M = 22.35$ hrs, $SD = 60.31$) to adapt to regenerative braking. There was considerable variance in the data. Whereas for some the adaptation process was completed after the initial test drive, others reported to have needed 2 weeks to adapt to the system. Driver descriptions of a quick learning process are supported by the vehicle data. Both braking parameters ($B_{\text{man}}, B_{\text{prop}}$) showed a rapid decrease at the beginning and then remained at constant. This means that not only the total number of braking manoeuvres per 100 km (B_{man}) rapidly decreased, but also that the proportion of brake pedal use in all deceleration manoeuvres (B_{prop}) declined. Due to the high variance in the data of parameter B_{man} , a log transformation was applied before fitting the learning curve on average performance. The adjusted values for B_{man} are plotted in Figure 1.

Insert Figure 1 here

Citation: Cocron, P., Bühler, F., Franke, T., Neumann, I., Dielmann, B., & Krems, J. F. (2013). Energy recapture through deceleration – regenerative braking in electric vehicles from a user perspective. *Ergonomics*, 56(8), 1203-1215. [dx.doi:10.1080/00140139.2013.803160](https://doi.org/10.1080/00140139.2013.803160)

The analysis of the second parameter B_{prop} also showed a rapid drop in the first 50 km of driving the EV. After the initial decrease the proportion of brake pedal use applied to decelerate quickly reached the asymptote. The mean values of participants and the learning curve, which is fitted to the average, are plotted in Figure 2. The best fitting power functions are displayed in Table 1. The indicator for the goodness of fit is the root mean square error (RMSE). Smaller RMSE values indicate higher accuracy of the model. Parameter estimation was calculated based on Cousineau and Lacroix (2006). Data from the data loggers suggest that in Study Period 1, learning to use regenerative braking instead of conventional braking follows a power function.

Insert Figure 2 here

Insert Table 1 here

Most of the adaptation process appeared to occur within the first 50 km of driving the test vehicle (Figure 2). Both learning rates (B_{man} : $c = -1.06$; B_{prop} : $c = -0.85$) reveal a steep decrease at the beginning of the interaction with the vehicle, whereupon B_{man} results in a better fit (Table 1). In the interviews, participants reported a considerable need to adapt, but

Citation: Cocron, P., Bühler, F., Franke, T., Neumann, I., Dielmann, B., & Krems, J. F. (2013). Energy recapture through deceleration – regenerative braking in electric vehicles from a user perspective. *Ergonomics*, 56(8), 1203-1215. [dx.doi:10.1080/00140139.2013.803160](https://doi.org/10.1080/00140139.2013.803160)

also mentioned a short learning phase. The user assessment of a quick adaptation phase is supported by the objective data from the data loggers in Study Period 1.

5.2.3 General Evaluation of the Regenerative Braking System

Overall, after extended driving experience the majority of the drivers (82%) evaluated the system very positively, in reducing the energy consumption, making conventional braking unnecessary and affording pleasure of use. The remaining 18% of our test drivers also mentioned negative aspects in the interviews, such as the layout of the system. The need to adapt to regenerative braking was often mentioned in the driver evaluation after three months (T1). When asked about regenerative braking in particular, fifty-six percent of drivers emphasized the need to adapt, during the interview at T1. According to test drivers, the driving task was affected by regenerative braking, although they reported to have learned quickly how to handle the system.

Nevertheless, some drivers reported difficulties when adapting to the system. During the first days of EV usage the automatic deceleration caused by the system was too strong for 15% of the drivers. Other drivers (13%) mentioned that at the beginning they often stopped too early, for instance, at a traffic light as they underestimated the deceleration of the system. However, they reported that after the initial adaptation phase they managed to decelerate quite accurately as they used the pedal more sensitively. One driver additionally explained that during stop-and-go the deceleration was sometimes too abrupt; another driver mentioned that in some situations he just wanted to coast. In the accompanying questionnaire after three months, 23% wished to modify the system themselves and 10% even wished to be able to switch-off the system.

Citation: Cocron, P., Bühler, F., Franke, T., Neumann, I., Dielmann, B., & Krems, J. F. (2013). Energy recapture through deceleration – regenerative braking in electric vehicles from a user perspective. *Ergonomics*, 56(8), 1203-1215. [dx.doi:10.1080/00140139.2013.803160](https://doi.org/10.1080/00140139.2013.803160)

According to the participants, driving with mainly one pedal becomes a routine and was increasingly automated. For some drivers the new form of deceleration became so automated that they reported the need to re-adapt to conventional ICE vehicles after extended EV usage. Twenty-five percent of the drivers referred to surprise effects when driving a conventional vehicle again. When lifting the foot from the accelerator, these drivers were expecting the strong deceleration of their EV while at first not noticing that they were driving another car. Closely related to those take-over situations in conventional vehicles was the notion that conventional friction brakes were only used for emergency braking. Thirteen percent of the drivers referred to the friction brake as a system only for emergency braking as they used regenerative braking for most deceleration manoeuvres.

Regarding the impact of the system on the surrounding traffic, 15% of the drivers were unsure if and when the brake lights of the EV would light up when using regenerative braking. After three months few drivers (10%) were still unsure about the deceleration of the system as they could not exactly predict the deceleration in differing driving situations. One driver reported that during deceleration manoeuvres, he kept his foot above the brake pedal to make sure that he could quickly apply the friction brake if needed.

The data from the questionnaires violated the assumptions of parametric tests, therefore non-parametric procedures were used. Effect sizes are calculated according to Rosenthal (1991, as quoted in Field 2009). Even if certain drawbacks and uncertainties existed concerning the regenerative braking system, the overall evaluation of the system is very positive. The van der Laan Acceptance Scale (Van der Laan, Heino, and de Waard 1997) ranging from -2 to +2, revealed quite high values on Satisfaction ($Mdn = 1.75$, $IQR = 0.75$) and very high values on Usefulness ($Mdn = 2.00$, $IQR = 0.40$), whereupon the system is significantly regarded as more useful than satisfying, $z = -2.79$, $p = .005$, $r = -.32$. Additional

Citation: Cocron, P., Bühler, F., Franke, T., Neumann, I., Dielmann, B., & Krems, J. F. (2013). Energy recapture through deceleration – regenerative braking in electric vehicles from a user perspective. *Ergonomics*, 56(8), 1203-1215. [dx.doi:10.1080/00140139.2013.803160](https://doi.org/10.1080/00140139.2013.803160)

analyses revealed negative correlations between the subjective duration of the learning phase and Usefulness ($r_s = -.46, p = .005$) of and Satisfaction ($r_s = -.52, p = .001$) with the system at T1.

