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Regenerative braking and low vehicle noise of electric vehicles – implications for the driver

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Zusammenfassung

Die dauerhafte Reduktion der von Menschen verursachten Emissionen ist eine der zentralen Herausforderungen unserer Zeit. Eine Strategie zur Reduzierung von Emissionen im Mobilitätssektor sind elektrisch betriebene Fahrzeuge, die je nach Typ teilweise oder vollständig mit Strom angetrieben werden. Für die Verkehrspsychologie stellt sich nun die Frage, ob und wie schnell sich Fahrer an die Nutzung von Elektrofahrzeugen gewöhnen und welche Herausforderungen sich aus Nutzersicht ergeben. Anhand von Studien mit vollelektrischen Fahrzeugen wurden in der vorliegenden Arbeit zwei grundlegende Eigenschaften von Elektrofahrzeugen aus psychologischer Perspektive untersucht:

Zum einen verfügen Elektrofahrzeuge über eine Rekuperationsfunktion, mit der es möglich ist, in Verzögerungsvorgängen kinetische in elektrische Energie umzuwandeln, also Energie rückzugewinnen und damit letztlich die Emissionen zu reduzieren.

Zum anderen beschränkt sich die mögliche Emissionsreduktion von Elektrofahrzeugen nicht nur auf den CO_2-Ausstoß, sondern betrifft auch die Geräuschentwicklung dieser Fahrzeuge. Fahrzeuge mit Elektroantrieb emittieren weniger Geräusche, was einerseits die Lärmbelastung durch Straßenverkehr reduzieren kann, zum anderen aber auch zu Bedenken z.B. blinder Verkehrsteilnehmer geführt hat. Gerade bei geringen Geschwindigkeiten sind Elektrofahrzeuge schlechter wahrnehmbar und dadurch eine potentielle Gefahr für andere Verkehrsteilnehmer.

Das erste Ziel der vorliegenden Dissertation bestand darin, die Auswirkungen einer über das Gaspedal gesteuerten Rekuperation aus verkehrspsychologischer Perspektive zu untersuchen. Die zur Nutzung der Rekuperation nötigen motorischen Fertigkeiten müssen erlernt und in unterschiedlichen Verkehrssituationen angewandt werden. Basierend auf dem Power Law of Practice (Newell & Rosenbloom, 1981) wurde der Fertigkeitserwerb bei der Nutzung der Rekuperationsfunktion eingehend betrachtet. Anhand von Fahrzeugdaten lassen sich eine sehr steile Lernkurve und damit ein kurzer Adaptationsprozess zeigen, der mit einer Powerfunktion beschrieben werden kann. Bereits innerhalb der ersten gefahrenen Kilometer nehmen die Anzahl der konventionellen Bremsmanöver und ihr zeitlicher Anteil an der gesamten Verzögerung rapide ab.

Das zweite Ziel der vorliegenden Dissertation war, die Auswirkungen der geringeren Geräuschemission auf das Verkehrsgeschehen zu prüfen. Dies erfolgte jedoch nicht, wie in anderen Studien bereits dargestellt, aus Fußgängerperspektive, sondern aus der Fahrerperspektive. Da die Fahrer gerade in der Anfangsphase eine zentrale Rolle bei der Entschärfung geräuschbedingter kritischer Situationen spielen, soll die Arbeit dazu beitragen,

diese Forschungslücke zu schließen, um eine umfassendere Bewertung der Geräuschthematik bei Elektrofahrzeugen zu ermöglichen.

In Anlehnung an Deerys (1999) Modell zu Fahrerreaktionen auf potentielle Gefahren, wurden Risikowahrnehmung (*risk perception*) und Gefahrenwahrnehmung (*hazard perception*) als entscheidende Determinanten der Fahrerreaktion auf geräuschbedingte Gefahrensituationen identifiziert.

Was die Risikowahrnehmung betrifft, so konnte gezeigt werden, dass diese sich mit zunehmender Erfahrung verändert. Risiken aufgrund der Geräuscharmut werden als weniger bedrohlich, das leise Fahren zunehmend als Beitrag zum Komfort gewertet. Zusätzlich wurden im Rahmen der Dissertation Situationen im Straßenverkehr näher untersucht, die aufgrund der Geräuscharmut von Elektrofahrzeugen auftraten. Darauf aufbauend wurde ein Katalog von geräuschbedingten Szenarien erstellt, der als empirische Grundlage für die nähere Betrachtung der Gefahrenwahrnehmung von Fahrern diente.

Ergebnisse daraus resultierender Experimente zur Detektion von geräuschbedingten Gefahren (hazard detection tasks) zeigten, dass die individuelle Erfahrung mit Elektrofahrzeugen offenbar lediglich eine untergeordnete Rolle bei der Erkennung und Reaktion auf geräuschbedingte Gefahren spielt. Erfahrene Fahrer von Elektrofahrzeugen unterschieden sich nur marginal von unerfahrenen Fahrern in der Reaktion in und der Bewertung von geräuschbedingten Gefahrensituationen, was darauf hindeutet, dass geräuschbedingte Gefahrensituationen auch von Fahrern ohne extensive Erfahrung mit Elektrofahrzeugen bewältigt werden können.

Das dritte, übergreifende Ziel der Dissertation bestand darin, die Bedeutung beider Eigenschaften für die Nutzerakzeptanz zu untersuchen. Neben der Untersuchung momentan existierender Barrieren (z.B. Reichweite, Preis, Batterielebensdauer), die eine weitreichende Adoption von Elektrofahrzeugen erschweren können, ist es ebenso wichtig, solche Eigenschaften zu identifizieren, die sich positiv auf das Nutzererleben auswirken. Sowohl die Rekuperation, als auch die Geräuscharmut spielen eine wichtige Rolle in der Nutzerbewertung, da beide Eigenschaften als zentrale, individuell erlebbbare Vorteile von Elektrofahrzeugen beurteilt werden. Im Hinblick auf die Geräuschemission lässt sich konstatieren, dass diese mit zunehmender Erfahrung des Fahrers fast ausschließlich als Vorteil statt als Barriere von Elektrofahrzeugen gewertet wird. Eine bemerkbare, über das Gaspedal gesteuerte Rekuperation scheint als Teil des Fahrererlebens ebenfalls eine zentrale Rolle in der Bewertung zu spielen. Ein hohes Maß an Nutzerakzeptanz und Vertrauen in das System unterstreichen die positive Evaluation einer solchen Funktionalität.

Aus verkehrspsychologischer Sicht haben die angeführten Eigenschaften von Elektrofahrzeugen Auswirkungen auf verschiedene Teilaufgaben der Fahrzeugführung. So sind nicht nur motorische Fertigkeiten in der Pedalnutzung (Stabilisierungsbene) erforderlich, sondern auch komplexere kognitive Prozesse, wie z.B. der Umgang mit möglichen Gefahrensituationen aufgrund der geringen Geräuschemission (Bahnführungsebene).

Insgesamt weisen die Ergebnisse der Dissertation darauf hin, dass Herausforderungen aufgrund beider oben genannten Fahrzeugeigenschaften gemeistert werden können. Zusätzlich zeigen die Ergebnisse, dass beide Eigenschaften von den Nutzern als willkommene Aspekte der technologischen Innovation geschätzt werden und somit zur allgemeinen Akzeptanz von Elektrofahrzeugen beitragen können. Da auch andere Fahrzeugkonzepte mit elektrischem Antriebsstrang diese beiden Eigenschaften aufweisen, lassen sich die gefundenen Ergebnisse auf andere Fahrzeugtypen übertragen.

Table of contents

Synopsis

1 Road transport and emissions

Assuming a world population of 9 billion by 2050, a recent transport outlook by the OECD suggested that global mobility will greatly increase. Especially outside the OECD passenger mobility is expected to increase by the factor of 5 to 6.5 due to strong expected economic growth. Private passenger vehicles (cars and light trucks) will stay the most important global mode of transport (OECD/ITF, 2011), even if in recent years a stagnation or even decrease in vehicle miles traveled (VMT) can be detected in high-income economies, for instance in the US (Puentes & Tomer, 2008). Although the benefits of global mobility are evident, especially in emerging economies, challenges regarding safety and the limits of infrastructure become an issue. Moreover, increasing mobility has direct implications on energy resources. In 2011, the transport sector was responsible for 22% of global CO_2 emissions, whereas road transport accounted for three quarters of these emissions (OECD/IEA, 2013). Against this background and the challenges related to peak oil (Hirsch, Bezdek, & Wendling, 2005), steps have been undertaken for a more sustainable transport system. One of the most discussed measures is the electrification of power trains of road vehicles (King et al., 2010). In this context Hybrid Electric Vehicles (HEVs), Plugin Hybrid Electric Vehicles (PHEVs) and Battery Electric Vehicles (BEVs) are most prominent, whereas in this dissertation the focus is on BEVs. Two characteristics of BEVs, which both contribute to lower emissions of road traffic, will be examined from a psychological perspective.

First, if charged with energy from renewable sources, BEVs can significantly reduce the CO_2 emissions (Doucette & McCulloch, 2011). Furthermore, as shown for HEVs, energy usage and therefore vehicle emissions can even be further reduced through the regenerative braking system (Romm & Frank, 2006), which transforms kinetic into electric energy during deceleration maneuvers. The electric energy can then be stored in the battery for later use (Cikanek & Bailey, 2002). Promising results of regenerative braking were also reported by Clarke, Muneer, and Cullinane (2010) who equipped a conventional diesel car with regenerative braking and reduced the CO_2 emissions from approximately 145 g/km to 67 g/km in urban driving.

Second, emissions of the transport sector not only involve CO_2 emissions, but also noise emissions. In 2000, the WHO published a report emphasizing that environmental noise constituted a major societal problem. Road traffic with noise levels beyond 55 dB(A) affected a substantial share of the EU population: 40% of the citizens were exposed to such levels during daytime and 30% during night time (Berglund, Lindvall, & Schwela, 2000). As road traffic noise has been found to be associated with issues such as sleep disturbances (e.g., Jakovljević, Lojević, Paunović, & Stojanov, 2006), cardiovascular risks (for an overview see Babisch, 2006) and affects the quality of life in general, measures to reduce noise emissions resulting from road traffic are needed. In this context, HEVs, PHEVs and BEVs could play an important role. Assuming a transition to a vehicle fleet consisting of 90% HEVs or 90% BEVs, Jabben, Verheijen, and Potma (2012) calculated an average reduction in noise emissions of 3 to 4 dB(A) for urban environments. They stated that especially at junctions and on roads with low average speeds, the greatest reduction could be achieved. Still, Jabben and colleagues argued that particularly at junctions and in quiet streets the sound difference could have detrimental effects due to conflicts with Vulnerable Road Users (VRUs). This creates a dilemma. Even if the reduced noise of vehicles with electric power train (EVs) was beneficial for urban residents, it might produce safety problems for VRUs.

In the present dissertation both BEV specific features are examined from a psychological perspective. Regenerative braking, as a system to regain energy during deceleration, is implemented in most vehicles with electric power trains. This could have enduring consequences on driver behavior. Currently, it is unclear to what extent drivers need to adapt to such a function. In the dissertation, it is investigated how drivers learn to utilize such a function and how they evaluate such a function with regard to acceptance and trust. As a second unique feature, low BEV noise contributes to lowering emissions, but is also regarded as a safety issue. Up to now, most studies focused on the perceptibility of such vehicles. In the dissertation, the issue is approached from the driver's perspective. Specifically, it is examined what incidents occur in urban traffic and how drivers evaluate BEV noise over time. Furthermore, it is investigated if drivers can benefit from their BEV experience when confronted with noise-related scenarios. Finally, specific features of BEVs such as the limited range are often regarded as barrier to BEV adoption (e.g., Egbue & Long, 2012). In the present dissertation specific barriers and advantages of BEVs are studied to identify those aspects which could foster adoption. As regenerative braking and low noise could play a crucial role in this context, they are focused on.

2 Overview of the dissertation

In the present dissertation, the impact of the regenerative braking function and the low noise emission on the driver are examined in detail. The cumulative dissertation comprises four research articles: upon submission of the dissertation two of them were published (paper I + II) and one was in press (paper III). The last article was accepted and published during the assessment phase (paper IV)[1]. One additional peer reviewed article has been published (Cocron, Bühler, Neumann, et al., 2011), which is referred to in the section on the methodology.

In the synopsis, regenerative braking and the low noise emission of BEVs are linked to more general theoretical frameworks of psychology (chapter 3) and the driving domain (chapter 4). In chapter 5, their relevance for the evaluation of drivers is discussed. Chapters 1-5 constitute the basis for the research objectives (chapter 6). An overview of the methodology is provided in chapter 7. In chapter 8, relevant findings for each research objective are summarized and discussed. The last chapter of the synopsis (chapter 9) provides an overview of possible implications of the obtained results. Subsequently, four papers are integrated in the dissertation.

Paper I focuses on regenerative braking assessment and usage over time, whereas the acquisition of regenerative braking skill, acceptance and the evolution of driver trust towards such a function are investigated. Paper II elaborates the driver assessment of low external vehicle noise by applying a risk perception approach. Based on drivers' reports, a catalogue of noise related incidents is compiled. Specific vehicle attributes of BEVs, such as regenerative braking and low noise emission, can hinder or facilitate acceptance of such a technology. If specific vehicle attributes, such as the low noise emission or regenerative braking, serve as advantage or disadvantage from a user perspective, is discussed in paper III. Based on the catalogue compiled in paper II, hazard detection in situations, which are related to BEV noise, is examined in paper IV. Utilizing a hazard perception approach, responses towards noise related incidents are studied with regard to individual BEV experience.

[1] The citation style of all papers was adapted to the APA manual (6th edition) for consistency. Due to journal requirements, paper I, II and IV were originally formatted differently. Graphs and tables are placed in the text to ease reading. All manuscripts were checked by a professional proofreader.

Paper I:

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

Paper II:

Cocron, P., & Krems, J.F. (2013). Driver perceptions of the safety implications of quiet electric vehicles. *Accident Analysis and Prevention*, *58*, 122-131. dx.doi: 10.1016/j.aap.2013.04.028

Paper III:

Bühler, F., Cocron, P., Neumann, I., Franke, T., & Krems, J.F. (2014). Is EV experience related to EV acceptance? Results from a German field study. *Transportation Research Part F: Traffic Psychology and Behaviour, 25*(A), 85-90. doi:10.1016/j.trf.2014.05.002

Paper IV:

Cocron, P., Bachl, V., Früh, L., Koch, I., & Krems, J.F. (2014). Hazard detection in noise-related incidents - the role of driving experience with battery electric vehicles. *Accident Analysis and Prevention, 73*, 380-391. dx.doi.org/10.1016/j.aap.2014.09.016

3 Specific features of BEVs from a psychological perspective

Whenever new technology is introduced to the traffic system, it is debated what implications this could have on humans. In-vehicle Information Systems (IVIS) and Advanced Driver Assistance Systems (ADAS) and their implications for the driving task have been studied in depth for the last decades, often focusing on behavioral adaptation (for an overview see Stevens, Brusque, & Krems, 2014). Behavioral adaptation is usually referred to "those behaviors which may occur following the introduction of changes to the road-vehicle-user system and which are not consistent with the initial purpose of the change" (OECD, 1990, p. 14). A detailed review of the relevant findings on ADAS and IVIS can be found in Wege, Pereira, Victor, and Krems (2014). Even if BEVs do not completely change the driving task, they exhibit certain features which drivers need to adapt to. The first feature of BEVs, which usually comes to mind, is their reduced range. A detailed examination of driver experiences and behaviors with BEV range is provided by Franke (2014). In the present dissertation, two other unique features and their impact on the driver are focus of research: regenerative braking and the low noise emission.

3.1 Regenerative braking

Regenerative braking in BEVs can either be triggered by accelerator, brake or both pedals, which has direct implications for the driver-vehicle interaction. Depending on the systems' design, the deceleration maneuver varies considerably. When driving a BEV with a regenerative braking system, which is triggered via accelerator, acceleration and deceleration with one pedal is possible. If the regenerative braking system is triggered via brake pedal, the driver has to slightly apply the brake to utilize regenerative braking. Whenever the brake pedal is pressed harder in such a system, the conventional brake is activated. The studies reported in paper I were both conducted with MINI E test vehicles in which regenerative braking is regulated via accelerator.

Romm and Frank (2006) argued that compared to vehicles with an Internal Combustion Engine (ICE), HEVs can improve the vehicle's fuel efficiency by 60% or more. According to the authors, this gain in efficiency mostly results from the regenerative braking system. Due to its potential to reduce vehicle emissions, regenerative braking could be regarded as sustainable technology, which has an impact on the driving task. In the present dissertation the focus of research is the actual usage and user assessment of such a function, but not the potential energy that could be recaptured through regenerative braking.

From a psychological perspective such a technology could have enduring consequences on the driving task. Regenerative braking usage can be considered as a motor task, which has to be learnt regardless of where the function is implemented. As a consequence, new deceleration strategies need to be acquired when driving BEVs and these might differ between vehicle brands. Based on these assumptions, one could describe regenerative braking usage as a perceptual-motor skill which requires practice.

Fitts and Posner (1967) postulated three phases in the acquisition of complex skills. In the first phase, usually referred to as *cognitive phase*, learners try to make sense of the task and its demands. Errors in the execution of the task are common. General sets, which were appropriate for already learnt skills, are applied to the new task. As a consequence, the skill to be acquired involves appropriate and inappropriate strategies. Related to regenerative braking, this would mean that drivers get to know where the regenerative braking function is implemented and how the system works.

In the second phase, the *associative phase*, learners refine their strategies and utilize more appropriate patterns. According to Fitts and Posner (1967), errors occur more seldom. Depending on the complexity of the task this phase is shorter or longer. Transferred to the regenerative braking utilization, drivers might apply old braking or deceleration routines and try new strategies such as decelerating with the accelerator pedal only. Fitts and Posner (1967) further argued that if the new task requires similar responses as an already mastered skill, this results in *positive transfer*. This could also apply to an accelerator triggered regenerative braking as utilizing the engine brake to decelerate is known from ICE vehicles.

The third and final phase of skill learning is labeled as *autonomous phase*, in which the task is executed more autonomously. Less cognitive control is necessary and other tasks can be carried out simultaneously with less interference. Improvement in skill acquisition can be detected, although at a declining rate. In relation to regenerative braking, this would mean that the system is used for most deceleration maneuvers and drivers can accurately decelerate to a particular point for instance a traffic light by only using regenerative braking. Paper I focuses on how drivers learn to utilize such a function by applying principles of skill acquisition to regenerative braking utilization.

