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Regenerative braking failures in battery electric vehicles and their impact on the driver

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ABSTRACT

A unique feature of battery electric vehicles (BEV) is their regenerative braking system (RBS) to recapture kinetic energy in deceleration maneuvers. If such a system is triggered via gas pedal, most deceleration maneuvers can be executed by just using this pedal. This impacts the driving task as different deceleration strategies can be applied. Previous research has indicated that a RBS failure leading to a sudden reduced deceleration represents an adverse event for BEV drivers. In the present study, we investigated such a failure's impact on the driver's evaluation and behavior. We conducted an experiment on a closed-off test track using a modified BEV that could temporarily switch off the RBS. One half of the 44 participants in the study received information about an upcoming RBS failure whereas the other half did not. While 91% of the drivers receiving prior information noticed the RBS failure, only 48% recognized it in the "uformed" group. In general, the failure and the perception of its occurrence influenced the driver's evaluation and behavior more than receiving prior information. Nevertheless, under the tested conditions, drivers kept control and were able to compensate for the RBS failure. As the participants drove quite simple maneuvers in our experiment, further studies are needed to validate our findings using more complex driving settings. Given that RBS failures could have severe consequences, appropriate information and warning strategies for drivers are necessary.

1. Introduction

Battery electric vehicles (BEV) used to reduce CO_2 vehicle emissions also impact the driving task. In particular, drivers must adapt to the limited range of BEV (Franke et al., 2012), which affects trip planning and vehicle choice. In addition, BEV driving alters more basic behaviors such as longitudinal control. Another key characteristic of BEVs is the capability of recapturing some energy during deceleration maneuvers with a regenerative braking system (RBS) (Cocron et al., 2011; Labeye et al., 2013; Vilimek and Keinath, 2014). Such RBS can be implemented in the accelerator pedal, the brake pedal or both. Depending on the system type, the driver may need to adapt their deceleration behavior (Schmitz et al., 2013). Specifically, if the gas pedal triggers the system, drivers can perform most braking maneuvers by simply utilizing the RBS deceleration (Cocron et al., 2013).

Previous research on accelerator-triggered RBS suggests that drivers try to avoid utilizing the mechanical brake to maximize RBS performance (Turrentine et al., 2011) to enhance vehicle energy efficiency. The question arises as to how drivers cope with situations in which an accelerator-triggered RBS is not working properly. Alike other technical systems, RBS can fail to operate due to low temperature, high state of charge or control system failures for instance. This could lead to complaints (Rosebro, 2010) or even serious safety issues in real-world traffic. Expecting the RBS deceleration to work properly, if a failure occurs, drivers need to quickly take control by conventionally applying the brake pedal. The current study aimed to investigate (1) whether drivers detect such a failure at all and how they evaluate such a failure based on (2) perceived risk and (3) controllability. Controllability refers to "the question whether a vehicle can be handled safely by the driver in the event of system malfunctions" (MISRA, 2007; ISO WD 2626-3, 2007; as cited in Neukum et al., 2008, p. 2). Moreover, how drivers compensate for a RBS failure through (4) braking and (5) steering was investigated. To examine those issues, we modified and instrumented a BEV to conduct a closed-off test track experiment.

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2. Background

2.1. Driver evaluation of RBS

As stated previously, BEV driving somewhat necessitates acquiring new behavioral patterns to make use of novel functions such as a RBS. Cocron et al. (2013) observed a quick learning process among BEV drivers when using an accelerator-triggered RBS based on two six-month field trials. Drivers learned to utilize the RBS deceleration even within the first 30 km. Drivers quickly adapted their behavior, substituting mechanical braking with RBS usage during most deceleration maneuvers. The learning curve in both trials demonstrated a comparable power function, suggesting a similar behavioral adaptation among BEV drivers. Subjective estimation matched the driving data's depiction of a quick acquisition process. Additionally, drivers positively evaluated the RBS placement in the accelerator pedal. Labeye et al. (2013), Turrentine et al. (2011) and Helmbrecht et al. (2014) presented similar results when asking participants to evaluate their RBS interaction.

These findings all relate to the same test vehicle which featured an accelerator-triggered RBS that decelerated quite rapidly. In that context, Eberl et al. (2012) suggested that noticeable ($-1.5\,m/s^2$) and strong ($-2.25\,m/s^2$) drag torques created a better user experience than deceleration resembling conventional vehicles ($-0.8\,m/s^2$) or freewheeling ("sailing"). Schmitz et al. (2013) presented similar findings, indicating that drivers perceived higher deceleration intensities (i.e. $-1.3\,m/s^2$ and $-2.0\,m/s^2$) as better than a lower deceleration intensity ($-1.0\,m/s^2$). It should be noted that Schmitz et al. (2013) conducted their study in a simulator. Moreover, Schmitz et al. (2013) compared evaluations of different RBS implementations, revealing that drivers preferred an accelerator-triggered RBS compared to a split pedal solution where energy was regained using the brake pedal.