5.3 Discussion

The main objectives of Study Period 1 were to examine how drivers (1) learned to interact with regenerative braking and how they (2) generally evaluated the system with regard to strengths and weaknesses. The subjective appraisal of a quick learning process is supported by the analysis of braking parameters. These parameters indicate that the amount of conventional braking, that is, decelerating via brake pedal, is substantially reduced over the first 50 km of driving. The skill acquisition in using regenerative braking instead of conventional friction braking appears to follow the Power Law of Practice. As reported by the participants, the greatest adjustments in braking behaviour occurred relatively quickly. In both braking parameters the asymptote was reached within 50 km.

The results further showed that drivers appreciate the regenerative braking function as it was implemented in the test vehicle. Acceptance of the system was high in our sample, although the system was regarded as more useful than satisfying. The opportunity to regain energy via deceleration appealed to the participants. Besides the positive evaluation, it became clear that the system had a substantial impact on the driving task, forcing the drivers to adapt to a new mode of deceleration. However, for the majority of the test drivers the subjective adaptation phase was completed within 1 day of driving the EV. As there existed a negative correlation between Acceptance and the reported learning duration, this could be accounted for in system design (see 7. Conclusions from the 1-Year Field Study).

Citation: Cocron, P., Bühler, F., Franke, T., Neumann, I., Dielmann, B., & Krems, J. F. (2013). Energy recapture through deceleration – regenerative braking in electric vehicles from a user perspective. *Ergonomics*, 56(8), 1203-1215. [dx.doi:10.1080/00140139.2013.803160](https://doi.org/10.1080/00140139.2013.803160)

User feedback from Study Period 1 also indicates, that some drivers had difficulties when adapting to the system. In the beginning, the automatic deceleration caused by the system was too strong for some participants; others reported that during the first days they frequently stopped too early at traffic lights as they could not predict the exact deceleration by the system.

After the adaptation phase was completed, some drivers reported surprise effects when driving a conventional vehicle again. Used to regenerative braking, they were somehow expecting a strong deceleration in their conventional car, although regenerative braking was missing there. This result is in line with Reason's assumption (2008) that slips, such as strong habit intrusions, are more likely to occur if features of the present and the familiar environment resemble each other much. This might also apply to switching between electric and conventional vehicle types. Still, these drivers reported no severe consequences of this temporary confusion and could manage such take-over situations. Related to the reported surprise effects in ICE vehicles is the notion of the friction brake as an emergency brake. After using regenerative braking for an extended period of time, the need to conventionally brake could be challenging for the drivers. Such take-over situations should be investigated in future studies.

Uncertainties about the system's status or actions and the absence of different deceleration intensities might hinder drivers from utilizing the system correctly. In order to drive safe and energy efficient, drivers need to be able to accurately predict the system's actions, which in turn requires trust. We assumed that especially the need to modify the system and the uncertainty about certain of its features are related to drivers' trust. Muir (1994) argues that in order for trust to be built, the user has to be able to test the system in varying situations. Therefore, in addition to validate the findings of Study Period 1, research

Citation: Cocron, P., Bühler, F., Franke, T., Neumann, I., Dielmann, B., & Krems, J. F. (2013). Energy recapture through deceleration – regenerative braking in electric vehicles from a user perspective. *Ergonomics*, 56(8), 1203-1215. [dx.doi:10.1080/00140139.2013.803160](https://doi.org/10.1080/00140139.2013.803160)

questions for Study Period 2 focussed more on (1) the initial phase of the learning process, (3) the evolution of trust and (4) acceptance to derive (5) suggestions for future regeneration systems.

6. Study Period 2

6.1 Methods

6.1.1 Sample

A second sample of 40 users (35 men, 5 women) drove an EV for six months in Study Period 2. The sample was on average 50 years old ($SD = 10.2$). Twenty percent of users reported some driving experience with the test vehicle; for instance, they had tested the MINI E of a friend. Besides that, 13% of the participants had previous experience with regenerative braking in a HEV. On average drivers possessed their driving license for 31 years ($SD = 9.9$). In this study period one participant dropped out.

6.1.2 Learning to Decelerate with Regenerative Braking – the Initial Phase

When the vehicles were handed over to the participants in Study Period 2, participants accomplished a test drive (T0.2) in their assigned vehicles. As participants drove the same route (approx. 2.5 km) during the test drive, learning conditions for the initial interaction with regenerative braking could therefore be controlled more. In Study Period 1 the greatest adjustments in braking behaviour could be seen during the first 50 km of driving the EV, so this range is focused in Study Period 2. Due to more monitoring and the explanation of the importance of the logger data especially at vehicle handover (T0), data from 37 drivers could be included in the analysis.

Citation: Cocron, P., Bühler, F., Franke, T., Neumann, I., Dielmann, B., & Krems, J. F. (2013). Energy recapture through deceleration – regenerative braking in electric vehicles from a user perspective. *Ergonomics*, 56(8), 1203-1215. [dx.doi:10.1080/00140139.2013.803160](https://doi.org/10.1080/00140139.2013.803160)

6.1.4 Evaluation of Regenerative Braking Regarding Trust and Acceptance

Based on the findings of Study Period 1, the participants were also asked about their expectations concerning the regenerative braking system before they drove the car for the first time. Special attention was paid to the longitudinal development of system (3) trust and (4) acceptance. General information about the functionality of the system was provided for the participants to ensure basic knowledge. Scale items on trust in cruise control (Cahour and Forzy 2009) were adapted to regenerative braking. The adapted short scale Trust consisted of four items on general confidence in the system, predictability, reliability and perceived efficiency. Muir (1994) emphasized the importance of longer testing periods for the development of system trust; therefore Trust was repeatedly assessed in the present study. Before the initial test drive (T0.1), after the first drive (T0.3), after 3 months (T1) and upon returning the EV after 6 months (T2), participants rated their trust in the regenerative braking system. Additional items on system modification (e.g. “I wish I could switch off regenerative braking if required.”) as a counterpart to the Trust scale were included in the midterm questionnaire at T1. Acceptance was assessed at T0.3 and at T1 via the van der Laan Acceptance Scale (Van der Laan, Heino, and de Waard 1997). Additionally, the number of system failures was assessed at T1.