3.2 Low external vehicle noise

The low noise emission is the second feature of BEVs which is examined in detail. Studies on the noise emission of HEVs usually investigate how such vehicles are detected by pedestrians. Experimental detection tasks revealed that at low speeds HEVs are perceived later than equivalent ICE vehicles (Garay-Vega, Hastings, Pollard, Zuschlag, & Stearns, 2010; Robart & Rosenblum, 2009). These findings raised questions about the safety of pedestrians, in particular of blind pedestrians (National Federation of the Blind, 2011) who rely on environmental sounds to navigate in traffic (Wall Emerson, Naghshineh, Hapeman, & Wiener, 2011). Still, one could argue from a psychological perspective that driving a quiet vehicle has also consequences on driver behavior. The interaction with other road users, particularly VRUs, changes as drivers have to anticipate that other road users might not perceive them in time. In the dissertation, the problem is approached from the drivers' perspective as these are crucial in mitigating risks resulting from reduced noise of BEVs.

Deery's (1999) model on driver responses to potential hazards is used to determine the ramifications of low noise on attitudes and behavior of BEV drivers. Even if Deery (1999) framed his model to the hazard and risk perception of novice drivers, it provides a useful structure to classify challenges resulting from driving a silent BEV. Deery (1999) stated that traffic hazards are rare events whose occurrence often lies beyond the control of the drivers. However, the driver can attenuate the consequences of such events through preventive actions. To do so, behavioral responses need to be acquired through individual experience. Deery (1999) noted in this context that "the learning of these responses to a range of potentially hazardous situations is probably one of the major contributions to driver safety" (p. 226). Deery's (1999) notion of the acquisition of adequate responses through experience can therefore be directly linked to driving a silent BEV.

In his model, Deery (1999) assumed that whenever a hazard occurs, it has to be detected and quantified by the driver. This first step therefore refers to hazard perception. The next steps involve the subjective experience of risk (risk perception) and the driver's assessment of his or her skill to handle a safety relevant incident (self-assessment of skill); these aspects are also interrelated. The behavioral outcome (behavior) is defined by the level of risk a driver is willing to take (risk acceptance) and the actual driving performance of a particular driver (driving skill). Risk perception and the self-assessment of skill are exemplified in paper II. Hazard perception, as a crucial skill when driving quiet BEVs, is examined in paper IV. An adapted version of Deery's (1999) model is displayed in Figure 1.

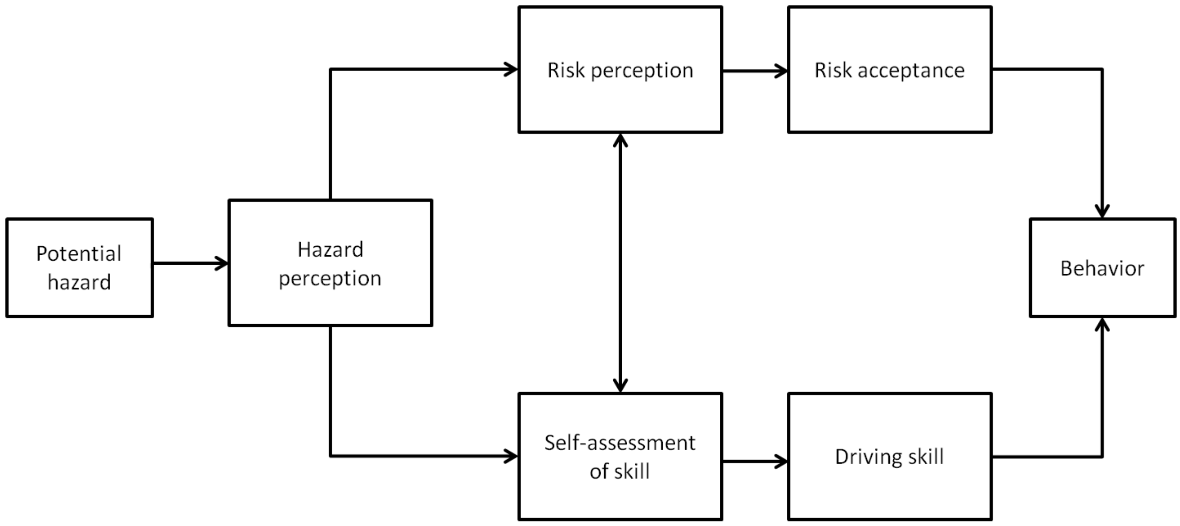

Figure 1 Model of processes underlying driving behavior in response to potential hazards (adapted from Deery, 1999)

Summing up, regenerative braking and low noise - as two distinct characteristics of BEVs - are examined to better understand the implications for the human interaction with BEVs. In the next section, it is discussed how both features concretely affect the driving task.

4 BEV specific attributes and their relevance for the driving task

In the driver models presented below, the driving task as a whole and its subtasks are discussed with particular emphasis on regenerative braking and the low noise emission of BEVs. Even though such models mainly focus on the description of relevant tasks and cannot serve as models of human information processing (Vollrath & Krems, 2011), models by Michon (1985) and Hollnagel and colleagues (Hollnagel, Nåbo, & Lau, 2003; Hollnagel & Woods, 2005; Engström & Hollnagel, 2007) can serve as a theoretical basis when structuring challenges which arise due to new technology in driving. These models are presented to highlight the implications of BEV specific features for driving on a general level. A detailed discussion of findings related to the driving task is presented in sections 8.1 and 8.2.

4.1 Michon's model

A common approach is to classify new transport systems according to Michon's (1985) model of the driving task. Michon (1985) postulated three different levels which are organized hierarchically.

The lowest level is labeled as *control* or *operational level* and includes automatic action patterns such as steering or lane keeping. Above this level, tasks such as obstacle avoidance, overtaking and turning are subsumed in the *maneuvering* or *tactical level*. Here, drivers interact with other road users while executing controlled action patterns. According to Michon (1985), the highest level is the *strategic level*, which refers to tasks such as trip planning and modal choice. Activities of this level include general plans and extend over longer periods of time. Incorporating a level on goals for life and skills for living from the GADGET-matrix (Christ et al., 1999), Panou, Bekiaris, and Papakostopoulos (2007) added the *behavioral level* as superior level to Michon's (1985) model. Here, attitudes and individual dispositions of the driver are integrated, which might have an influence on driver behavior and accident risk.

Michon's (1985) model has already been applied to driving BEVs by Labeye, Hugot, Regan, and Brusque (2012) who discussed challenges which arise due to specific features of BEVs. Labeye and colleagues (2012) argued that the limited range of BEVs places additional cognitive demand on drivers, for instance in trip planning. Therefore, they related the limited range to the strategic level. The maneuvering level is affected insofar as driving a quiet BEV requires more attentive driving as pedestrians and bicyclists might not perceive the vehicle in due time. Furthermore, the authors argued that, because of the regenerative braking function, the operational level is also altered when driving a BEV. The proposed allocation by Labeye and colleagues (2012) served as a fruitful foundation for the identification of potential changes when driving BEVs. Using this foundation one could argue that the specific characteristics of BEVs might affect more than just one level. Regenerative braking usage as an operational task could also impact superior goals such as driving as energy efficient as possible (strategic level). Besides, it could have an effect on deceleration strategies when approaching traffic lights (maneuvering level).

In this context Engström and Hollnagel (2007) stressed that Michon's model failed to incorporate the dynamic nature of driving and a clear description of the relations between the different layers. Focusing on the performance instead of information processing, they referred to the Extended Control Model (ECOM), which was proposed by Hollnagel et al. (2003).

4.2 The ECOM model

Engström and Hollnagel (2007) defined driving as a goal-directed activity and also utilized control as key construct, whereas the authors differentiated between feedback (compensatory) control and feedforward (anticipatory) control. Thus, feedback relates to corrective actions whenever an actual state differs from a goal, while feedforward represents proactive actions based on predictions. According to Engström and Hollnagel (2007), driving involves both facets. In the ECOM model, four layers were suggested whereas targets of a particular level are determined by control processes of the level above. Based on Hollnagel and Woods (2005), the different layers and their relevance to identify challenges due to specific BEV attributes are discussed in the next sections.

Tracking as the lowest level refers to feedback activities such as keeping a certain speed or instantaneous reactions towards an unexpected event. The maximum duration of activities in the tracking layer is one second; their performance is mostly unattended and automatic. Experienced drivers only need to invest little effort in such tasks, whereas for novice drivers the same tasks can be assigned to the regulating level as attention is needed to perform the task. Hollnagel and Woods (2005) further argued that tracking activities can be disrupted by disturbances which require immediate action. Such disturbances could be a pedestrian suddenly crossing the street or a failure of an ADAS leading to a take-over situation. Low external vehicle noise of BEVs has implications for the tracking layer as the probability of pedestrians suddenly crossing the vehicle's path could increase. As different regenerative braking strategies are possible in BEVs, the deceleration as a motor task is altered. Therefore, the tracking layer in the ECOM model is also changed through the regenerative braking system.

Regulating as the next level involves feedback and feedforward control. More awareness of the driver is required because safety margins to other road users have to be kept for instance during overtaking and obstacles need to be avoided. Hollnagel and Woods (2005) stated that the regulating layer is related to "the position of the car relative to other traffic elements" (p. 150). Typically such activities last between one second and one minute. Attention demands are high in uncommon and low in common tasks. A possible example of the regulating activity in BEVs could be the approach of a pedestrian crossing while gradually decelerating through regenerative braking to maximize energy recapture. Related to the low noise emission a possible example would be to increase the distance to pedestrians when passing them in a parking lot.

In the *monitoring* layer above the system and its condition are monitored for instance through periodic checks of the consumption display in the car. The attention demands are low; activities are sporadic, but regular. Furthermore, traffic signals, restrictions (e.g., speed limits) and warnings signs need to be observed. Other monitoring activities relate to the location of "the vehicle relative to reference points in the environment" (Hollnagel & Woods, 2005, p. 151) which involve navigation tasks. The *monitoring* layer can also be linked to BEV specific features: due to the limited range of BEVs, the energy consumption and regenerative braking performance needs to be monitored. As a consequence of the low vehicle noise of BEVs the observation of pedestrian crossings are particularly important.

The top level in the ECOM model is called *targeting* layer. Here, general goals of the driving task are defined which in turn determine the goals of the monitoring level. The frequency of such activities is low. The demands to attention are high; feedforward control is essential. General goals when driving a BEV could be choosing an energy efficient route or even avoiding traffic calming zones for safety reasons.

Engström and Hollnagel (2007) associate *tracking* with compensation strategies (feedback), whereas *monitoring* and *targeting* are more linked to anticipatory control (feedforward). *Regulating* contains both, feedback and feedforward control. Anticipation (feedforward) in particular appears to be a crucial skill when driving a BEV. Due to the low noise the driver has to anticipate that other road users might not perceive the approaching BEV. Such skill is a prerequisite for hazard perception which is addressed in paper IV. Even if regenerative braking usage also requires anticipation for instance to avoid unnecessary use of the friction brakes, it is rather regarded as a motor task which needs to be regulated. In Figure 2 regenerative braking and low noise emission as characteristics of BEVs are assigned to levels of the ECOM framework.

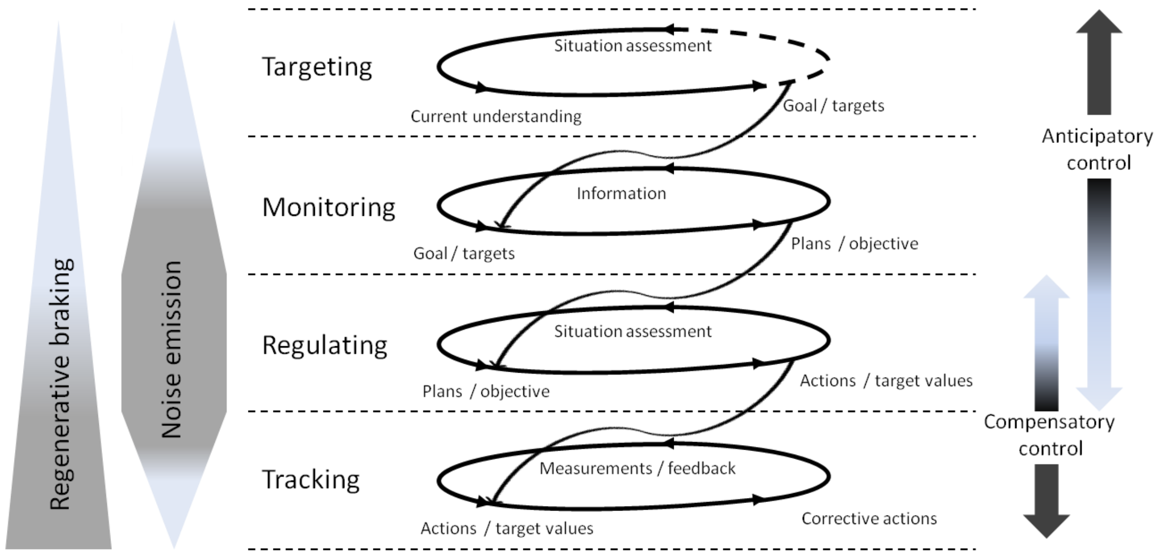

Figure 2 BEV specific features linked to the ECOM model (adapted from Hollnagel & Woods, 2005)

5 BEV specific attributes and their relevance for driver acceptance

As discussed above, regenerative braking systems and low external vehicle noise are significant issues for traffic psychology, if larger portions of the total vehicle fleet are electrically propelled. One could argue that most gained knowledge in this thesis is transferable to other vehicle types such as HEVs and PHEVs. However, for lasting market success, driver acceptance is a prerequisite. Potential barriers to larger adoption of BEVs are manifold (Egbue & Long, 2012); hence it appears necessary to identify those aspects which could help overcoming such barriers. In turn, this could help to establish BEVs as sustainable means of transport. Due to the focus on regenerative braking and low noise emission, these aspects and their potential to hinder or facilitate BEV adoption are focused on. A detailed discussion of the results related to acceptance is presented in section 8.3.

5.1 Regenerative braking and acceptance

Even though regenerative braking as a specific attribute was only rarely addressed in past user research on BEVs, several recent studies mentioned its relevance for the assessment of vehicle performance and in turn also for acceptance of BEVs. Turrentine, Garas, Lentz, and Woodjack (2011) conducted a field study in the US with MINI E test vehicles and reported that regenerative braking via accelerator was appreciated by the participants. Drivers reported to have quickly adapted to driving with one pedal. Furthermore, drivers stated that they tried to use the friction brakes as little as possible. According to the drivers, regenerative braking also contributed to the direct feel of the vehicle. Similar results were reported in studies with MINI E test vehicles from

France (Labeye, Adrian, Hugot, Regan, & Brusque, 2013) and the UK (Everett, Walsh, Smith, Burgess, & Harris, 2010). Driving mainly with one pedal was regarded positively and appeared to convey an innovative feel. Still, the aforementioned studies all used the MINI E as test vehicle which exhibited quite a strong drag torque and therefore considerable deceleration due to regenerative braking. Technical details on regenerative braking systems are explained in detail by Eberl (2014).

Eberl, Terhorst, Stroph, and Pruckner (2012) studied to what extend user experience is related to the deceleration intensity of a regenerative braking system. Assessing the hedonic and pragmatic quality of different regenerative braking layouts through the AttrakDiff mini questionnaire (Hassenzahl & Monk, 2010), Eberl and colleagues indicated that noticeable (-1.5 m/s^2) and strong (-2.25 m/s^2) drag torques were rated higher than ICE like deceleration (-0.8 m/s^2) or freewheeling (“sailing”). The comparison between drivers who had driven extensively with a strong regenerative braking function and inexperienced drivers showed a differentiated assessment. While experienced drivers appreciated the strong system configuration, inexperienced drivers favored the noticeable regenerative braking system. The results presented by Eberl et al. (2012) coincide with findings presented in paper I, which showed that drivers learned to appreciate the strong deceleration in the test vehicle.

Different intensities of regenerative braking systems were also studied in the simulator. Schmitz, Maag, Jagiellowicz, and Hanig (2013) found that drag torques yielding in higher deceleration intensities (-1.3 m/s^2 and -2.0 m/s^2) were rated better than a lower deceleration intensity (-1.0 m/s^2) of the regenerative braking system. In a second study, Schmitz et al. (2013) compared a regenerative braking system which was triggered via brake pedal with an accelerator triggered system. Drivers preferred a system which was controlled via accelerator and assumed that they could drive more efficiently with such a system.

The presented findings on regenerative braking evaluation and acceptance indicate that drivers are pleased about stronger deceleration and prefer regeneration via accelerator pedal. In paper I and III, regenerative braking and its relevance for driver acceptance is investigated in detail.

5.2 Low noise emission and acceptance

The second attribute of interest, low external noise of EVs, elicits opposing opinions. The National Federation of the Blind (2011) and researchers (Rosenblum, 2009), who studied the perceptibility of quiet vehicles, expressed concerns about the safety of VRUs. Several studies found that particularly at lower speeds vehicles with electric power trains are harder to hear (Garay-Vega et al., 2010; Morgan, Morris, Keigan, & Muirhead, 2010; Robart & Rosenblum, 2009; Wall Emerson et al., 2011). Nevertheless, as reported above, EVs could decrease the general noise level in urban areas (Jabben et al., 2012), which would have beneficial effects for the quality of life of inner city residents. Furthermore, in studies on acceptance of BEVs, noise emission was regarded as part of the driving pleasure (Gärling, 2001; Labeye et al., 2012) or as a generally desirable feature of BEVs (Jabeen, Olaru, Smith, Braunl, & Speidel, 2012). In other studies, drivers also expressed concerns for VRUs (Carroll, 2010; Everett et al., 2010) or mentioned missing vehicle feedback due to the lack of noise (Graham-Rowe et al., 2012).

Summarizing the findings above, it becomes apparent that both perspectives on EV noise need to be accounted for in the discussion which features can hinder or foster EV acceptance. In the dissertation, paper III in particular addresses BEV acceptance. In paper II and IV the balancing act between safety concerns and comfort is discussed.

6 Research objectives of the dissertation

As electrically propelled vehicles will play an increasingly important role in road traffic, it is important to specify the challenges that arise for the driving task and acceptance. The present work aims to define what can be expected in these matters. In particular, the goal was (1) to study adaptation processes in regenerative braking usage, (2) the interaction with other road users due to the low noise emission and (3) the implications of these attributes for driver acceptance. Three research objectives were delineated, which are presented below:

6.1 Research objective 1: Examination of regenerative braking skill acquisition and system trust

The possibility to regain some of the used energy through regenerative braking is a common feature in vehicles with electric power trains. No matter where the function is implemented in the vehicle (accelerator, brake or both pedals), drivers need to learn to identify situations where they can regain energy, for example downhill or when approaching a traffic light. More important, this also requires the acquisition of motor skills as the adequate level of pedal pressure needs to be regulated. The first objective was therefore to examine in more detail, if and how drivers learn to utilize such a function. In vehicles where the regenerative braking function is triggered via accelerator, drivers need to learn to accelerate and decelerate with one pedal only (single pedal driving). To do so, drivers need to learn to trust and rely on such a system in deceleration maneuvers. Applying the Power Law of Practice (Newell & Rosenbloom, 1981) and the conceptualization of trust by Rajaonah, Anceaux, and Vienne (2006) this research objective was examined in paper I.