Summarizing the previously mentioned findings, research suggests that drivers positively evaluated accelerator-triggered RBS. So-called "single pedal driving" seemingly contributes to the innovative feel of BEV driving. Furthermore, drivers tend to prefer higher deceleration intensities. This leads to the questions of which and to what extent RBS affect the driving task.

2.2. Regenerative braking usage as part of the driving task

Relating unique BEV characteristics to different levels of the driving task, Labeye et al. (2012) allocated RBS usage to the basic operational level in Michon's model (1985). Adapting Hollnagel and Woods' (2005) ECOM model to BEV driving, Cocron (2014) suggested a similar approach, allocating RBS usage to the tracking layer that consists of mostly unattended and automatic activities. Both models could be applied to different technical strategies in how to implement RBS in BEV. When the brake pedal triggers the RBS, drivers only need to make minor adaptations to their behavior as deceleration strategies mostly remain constant. The only adaptation necessary is the amount of force applied to the brake pedal as the initial pedal movement regenerates energy. Conversely, more behavioral adaptation seems necessary if the RBS is triggered via accelerator. Here, the acquisition of new deceleration skills is necessary as the accelerator pedal is used to decelerate in most deceleration maneuvers. As a result, the conventional friction brake is only rarely used. BEV drivers reported using it only for rapid decelerations or emergency braking (Cocron et al., 2013). This could be problematic as drivers' braking skills for adequate emergency response might deteriorate. Hollnagel and Woods' (2005) model also suggested that sudden disturbances such as advanced driver assistance system (ADAS) failures can interfere with tracking activities, thus requiring sudden driver corrective actions to take control. Such take-over situations have been studied extensively (e.g. Gold et al., 2013; Rajaonah et al., 2006; Seppelt and Lee, 2007). The objective of the present study is to examine take-over situations caused by RBS failures.

3. Research objectives

Findings reported previously indicate that RBS play an important role in future vehicle technology. Like any other technical system, the RBS can fail, forcing drivers to compensate for such behavior. In our research we investigated (1) if drivers recognize a RBS failure (reduced deceleration) and how drivers evaluate the failure's impact on (2) perceived risk and (3) controllability. Apart from subjective measures, we studied participants' corrective actions such as (4) braking and (5) steering upon RBS failure. In the context of driving, especially with increasing vehicle automation such as adaptive cruise control (ACC), Stanton and Salmon (2009) argued that mode awareness is crucially important to predict a system's actions. In our view, this is also relevant when utilizing RBS in BEV. At all times, drivers must know the system's status given decelerating maneuvers need to be safely executed. A system acting incongruently to the user's expectation could lead to mode confusion about the system's status. In our research, we used a simple concept of mode awareness by indicating information on an impending failure to study RBS failure's impact. Certainly, another opportunity to inform drivers could be through an interface to monitor system status. However, the study's first step addressed the question of whether simply giving informing about failures changes the reaction to it. To vary mode awareness, one group received information about the upcoming RBS failure, whereas the second group did not receive such prior information. Both groups completed a driving task on a test track closed to the public. The participants' task was to drive through the course while maintaining a speed of 50 km/h. The exact course is described in a later section. Drivers were asked to use the RBS to decelerate on road curves. After completion of the practice and two experimental rounds, the RBS was made to suddenly reduce deceleration just before entering Curve 1. With respect to (1), we assumed that more people in the informed group would notice the RBS failure (H1). While such a difference is expected due to the manipulation, we were particularly interested in the percentage of *uniformed* drivers noticing the RBS failure. Concerning the subjective evaluation (2, 3) of the RBS failure, we assumed that (H2.1) prior information and the failure occurrence itself both impact perceived risk. Apart from that, we hypothesized (H2.2) that failure perception affects risk perception in the failure condition. With regard to (3) controllability, we expected (H3) that prior information impacts the evaluation of controllability more than the perception of the failure.

Regarding (4) braking as a behavioral measure, we expected (H4.1) that due to the prior information and the opportunity to prepare, a higher percentage of informed participants would brake following the RBS failure. Relatedly, we assumed (H4.2) that prior information affects the maximum brake pressure applied following the RBS failure. In other words, we studied participants' braking force following the RBS failure. Examining steering reactions (5), we also assumed (H5.1) there would be a difference in steering angles based on receiving prior information. In our view, prior information most likely enhances preparedness which could result in different steering patterns. Additionally (H5.2) we expected greater steering wheel angles among those who did not brake to compensate for the RBS failure. Using an explorative approach, we also investigated the maximum steering angle intensity after the RBS failure. All hypotheses were tested on a closed-off test track (described in the next section).

4. Methods

The current study was conducted as a part of the EVERSAFE project, which investigated active (Cocron et al., 2014) and passive BEV safety (Wisch et al., 2014) to recommend new safety requirements and research (Thomson, 2014).