6.2 Results

6.2.1 Learning to Decelerate with Regenerative Braking – the Initial Phase

The first objective of Study Period 2 was to validate the learning curves identified in Study Period 1. As performed in Study Period 1, values of B_{man} were log-transformed. In Study Period 2 the number of braking manoeuvres also rapidly decreased (B_{man} : $c = -1.01$) and the resulting asymptote ($a = 1.26$) was comparable to Study Period 1 ($a = 1.63$). The second

Citation: Cocron, P., Bühler, F., Franke, T., Neumann, I., Dielmann, B., & Krems, J. F. (2013). Energy recapture through deceleration – regenerative braking in electric vehicles from a user perspective. *Ergonomics*, 56(8), 1203-1215. [dx.doi:10.1080/00140139.2013.803160](https://doi.org/10.1080/00140139.2013.803160)

braking parameter (B_{prop}) revealed a similar picture. The rapid adjustment of braking behaviour was also detected. The resulting asymptote in Study Period 2 ($a = 3.28$) reached a similar level as that in Study Period 1 ($a = 3.86$). In both parameters the asymptote was reached within the first 50 km. Details on the power function can be found in Table 2.

Insert Table 2 here

In Study Period 2, the (1) initial learning process was evaluated in more detail. Since the test drive was conducted on the same standardized route for all participants, the initial learning conditions were comparable. Nevertheless, traffic conditions, such as congestion and signal phases could not be controlled for. The analysis of the first interaction reveals that the greatest adjustments in braking behaviour already took place during the test drive and the first kilometres driven that followed. B_{man} is plotted in Figure 3, B_{prop} in Figure 4.

Insert Figure 3 here

Insert Figure 4 here

Citation: Cocron, P., Bühler, F., Franke, T., Neumann, I., Dielmann, B., & Krems, J. F. (2013). Energy recapture through deceleration – regenerative braking in electric vehicles from a user perspective. *Ergonomics*, 56(8), 1203-1215. [dx.doi:10.1080/00140139.2013.803160](https://doi.org/10.1080/00140139.2013.803160)

The results from Study Period 2 support the notion of a quick learning process, especially due to the standardized test drive. Major adjustments in braking behaviour occurred as early as during the first interaction with the vehicle during the test drive.

6.2.2 Evaluation of Regenerative Braking Regarding Trust and Acceptance

Another main objective of Study Period 2 was to further investigate (3) the development of system trust towards regenerative braking. The data satisfied standard requirements (i.e. KMO, Bartlett's test) for performing factor analyses (main component analyses). The factor analysis at T0.1 indicated that one factor, labelled as Trust, explained 76.51% of the variance. The scale Trust revealed acceptable reliabilities in the following times of measurement ($.60 \leq \text{Cronbach's } \alpha \leq .89$). As in Study Period 1 the data violated the assumptions of parametric tests, therefore non-parametric procedures such as Friedman's ANOVA were used. Follow-up pairwise comparisons are calculated using Wilcoxon tests. Effect sizes are calculated according to Rosenthal (1991, as quoted in Field 2009). The results are illustrated in Figure 5.

Insert Figure 5 here

Friedman's ANOVA showed a considerable increase in trust towards regenerative braking, $\chi^2(3, N = 38) = 23.97, p < .001$. Post hoc tests showed that system trust increased significantly from T0.1 to T0.3, $p < .001, r = -.47$ and then remained relatively constant.

Citation: Cocron, P., Bühler, F., Franke, T., Neumann, I., Dielmann, B., & Krems, J. F. (2013). Energy recapture through deceleration – regenerative braking in electric vehicles from a user perspective. *Ergonomics*, 56(8), 1203-1215. [dx.doi:10.1080/00140139.2013.803160](https://doi.org/10.1080/00140139.2013.803160)

Acceptance of regenerative braking as an additional focus of research (4) showed a similar trend as Trust. Acceptance for the system was already high at T0.3 in both subscales, Usefulness ($Mdn = 1.80$, $IQR = 0.40$) and Satisfaction ($Mdn = 1.38$, $IQR = 0.94$). A significant increase until T1 was found only in Satisfaction ($Mdn = 1.75$, $IQR = 0.94$), $z = -2.18$, $p = .029$, $r = -.24$. The participants rated Usefulness equally high as in the beginning of the study, $Mdn = 1.80$, $IQR = 0.60$; $z = -7.21$, $p = .471$, $r = -.08$.

As counterpart to Trust and Acceptance, three items on the need to modify regenerative braking were again included in Study Period 2. Together they form one factor Modify, which explained 65.73% of the variance (Cronbach's $\alpha = .70$). Although the need to modify the system is relatively low on the 6-point Likert scale ($Mdn = 2.0$, $IQR = 1.67$), some participants expressed the need to customize regenerative braking. For those, the system was also less trustworthy, $r_s = -.41$, $p = .008$. Additional analyses revealed an inverse relationship between Modify and Satisfaction, $r_s = -.46$, $p = .003$, as well as between Modify and Usefulness, $r_s = -.47$, $p = .002$.

The reported number of system failures within the first 3 months was also negatively associated with trust, although this was not significant, $r_s = -.22$, $p = .175$. In this context it should be noted that according to the drivers, the regenerative braking system failed on average less than once ($M = 0.78$, $SD = 1.96$) during the first three months of usage.

6.2.3 The Relation between System Usage and System Evaluation

The results reported above indicate a positive development of system trust over the course of the study, high acceptance and a quick learning process. In Trust and the learning process changes occurred within a short period of time. Data on Trust from T1 and T2, Modify as well as Usefulness and Satisfaction were correlated with mean performance scores of the braking

Citation: Cocron, P., Bühler, F., Franke, T., Neumann, I., Dielmann, B., & Krems, J. F. (2013). Energy recapture through deceleration – regenerative braking in electric vehicles from a user perspective. *Ergonomics*, 56(8), 1203-1215. [dx.doi:10.1080/00140139.2013.803160](https://doi.org/10.1080/00140139.2013.803160)

parameters B_{man} and B_{prop} . For T1 and T2, mean scores for the week before each data collection were calculated.

Muir and Moray (1996) showed that system trust and system usage correlate. In Study Period 2, this relationship was also examined as part of the research objectives on trust (3). The results show no significant relationships between the braking parameters and system trust over the course of the study (Table 3). A positive relation between the usage of an Intelligent Speed Adaptation (ISA) system and acceptance has been reported by Jamson (2006). This was investigated as part of the research objectives on (4) acceptance. In the present study Usefulness and Satisfaction are not significantly related to B_{man} and B_{prop} at T1. Significant relations between actual behaviour and the evaluation can be shown in the scale Modify. As a counterpart to Trust and Acceptance Modify is positively related to the braking parameter B_{man} at T1, $r_s = .34$, $p = .041$ and at T2, $r_s = 0.38$, $p = .029$. Furthermore at T2 Modify is also positively related to B_{prop} , $r_s = .38$, $p = .032$. Participants who feel the need to modify the system tend to use conventional braking strategies more and vice versa (Table 3).