6.2 Research objective 2: Low noise emission and its implications for risk and hazard perception of drivers

As reported above, anticipatory skills are not only needed during deceleration maneuvers, but even more in the interaction with other road users. BEVs are harder to hear, which could result in hazardous situations. The second objective of the present dissertation was therefore to assess the experiences of participants driving a quiet vehicle over an extended period of time. Based on day-to-day experiences of urban BEV drivers, it was intended to validate and expand findings on HEV accidents with VRUs (e.g., Hanna, 2009). Utilizing Deery's (1999) model on drivers' responses to potential hazards, risk perception and hazard perception were identified as crucial factors in the drivers' response towards hazards due to low BEV noise. It was specifically examined in paper II, if and to what extend drivers adjust their risk estimations regarding the low noise emission. Hazard perception as further crucial factor in Deery's (1999) model was investigated in paper IV. Initial feedback of BEV drivers (Cocron, Bühler, Franke, Neumann, & Krems, 2011) and paper II showed that drivers reported to adopt a more cautious driving style in order to account for pedestrians and bicyclists. If BEV experience plays a role in this context, was studied in paper IV.

6.3 Research objective 3: Regenerative braking and low noise emission as crucial factors for acceptance of BEVs

As mentioned above, both attributes of BEVs play an important role in the assessment of BEV technology. Nevertheless, individual barriers can hinder BEV adoption (Egbue & Long, 2012). Such perceived barriers often originate from traditional views of BEVs as vehicles with insufficient performance (Burgess, King, Harris, & Lewis, 2013). In the initial dissertation phase, existing literature on people's perceptions of BEVs rarely covered regenerative braking and low noise emission as relevant factors for the assessment of BEVs. Even if some remarks related to low noise were made (Chéron & Zins, 1997; Gärling, 2001), issues such as range, purchase price and mobility patterns were of much more interest (e.g., Bunch, Bradley, Golob, Kitamura, & Occhiuzzo, 1993; Golob & Gould, 1998). In the meantime low noise emission and vehicle performance have been of increasing interest when investigating the evaluation and acceptance of EVs (e.g., Burgess et al., 2013; Jabeen et al., 2012; Turrentine et al., 2011). As reported above, safety issues due to vehicle noise exist (Garay-Vega et al., 2010; Morgan et al., 2010; Robart & Rosenblum, 2009; Wall Emerson et al., 2011); this could have detrimental effects on EV acceptance. The third research objective therefore focused on the driver assessment of both features. Some aspects regarding driver comfort and acceptance were examined in paper I and II. Paper III in particular, focused on the assessment of changes in perceived advantages and disadvantages of BEVs. Paper III also comprised a wide range of factors, which are related to acceptance, whereas in the present dissertation regenerative braking and acoustics are emphasized.

7 Overview of methodology

The framework for the present work were the German MINI E field trials *MINI E Berlin – powered by Vattenvall* (Krems, 2011; Krems, Weinmann, Weber, Westermann, & Albayrak, 2013) and *MINI E Berlin V2.0* (Krems et al., 2011, Bühler et al., 2013). These projects provided the opportunity to investigate specific features of BEVs and their impact on the driver. The German MINI E studies were part of a series of international field trials on acceptance of BEVs (Vilimek, Keinath, & Schwalm, 2012). Apart from the German MINI E field studies, trials were conducted in the US (Turrentine et al., 2011), the UK (Burgess et al., 2013), France (Labeye et al., 2013) as well as in China and Japan.

The present dissertation utilizes the pillared structure for the evaluation of BEVs, which was proposed by Cocron, Bühler, Neumann, et al. (2011). We presumed four organizing principles to be decisive for the evaluation of BEVs from a psychological perspective: *(1) mobility*, *(2) Human-Machine Interaction (HMI)*, *(3) traffic and safety implications* and *(4) acceptance*. Although each MINI E trial emphasized different aspects, specific results of the abovementioned studies can be assigned to the four pillars. Detailed findings on range and mobility were presented by Franke and Krems (2013a, 2013b) and Franke, Neumann, Bühler, Cocron, and Krems (2012). Issues related to the HMI and charging were reported by Neumann, Franke, Cocron, Bühler, and Krems (2014), Franke and Krems (2013c) and Bunce, Harris, and Burgess (2014). Questions on acceptance of BEVs and emobility in general were addressed by Turrentine et al. (2011) as well as by Burgess et al. (2013).

Here, the focus is on regenerative braking and low noise as two unique features of BEVs, therefore the third pillar is of utmost importance. The fourth pillar is of additional interest, because both vehicle attributes were also studied with regard to acceptance. A slightly adapted version of the four pillar structure by Cocron, Bühler, Neumann, et al. (2011) is displayed below in Figure 3.

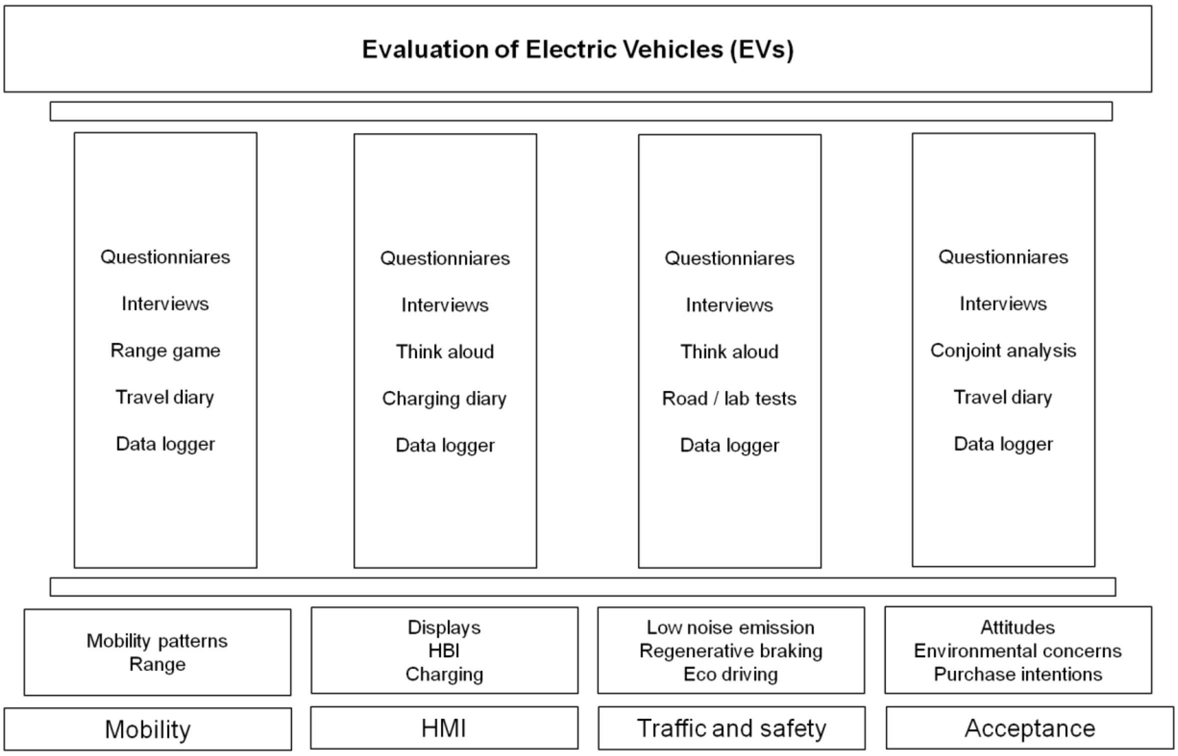

Figure 3 Four pillars in the psychological evaluation of BEVs (adapted from Cocron, Bühler, Neumann, et al., 2011)

Similar to the other pillars, a multi-method approach was adopted to assess the impact of BEV specific features on driver behavior and acceptance. As first steps, qualitative methods such as think aloud (e.g., Van den Haak, de Jong, & Schellens, 2004) and user requirement interviews (Maguire, 2001) were applied to identify key topics from the user perspective. In a next step, this empirical base was used to refine the research objectives for both topics and to derive hypotheses which could be tested statistically. The last step included focused experiments under more controlled conditions. Data were collected in two MINI E field trials (paper I-III) and specific experimental test series (paper IV). An overview of the methodology of the first MINI E field trial in Berlin can also be found elsewhere (Bühler et al., 2010; Franke, Bühler, Cocron, Neumann, & Krems, 2012; Neumann, Cocron, Franke, & Krems, 2010). In Figure 4 only those methods are displayed which were relevant for the dissertation. A detailed account of the applied methods is presented in each paper.

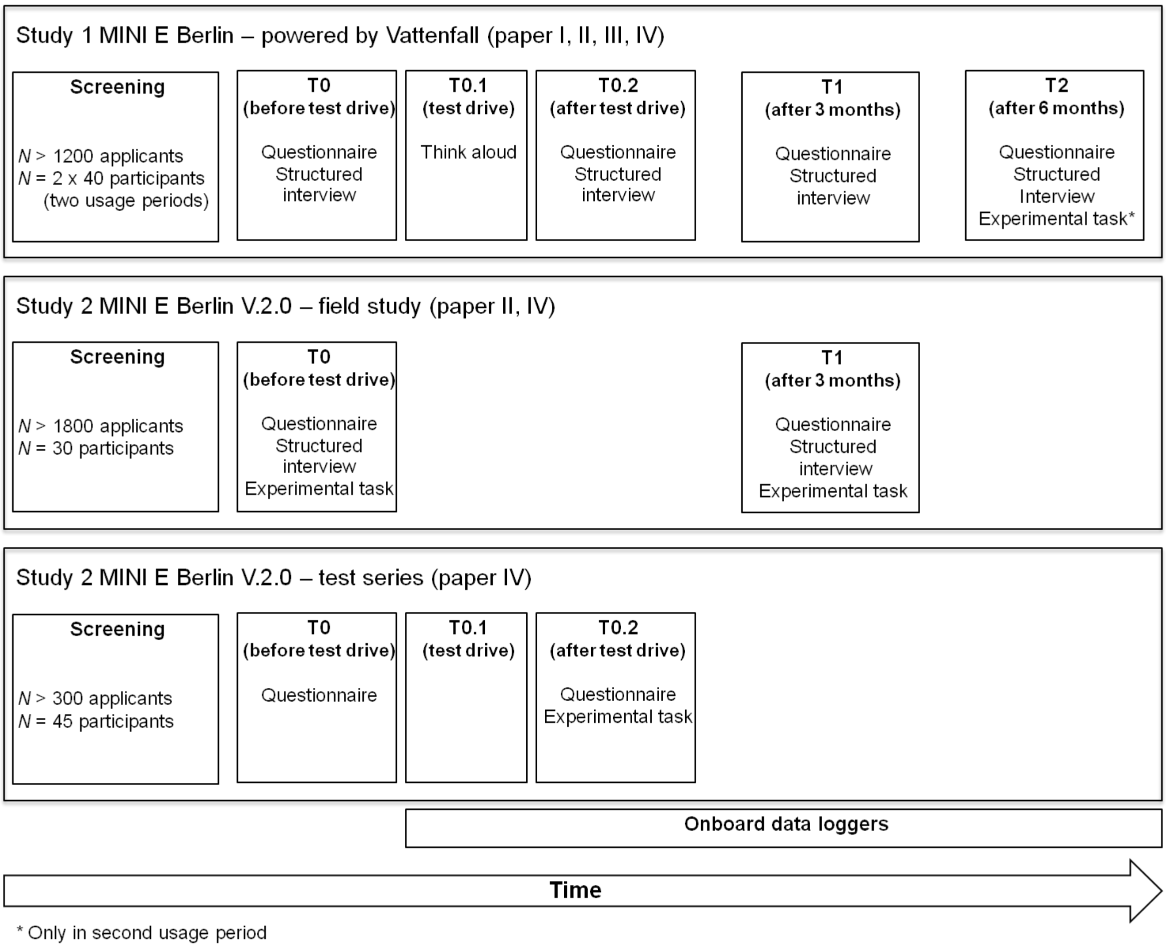

Figure 4 Overview of the methodology (adapted from Cocron, Bühler, Neumann, et al., 2011)

Figure 4 shows that both field studies were set up as longitudinal studies assessing the effects of individual BEV experience on driver behavior and attitudes. In the context of the greater projects, low noise, regenerative braking and their meaning for acceptance could be examined in more detail. The significance of individual BEV experience for the formation of preferences and informed opinions was already highlighted previously (Kurani, Turrentine, & Sperling, 1994). The test series as part of study 2 were set up to examine the low noise emission of BEVs under more controlled conditions.

8 Discussion and critical reflection of results

Regenerative braking and low noise emission are attributes which are not only unique for BEVs, but also for HEVs, PHEVs and even fuel cell vehicles (FCVs). In turn, findings reported here could serve as input in the discussion about potentials and drawbacks of different types of alternative fuel vehicles.

Taken together, both attributes affect the driving task on different levels. The ECOM model (e.g., Hollnagel & Woods, 2005) provided a reasonable structure to identify challenges for the driving task. Whereas regenerative braking usage as a motor task mainly impacts the *tracking* layer, the low noise emission calls for adaptations in the *regulating* layer. Nevertheless, both attributes require anticipatory skills. Other road users might not perceive the car in time; in turn this has to be accounted for by the drivers. Using regenerative braking, anticipatory behavior means to regulate pedal pressure to come to a halt at a desired location, for instance in front of traffic lights. The role of anticipation for energy efficient BEV driving has also been emphasized by Helmbrecht, Bengler, and Vilimek (2013). They referred to Rommerskirchen, Helmbrecht, and Bengler (2013) who defined a natural anticipation horizon as “the time he [the driver] looks ahead to act” (p. 574). Establishing such a natural anticipation horizon appears to be necessary to account for challenges due regenerative braking and low noise emission.

The studies which provided the empirical fundament of the present dissertation exhibited some characteristics, which have to be kept in mind when considering the results:

First, study 1 (*MINI E Berlin – powered by Vattenfall*) and study 2 (*MINI E Berlin V2.0*) were both designed as field studies. Therefore, external factors such as the different road environments, varying traffic densities and individual driving patterns could not be controlled for. In order to address this issue and to test assumptions under more controlled conditions, test series on the low emission were conducted in study 2 (test series). Nevertheless, all studies involved driving a BEV under real conditions, which supports the ecological validity of the presented findings.

Second, all studies were conducted with highly educated samples which showed considerable interest in technology and sustainability (‘early adopters’). Moreover, the Berlin samples were able and willing to pay for their participation in the trials. Therefore, one could argue that these participants might not representative for the German mobile population. Still, the tested samples will most likely reflect the characteristics of early buyers of such vehicles which are crucial in the adoption phase.

Third, the test vehicle which was used for all studies was a MINI E which possessed certain characteristics (e.g., performance, passenger-compartment space, size) which might be different in other BEVs. For the present dissertation, this seems more relevant for the regenerative braking function than for the external noise emission as the latter is likely to be similar across brands. Regarding the regenerative braking function it has to be noted that findings in the simulator (Schmitz et al., 2013) and different vehicle types (Eberl et al., 2012) have yielded comparable results.

Fourth, due to the lack of specific literature on both features, qualitative methods such as think aloud (e.g., Van den Haak et al., 2004) and user requirement interviews (Maguire, 2001) were applied in the beginning. These were supplemented by questionnaires on each topic and, whenever possible, recordable, objective measures (braking and reaction parameters) to obtain quantifiable results. As a consequence such a multi-method approach allowed for a consideration from different perspectives.

8.1 Research objective 1: Examination of regenerative braking skill acquisition and trust

In paper I, it was studied how drivers learn to utilize and evaluate a regenerative braking function, which was triggered via accelerator. Findings of two usage periods (each N = 40) suggested a quick learning process in regenerative braking usage. Asked how long it took them to adapt to regenerative braking, drivers estimated less than a day to manage driving with regenerative braking. The subjective assessments were also reflected in the logger data.

8.1.1 Objective parameters

Regenerative braking usage was operationalized by two braking parameters, whereas braking was defined as deceleration using the brake pedal. B_{man} as the first braking parameter reflected the number of conventional braking maneuvers per 100 km. B_{prop} represented the proportion of conventional braking maneuvers in total deceleration time. Both braking parameters revealed a rapid decrease in conventional braking maneuvers during the first kilometers of driving the test vehicle. The braking performance could be described with a power law, whereas both samples revealed comparable determinants of skill acquisition. This suggested that drivers quickly acquired regenerative braking skills and substituted conventional braking with regenerative braking maneuvers.

As discussed above, regenerative braking utilization can be regarded as a motor skill which is acquired rapidly; the *cognitive* and *associative* phases in Fitts and Posner’s (1967) conceptualization of motor learning are passed through rapidly and drivers often entered the autonomous phase within the first test drive. In this context *positive transfer* (Fitts & Posner, 1967) supposedly played a decisive role in regenerative braking skill acquisition. Drivers were familiar with deceleration through engine braking from ICE vehicles and transferred this skill to using regenerative braking to decelerate. A quick learning process was also reported by Schmitz et al. (2013) who showed that, with an accelerator triggered regenerative braking system, drivers could manage a simulator drive with only few brake applications. When driving with a regenerative braking system, which was triggered via brake pedal, the friction brakes were applied more often. With regard to the ease of mastering regenerative braking skills, regenerative braking via accelerator pedal appears to be a feasible option.

8.1.2 Subjective parameters

In paper I results on the subjective evaluation were presented, as well. Drivers in both study periods emphasized the need to adapt to the regenerative braking system. Particularly in the beginning, some drivers reported difficulties in regulating the appropriate pedal pressure. As a consequence these drivers stopped too early at traffic lights because they underestimated the intensity of the deceleration. Such occasions could be linked to Fitts and Posner's (1967) *cognitive* phase when failures occur often and drivers try to make sense of the task and its demands.

Other aspects, which were considered in paper I, were a general evaluation of the system and the development of drivers' trust towards regenerative braking. In the first usage period, some people reported temporary confusion when switching back to their conventional vehicles. As they were accustomed to driving a BEV with considerable drag torque, they were caught off guard when their ICE vehicle was not decelerating as the BEV. Some other drivers reported in the first usage period that the deceleration was too strong for them. Rajaonah et al. (2006) argued that, in decision making situations, users decide to delegate functions to automated systems or not. To do so, trust in the system needs to be built. In the second usage period, trust towards regenerative braking and the wish to modify the system were included as subjective measures. The second study period revealed that trust quickly increased after the test drive and then remained constantly high. No significant relationship between trust and the braking parameters could be detected. Still, the need to modify revealed a positive relationship with the usage of conventional braking strategies. This suggested that drivers, who wished to modify the regenerative braking system, braked more often conventionally and vice versa.

The subjective evaluation of system trust and the need to modify highlighted two facts. First, drivers appeared to be comfortable in decelerating with the accelerator pedal. System trust towards the regenerative braking function quickly increased and then remained constantly high. Second, there was a positive relationship between the need to modify the system and conventional brake pedal usage. Even if no causal conclusion can be drawn, this finding could be an indicator of suboptimal system usage which needs to be accounted for in the design of the regenerative braking system (see chapter 9).

8.2 Research objective 2: Low noise emission and its implications for risk and hazard perception of drivers

The second research objective of the present dissertation aimed at answering the question what consequences can be expected due to low external vehicle noise. As discussed above, low noise emission has direct implications for the *regulating* layer of the ECOM model (Hollnagel & Woods, 2005). In contrast to other studies examining the ramifications of BEV noise, in the current work this topic was addressed from the drivers' perspective. Especially during the transition phase with only limited numbers of BEVs on the roads, drivers are an important factor in mitigating hazards due to low vehicle noise. Assessing drivers' experiences in daily traffic and their perceptions of safety relevance appeared necessary to complement perceptibility studies with pedestrians. The research approach involved three steps, while Deery's (1999) model on driver responses to potential hazards served as a theoretical framework to investigate the noise issue.

8.2.1 Step 1: Creation of a catalogue of noise related scenes

The first step entailed compiling relevant scenarios based on the experience of BEV drivers. Hence, a catalogue of noise related incidents was created, which is published in paper II. Questioning BEV drivers of the first MINI E study (2nd usage period) after three months, six categories of situations were identified, which were related to BEV noise: (1) <30 km/h, (2) Traffic light / Turning, (3) Overtaking / Passing, (4) Exit / Parking lots, (5) Straight ahead driving and (6) Other maneuvers. Two-thirds of the participants (67.5%) in the second usage period (N = 40) reported such events. Mainly pedestrians and bicyclists were involved in such events; no accident occurred. Given that the majority of incidents occurred at low speeds, one could argue, in accordance with Garay-Vega et al. (2010), that there might be enough time for drivers and pedestrians to react. Still, driver and pedestrian distraction can level off such an effect.

In general, the degree of hazard of such events was rated as low to medium. The frequency of reported incidents was also low, even if most of the participants regularly drove in the center of Berlin. Chapman and Underwood (2000) argued that forgetting near accidents might lead to under-reporting, whereas more severe incidents are less likely to be forgotten. With respect to noise related situations, one could argue that serious incidents would have been remembered and merely less severe incidents were under-reported. The categories of the catalogue revealed some overlap with situations which were described by Hanna (2009) based on HEV accident statistics. Whereas noise emission as cause of accident cannot be reliably inferred from accident reports, situations presented in the catalogue are particularly framed on noise emission. The catalogue can therefore contribute to answering the question, which situations are particularly dangerous for VRUs.

8.2.2 Step 2: Driver assessment of low noise emission of BEVs (risk perception)

In the first field trial, also the second step was initiated. BEV noise and its consequences were assessed from the driver's perspective. Two studies were reported in paper II: *MINI E Berlin – powered by Vattenfall* and *MINI E Berlin V2.0*. Both studies revealed that concerns due to the low external noise of BEVs decreased over time. Even if at vehicle handover safety concerns were not rated high, participants expressed concern for other road users due to low vehicle noise. Similar results were reported by Carroll (2010) who also found variations in the evaluation of BEV noise.

Some referred to environmental improvements, others mentioned public safety concerns. The safety concerns reported in paper II decreased within the first 3 months of usage and then remained constant. As counterpart to safety concerns, drivers also rated the perceived comfort due to low noise. A contrary trend can be detected here. With increasing experience BEV noise was more regarded as a comfort feature than as a safety threat. In the second study similar results occurred. Low noise raised less safety concerns and was more associated with driving comfort.

In the second study (*MINI E Berlin V2.0*), risk perception as an additional theoretical construct was assessed. Rundmo and Iversen (2004) named two factors which determine risk perception: 1) A rational, cognitive component, which involves probability judgments and 2) an affective, emotional component, which comprises emotional reactions to traffic risks. This conceptualization was also used in paper II. The second study also revealed a significant decrease in the *worry and concerns* subscale (emotional component) of risk perception, which resembled the findings reported above. The cognitive component (*cognition*) only revealed a downward trend, which suggested that the perceived likelihood of harming other road users remained on a similar level.

Based on Deery's (1999) model, self assessment of skill labeled as *efficacy* was also addressed in paper II. The results implied that drivers regarded themselves as highly capable in compensating for noise related hazards. Furthermore, drivers stated to be especially vigilant to pedestrians and bicyclists.

In general, the evaluation of the low noise emission appeared to be adjusted through individual driving experience. When the first MINI E study was conducted, safety issues related to the low noise emission were discussed in the popular press. Moreover, the NHTSA report on HEV accidents was already published (Hanna, 2009) and the Pedestrian Safety Enhancement Act (2009) in the US was put in motion. Based on such information, drivers might have expressed these concerns at first. After driving the BEV for three months, drivers adapted their assessment of BEV noise. Different causes for the adapted risk estimation can be put forward:

First, drivers could just have been desensitized to risk due to repeated exposure. Such an 'optimistic bias' (Weinstein, 1989) seemed less likely as our samples consisted of experienced drivers with extended experience driving in dense, urban traffic.

Second, as reported in the catalogue, not many critical incidents occurred during three months. If incidents were reported, their degree of danger was rated as low to medium. This could also have led to the adjusted estimation of risk.

Third, hazards due BEV noise might be less severe than previously assumed. The samples in both studies mainly drove in the city of Berlin and therefore gained extensive experience interacting with VRUs, which contributed to the validity of their assessments. Drivers regarded themselves as highly proficient in mitigating the risks due to noise and stated that they paid particular attention to VRUs. The latter notion and findings from the first usage period of the first MINI E trial (Cocron, Bühler, Franke, et al., 2011) suggested that BEV drivers were capable in reacting appropriately in noise related situations. How drivers actually react in such situations, was examined in step 3.

8.2.3 Step 3: Development of a task to study driver responses in noise related incidents (hazard perception)

The third step in the investigation of research objective 3 contained developing a specific hazard detection task and testing it with drivers of differing BEV experience. These experiments are presented in paper IV. Deery (1999) identified hazard perception as a crucial prerequisite of adequate responses towards traffic hazards. In a typical test setup, participants view traffic videos from the driver's perspective and are instructed to press a response button as soon as they detect a hazard. Response latencies and the number of reactions are usually recorded as performance measures (Horswill & McKenna, 2004).

Hazard perception is regarded as skill which is acquired through individual experience. It has been repeatedly shown that novice drivers perform worse in those tests compared to experienced drivers (Horswill et al., 2008; McKenna & Crick, 1994; Sexton, 2000; Wallis & Horswill, 2007; Wetton et al., 2010). Still, the empirical evidence is not consistent as other studies did not reveal such an effect of experience (Borowsky, Shinar, & Oron-Gilad, 2007; Chapman & Underwood, 1998; Crundall, Underwood & Chapman, 2002; Crundall, Chapman, Phelps, & Underwood, 2003; Sagberg & Bjørnskau, 2006). Lacking validity as suggested by Horswill et al. (2008), a different experimental setup (Borowsky, Oron-Gilad, & Parmet, 2009) or different characteristics of the used hazards (Underwood, Crundall, & Chapman, 2011) might be the cause for the diverging results.

The hazard perception task presented in paper IV comprised several scenes, in which another road user failed to notice a BEV due to its low noise. The scenes were staged based on the report by Hanna (2009) and the catalogue presented in paper II. The tested scenes were shot from the BEV driver's perspective, whereas the BEV typically approached from behind. The task involved critical and uncritical scenes. Response frequencies, reaction times and hazard evaluations were recorded to examine if BEV experience has an influence on these variables.

In both experiments, drivers with extended BEV experience were compared to novice BEV drivers. Results indicated that the criticality of the scenes played a much more important role in responses and evaluations than BEV experience. Only tendencies for faster response latencies among BEV drivers could be found in both experiments. Participants, who were previously sensitized to the noise difference between ICEs and BEVs, also showed no substantial differences in performance. In the first usage period of the first MINI E trial (Cocron, Bühler, Franke, et al., 2011) and in paper II, BEV drivers stated that they adapted their driving behavior due to BEV noise. The results of both experiments did not support the assumption of a BEV specific experience effect. Different explanations are possible:

As suggested by Horswill et al. (2008), validity issues of the task could be the reason for the absence of experience related differences. As scenes were created based on empirical data (Hanna, 2009; paper II), lacking validity of the material seems less likely. Still, one could argue that BEV specific experience might not be reflected in simple responses. Similar to Crundall et al. (2003) it might be reasonable to investigate scanning in noise related situations.

Moreover, it can be argued that the scenes might have been too obvious or easy to interpret for the participants. Including more ambiguous scenes in hazard perception tests was also proposed by Underwood et al. (2011). In such scenes, individual BEV experience might make a difference in performance.

Finally, the absence of significant experience effects could also be explained with sample characteristics. In studies on hazard perception, novices with up to three years of driving experience are often compared to drivers with extended driving experience (McKenna & Crick, 1994; Sexton, 2000; Wetton et al., 2010). In the current study, drivers differed in their BEV experience, but had extended experience driving ICEs. This could imply that even drivers with no extended BEV can anticipate noise related hazards as accurately as experienced BEV drivers. One could therefore argue that extended ICE experience might be sufficient to adequately respond to hazards due to low BEV noise.

8.3 Research objective 3: Regenerative braking and low noise emission as crucial factors for acceptance of BEVs

The third research objective of the dissertation focused on the perception and acceptance of both attributes on a more general level. As barriers to the adoption of BEVs are broadly discussed (e.g., Egbue & Long, 2012; Ziegler, 2012), it appeared necessary to also identify those vehicle characteristics which could help fostering the adoption of BEVs. In this context regenerative braking and low noise emission could play a crucial role.

In paper III, data from both samples of the first MINI E trial were analyzed with regard to perceived advantages and disadvantages as well as acceptance. The focus of the present dissertation is on regenerative braking and noise emissions, therefore results on these features and their role as potential advantage or barrier are presented in more detail.

As the first research question, it was examined in paper III which advantages and barriers drivers perceive and if these change after using BEVs for an extended period of time. Open-ended questions on perceived advantages and barriers were asked at vehicle handover (T_0) and after three months (T_1). Once the answers were coded, the frequencies of the reported categories were used for statistical analyses. In the analyses a distinction was made between issues which could be directly experienced ("experiential") and issues which could not be directly experienced ("non-experiential"). This distinction is of great importance for the evaluation of regenerative braking and low noise as both can be directly experienced by the drivers. Hence, experiential aspects are focused on.

8.3.1 Experiential advantages

In general, findings reported in paper III substantiated the importance of individual experience for the evaluation of BEV specific attributes. Low external vehicle noise turned out to be the most frequently reported experiential advantage and was even mentioned significantly more at T_1 (56.4%) compared to T_0 (38.5%). Driving experience as another experiential aspect received the second highest number of mentions, which also significantly increased from T_0 (17.9%) to T_1 (47.4%). Driving experience as a main category is insofar relevant, as it comprised *regenerative braking* together with *acceleration*, *fun* and *pleasant driving*. Regenerative braking was mentioned more often at T_1 (11.5%) compared to T_0 (3.8%), but this difference was not significant. Other experiential aspects were also mentioned significantly more often after three months: low refueling costs (T_0: 11.5%, T_1: 28.2%), home charging (T_0: 1.3%, T_1: 16.7%) and less driving with a bad conscience (T_0: 0%, T_1: 12.8%). The number of mentions of the category high energy efficiency/low consumption remained equal over time (T_0: 10.3%, T_1: 11.5%).

The analysis of experiential advantages in paper III underlined the importance of low noise and the driving experience for driver acceptance of BEVs. The role of BEV performance for acceptance has also been emphasized by Burgess et al. (2013) who stated that "performance helps overcome initial preconceptions, and change negative attitudes" (p. 40).

Even if other experiential aspects also gained importance over time, the aforementioned features, low noise emission and driving experience, were most prominent in the user assessment of advantages of BEVs. As low noise was also regarded as a barrier to acceptance, all findings related to noise and acceptance are discussed further down.

In paper I, regenerative braking was also evaluated regarding system acceptance. Findings suggested that even if drivers had to adapt to regenerative braking, interacting with the system was regarded as part of the BEV driving experience. Specially framed to regenerative braking, drivers rated the system as useful and satisfying in the Van der Laan Acceptance Scale (Van der Laan, Heino, & De Waard, 1997).

The findings on regenerative braking acceptance suggest that the system was accepted as it was implemented in the test vehicle MINI E. Moreover, it was considered as a contribution to the overall BEV driving experience. Similar findings were also reported in other MINI E trials (e.g., Labeye et al., 2012). Even if the drag torque was strong (-2.25 m/s^2, as reported by Eberl et al., 2012), this seemed to appeal to drivers. Other studies also reported preferences for stronger drag torques in BEVs (Eberl et al., 2012; Schmitz et al., 2013) and for an accelerator triggered regenerative braking system (Schmitz et al., 2013).

Nevertheless, in paper I the subjective learning duration correlated negatively with the acceptance measures in the first usage period. The second usage period further revealed that the wish to modify the system also correlated negatively with system acceptance. Such results could be accounted for in future system design (see 9. Implications and conclusions).

8.3.2 Experiential barriers

As a counterpart to advantages, perceived barriers to acceptance were also reported in paper III. Findings on the experiential barriers revealed that limited range was a major perceived barrier and was reported more frequently as barrier after three months, even though the difference was not significant (T_0: 56.4%, T_1: 70.5%). Limited space due to battery size was significantly more often considered a barrier at T_1 (57.7%) than at T_0 (41.0%). Charging as a main category was mentioned slightly, but not significantly, less often (T_0: 34.6%, T_1: 29.5%), whereas the long charging duration was significantly mentioned less often (T_0: 16.7%, T_1: 5.1%). The state of battery technology and its weight were subsumed in the main category battery, which was significantly less often reported as a barrier (T_0: 32.1%, T_1: 14.1%). Low noise as a safety issue was also significantly less often mentioned as barrier (T_0: 14.1%, T_1: 2.6%). Limited usability (T_0: 9.0%, T_1: 16.7%) and limited flexibility (T_0: 9.0%, T_1: 7.7%) were the last two categories in the list of experiential barriers. The frequency of these perceived barriers did not significantly change.

Notably, an in-depth analysis revealed that some drivers were initially conflicted about low noise and regarded this attribute both as an advantage and a barrier (T_0: 10.3%). This was less the case after three months (T_1: 2.6%). Additionally, after three months none of the participants regarded the low noise solely as a barrier; more than half of the participants rated this feature exclusively as an advantage (53.8%).

With respect to low noise as a safety issue, the results on the perceived barriers highlighted two things. First, in comparison to other perceived experiential barriers related to range, space, battery or charging, safety issues due to low noise emission were not mentioned as major barriers to BEV acceptance. Second, safety issues due to the noise emission became less salient over time, which supports the findings reported in paper II. Whereas paper II specifically focused on the evaluation of low vehicle noise of BEVs, paper III provided the opportunity to further examine its potential relevance for BEV acceptance. In the open questions no specific attribute of BEVs were triggered, therefore the evaluation reported above underlines the importance of noise for BEV acceptance.

The potential importance of low vehicle noise for acceptance was also reflected in the perceived experiential advantages of BEVs. Low noise was the most frequently reported experiential advantage. Only the main category environmental friendliness was mentioned more often, but this was classified as non-experiential advantage. After three months, even more participants regarded low noise as an advantage. Again, the findings obtained in open questions confirm the questionnaire results reported in paper II. With increasing experience, low noise is regarded more as a comfort feature than as a safety issue. Notably, such an effect can be found even after a short drive (paper IV).

9 Implications and conclusions

The objective of the present dissertation was to investigate key BEV attributes from a psychological perspective. Regenerative braking and the low noise emission and their impact on user behavior and experience were examined in detail. Findings of paper I, II and IV suggest that drivers quickly adapted to driving with BEVs. Furthermore, both attributes seemed to play an important role in the evaluation of BEVs (paper III).

As discussed above, the *tracking* and *regulating* layer of the driving task are altered due regenerative braking and low noise emission. In the future, this could have implications for driver education. If the majority of acceleration and deceleration maneuvers can be executed with one pedal, curricula might have to be adjusted. Especially as conventional braking maneuvers occur less often, it has to be ensured that conventional braking skills are maintained to take over control in emergency situations. Additionally, anticipatory skills appear to be crucial to compensate for safety problems arising from the low noise emission. Developing such skills will be even more important in driver education.

9.1 Specific implications of regenerative braking

Findings of paper I and III and studies by other researchers (Schmitz et al., 2013; Eberl et al., 2012) showed that drivers quickly adapted and appreciated a regenerative braking system, which was relatively strong and triggered via accelerator pedal. Using regenerative braking to accurately decelerate to a predefined location also seems to be learnt rapidly. This was shown in an additional study by Witzlack, Cocron, and Krems (2013).

Nevertheless, paper I revealed that the wish to adjust the intensity of regenerative braking corresponded positively with a conventional braking strategy instead of regenerative braking utilization. Offering customizable levels of regenerative braking intensity appear to be a viable solution in this context. The impact of different regenerative braking modes on driver behavior and acceptance should be addressed in future research.

Moreover, some drivers reported on temporary confusion when switching between vehicle types. When driving a conventional vehicle after extended BEV usage, these drivers were expecting the strong drag torque and were then surprised about its absence. Similar effects could occur if regenerative braking fails, temporarily or permanently. In such cases, drivers need to quickly take over control and apply the friction brakes. Similar failures have already been studied in ACC systems, for instance by Nilsson, Strand, Falcone, and Vinter (2013). Initial steps to better understand the impact of regenerative braking failures on driver behavior and acceptance have been undertaken by the EVERSAFE project (http://www.eversafe-project.eu). With respect to system design, appropriate information about the system's implementation (accelerator, brake pedal or both) and feedback on its status (working vs. not working) seem essential.

Finally, the regenerative braking tested in the dissertation provided direct feedback which could have contributed to its positive evaluation. Due to *positive transfer* (Fitts & Posner, 1967) of already acquired skills, changing from ICE to BEV driving seems undemanding. Notably, braking and accelerating with one pedal has already been tested in ICE vehicles. Comparable to results discussed in paper I, Nilsson (2002) reported a short learning phase and a positive evaluation of such a pedal solution. Taken together, these findings could provide input how to trigger regenerative braking in EVs.

9.2 Specific implications of low noise

Findings reported in paper II, III and IV emphasized that drivers were fond of the low noise emission of their BEV. With increasing driving experience, noise as a specific BEV attribute was regarded less as a safety issue and more as a comfort feature. This effect even occurred after a short test drive. Moreover, no substantial differences could be found between experienced and novice BEV drivers in a specific hazard detection task. The latter finding implied that even without extended BEV experience drivers could detect noise related hazards and react accordingly.