6.3 Discussion

The notion of a short adaptation phase is supported by the data from the two braking parameters. To obtain a better understanding of the initial interaction with the system, the first 50 kilometres driven were assessed in more detail. The braking manoeuvres per 100 km and the proportion of braking in all deceleration manoeuvres rapidly decreased. Learning curves in both parameters showed the typical shape of a learning curve. The curvatures of the calculated parameters identified in Study Period 1 could be replicated in Study Period 2 and the adjustment phases were comparable.

Although drivers needed to adapt to the regenerative braking system, accelerating and

Citation: Cocron, P., Bühler, F., Franke, T., Neumann, I., Dielmann, B., & Krems, J. F. (2013). Energy recapture through deceleration – regenerative braking in electric vehicles from a user perspective. *Ergonomics*, 56(8), 1203-1215. [dx.doi:10.1080/00140139.2013.803160](https://doi.org/10.1080/00140139.2013.803160)

decelerating with one pedal is appreciated among the drivers of Study Period 2. Participants of Study Period 2 generally trusted and accepted the regenerative braking system as it was implemented in the test vehicle. Even though the system was perceived as trustworthy before driving the car for the first time, trust increased, in particular, after the first interaction with the vehicle. Afterwards, system trust remained constantly at a high level. Although system faults could only be reported retrospectively, our findings are comparable to past research on user trust (Kazi et al. 2007; Lee and Moray 1992). As in Trust, results of the Satisfaction scale implied that drivers appreciated the system even more after some experience; the perceived usefulness remains constantly high. Our findings on acceptance therefore point in a similar direction as results of Turrentine et al. (2011) and Schmitz et al. (2012) for one pedal driving.

Nevertheless, the wish to modify the system individually seems to play an essential role in the evaluation of regenerative braking. The Modify scale negatively corresponded with Trust, Satisfaction and Usefulness thus implying that modifications of the system appeared to be necessary for some drivers. Self-reported system failures usually have a negative effect on trust, although this could not be detected in the present study. In general, the system was evaluated as functioning very reliably.

Research on operator trust suggests that the more an operator trusts a system, the more he uses it (Muir and Moray 1996). Similar findings for system acceptance and system usage are reported by Jamson (2006). Based on those findings we assumed that the less frequently participants use conventional friction braking, the more they trust and accept regenerative braking. However, no significant relationship between system usage and trust or acceptance could be detected in our study. A possible explanation could be the high variance in the braking data. Decelerating only with the accelerator pedal depends heavily on the traffic

conditions, faced by each participant. Therefore, each participant had varying opportunities to apply regenerative braking.

In our study the need to modify the system as part of the driver evaluation correlated positively with the behavioural braking parameters. Drivers who expressed the wish to modify or switch off the system also used more conventional braking strategies instead of decelerating via regenerative braking. This emphasizes the findings of Study Period 1, which showed that some people reported some difficulties with the system and took longer to adapt in general. For those participants it appears reasonable to provide more information about the functionalities and potential of the system as well as give the opportunity to technically customize the amount of deceleration caused by regenerative braking. The possibility of changing regeneration intensities or even switching off the system appears promising in this context.

7. Conclusions from the 1-Year Field Study

If electrically propelled vehicles are marketed on a larger scale, the driving task, particularly the deceleration, will change. In our study participants appreciated regenerative braking which was triggered via accelerator. System trust quickly developed, the learning curve revealed a short adjustment phase. Drivers' feeling of control was enhanced by the possibility of regaining some of the usually lost kinetic energy. Moreover, the system decelerated quite rapidly, which contributed to the sporty feel of the vehicle. This and the notion of interacting with a sustainable technology seemed to appeal to the drivers.

Our findings have (5) implications for different stakeholders of the traffic system. The study suggests that drivers quickly adapt to a regeneration system which decelerates

Citation: Cocron, P., Bühler, F., Franke, T., Neumann, I., Dielmann, B., & Krems, J. F. (2013). Energy recapture through deceleration – regenerative braking in electric vehicles from a user perspective. *Ergonomics*, 56(8), 1203-1215. [dx.doi:10.1080/00140139.2013.803160](https://doi.org/10.1080/00140139.2013.803160)

considerably. Furthermore, drivers generally appreciate driving with one pedal. The potential of haptic feedback via pedal was also recently discussed in the context of eco-driving with conventional vehicles (Birrell, Young, and Weldon, 2013). Manufacturers could include the findings in decisions on the system's intensity and if regeneration should be triggered mainly by the accelerator or the brake pedal. As some drivers wished to modify the system individually and there exists a negative relation between acceptance and the reported learning duration, it may be reasonable to integrate different levels of regeneration in future EVs. As a consequence drivers could modify the system individually and could gradually increase the deceleration during the early days of usage. Drivers might therefore have fewer problems while learning to use the system. Afterwards different levels of regeneration would enable the drivers to flexibly react towards different driving situations, such as driving in stop-and-go traffic or going downhill. Driver's preferences could be accounted for, especially for those who reported difficulties in the beginning. To avoid temporary confusion when switching between vehicle types, drivers should be informed about the existence and layout of regenerative braking when starting the vehicle.

As soon as EVs become more widespread, the existence of regenerative braking in vehicles might also have implications for driver training as curricula might have to be adjusted. As considerable barriers exist already among potential buyers (Egbue and Long 2012), it appears necessary to emphasize that even if the driving task might be different in an EV with accelerator triggered regeneration, drivers usually quickly adapt to the new system.

Findings of the large field study on user interactions with EVs suggest that accelerator triggered regenerative braking can be integrated in the driving task rapidly. A future system could benefit from the option to modify the deceleration intensity or even to deactivate it.

Citation: Cocron, P., Bühler, F., Franke, T., Neumann, I., Dielmann, B., & Krems, J. F. (2013). Energy recapture through deceleration – regenerative braking in electric vehicles from a user perspective. *Ergonomics*, 56(8), 1203-1215. [dx.doi:10.1080/00140139.2013.803160](https://doi.org/10.1080/00140139.2013.803160)

8. Acknowledgements

The present study was funded by the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety. We are grateful for the support of our consortium partners, Vattenfall Europe AG (Dr. C. F. Eckhardt and F. Schuth) and the BMW Group (G. Schmidt, Dr. M. Hajesch, Dr. A. Keinath and Dr. M. Schwalm) which made our research possible. We thank Dr. M. Hajesch for his valuable comments on the manuscript. We also gratefully thank Katja Gabler, Florian Fritzsche and their colleagues at the BMW Group for performing data pre-processing of the logger data.