These findings could serve as input to the discussion about the safety of EVs. Similar to the US and Japan, the EU (European Commission, 2014) decided on Acoustic Vehicle Alerting Systems (AVAS) to alert pedestrians and bicyclists. The rule will be mandatory after a transitional period of 5 years. As reported in paper II, BEV drivers did not favor artificial sounds. This is comprehensible as noise related incidents were reported rarely and were mostly rated as not too dangerous. Still, given that artificial sounds of EVs will be mandatory soon, it needs to be understood how to implement these systems. Cottrell and Barton (2012) tested different vehicle sounds for pedestrians and found that a warning system, which had to be operated manually, produced higher stress when compared to no external noise and an automated system. Related to the benefit of AVAS, Sandberg (2012) argued that these might result only in marginal safety improvements which could easily be evened out by an inadequate notion of safety among drivers and pedestrians.

To sum up, addressing safety issues due to low vehicle noise appears complex as different perspectives need to be accounted for. The mandatory integration of AVAS might not solve the problem alone. While automated AVAS appear promising, permanent noise at low speeds could compromise the environmental benefit of EVs. Other strategies such as driver and pedestrian training and cooperative systems should also be pursued. A combination of approaches appears most promising to benefit from low noise as important advantage of EVs.

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Paper I:
Energy recapture through deceleration – regenerative braking in electric vehicles from a user perspective

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Energy recapture through deceleration – regenerative braking in electric vehicles from a user perspective

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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.

1 Introduction

In the debate about decreasing CO_2 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 & 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 & 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 & 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 & 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, & Schwalm, 2012) these issues were addressed in a German 1-year field study (Cocron et al., 2011; Franke, Bühler, Cocron, Neumann, & Krems, 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, Sharma, Stroph, Schumann, and Pruckner (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, Jagiellowicz, Maag, and Hanig (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, Walsh, Smith, Burgess, & Harris, 2010). Results of a field study from the US (Turrentine, Garas, Lentz, & Woodjack, 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, Carroll, Eastlake, and Blythe (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 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 & 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 & Rosenbloom, 1981, as quoted in Ritter & Schooler, 2001), its applicability to learning data has been questioned mainly with regards to averaging performance scores across participants (Brown & 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 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 & Parker, 2004; Kazi, Stanton, Walker, & Young, 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.

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 & Rosenbloom, 1981). Analogical to research on in-vehicle information systems (Jahn et al., 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).

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 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 (T0)

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, & 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.

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 et al., 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 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_{man}, B_{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.

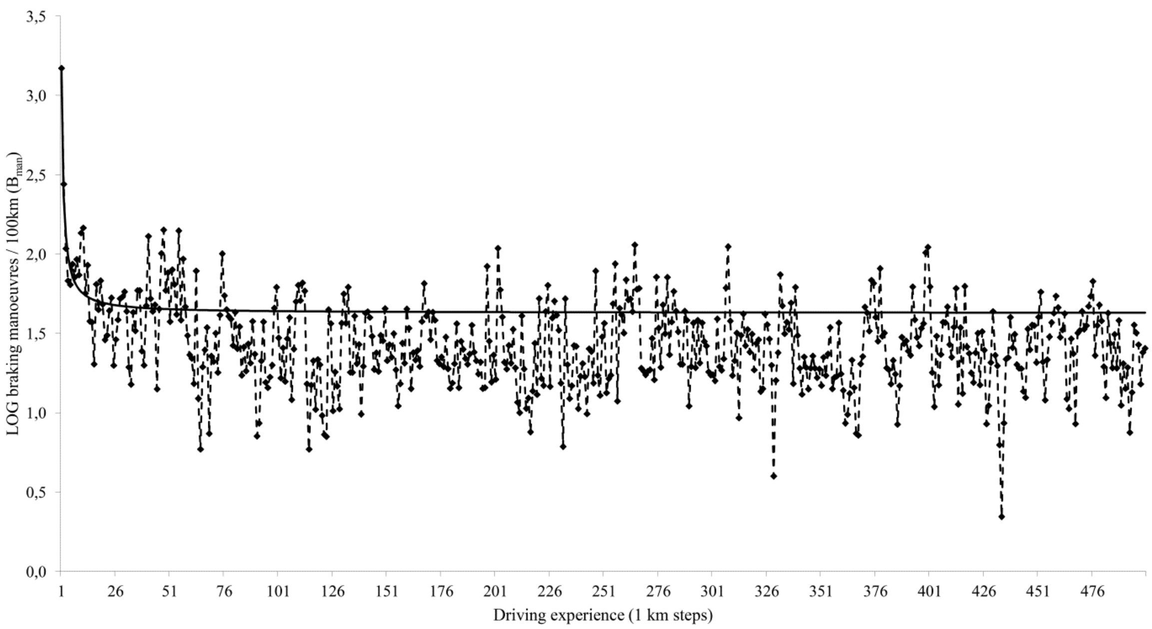

Figure 1 Study Period 1: Mean number of braking maneuvers per 100 km (LOG) fitted with a power function

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.

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

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

Note: RMSE = root mean square error

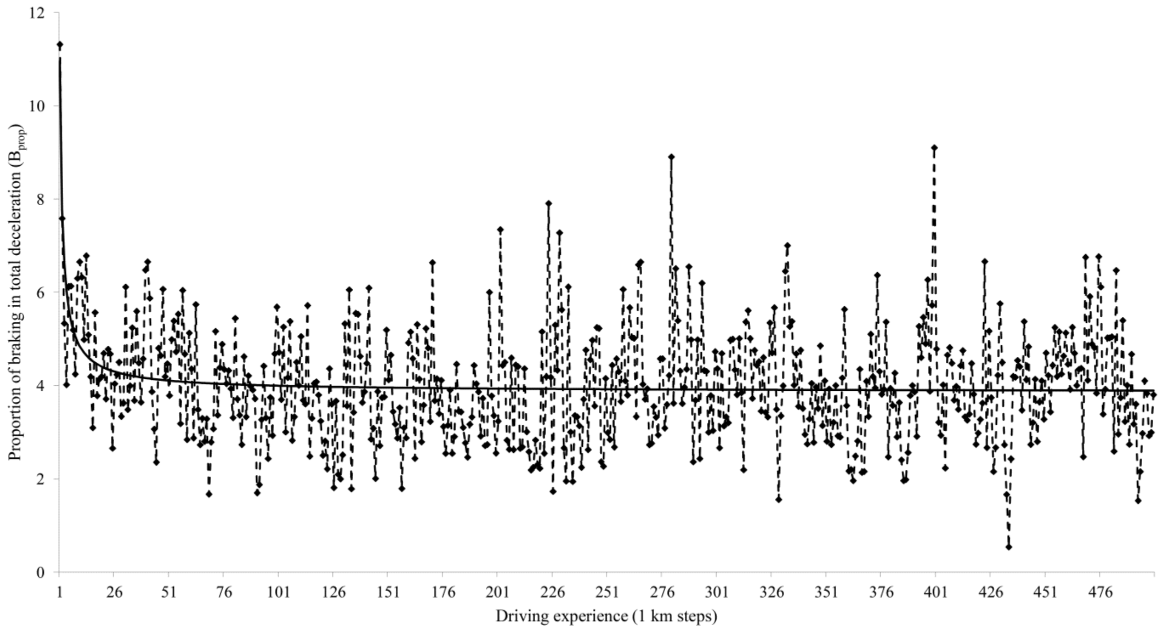

Figure 2 Study Period 1: Mean proportion of braking in total deceleration fitted with a power function

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 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.

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 et al., 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 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).

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 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.

6.1.3 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 & 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 et al., 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 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.

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

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

Note: RMSE = root mean square error

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.

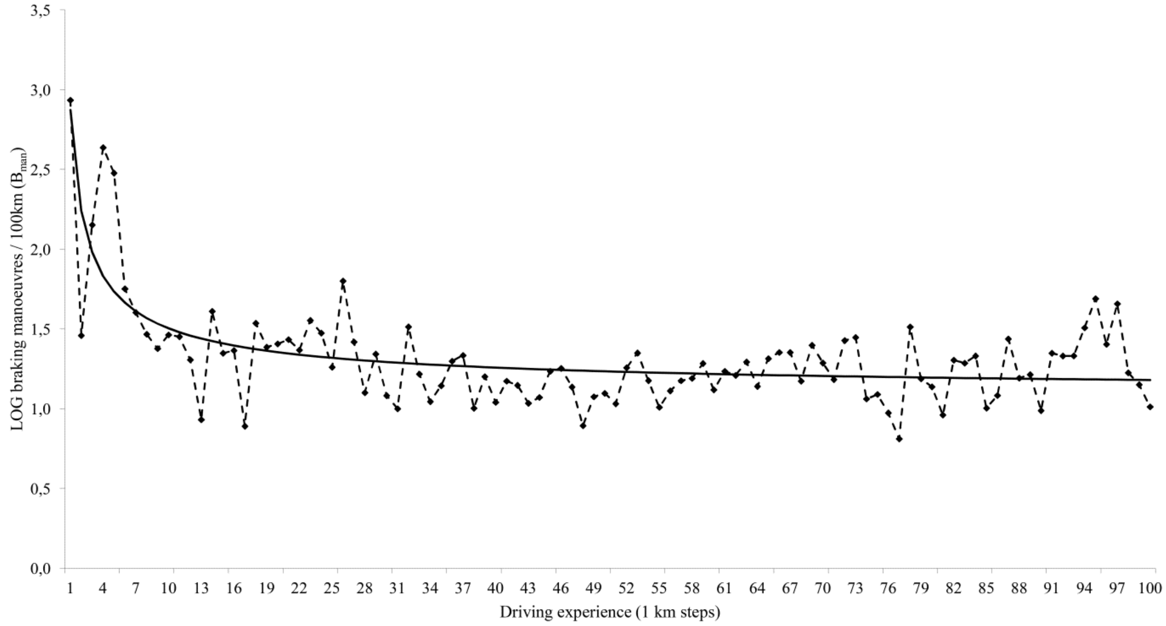

Figure 3 Study Period 2 (0–100 km): Mean number of braking maneuvers per 100 km (LOG) fitted with a power function

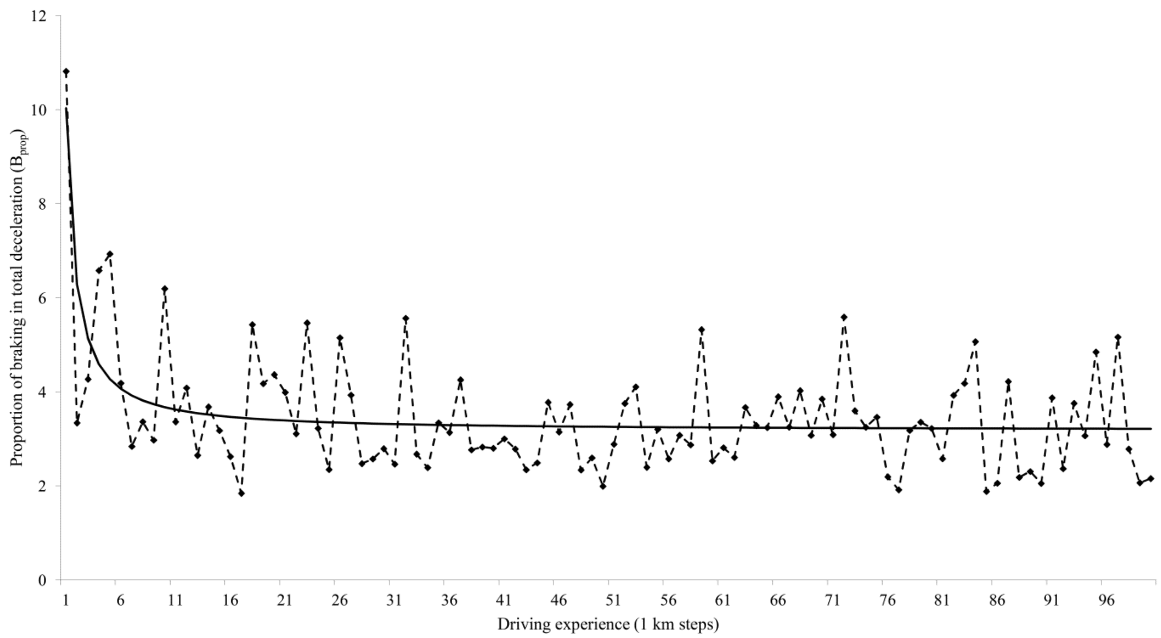

Figure 4 Study Period 2 (0–100 km): Mean proportion of braking in total deceleration, fitted with a power function

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 internal consistencies in the following times of measurement ($.60 \leq$ 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.

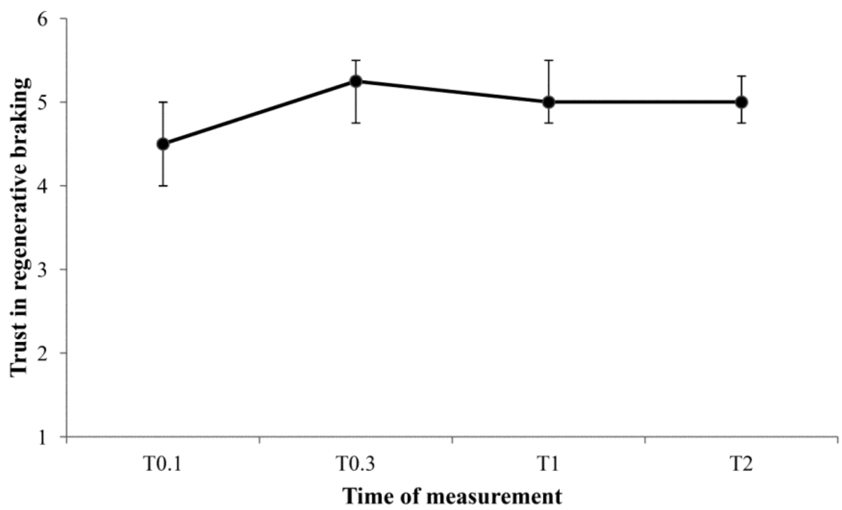

Figure 5 Study Period 2: Trust in regenerative braking (medians, error bars represent *IQR*)

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. 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 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).

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.

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 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 & 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 & 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 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, & 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 & 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.

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Paper II:
Driver perceptions of the safety implications of quiet electric vehicles

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Driver perceptions of the safety implications of quiet electric vehicles

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Previous research on the safety implications of quiet electric vehicles (EVs) has mostly focused on pedestrians' acoustic perception of EVs, and suggests that EVs are more difficult for pedestrians to hear and, therefore, compromise traffic safety. The two German field studies presented here examine the experiences of 70 drivers with low noise emissions of EVs and the drivers' long-term evaluation of the issue. Participants were surveyed via interviews and questionnaires before driving an EV for the first time, after 3 months of driving, and in the first study, again after 6 months. Based on participants' reports, a catalogue of safety-relevant incidents was composed in Study 1. The catalogue revealed that low noise-related critical incidents only rarely occur, and mostly take place in low-speed environments. The degree of hazard related to these incidents was rated as low to medium. In Study 1, driver concern for vulnerable road users as a result of low noise diminished with increasing driving experience, while perceived comfort due to this feature increased. These results were replicated in Study 2. In the second study, it was additionally examined, if drivers adjust their perceived risk of harming other road users over time. Results show that the affective assessment of risk also decreased with increased driving experience. Based on individual experience, drivers adjust their evaluation of noise-related hazards, suggesting that dangers associated with low noise emissions might be less significant than previously expected.

Key Words: electric vehicles, low noise, risk perception, traffic safety

1 Introduction

The increasing electrification of the power train in cars has led to intense debate about the advantages and disadvantages of hybrid electric vehicles (HEVs) and electric vehicles (EVs). One issue, which has more recently attracted public attention, is the low noise emitted by vehicles with a full or partial electric power train. HEVs drive on electricity at low speeds and during acceleration, while EVs are exclusively propelled by electricity. Concerns have been raised, especially regarding the safety of visually impaired pedestrians (National Federation of the Blind, 2011), who depend heavily on environmental sounds to navigate in traffic (Wall Emerson, Naghshineh, Hapeman, & Wiener, 2011). The objective of the present article is to investigate (1) what kind of noise related incidents occur in everyday traffic and how these could be characterized, and (2) how actual drivers perceive the safety implications of quiet EVs. In particular, we examine (3) if EV drivers express concern for other road users and if (4) this evaluation is altered by individual driving experience. Finally, we aim to advance understanding of (5) how drivers evaluate artificial sounds as countermeasures. These issues were addressed in two field studies with a total of 70 drivers who drove an EV for an extended period of time.

1.1 Safety concerns and accident characteristics

Recently, the National Highway Traffic Safety Administration (NHTSA) published a report on accident characteristics of HEVs (Hanna, 2009). In the report, incidence rates of accidents involving HEVs were compared to accidents involving conventional vehicles with an internal combustion engine (ICE). In general, for crashes involving pedestrians, HEVs had a significantly higher incidence rate than ICE vehicles. Based on accident statistics of 12 US states, HEVs were twice as likely to be involved in pedestrian crashes during maneuvers, such as slowing or stopping, backing up, entering or leaving a parking space, than ICE vehicles. In the report, these maneuvers were grouped into one category as they all occurred at low speeds, where the difference in sound volume between vehicle types is maximal. Incidence rates of pedestrian crashes were also higher for HEVs when the vehicles were turning. The analysis of bicycle-related crashes showed a similar pattern; incidence rates for HEVs were higher than for ICEs in low-speed situations. Due to low registration rates, the numbers of HEVs reported in the NHTSA analysis were very small. The NTHSA report has recently been questioned as it failed to clarify if, and to what extent, low noise was responsible for the high number of pedestrian crashes (Verheijen & Jabben, 2010). Nevertheless, we argue that based on data from the US, it is possible to identify those maneuvers and situations which will most likely pose the greatest danger for pedestrians and bicyclists, if HEVs and EVs should become more widespread.

For the UK, similar results were reported (Morgan, Morris, Keigan, & Muirhead, 2010). EVs and HEVs in the UK were two times more likely to be involved in accidents that resulted in pedestrian casualties than ICE vehicles. Again, the absolute numbers of EVs and HEVs involved in pedestrian accidents was very low. The authors concluded that accidents were more likely to occur in areas with speed limits of less than approximately 64 km/h (40 mph) and that risk was also increased while engaging in slow maneuvers.

In contrast to findings from the US and the UK, a Dutch study found no statistical evidence for a higher incidence rate for accidents between HEVs and pedestrians or bicyclists. The number of examined accidents was also very low, even though the market share of HEVs in The Netherlands is the highest in Europe (Verheijen & Jabben, 2010). Due to low registration rates of EVs and HEVs, detailed and valid data on accidents involving these vehicles are still rare. The reported accident statistics from the US, UK and The Netherlands provide an inconsistent picture, indicating either an increased, or no increased risk for HEV/EV accidents involving, for example, pedestrians. Additionally, based on simple accident data it is almost impossible to determine if low vehicular noise emissions or other factors, such as inattention, caused the accident.

1.2 Noise emissions and auditory detection of HEVs and EVs

In addition to studies reporting accident statistics, HEVs and EVs have also been studied to determine the extent to which noise emissions and pedestrian detectability impact traffic safety. Morgan et al. (2010) recorded vehicle noise in different maneuvers and compared the noise characteristics of EVs and HEVs with conventional ICE vehicles. The analysis showed that during a pass-by at a steady speed of 7-8 km/h (4-5 mph), the maximum recorded noise levels tended to be, on average, lower for HEVs and EVs (52-56 dB(A)) than ICEs (51-58 dB(A)), although the authors argued that modern ICE vehicles may also be as quiet as their electric equivalents. In the initial phase of acceleration, at 0.5 ms^{-2}, EVs and HEVs (62-64 dB(A)) were marginally quieter than ICE vehicles (63-64 dB(A)) and at higher speeds (e.g. 20 km/h), noise levels were comparable (EVs/HEVs: 63-66 dB(A) vs. ICEs: 62-66 dB(A)) as road and tire noises became more dominant. Similar findings have been reported by Garay-Vega, Hastings, Pollard, Zuschlag, and Stearns (2010), who also compared noise levels of HEVs and their ICE counterparts. The maximum noise difference (2-8 dB(A)) between vehicle types was observed when vehicles were approaching at approximately 9.5 km/h (6 mph). Smaller differences occurred at approximately 16 km/h (10 mph) and no significant differences were observed at approximately 32 km/h (20 mph) and above. Robart and Rosenblum (2009) compared the auditory detection of conventional ICE vehicles with HEVs and showed that subjects could determine the direction of slowly (5 mph) approaching ICE vehicles much sooner than HEVs. If background noises were added, HEVs were not perceived until very close to subjects. When both sets of stimuli were tested on blind pedestrians, similar results occurred.

Tests with blind pedestrians were also conducted by Garay-Vega et al. (2010); these tests were of auditory detection of HEVs and ICE vehicles with different ambient noise levels, and allowed comparison of both vehicle types and their maneuvers. The time-to-vehicle-arrival, i.e. the time from first detection to the moment the vehicle passed the subject, was found to be shorter for HEVs than for ICE vehicles in the backing out (8 km/h, 5 mph) and vehicle approaching (9.5 km/h, 6 mph) maneuvers. In other words, HEVs were closer to pedestrians by the time they were first noticed. Only when slowing was the HEV detected earlier, a finding that is most likely due to the noise emitted by its regenerative braking system during deceleration. The authors argue that the resulting detection times would normally be sufficient for pedestrians or drivers to avoid a collision. Nevertheless, it should be noted that in the experiment the pedestrians could devote their full attention to the task, which might not be possible under normal traffic conditions with multiple vehicles present. How and when blind pedestrians decide to cross a street was studied by Wall Emerson et al. (2011), where passing vehicles were either conventional ICE vehicles or HEVs. HEV speeds below 20 mph (32km/h) also turned out to be most difficult to detect for blind pedestrians. The Toyota Prius, one of the HEVs tested, was only detected when the vehicle was an average of 2 s away, which equals 56.6 feet (17 m) at 20 mph (32km/h). When the test vehicles were approaching at higher speeds, Toyota Prius, Honda hybrids and the ICE vehicles were similarly detected at 4-5 s away, although even this time period was not sufficient to safely cross the street.

A study on search behavior at intersections revealed that sighted pedestrians tend not to search visually for oncoming vehicles; instead, they tend to rely on auditory cues (Van Houten, Malenfant, Van Houten, & Retting, 1997). Compared to situations in which vehicles approached from the side or head-on, the least search behavior occurred when vehicles approached from behind the pedestrian. Only approximately 30% of the pedestrians searched for vehicles approaching from behind, which suggests that with more EVs/HEVs available, these situations will also become increasingly relevant for sighted pedestrians.

In sum, findings on HEV noise emissions suggest that particularly when traveling at speeds of up to 20 mph (32km/h), noise emissions differ between vehicle types, which makes it especially difficult for blind pedestrians to detect HEVs. To date, studies on noise emissions of HEVs and EVs have focused exclusively on perceptibility, in particular of HEVs. Here, we also examine driver experiences with EVs.

1.3 Driver experience and the evaluation of low noise

Thus far, research on how drivers evaluate low noise is still sparse and is mainly limited to general statements. In a study examining user acceptance of EVs from Sweden, participants reported that low noise contributed to driving pleasure (Gärling, 2001). Results from a study on EV fleet usage (Carroll, 2010) show that drivers generally appreciate low noise and the environmental feel-good factor; however, considerable variation in user evaluations was observed. Additionally, some participants reported that lack of noise was beneficial for the environment, and others mentioned safety concerns. Initial results from another UK trial revealed drivers' concerns about pedestrian and bicyclist safety prior to driving an EV for the first time (Everett, Walsh, Smith, Burgess, & Harris, 2010). Similar findings were also reported in a German field study on EVs (Cocron, Bühler, Franke, Neumann, & Krems, 2011); although drivers generally appreciated the EVs' low noise, concern for the safety of other road users was expressed prior to driving the vehicles for the first time. As practice with an EV increased, these concerns decreased. To further investigate these effects, the theoretical framework of risk perception was used as a reference.

1.4 Risk perception

Risk perception, or the subjective experience of risk in hazardous situations, is usually referred to in discussions about the augmented accident risks of young novice drivers, who tend to perceive lower levels of risk compared to other groups (Deery, 1999). According to Brown and Groeger (1988), risk perception is determined by two factors: (1) information about the potential hazard within a traffic context (i.e. hazard perception) and (2) information regarding the ability of both the driver and the vehicle to prevent the potential hazard from turning into an accident. Hazard perception, according to Brown and Groeger (1988), consists of the identification of a hazard and the quantification of its hazardous potential. Building on this, Deery (1999) proposed a model of behavioral response to traffic hazards. If a hazard is encountered, the driver first needs to detect the hazard and quantify its degree (hazard perception). Associated processes are the subjective experience of risk, i.e. risk perception, and the self-assessment of skill. Actual behavior is then defined by the subjective risk threshold and the driver's skill in operating the vehicle.

Rundmo and Iversen's (2004) concept of risk perception resembles Brown and Groeger's in proposing two influential factors for risk perception. Nevertheless, Rundmo and Iversen focus more on the interpretation of the perceived risk, assuming that risk perception consists of a rational, cognitive component and an affective, emotional component. The rational component comprises the probability judgments and beliefs about traffic risks, whereas the affective component is composed of worry and other emotional reactions to the possibility of traffic risks. In our study, we conceptualized risk perception in accordance with Rundmo and Iversen (2004), assuming that risk perception of hazards due to low EV noise is made up of a rational cognitive and an affective component.

Thus far, discussions about quiet cars and their impact on traffic safety have been primarily based on perceptibility studies. We propose not only to include the driver's perspective, but also to investigate further if and to what extent driving silently in everyday traffic is perceived as risky for other road users. It should be noted that the personal risk for the driver is low in crashes with pedestrians or bicyclists, regardless of vehicle type. Along these lines, one might expect that the risk perceived by the drivers would not differ between vehicle types. Given that low noise emissions seem to put certain road users at risk, we therefore devote specific attention to the question of whether EV drivers perceive a risk of harming other road users.

Accordingly, it is of vital interest to examine how the perception of risk associated with low noise develops over time. The relationship between risk perception and individual experience of risk has already been studied in other fields. In the context of nuclear energy, MacGregor et al. (1994) reported that people living far from a nuclear waste transport corridor tend to be equally, or even more, concerned as those living close to the corridor. Similar results concerning the perception of hazardous facilities were reported by Lindell and Earle (1983). Barnett and Breakwell (2001) argue that habituation might be influential in the relationship between risk perception and experience. Habituation is defined as a process in which the tendency to respond to a potentially dangerous stimulus decreases due to repeated exposure (Rankin et al., 2009). Here, we investigate if the reported effects of individual experience also apply to the perception of risks related to low noise of EVs.

1.5 Research objectives

In the present paper, we focused on EV drivers' perceived risk of involvement in critical incidents with other road users, due to the low noise of their EV. In particular, Study 1 aimed to determine how drivers generally evaluate low noise over time and what kind of noise related incidents they encounter. The purpose of Study 2 was to validate findings obtained in Study 1 and to determine if drivers' perceived risk of harming other road users changes over time. Considering the issue from the perspective of pedestrians, ability to detect these vehicles has clear implications for safety. Nevertheless, until now, there has been no empirical investigation about what happens in everyday traffic, even though HEVs have been on the market for quite some time. Currently, the likelihood of a pedestrian encountering a low noise EV in normal traffic is lower than that of an EV driver encountering a pedestrian. Therefore, it seems reasonable to account for the experience of the individuals potentially causing harm.

We posed the following research questions: (1) What kind of critical situations arising from low noise occur and how can these be characterized? (2) Is low noise perceived more as a safety issue or as a contribution to driving comfort? (3) To what extent do concerns about the safety of other road users exist? (4) Does risk perception change with experience? (5) How do drivers evaluate artificial sound as a potential countermeasure?

2 Study 1

Study 1 is nested within a large-scale field study examining acceptance and road capability of EVs, which was conducted in the Berlin metropolitan area. The field study was set up in cooperation with the BMW Group and Vattenfall Europe, and was funded by German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety. Interested participants completed an online application, which was advertised via local newspapers and online media. The field study consisted of two 6-month trials, with 40 test drivers in each trial. Study 1 is the second trial of the study referred to as the *MINI E Berlin field study*. The methodology for the field study has been described previously (Cocron, Bühler, Neumann, et al., 2011; Franke, Bühler, Cocron, Neumann, & Krems, 2012).

2.1 Method

2.1.1 Participants

Out of 498 applicants, 40 drivers were selected to drive an EV for 6 months in the Berlin metropolitan area. Main prerequisites for participation in the project were current residence in the Berlin metropolitan area, along with willingness to install a private charging box, take part in the scientific study, and pay a monthly leasing rate. For their participation in the study, participants were compensated through a reduced monthly leasing rate, which resembled the monthly leasing rate of an equivalently equipped gasoline model under similar leasing conditions. At the beginning of the study, participants were informed about the objectives of the greater research project and gave their written consent that data could be collected and analyzed for scientific purposes. Mobility-related (e.g. mileage, vehicle fleet) and sociodemographic variables (e.g. age, gender, education) were also taken into account to select a sample, which was as broadly distributed as possible.

The average age of test drivers was 50 years (*SD* = 10.2), and the sample comprised 35 male and 5 female participants. Fifty-eight percent of the selected participants had driven 15,000 km (~9300 miles) or more in the preceding year; the remaining participants drove less. Forty percent of participants reported that they had previously driven an EV, HEV or electric scooter, primarily during short test drives. One participant withdrew from the study prior to completion. Upon returning the vehicles, participants had gained considerable experience driving an EV, *Mdn* = 5537 km (~3300 miles). The sample in Study 1 is best characterized as consisting of environmentally aware early adopters, who are expected to play a crucial role in the adoption process of EVs (Egbue & Long, 2012). Therefore, the evaluations reported here are expected to reflect the viewpoint of early EV drivers.

2.1.2 Procedure

Participants in the study were questioned before receiving the test vehicles (T0), after 3 months of EV usage (T1) and upon returning the vehicles after 6 months (T2). Each interview involved closed and open-ended questions on different aspects of EVs, and lasted between 2 and 3 h. The interviews involved quantitative and qualitative elements. A detailed field manual ensured that the interviews were conducted similarly and questionnaires were administered correctly. In order to avoid priming, the topics of noise and safety were not broached in the interviews until the participants answered the questionnaire items. Still, the participants might have read about safety issues in the press before participating in the study. The views of participants at T0, therefore, most likely reflect the views of novice EV drivers.

2.1.3 Test vehicles

In Study 1, participants drove a standard MINI Cooper, which was converted to a battery-powered vehicle. The MINI E was powered by a 150-KW electric engine and could reach a top speed of 152 km/h (~95 mph). Further technical information on the test vehicles used in this study is available online (Minispace.com, 2012); though, detailed information on the vehicles' noise emissions is not publicly accessible.

2.1.4 Long-term evaluation of the low noise

At T0, drivers were first asked about their expectations concerning low noise, and at T1 and T2, about their experiences related to low EV noise. In order to address the research objectives of Study 1, two aspects were assessed: (1) the change in the driver's evaluation over time and (2) the subjective differentiation between the pleasure of silent driving and the risk of endangering other road users. In Study 1, *Danger* was assessed via the item 'I believe that the lack of noise from [an electric vehicle[1]] is dangerous for road traffic'[2].

Pleasure was assessed via the item 'The quietness of [an electric vehicle] will be/is pleasing'[3]. Each item was rated using a 6-point Likert scale ranging from 1 (*completely disagree*) to 6 (*completely agree*).

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[1] The vehicle's name [MINI E] was used in the German questionnaire.
[2] German: 'Ich schätze die Geräuschlosigkeit des MINI E als Gefährdung des Straßenverkehrs ein.'
[3] German: 'Die geringe Geräuschkulisse des MINI E wird mir gefallen/gefällt mir.'

2.1.5 Characteristics of critical situations

In the 3-month interview (T1), participants were asked to describe in detail personal experiences that were related to the low noise of their EV. To obtain a comprehensive and comparable description of these incidents, participants filled in a matrix consisting of closed and open-ended questions. In the open section, participants briefly described and labeled the incidents. In the closed section, these incidents were rated. Here, variables of interest were the *type of road user* involved (pedestrian, cyclist, motorcycle, passenger car, truck, other), *current speed of the involved parties*, the *degree of hazard of the situation* ranging from 1 (*not dangerous*) to 10 (*extremely dangerous*), and the *frequency of these situations* during the first 3 months. This catalogue of noise-related events experienced by EV drivers aims to document important characteristics of critical situations involving EVs and other road users.

2.1.6 Potential countermeasures from the driver perspective

After 6 months, drivers were also asked to suggest how potential safety issues due to low noise should be addressed in the future. Drivers rated five possible strategies, attributing a total of 100 points to the following five options: (1) no tone/increased awareness, (2) automatic pedestrian detection system, including driver warning, (3) continuous external sound, (4) additional sound at speeds < 30 km/h (~19 mph) and (5) other.

2.2 Results

For the most part, the data reported here violated the assumptions of normality. Therefore, non-parametric analyses were conducted and medians (*Mdn*), as well as interquartile ranges (*IQR*) are reported. Parametric tests, which were conducted additionally, revealed similar results. The effect size *r* was calculated according to Field (2009), and classification of effect sizes was made following suggestions by Cohen (1992).

2.2.1 Drivers' long-term evaluation of low noise

Results of drivers' subjective evaluation of low noise emissions show that this feature was generally appreciated. *Pleasure* was already high at T0 (*Mdn* = 5.0, *IQR* = 1), slightly increased at T1 (*Mdn* = 6.0, *IQR* = 1) and then remained equally high at T2 (*Mdn* = 6.0, *IQR* = 1). Friedman`s ANOVA showed a significant effect of time, χ^2 (2, *N* = 39) = 10.61, *p* = .005. Follow-up pairwise comparisons revealed significant differences between T0 and T1 (*p = .002*, *r* = – .35). With increasing driving experience, low noise was perceived as significantly less dangerous for other road users, χ^2 (2, *N* = 39) = 24.06, *p* < .001. The low noise emissions of the vehicles were regarded as dangerous to some extent before receiving the vehicles at T0 (*Mdn* = 3.0, *IQR* = 2), less so at T1 (*Mdn* = 2.0, *IQR* = 2) and T2 (*Mdn* = 2.0, *IQR* = 2). Again, post hoc tests revealed significant differences between T0 and T1 (*p* < .001, *r* = – .46). The effect on pleasure can be considered as medium, the effect on perceived danger as medium to large. The items evaluating the degree to which low noise emissions were associated with pleasure or danger are displayed in figure 1.

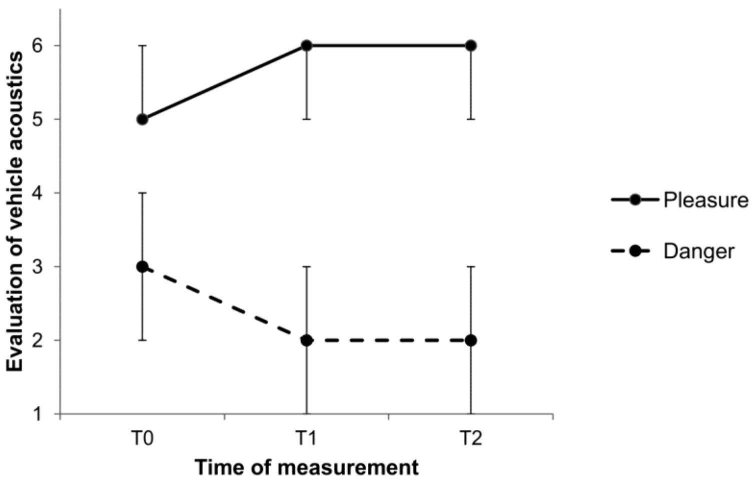

Figure 1 Study 1: Driver evaluation of low noise (medians, error bars represent IQR)

2.2.2 Catalogue of noise-related incidents

Based on the situations described by participants in structured interviews at T1, a catalogue of potentially critical situations due to low noise was compiled. Some participants described the situations in terms of general categories, e.g., driving speed at the time of the event, while others described events in more detail. Participants assigned labels to incidents, whereas similar incidents were grouped into the same label (e.g. parking lot). The main categories, such as type of road user involved and degree of hazard, had to be filled in for each label, thereby allowing a comparable description of incidents. Based on the information provided by participants, as well as, the labels they assigned to incidents, similar incidents were grouped in six different categories of noise-related events: (1) <30 km/h (~19mph), (2) Traffic light / Turning, (3) Overtaking / Passing, (4) Exit / Parking lots, (5) Straight ahead driving and (6) Other maneuvers (table 1). In addition, each incident was described according to other relevant variables, such as characteristics of other involved road users, speed and the degree of hazard.