Citation: Cocron, P., Bühler, F., Franke, T., Neumann, I., Dielmann, B., & Krems, J. F. (2013). Energy recapture through deceleration – regenerative braking in electric vehicles from a user perspective. *Ergonomics*, 56(8), 1203-1215. [dx.doi:10.1080/00140139.2013.803160](https://doi.org/10.1080/00140139.2013.803160)

9. References

- Berman, B. 2011. "Honda Reinvents Regenerative Braking for Fit EV." Plugincars.com. Accessed October 24 2012. <http://www.plugincars.com/honda-reinvents-regenerative-braking-fit-ev-110596.html>
- Birrell, S. A., M. S. Young, and A. M. Weldon. 2013. "Vibrotactile pedals: provision of haptic feedback to support economical driving." *Ergonomics*, 56 (2): 282-292.
- Brown S., and A. Heathcote. 2003. "Averaging Learning Curves Across and Within Participants." *Behavior Research Methods, Instruments, & Computers*, 35: 11-21.
- Cahour, B., and J. F. Forzy. 2009. "Does Projection Into Use Improve Trust and Exploration? The Case of a Cruise Control System." *Safety Science*, 47 (9): 1260-1272.
- Cikanek, S. R., and K. E. Bailey. 2002. "Regenerative Braking System For A Hybrid Electric Vehicle." Paper presented at the American Control Conference, Anchorage, AK, May 8-10.
- Cocron, P., F. Bühler, I. Neumann, T. Franke, J. F. Krems, M. Schwalm, and A. Keinath. 2011. Methods of evaluating electric vehicles from a user's perspective - the MINI E field trial in Berlin. *IET Intelligent Transport Systems*, 5 (2): 127-133.
- Comte, S. L. 2000. "New Systems: New Behaviour?" *Transportation Research Part F*, 3: 95-111.
- Cousineau, D., and G. L. Lacroix. 2006. "Getting Parameters from Learning Data." *Tutorials in Quantitative Methods for Psychology*, 2 (2): 77-83.
- Eberl, T., R. Sharma, R. Stroph, J. Schumann and A. Pruckner. 2012. "Evaluation of interaction concepts for the longitudinal dynamics of electric vehicles." In *Advances in Human Factors and Ergonomics 2012- 14 Volume Set: Proceedings of the 4th AHFE Conference 21-25 July 2012*, edited by G. Salvendy & W. Karwowski. San Francisco: CRC Press.
- Egbue, O., and S. Long. 2012. "Barriers of Widespread Adoption of Electric Vehicles: An Analysis of Consumer Attitudes and Perceptions." *Energy Policy*, 48: 717-729.
- Everett, A., C. Walsh, K. Smith, M. Burgess, and M. Harris. 2010. "Ultra Low Carbon Vehicle Demonstrator Programme." Paper presented at the 25th World Battery, Hybrid and Fuel Cell Electric Vehicle Symposium & Exhibition, Shenzhen, China, November 5-9.
- Field, A. 2009. *Discovering Statistics Using SPSS*. London: Sage.

Citation: Cocron, P., Bühler, F., Franke, T., Neumann, I., Dielmann, B., & Krems, J. F. (2013). Energy recapture through deceleration – regenerative braking in electric vehicles from a user perspective. *Ergonomics*, 56(8), 1203-1215. [dx.doi:10.1080/00140139.2013.803160](https://doi.org/10.1080/00140139.2013.803160)

- Franke, T., F. Bühler, P. Cocron, I. Neumann and J.F. Krems. 2012. "Enhancing sustainability of electric vehicles: A field study approach to understanding user acceptance and behavior." In *Advances in Traffic Psychology*, edited by M. Sullman & L. Dorn. 295-306. Farnham, UK: Ashgate.
- Gould, J., and T. F. Golob. 1998. "Clean Air Forever? A Longitudinal Analysis of Opinions About Air Pollution and Electric Vehicles." *Transportation Research Part D: Transport and the Environment*, 3 (3): 157-169.
- Haslam, R., and P. Waterson. 2013. "Ergonomics and Sustainability." *Ergonomics*, 56 (3): 343-347.
- Jahn, G., J. F. Krems, and C. Gelau. 2009. "Skill Acquisition While Operating In-Vehicle Information Systems: Interface Design Determines the Level of Safety-Relevant Distractions." *Human Factors*, 51 (2): 136-151.
- Jamson, S. 2006. "Would Those Who Need ISA, Use It? Investigating the Relationship Between Drivers' Speed Choice and Their Use of a Voluntary ISA System." *Transportation Research Part F: Traffic Psychology and Behaviour*, 9 (3): 195-206.
- Kazi, T. A., N. A. Stanton, G. H. Walker, and M. S. Young. 2007. "Designer Driving: Drivers' Conceptual Models and Level of Trust in Adaptive Cruise Control." *International Journal of Vehicle Design*, 45 (3): 339-360.
- Lacroix, G. L., and D. Cousineau. 2006. "The Introduction to the Special Issue on " $RT(N) = a + bN^{-c}$ ": The Power Law of Learning 25 years later." *Tutorials in Quantitative Methods for Psychology*, 2 (2): 38-42.
- Lee, J., and N. Moray. 1992. "Trust, Control Strategies and Allocation of Function in Human-Machine Systems." *Ergonomics*, 35 (10): 1243-1270.
- Muir, B. M. 1994. "Trust in Automation: Part 1. Theoretical Issues in the Study of Trust and Human Intervention in Automated Systems." *Ergonomics*, 37: 1905-1922.
- Muir, B. M., and N. Moray. 1996. "Trust in Automation: Part II. Experimental Studies of Trust and Human Intervention in a Process Control Simulation." *Ergonomics*, 39 (3): 429-460.
- Newell, A., and P. S. Rosenbloom. 1981. "Mechanisms of Skill Acquisition and the Law of Practice." In *Cognitive skills and their acquisition*, edited by J.R. Anderson, 1-55. Hillsdale, NJ: Erlbaum.

Citation: Cocron, P., Bühler, F., Franke, T., Neumann, I., Dielmann, B., & Krems, J. F. (2013). Energy recapture through deceleration – regenerative braking in electric vehicles from a user perspective. *Ergonomics*, 56(8), 1203-1215. [dx.doi:10.1080/00140139.2013.803160](https://doi.org/10.1080/00140139.2013.803160)

- Rajaonah, B., F. Anceaux, and F. Vienne. 2006. "Trust and the Use of Adaptive Cruise Control: A Study of a Cut-in Situation." *Cognition, Technology and Work*, 8 (2): 146-155.
- Reason, J. 2008. *The Human Contribution: Unsafe Acts, Accidents, and Heroic Recoveries*. Burlington: Ashgate.
- Ritter, F. E., and L. J. Schooler. 2001. "The Learning Curve." In *International Encyclopedia of the Social and Behavioral Science*, edited by N. Smelser and P. Baltes, 8602-8605, Amsterdam: Pergamon.
- Romm, J., and A. Frank. 2006. "Hybrid Vehicles Gain Traction." *Scientific American*, 294 (4): 72-79.
- Rosenthal, R. 1991. *Meta-analytic procedures for social research*. Newbury Park, CA: Sage.
- Rudin-Brown, C.M. and H.A Parker. 2004. "Behavioural Adaptation to Adaptive Cruise Control (ACC): Implications for Preventive Strategies." *Transportation Research Part F: Traffic Psychology and Behaviour*, 7: 59-76.
- Schmitz, M., M. Jagiellowicz, C. Maag, and M. Hanig. 2012. "The Impact of Different Pedal Solutions for Supporting Efficient Driving with Electric Vehicles." In *Proceedings of European on Human Centered Design for Intelligent Transport Systems (HUMANIST)*, edited by P. V. Mora, J.-F. Pace and L. Mendoza, 21-27. Lyon: Humanist Publications.
- Solberg, G. 2007. "The Magic of Tesla Roadster Regenerative Braking." *Teslamotors.com*. Accessed October 24 2012. <http://www.teslamotors.com/blog/magic-tesla-roadster-regenerative-braking>
- Turrentine, T., D. Garas, A. Lentz, and J. Woodjack. 2011. "The UC Davis MINI E Consumer Study". UCD-ITS-RR-11-05. Accessed October 24 2012. http://publications.its.ucdavis.edu/publication_detail.php?id=1470
- Van den Haak, M., M. de Jong, and P. Schellens. 2004. "Employing Think-aloud Protocols and Constructive Interaction to Test the Usability of Online Library Catalogues: A Methodological Comparison." *Interacting with Computers*, 16: 1153-1170.
- Van der Laan, J. D., A. Heino, and D. De Waard. 1997. "A Simple Procedure for the Assessment of Acceptance of Advanced Transport Telematics." *Transportation Research Part C: Emerging Technologies*, 5 (1): 1-10.

Citation: Cocron, P., Bühler, F., Franke, T., Neumann, I., Dielmann, B., & Krems, J. F. (2013). Energy recapture through deceleration – regenerative braking in electric vehicles from a user perspective. *Ergonomics*, 56(8), 1203-1215. [dx.doi:10.1080/00140139.2013.803160](https://doi.org/10.1080/00140139.2013.803160)

- Vilimek, R., A. Keinath, and M. Schwalm. 2012. "The MINI E field study - Similarities and differences in international everyday EV driving." In *Advances in Human Factors and Ergonomics 2012- 14 Volume Set: Proceedings of the 4th AHFE Conference 21-25 July 2012*, edited by G. Salvendy & W. Karwowski. San Francisco: CRC Press.
- Walsh, C., S. Carroll, A. Eastlake, and P. Blythe. 2010. "Electric Vehicle Driving Style and Duty Variation Performance Study." Accessed October 24 2012.
<http://www.nichevehiclenetwork.co.uk/LinkClick.aspx?fileticket=WTmGSFXB8qA%3d&tabid=531>

Citation: Cocron, P., Bühler, F., Franke, T., Neumann, I., Dielmann, B., & Krems, J. F. (2013). Energy recapture through deceleration – regenerative braking in electric vehicles from a user perspective. *Ergonomics*, 56(8), 1203-1215. [dx.doi:10.1080/00140139.2013.803160](https://doi.org/10.1080/00140139.2013.803160)

Indication of figures and tables

Figure captions

- Figure 1. Study Period 1: Mean number of braking manoeuvres per 100km (LOG) fitted with a power function.
- Figure 2. Study Period 1: Mean proportion of braking in total deceleration fitted with a power function.
- Figure 3. Study Period 2 (0–100km): Mean number of braking manoeuvres per 100km (LOG) fitted with a power function.
- Figure 4. Study Period 2 (0–100km): Mean proportion of braking in total deceleration, fitted with a power function.
- Figure 5. Study Period 2: Trust in regenerative braking (medians, error bars represent IQR).

Tables with captions:

- Table 1. Study Period 1: Power functions fitted to braking parameters (BP): Braking manoeuvres per 100 km (B_{man}) and proportion of braking manoeuvres (B_{prop}).
- Table 2. Study Period 2: Power functions fitted to braking parameters (BP): Braking manoeuvres per 100 km (B_{man}) and proportion of braking manoeuvres (B_{prop}).
- Table 3. Study Period 2: Relationship between Trust, Modify, Acceptance and Braking Parameters.

Citation: Cocron, P., Bühler, F., Franke, T., Neumann, I., Dielmann, B., & Krems, J. F. (2013). Energy recapture through deceleration – regenerative braking in electric vehicles from a user perspective. *Ergonomics*, 56(8), 1203-1215. [dx.doi:10.1080/00140139.2013.803160](https://doi.org/10.1080/00140139.2013.803160)

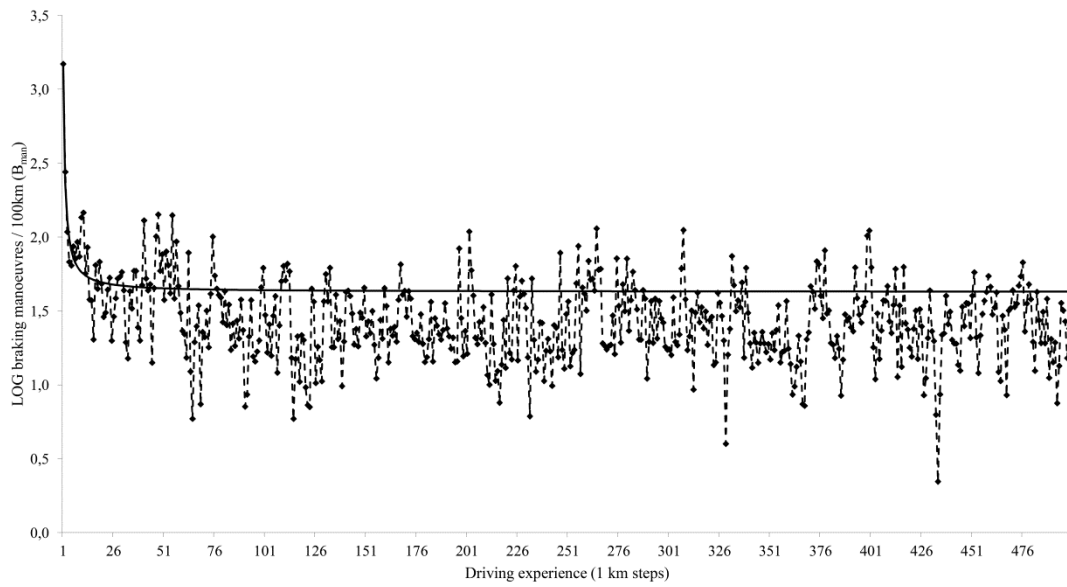


Figure 1 Study Period 1: Mean number of braking manoeuvres per 100km (LOG) fitted with a power function.