Overall, 67.5% of participants reported incidents that were related to the low noise emissions of EVs. None of the reported low noise-related incidents resulted in an accident. Due to the considerable variance in the data, the medians are reported in this paper. For the first 3 months of driving the EV, a median of three noise related incidents was reported by the participants (*Mdn* = 3.0, *IQR* = 9.50). The median degree of hazard of these incidents was regarded as low to medium, *Mdn* = 4.0 (*IQR* = 3.13) on a 10-point scale (1=*nonhazardous* to 10=*extremely hazardous*). Most reported noise-related incidents fell in the category (1) <30 km/h (~19mph). Eighteen out of 40 participants reported incidents of this kind. The degree of hazard associated with these incidents was rated as relatively low (*Mdn* = 3.5, *IQR* = 3.0). At (2) traffic lights or while turning, noise-related incidents were reported, as well: Ten drivers reported incidents with a medium degree of hazard (*Mdn* = 5.0, *IQR* = 4.25). Nine drivers reported safety-relevant situations in (3) overtaking and passing maneuvers. The degree of hazard in these situations was also rated as medium (*Mdn* = 5.0, *IQR* = 3.75). Incidents occurring at (4) exits / parking lots, while (5) driving straight ahead or during (6) other maneuvers were only reported by relatively few participants ($N \leq 5$ each). Based on drivers' reports, pedestrians and bicyclists were mainly involved in noise-related situations. Drivers also reported the frequency of these incidents within a 3-month period. The medians of the reported frequencies reveal that noise-related incidents seldom occurred within the first 3 months of Study 1. The drivers also rated the speed of their own vehicles and the speed of the other road user involved in the incident. Except for the category (5) driving straight ahead, the speed difference between the EV and the other road user was ≤ 15 km/h (~9 mph). The characteristics of each category of incidents are shown in Table 1.

2.2.3 Potential countermeasures from the drivers' perspective

After 6 months, drivers rated the desirability of different countermeasures to address low noise-related safety issues, from which a total of 100 points could be allocated. Results from a Friedman's ANOVA show that drivers regarded the status quo (no additional noise, increased attention) as sufficient (*Mdn* = 60.0, *IQR* = 60.0) to address potential safety issues, $\chi^2(4) = 60.07$, $p < .001$, $w = 0.39$. Additional noise at speeds < 30 km/h (*Mdn* = 10.0, *IQR* = 30.0) and an automatic pedestrian detection system that warns the driver (*Mdn* = 10.0, *IQR* = 20.0) were endorsed far less by participants. Continuous external sound of the vehicle was not regarded as a reasonable countermeasure (*Mdn* = 0.0, *IQR* = 0.0). Few drivers suggested additional lights or an automatic pedestrian detection system, which warns the pedestrian as other possible options. The findings regarding potential countermeasures are also reflected in the accompanying interviews. Drivers reported that they purposefully looked out for bicyclists and pedestrians to proactively prevent critical incidents.

Table 2 Study 1: Catalogue of noise-related incidents during the first 3 months (T0–T1)

Type of incident	Number of participants reporting		Frequency in 3 months (T0–T1)		Other road user involved (%)				Speed of EV (km/h)		Speed of other road user (km/h)		Degree of hazard (1=nonhazardous -- 10=extremely hazardous)	
	N	Percentage (%)	*Mdn*	*IQR*	Pedestrian	Bicyclist	Car	Other	*Mdn*	*IQR*	*Mdn*	*IQR*	*Mdn*	*IQR*
≤30 km/h	18	45.0	4.5	5.0	40	5.0	–	–	20.0	11.88	4.5	2.00	3.5	3.00
Traffic lights / Turning	10	25.0	3.0	3.0	15	10.0	–	–	20.0	21.25	7.5	15.25	5.0	4.25
Overtaking / Passing	9	22.5	3.0	8.0	–	22.5	–	–	30.0	22.50	15.0	5.00	5.0	3.75
Exit / Parking lot	4	10.0	3.5	11.0	10	–	–	–	10.0	7.50	3.0	2.25	2.5	5.50
Straight ahead driving	4	10.0	7.0	10.0	10	–	–	–	42.5	8.75	1.0	–	5.5	3.75
Other maneuver	5	12.5	5.0	5.0	2.5	5.0	2.5	2.5	10.0	22.50	15.0	12.75	5.0	5.50

2.3 Discussion

While safety concerns were not considered paramount at vehicle handover, participants expressed concern for other road users on the questionnaires. Results from the longitudinal analysis of low noise emissions indicate a significant decrease in safety concerns among the drivers within the first 3 months of EV usage. Thereafter, these concerns remained at a low level. Initial concerns, which decreased over time, were also reflected in the accompanying interviews. Initial skepticism among the participants might have been a result of a lack of experience. Furthermore, participants might have read or heard about potential safety issues related to low noise emissions in the German (e.g. Rheinische Post, 2009; Schwarzer, 2010; Wilms and Görmann, 2010; Berliner Zeitung, 2011) or international (e.g. Birch, 2009; Rosenblum, 2009; Motavalli, 2009) popular press and might have expressed these concerns in the first questionnaire. An opposite effect is seen when the attribute, low noise emissions, is regarded as a comfort feature. These contrary trends in both items related to the issue of noise indicate that drivers' evaluation of low noise appears to have undergone a significant change. As participants gained EV driving experience, they tended to evaluate low noise as contributing to driving comfort, rather than as compromising safety. In addition, this belief might have been reinforced, because drivers only rarely encountered critical situations due to the lack of noise. These findings are especially remarkable, as the study was conducted in the city of Berlin, which is characterized by high street traffic volume, including vehicles, pedestrians and bicyclists.

Still, one could argue that drivers might not have been able or willing to report all noise-related incidents that occurred within the first three months. Indeed, Chapman and Underwood (2000) argue that forgetting near accidents is a potential threat to validity when using retrospective reports of drivers. The authors further state that with increasing severity of near accidents, the events were less likely to be forgotten. In our study, one could assume that noise-related incidents of low danger might have been under-reported. This would also support the notion that low criticality incidents most commonly occurred during the study period. Given that suitable cues can enhance the recollection of past events (Schwarz & Oyserman, 2001), we included questions evaluating specific circumstances in our assessment of critical incidents.

Comparable to US accident data on HEVs (Hanna, 2009), EV drivers in Study 1 reported that low noise-related critical incidents usually occurred in low-speed environments, such as side streets or at traffic lights. The reported low-speed values and, therefore, the speed differences are consistent with this fact. Given that the difference between ICEs and HEVs/EVs in perceptibility is highest at low speeds (Hastings, Scarpone, Samiljan, Garay-Vega, & Pollard, 2011), one could argue that since the vehicle is moving slowly, pedestrians and drivers would still normally have sufficient time to react. This argument has also been made regarding the time needed for blind pedestrians to detect HEVs (Garay-Vega et al., 2010). Nevertheless, one must take into account that distraction or inattention of drivers, as well as pedestrians, might adversely affect reaction time in real traffic.

Drivers reported that the addition of sound to EVs is unnecessary. This seems logical, considering that many drivers positively evaluated low noise and simultaneously reported a decrease in safety concerns over the course of the study. Although the status quo was sufficient for most participants, some drivers supported adding noise to EVs for speeds < 30 km/h and driver warning systems. We are aware that our results might be biased as we questioned EV drivers. Nevertheless, long-term, longitudinal studies on EV-related perceptions are still rare; research examining low noise usually relies on perceptibility studies with pedestrians, in particular blind pedestrians. Drivers who take part in a long-term field study with EVs in a metropolitan area gain extensive practice, especially in interacting with other road users in dense traffic. Therefore, the driver perspective contributes valuable input to the sometimes emotional discussion about EV safety.

3 Study 2

Similar to Study 1, Study 2 took place in the Berlin metropolitan area and aimed to investigate acceptance, and road capability, of EVs (Krems et al., 2011). Study 2 employed the same research consortium that conducted Study 1 and was also funded by the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety. Further, participants also drove a MINI E for an extended period of time. As in Study 1, interested participants completed an online application, which was advertised via local newspapers and online media. For Study 2, we hypothesized that driver evaluation of low noise emissions would follow similar patterns as those observed in Study 1, i.e., drivers would evaluate low noise less as a safety issue and more as a comfort feature, with increasing driving experience. Furthermore, we hypothesized that decrease in safety concerns is due to changes in individual risk estimation. Accordingly, perceived risk of low noise was assessed in more detail in Study 2. We hypothesized that similar to Study 1, the perception of risk associated with low noise would decrease, as well.

3.1 Method

3.1.1 Participants

Out of 1867 study applicants, 30 individuals were selected to drive an EV between 3 and 6 months in the Berlin metropolitan area. Main inclusion criteria for participation in Study 2 were similar to Study 1, except that participants who did not have the opportunity to install a private charging box could still be included in Study 2. As in Study 1, participants were compensated through a reduced monthly leasing rate, which resembled the monthly leasing rate of an equivalently equipped conventional ICE model under similar leasing conditions. At the beginning of Study 2 participants were also informed about the objectives of the greater research project and provided written consent that their data could be collected and analyzed for scientific purposes. Mobility-related (e.g. mileage, vehicle fleet) and sociodemographic (e.g. age, gender, education) variables were again taken into account to select a sample, which was as broadly distributed as possible. Test drivers were an average 46 years old (SD = 11.7), and the sample consisted of 26 males and 4 female participants. Forty-seven percent of selected participants had driven at least 15,000 km (~9300 miles) in the preceding year; the remaining participants drove less. Comparable to Study 1, 43% of participants had previous experience with an EV, a HEV or an electric scooter, primarily during short test drives. One participant withdrew from the study prior to completion. As in Study 1 the sample in Study 2 could be best characterized as environmentally aware, early adopters who are expected to resemble early EV drivers in relevant characteristics.

3.1.2 Procedure

Due to changes in the project structure, the participants were only interviewed at two times: before receiving the test vehicles (T0) and after 3 months (T1). Again, each interview involved closed and open-ended questions about different aspects of EVs. Data collection lasted between 2 and 3 h. As in Study 1, a detailed field manual was used and topics relating to noise and safety were not broached in the interviews until the participants answered the questionnaire items, to avoid priming.

3.1.3 Long-term evaluation of low noise

Similar to Study 1, drivers were first asked to comment on their expectations about low noise emissions in the T0 questionnaire. After 3 months of EV usage (T1), participants were asked to evaluate low noise again. In order to replicate the findings from Study 1, the questionnaire contained items that discriminated between driving pleasure associated with low-noise and potential danger to other road users associated with low-noise. In order to represent these two concepts more comprehensively, additional items measuring the two dimensions were included in the Study 2 questionnaire. The item 'I believe that the lack of noise from [an electric vehicle[1]] is dangerous for road traffic'[2] was supplemented by the items 'Even if [an electric vehicle] is harder to hear, other road users are not at higher risk'[3] and 'The lack of engine noise will/has cause/caused problems for other road users'[4] together forming the *Safety Concerns* scale. In the second dimension, the item 'The quietness of [an electric vehicle] will be/is pleasing'[5] was supplemented by the additional item 'The lack of engine noise of electric vehicles increases driving comfort'[6] together forming the scale *Comfort*. Items in both scales were assessed using a 6-point Likert scale ranging from 1 (*completely disagree*) to 6 (*completely agree*).

3.1.4 Risk perception

Our risk perception questionnaire was adapted from Rundmo and Iversen (2004), who recommended differentiating between a cognitive and an affective component when measuring perceived risk. Apart from translation, the study items were adapted to account for a change in perspective. Whereas Rundmo and Iversen's work focused on road users' perceived risk of being harmed by others, Study 2 focuses on road users' perceived risk of causing others harm.

In total, 10 items were used to measure different aspects of risk perception. All subscales of risk perception were assessed using 7-point, bipolar scales.

In the *Cognition* scale, higher scores represented higher perceived accident probabilities due to low EV noise. *Cognition* was assessed via the German translation of the following items:

- 'It is (*very improbable / very probable*) that I could injure other road users in a traffic accident due to low noise of [an electric vehicle[7]].'
- 'It is (*very improbable / very probable*) that electric vehicle drivers in general could injure other road users in a traffic accident due to low noise.'

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[1] The vehicle's name [MINI E] was used in the German questionnaire.
[2] German: 'Ich schätze die Geräuschlosigkeit des MINI E als Gefährdung des Straßenverkehrs ein.'
[3] German: 'Auch wenn der MINI E schlechter zu hören ist, sind dadurch andere Verkehrsteilnehmer nicht stärker gefährdet.'
[4] German: 'Das Fehlen der Motorgeräusche wird/hat anderen Verkehrsteilnehmern Probleme bereiten/bereitet.'
[5] German: 'Die geringe Geräuschkulisse des MINI E wird mir gefallen/gefällt mir.'
[6] German: 'Die fehlenden Motorgeräusche in Elektrofahrzeugen erhöhen den Fahrkomfort.'
[7] The vehicle's name [MINI E] was used in the German questionnaire.

Machin and Sankey (2008) assessed perceived confidence of driving in certain conditions, e.g. on unfamiliar roads, labeling this variable as *Efficacy*. Following this approach, we included additional items assessing perceived efficacy of driving an EV while accounting for potential risks due to low noise. Higher efficacy scores indicated higher perceived confidence in one's ability to account for potential risks.

- 'I estimate that possibilities for me as [an electric vehicle] driver (*do not exist / exist*), to minimize potential risks to traffic safety related to low noise of [an electric vehicle].'
- 'I think I possess (*none of the necessary abilities / all of the necessary abilities*), to minimize potential risks to traffic safety related to low noise of [an electric vehicle].'

Six additional items adapted from Rundmo and Iversen (2004) assessing worry and concern about traffic injury and risks were translated into German and integrated into a *Worry and Concern scale,* a procedure that was previously reported in Machin and Sankey (2008). Higher scores on the worry and concern scale represented higher perceived risk.

- 'I feel (*certain / very uncertain*) that I could injure other road users in a traffic accident due to low noise of [an electric vehicle].'
- 'I feel (*certain / very uncertain*) that electric vehicle drivers in general could injure other road users in a traffic accident due to the low noise.'
- 'I am (*not at all worried / very worried*) that I could injure other road users in a traffic accident due to low noise of [an electric vehicle].'
- 'I am (*not at all worried / very worried*) that electric vehicle drivers in general could injure other road users in a traffic accident due to low noise.'
- 'I am (*not at all concerned / very concerned*) that I could injure other road users in a traffic accident due to low noise of [an electric vehicle].'
- 'I am (*not at all concerned / very concerned*) that electric vehicle drivers in general could injure other road users in a traffic accident due to low noise.'

3.2 Results

Similar to Study 1, data from Study 2 generally violated the assumptions of normality. Therefore, non-parametric analyses were conducted. Parametric tests, which were also conducted, revealed similar results. Again, all effect sizes reported here were calculated according to Field (2009) and labeled according to Cohen (1992).

3.2.1 Longitudinal evaluation of low noise

The primary objective of Study 2 was to determine if the trends observed in Study 1 could be replicated in a different sample of EV drivers. In single item analysis of drivers' noise-related perceptions, findings from Study 2 largely replicated those from Study 1. Specifically, Study 2 test drivers also appreciated the low noise of the EV and were less concerned about safety after 3 months. Similar to Study 1, pleasure increased, $z = –3.18$, $p = .001$, $r = –.41$ and perceived danger to others decreased significantly over time, $z = –2.62$, $p = .009$, $r = – .35$. The change in perception of noise-related danger was a medium effect, whereas the change in perception of noise-related pleasure was a medium to large effect.

To enhance the results obtained in via single-item measurement, additional items were included in the questionnaire to create the *Comfort* and *Safety Concerns* scales. Perceived comfort resulting from low noise was evaluated positively before driving the EV for the first time at T0 (*Mdn* = 5.0, *IQR* = 1.5) and ratings of comfort resulting from low noise increased over the course of the study (T1: *Mdn* = 6.0, *IQR* = 1.0). The internal consistency of the *Comfort* scale was sufficient (T0: α = .72, T1: α = .82). The differences in comfort between T0 and T1 were significant, $z = –3.34$, $p = .001$, $r = –.43$. As expected, based on Study 1, a decreasing trend was observed for safety concerns. The internal consistency of the *Safety Concerns* scale was sufficient (T0: α = .58, T1: α = .91). The decrease in safety-related concerns between T0 (*Mdn* = 4.0, *IQR* = 1.0) and T1 (*Mdn* = 2.33, *IQR* = 2.0) was significant, $z = –3.13$, $p = .002$, $r = – .40$. The effect size of changes in both *Comfort* and *Safety Concerns* scale scores was interpreted as medium to large. Both scales are displayed in Figure 2.

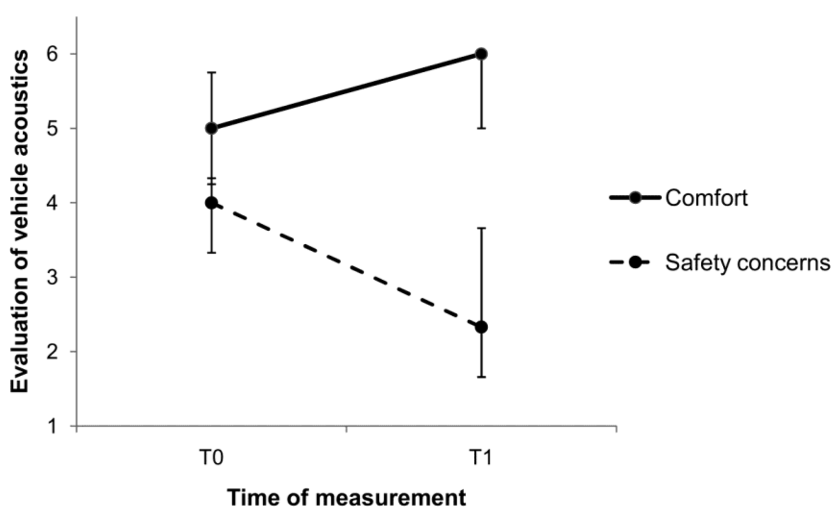

Figure 2 Study 2: Driver evaluation of low noise (medians, error bars represent *IQR*)

3.2.2 Risk perception

Results of analyses of drivers' risk perception are similar to results obtained in the long-term evaluation and, therefore, also confirm our previous findings. The worry and concern component of noise-related risk perception decreased considerably from T0 (*Mdn* = 3.67, *IQR* = 1.92) to T1 (*Mdn* = 2.67, *IQR* = 2.08). The internal consistency of the *Worry and Concern* scale was good at both points of measurement (T0: α = .87, T1: α = .96). The Wilcoxon test showed a significant difference between T0 and T1 with a medium sized effect, $z = -2.96$, $p = .003$, $r = -.38$. For the cognitive component of risk perception, only a slight decrease was detectable from T0 (*Mdn* = 3.5, *IQR* = 2.5) to T1 (*Mdn* = 3.0, *IQR* = 2.0). The internal consistency of the *Cognition* scale of risk perception was also good (T0: α = .89, T1: α = .96). The difference between the two points of measurement was not significant and only a small effect could be identified, $z = -1.04$, $p = .300$, $r = -.13$. The median score of the third subscale of risk perception, *Efficacy* (T0: α = .57, T1: α = .84), remained constant over time (T0: *Mdn* = 6.0, *IQR* = 1.0 T1: *Mdn* = 6.0, *IQR* = 1.25). Nevertheless, the Wilcoxon test showed a significant increase in perceived efficacy from T0 to T1, $z = -2.19$, $p = .029$, and revealed a medium effectsize, $r = -.28$. The risk perception scales are displayed in figure 3.