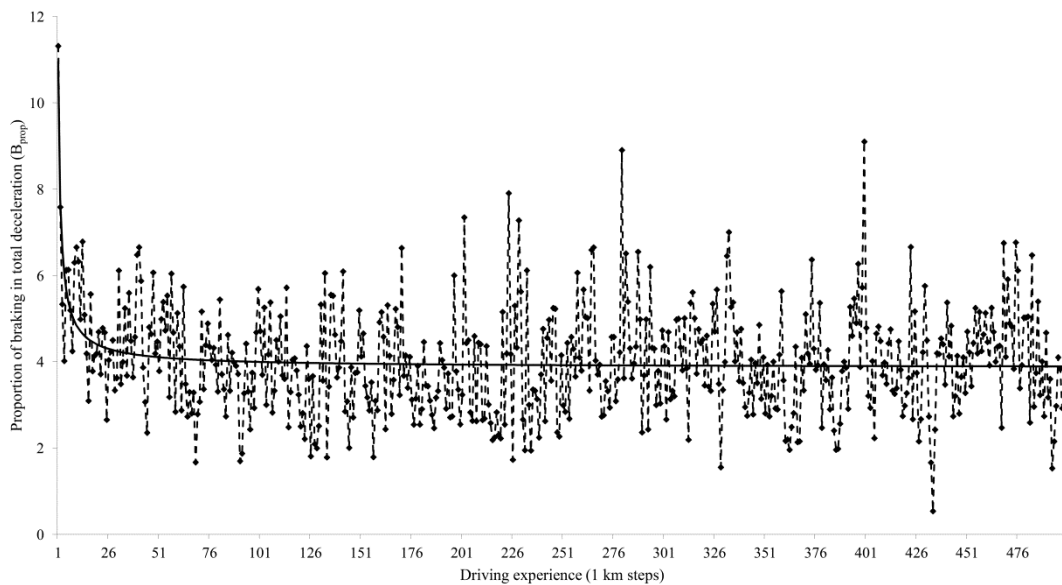


Figure 2 Study Period 1: Mean proportion of braking in total deceleration fitted with a power function.

Citation: Cocron, P., Bühler, F., Franke, T., Neumann, I., Dielmann, B., & Krems, J. F. (2013). Energy recapture through deceleration – regenerative braking in electric vehicles from a user perspective. *Ergonomics*, 56(8), 1203-1215. [dx.doi:10.1080/00140139.2013.803160](https://doi.org/10.1080/00140139.2013.803160)

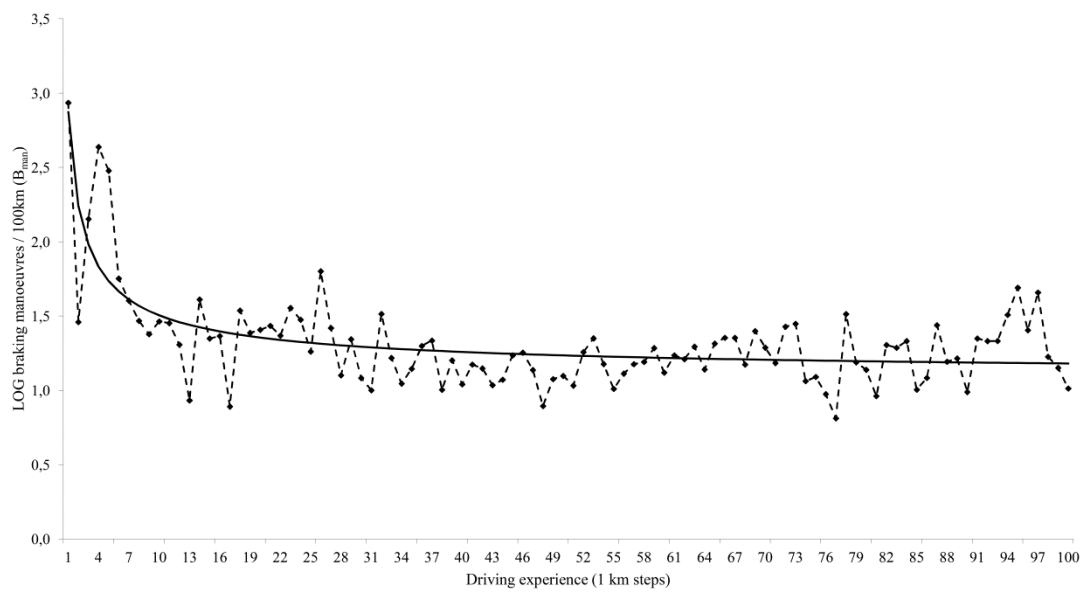


Figure 3 Study Period 2 (0–100km): Mean number of braking manoeuvres per 100km (LOG) fitted with a power function.

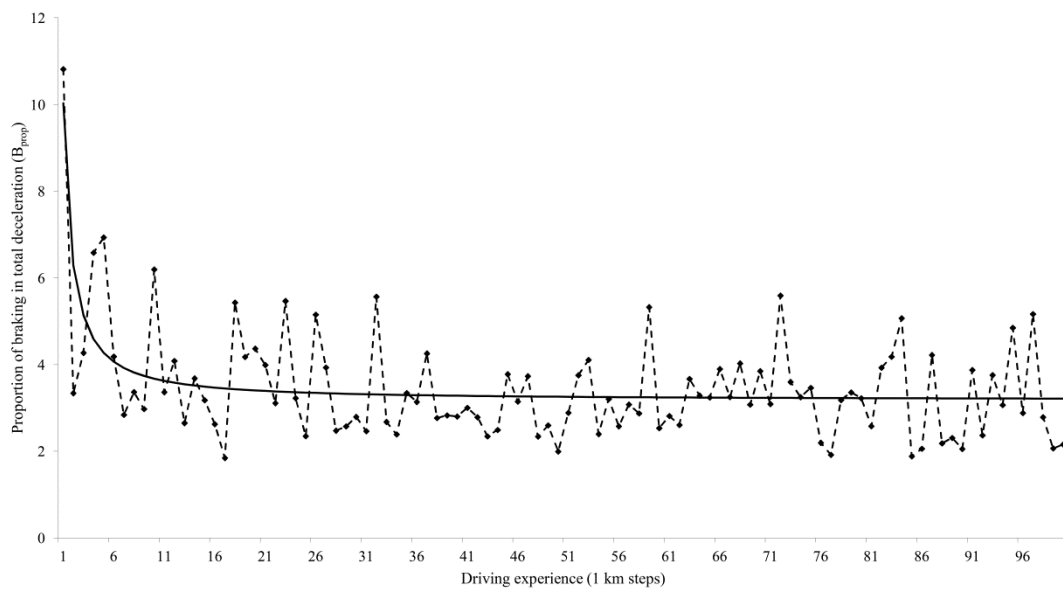


Figure 4 Study Period 2 (0–100km): Mean proportion of braking in total deceleration, fitted with a power function.

Citation: Cocron, P., Bühler, F., Franke, T., Neumann, I., Dielmann, B., & Krems, J. F. (2013). Energy recapture through deceleration – regenerative braking in electric vehicles from a user perspective. *Ergonomics*, 56(8), 1203-1215. [dx.doi:10.1080/00140139.2013.803160](https://doi.org/10.1080/00140139.2013.803160)

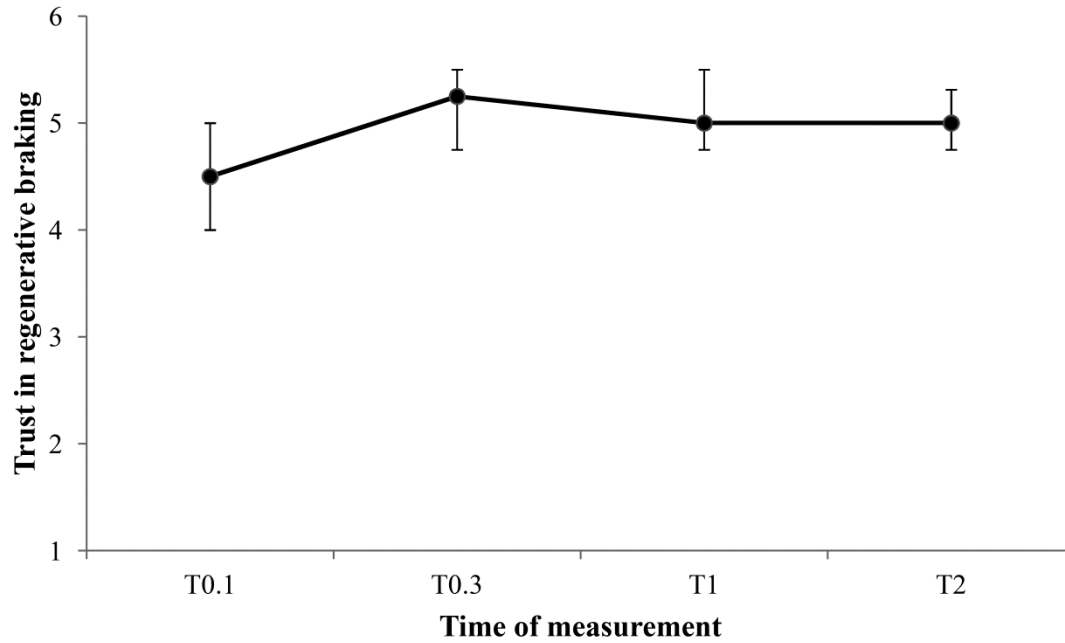


Figure 5 Study Period 2: Trust in regenerative braking (medians, error bars represent IQR).

Table 1 Study Period 1: Power functions fitted to braking parameters (BP): Braking manoeuvres per 100 km (B_{man}) and proportion of braking manoeuvres (B_{prop}).

Variable	BP ($N a,b,c$) = $a + bN^{-c}$	RMSE	Driving experience	Participants
B_{man}	$B_{\text{man}} = 1.63 + 1.55N^{-1.06}$	0.34	500×1 km	27
B_{prop}	$B_{\text{prop}} = 3.86 + 7.09N^{-0.85}$	1.20	500×1 km	27

Note: RMSE = root mean square error

Citation: Cocron, P., Bühler, F., Franke, T., Neumann, I., Dielmann, B., & Krems, J. F. (2013). Energy recapture through deceleration – regenerative braking in electric vehicles from a user perspective. *Ergonomics*, 56(8), 1203-1215. [dx.doi:10.1080/00140139.2013.803160](https://doi.org/10.1080/00140139.2013.803160)

Table 2 Study Period 2: Power functions fitted to braking parameters (BP): Braking manoeuvres per 100 km (B_{man}) and proportion of braking manoeuvres (B_{prop}).

Variable	BP ($N a,b,c$) = $a + bN^{-c}$	RMSE	Driving experience	Participants
B_{man}	$B_{\text{man}} = 1.26 + 1.74N^{-1.01}$	0.22	500×1 km	$N = 37$
B_{man}	$B_{\text{man}} = 1.08 + 1.79N^{-0.63}$	0.23	100×1 km	$N = 37$
B_{prop}	$B_{\text{prop}} = 3.28 + 7.01N^{-1.37}$	0.97	500×1 km	$N = 37$
B_{prop}	$B_{\text{prop}} = 3.17 + 6.85N^{-1.14}$	1.03	100×1 km	$N = 37$

Note: RMSE = root mean square error

Table 3 Study Period 2: Relationship between Trust, Modify, Acceptance and Braking Parameters.

		T1						T2		
		B _{man}	B _{prop}	Trust	Modify	Usefulness	Satisfaction	B _{man}	B _{prop}	Trust
T1	B _{man}	-	.81**	-.20	.34*	-.17	-.16	.53**	.50**	-.16
	B _{prop}	.81**	-	-.19	.29	-.15	-.12	.39*	.51**	-.19
	Trust	-.20	-.19	-	-.41**	.33*	.29	-.10	-.11	.67**
	Modify	.34*	.29	-.41**	-	-.47**	-.46**	.38*	.38*	-.41*
	Usefulness	-.17	-.15	.33*	-.47**	-	.76**	-.26	-.34	.49**
	Satisfaction	-.16	-.12	.29	-.46**	.76**	-	-.29	-.31	.34*
T2	B _{man}	.53**	.39*	-.10	.38*	-.26	-.29	-	.83**	-.09
	B _{prop}	.50**	.51**	-.11	.38*	-.34	-.31	.83**	-	-.20
	Trust	-.16	-.19	.67**	-.41*	.49**	.34*	-.09	-.20	-

T1 = after 3 months, T2 = after 6 months

Note: correlations according to Spearman, * $p < .05$, ** $p < .01$, two-tailed.

Citation: Cocron, P., Bühler, F., Franke, T., Neumann, I., Dielmann, B., & Krems, J. F. (2013). Energy recapture through deceleration – regenerative braking in electric vehicles from a user perspective. *Ergonomics*, 56(8), 1203-1215. [dx.doi:10.1080/00140139.2013.803160](https://doi.org/10.1080/00140139.2013.803160)