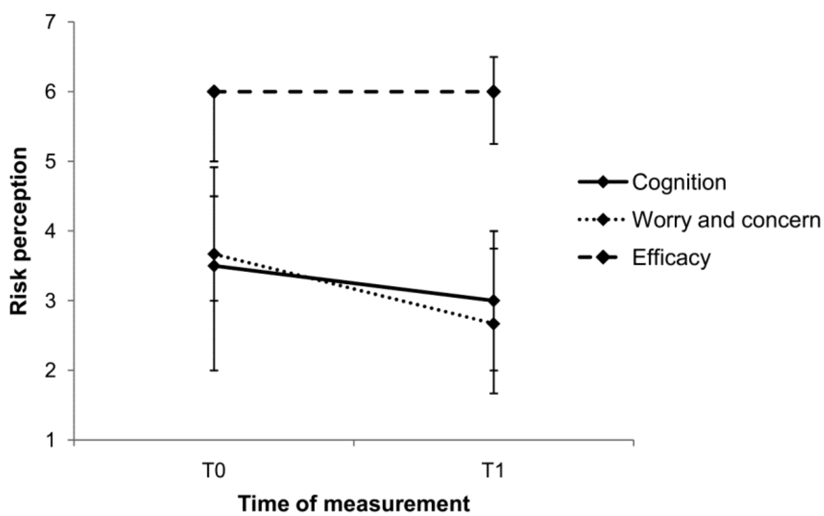

Figure 3 Study 2: Risk perception (medians, errors bars represent IQR)

The affective component of risk perception, in general, changed the most with increasing EV experience. In contrast, the cognitive component of risk perception decreased only to a small extent, whereas perceived efficacy of overcoming risks associated with low noise remained consistently high.

3.3 Discussion

3.3.1 Longitudinal evaluation

Similar to results in Study 1, participants evaluated low noise emissions of EVs differently after gaining some experience driving the EV in everyday traffic. Specifically, low noise was initially perceived as a risk for other road users; however, this perception diminished as participants drove the vehicles for a longer period of time. In addition, participants initially rated low EV noise as a positive feature and their positive ratings of this attribute continued to increase with more driving experience. To enhance the findings of Study 1, we included additional items to create the *Comfort* and *Safety Concerns* scales. When noise-related driver perceptions were measured with these scales, the same pattern of changing perceptions was observed, thus, providing additional support to the notion that driving experience changes driver perception in systematic ways. In sum, results clearly show that EV drivers perceive low noise as contributing to increased comfort, rather than decreased traffic safety.

3.3.2 Risk perception

The addition of the concept risk perception allowed us to examine drivers' evaluation of low noise emissions in more detail. In our study, the experience of driving an EV for a longer period of time appeared to have had some impact on drivers' perceived risk associated with low noise. Rundmo and Iversen (2004) argued that when measuring risk perception, cognitive and affective components of risk should be assessed separately. Differentiating between these two components of risk and adding efficacy proved valuable in the present study. Interestingly, and consistent with Study 1, participants worried more about noise-related traffic risks before driving an EV for the first time than after gaining some driving experience. As participants gained experience with the EV, worries and concerns significantly decreased. This was not the case for the cognitive component of risk; the subjective probability assessments of harming other road users remained almost constant over time. As in Study 1, it could be argued that participants might have heard or read about potential hazards associated with EVs in the German (e.g. Rheinische Post, 2009; Schwarzer, 2010; Wilms & Görmann, 2010; Berliner Zeitung, 2011) or international popular press (e.g. Birch, 2009; Rosenblum, 2009; Motavalli, 2009), and might have expressed their concerns in the initial questionnaire. These beliefs likely decreased over the course of the study, because drivers did not encounter as many critical noise-related situations as they might have anticipated. However, drivers' cognitive risk perception, i.e. the perceived likelihood of an accident due to low noise did not significantly change over time.

The third component of the risk perception evaluation involved an assessment of the extent to which drivers considered themselves capable of overcoming the potential safety disadvantages of the EV. Analyses of *Efficacy* scale data indicate that drivers perceived themselves as being capable of compensating for low noise before driving the EV for the first time. This belief slightly increased as drivers gained more experience, indicating that drivers became even more confident with managing the low noise of the EV. The different effects that driving experience had on drivers' worries and concern, cognitive risk perception, and efficacy underscore the importance of measuring different facets of risk perception. As expected, individual practice had an impact on risk perception. The more experience drivers gained, the less concerned they were about risks related to low noise. Accordingly, drivers regarded themselves as highly capable of compensating for the risks arising from low noise.

In sum, incorporating day-to-day experiences of actual EV drivers is necessary to complement studies of perceptibility of EVs or HEVs, which represent only one side of the issue. The detailed data generated from long-term studies of quiet vehicles will contribute to a more accurate understanding of how threatening EVs are to the general public. What can be done about the discrepancy between the need for safety of vulnerable road users and the perspective of drivers, who may potentially challenge the view of EVs as a safety threat? This will be discussed in the next section.

4 General discussion and conclusion

Data from both studies suggest that concerns related to low noise of EVs decrease over time. Study 1 revealed that drivers experienced a major shift in their perception of EV-related noise within the first 3 months of driving an EV. As participants gained driving experience, they increasingly regarded low noise as contributing to an increase in comfort rather than as a threat to other road users. These trends were also observed in Study 2. Although our findings paint a rather positive picture of low noise, several important considerations should be kept in mind:

First, is there justification for drivers to be more confident and less concerned over time? Drivers might have simply underestimated their risk of harming other road users, because of the 'optimistic bias', i.e., people tend to be overly optimistic regarding their personal risks (Weinstein, 1989). Given the characteristics of our sample, we doubt that drivers would misinterpret or even habituate to the risks associated with the low noise emissions. The sample in both studies comprised rather experienced drivers, who were accustomed to driving in high-volume urban traffic, also involving pedestrians and bicyclists. During the course of the study, drivers regularly drove in urban traffic and, therefore, had to constantly account for the presence of pedestrians and bicyclists.

Furthermore, drivers reported that they were especially vigilant in attending to bicyclists and pedestrians, trying to prevent critical situations through cautious driving. West, French, Kemp, and Elander (1993) found that self-reported driving style significantly correlated with observed driving behavior. Still, the driving adaptations reported by participants in our study are susceptible to response bias. Accordingly, driving tests, e.g. on turning behavior, are needed to better determine whether drivers actually alter their driving style. On-road experiments at roundabouts revealed that the presence of pedestrians with a white cane can positively influence the yielding behavior of ICE drivers (Geruschat & Hassan, 2005). We propose that these findings support the notion that the reduction of concern reflects the result of practice, rather than representing simple desensitization to risk.

The participants in both of our studies are best characterized as early adopters. Therefore, our sample may not be representative of the population of all drivers; however, our sample is likely representative of the population of early EV buyers, which are considered crucial for adoption of such technology. Still, we expect that the effect of experience on risk estimation that we observed in this sample, i.e. perceived risk decreases as experience increases, would also be observed in a sample of individuals who are more cautious about adopting new technology. We argue that risk estimation depends less on attitudes towards technology than other factors. For example, the living and driving environment of a particular sample might have more influence on risk assessment than attitude towards technology in general. Compared to the urban drivers of our studies, rural drivers might not be as accustomed to accounting for bicyclists and pedestrians. This could in turn have an effect on their assessment of risk associated with low EV noise. Against the background of both samples' composition, future research should address how a more random sample, including rural, young and inexperienced drivers, manages and perceives noise-related issues. This might be particularly interesting, as young drivers tend to underestimate potential risks in traffic (Deery, 1999).

Perhaps, the most important research question is whether artificial noise for EVs and HEVs increases the safety of vulnerable road users. Although vehicular noises, especially at low speeds, appear to be essential, a technological solution alone might not solve the problem. In this context, Morgan et al. (2010) argued that any measure to enhance the sound of EVs or HEVs should be applied to quiet ICE vehicles, as well. Sandberg, Goubert, and Mioduszewski (2010) emphasized that a significant number of currently available ICE vehicles are so quiet that it is hard to perceive a difference between EVs and these ICE vehicles in urban areas. Sandberg et al. also stressed that quiet vehicles have been part of the general vehicle fleet for quite some time, without evoking such intense reactions. Given that pedestrians report using sound cues during street crossing, Wogalter, Ornan, Lim, and Chipley (2001) argue that even road users without visual impairment could benefit from enhanced acoustic feedback of EVs. Ashmead et al. (2012) studied auditory perception of motor vehicle travel paths while navigating in traffic. The authors found that if moderate background traffic noises were added, pedestrians' ability to differentiate between straight and turning paths significantly deteriorates. As the correct identification of vehicle movements in traffic is essential, the authors argue that simply enhancing vehicular noise might not increase pedestrian safety in situations involving multiple vehicles.

In Study 1, we asked participants to rate different strategies for addressing the noise issue after they had gained considerable experience driving an EV. Drivers in Study 1 clearly did not favor adding artificial noise to their EVs. This belief is in line with their positive evaluation of the low noise of EVs. As Study 1 drivers only rarely encountered serious noise-related incidents, they believed that the issue could be addressed by adapting a more anticipatory driving style. The question therefore arises, does the addition of artificial noise to all kinds of quiet vehicles result in an increase in traffic safety for affected road users, such as pedestrians? The reduction of overall noise levels is also particularly relevant for inner-city residents, as road traffic noise has been found to be related to sleep disturbances in urban areas (Jakovljević, Lojević, Paunović, & Stojanov, 2006). Quiet vehicles may benefit the public by reducing overall noise levels, a gain that might be reversed by making these vehicles louder again. The trade-off between safety and annoyance has also been discussed regarding other vehicle motion alarms, such as backup beepers (Holzman, 2011).

In accordance with Sandberg et al. (2010), we argue that adding artificial noise to EVs should be considered only as one among many potential safety measures that could be applied to address the quiet car issue. The impact of low EV noise emissions on driver behavior should be addressed in future research. In particular, do drivers incorporate this feature into their driving style? Additionally, how does driver inattention affect driver behavior? Can the decrease in safety concerns also be detected among pedestrians when they interact more frequently with EVs? Assistance systems that warn drivers and driver training could be valuable options to explore. We believe that broadening our focus to consider a variety of potential safety measures will help EVs reach their full potential.

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Paper III:
Is EV experience related to EV acceptance? Results from a German field study

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Is EV experience related to EV acceptance? Results from a German field study

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Electric Vehicles (EVs) provide a promising solution to rising CO_2 emissions and, in the long term, the dependence on oil. In the present study, we examined how the current state of EV technology is perceived and accepted by a sample of early adopters and how experience influences the evaluation and acceptance of EVs. In a 6-month field trial, data from 79 participants who drove an EV in the Berlin metropolitan area were assessed at three data collection points (before receiving the EV, after 3 and 6 months of usage). Participants reported a wide range of advantages, but also barriers to acceptance. They perceive EVs positively and show positive attitudes towards EVs and possess moderate purchase intentions. Experience can significantly change the perception of EVs. Many advantages became even more salient (e.g., driving pleasure, low refueling costs) and several barriers (e.g., low noise) were less frequently mentioned. Experience had a significant positive effect on the general perception of EVs and the intention to recommend EVs to others, but not on attitudes and purchase intentions. Our findings reveal that EVs are already evaluated positively, but in order to achieve widespread market success in Germany, solutions are needed for important barriers like acquisition costs. Providing real-life experience could be a promising marketing strategy.

Key Words: Electric vehicle, acceptance, experience, advantages and barriers, purchase intentions, field study

1 Introduction

1.1 Background

In an era when climate change and limited fossil fuel resources are highly relevant concerns, the widespread adoption of renewable energy-based transportation has become critically important. In the EU, one fifth of CO_2 emissions are produced by automobiles (European Commission, 2012). In order to comply with the Kyoto protocol, the EU must reduce emissions by approximately 20% by 2020 (German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety), and therefore, automobile emissions must be significantly reduced. These facts underline the need for the development of alternative propulsion systems. Electric vehicles[1] (EVs), vehicles with an electric power train that only work on a battery, represent one promising technological development that has the potential to significantly reduce CO_2-emissions emitted by automobiles (King, 2010). Still, there is a debate about the real environmental benefit of EVs. According to Hawkins, Singh, Maieau-Bettez, and Strømman (2012), the real amount of potential CO_2-emissions savings depends on many factors (e.g., production, electricity mix used for charging). In addition to questions concerning the real environmental benefit of EVs, the question concerning the future market success of EVs is of interest. Driving an EV involves many aspects to which a driver of conventional cars has to adapt, including limited range, the charging procedure, regenerative braking, and extremely low noise (Urban, Weinberg, & Hauser, 1996). Potential EV consumers must be willing to manage these additional challenges and currently pay a relatively high purchase price; though, the lower energy prices for recharging would (partly) offset the higher acquisition costs over time (Wietschel et al., 2012). In order to support the widespread adoption of EVs, it is important to develop a better understanding of potential consumers' perceptions of EVs. Specifically, it is important to learn which advantages they are aware of, whether some barriers are insurmountable for them, and if they are willing to manage the challenges of an EV. This study aims to investigate the perception of EVs, including advantages and barriers, as well as acceptance of EVs. Furthermore, the present research aims to help determine whether consumers' perception and acceptance changes after intensive EV usage. These issues were addressed in a field study with drivers who lived in the Berlin metropolitan area and drove an EV for 6 months.

[1] With the term electric vehicle (EV) we refer to a pure battery electric vehicle (BEV) in the present paper. However, several results and conclusions may also generalize to plug-in hybrid electric vehicles (PHEVs) and BEVs with range extender (EREVs).

1.2 Perception and acceptance of EVs

To assess the willingness of potential consumers to adopt EVs, researchers in several countries have investigated the potential market share of EVs, including Australia (Higgins, Paevere, Gardner, & Quezada, 2012), Japan (Kuwano, Tsukai, & Matsubara, 2012), Canada (Ewing & Sarigöllü, 1998), the USA (Hidrue, Parsons, Kempton, & Gardner, 2011), and Germany (Lieven, Mühlmeier, Henkel, & Waller, 2011). The typical conclusion from this research is that EVs are not fully competitive (Dagsvik, Wennemo, Wetterwald, & Aaberge, 2002) and the demand is weak (e.g., Achtnicht, Bühler, & Hermeling, 2012). Reasons for this might be several concerns of potential consumers including identified limited range, high costs, limited charging infrastructure (e.g., Ziegler, 2012; Egbue & Long, 2012) and charging time (e.g., Hidrue et al., 2011). These findings provide a clearer picture of the potential for EV adoption; however, the aforementioned research is based on people who typically had no prior experience with EVs. Potential consumers tend to inaccurately predict their interest in products with which they have no experience (Hoeffler, 2003). Given this tendency, it seems promising to focus more on studies that examine acceptance of EVs within the context of real-life experience.

1.2.1 Perception and acceptance of EVs after testing EVs

Some previous studies have assessed perception and acceptance of EVs after providing participants with direct EV experience. In the UK, Skippon and Garwood (2011) as well as Graham-Rowe et al. (2012) gave drivers the opportunity to test an EV on a 10 mile route for 7 days. Skippon and Garwood (2011) reported that participants endorsed the environmental benefits of EVs, assumed that refueling costs are lower compared to a conventional car and were partly willing to consider an EV with 150 km range as a second car. In contrast, Graham-Rowe et al. (2012) reported that participants were rather skeptical about EVs' suitability for daily driving needs and many improvements were needed before participants would be willing to purchase an EV. Additionally, Graham-Rowe et al. (2012) reported that on the one hand many participants were skeptical about the overall CO_2 production of EVs, but on the other hand some individuals reported a "feel-good factor" due to the environmental benefits of the EV. Carroll (2010) studied fleet users and managers who reported that they were more positive about EVs after they had tested them between 1 to 4 weeks. Turrentine, Garas, Lentz, and Woodjack (2011) found similar results: Drivers reported that they have more favorable opinions of EVs and higher purchase intentions after a one year lease of an EV. Taken together, in studies with drivers that have directly experienced EVs, perceptions of EVs vary and purchase intentions were relatively high (e.g., Skippon & Garwood, 2011; Jabeen, Olaru, Smith, Braunl, & Speidel, 2012) compared to those of EV-inexperienced drivers.

When comparing findings of studies with EV-experienced (e.g., Gärling & Johansson, 1999; Graham-Rowe et al., 2012) and EV-inexperienced drivers (e.g., Egbue & Long, 2012), concerns about EVs were found to be mostly similar, including range, costs, infrastructure, charging time, battery issues, lack of noise, reliability, uncertainty with service availability and safety concerns. Furthermore, people with or without EV experience perceive environmental friendliness, high energy efficiency, being the future of automobile travel and financial benefits such as lower running costs as advantages (e.g., Egbue & Long, 2012; Jabeen et al., 2012). Still, there seem to be important differences between EV-inexperienced and experienced drivers: Barriers such as 'trip planning' (Jabeen et al., 2012) and advantages including fun driving (e.g., Turrentine et al., 2011), smooth driving, high torque and low noise (e.g., Jabeen et al., 2012) seem to be more salient after gaining EV experience, as they were only reported in studies with EV-experienced drivers. Better insight into the effect of experience on EV acceptance is attainable by utilizing pre-post comparisons.

1.2.2 Perception and acceptance of EVs in pre-post studies

Only a few studies with pre-post comparisons exist in which the change in attitudes towards EVs and willingness to pay for, purchase or use was investigated within the context of ongoing EV experience. In an 11-week trial, EV users' attitudes did not change with increasing experience, but willingness to purchase and perceived safety decreased over time (Gärling & Johansson, 1999). Gould and Golob (1998) found an increase in perceived environmental friendliness after a 2-week field trial. In a more recent study, Carroll (2010) showed that experience produced an observable influence: More drivers were willing to use an EV after a test drive than before. With a stated preference approach, Jensen, Cherchi, and Mabit (2013) found that participants' willingness to pay for range, battery life and top speed after EV usage increased within a 3-month field trial.

To our knowledge, there are no studies that explicitly investigated changes in consumers' reports of EV advantages and barriers during the process of gaining EV experience. Jensen et al. (2013) investigated selected EV attributes that are potential disadvantages when using EVs (e.g., purchase price, range). Many potential advantages and barriers were not included in these analyses. When reviewing the literature, it became apparent that there are advantages and barriers that were only reported in studies with EV-experienced drivers. Furthermore, most of those advantages and barriers are features that can be directly experienced when testing an EV (e.g., low noise, smoothness). It might be the case that these EV-specific attributes become more salient when experiencing an EV. As the available literature on EVs indicates that the market potential of EVs is relatively low (e.g., Ziegler, 2012) and that several concerns exist (e.g., Egbue & Long, 2012), it is important to identify the advantages and barriers that are perceived and can be reinforced or positively changed through experience with EVs. This leads to our first research questions: *Which advantages and barriers do users/potential consumers perceive?* Given the reviewed literature, we can further specify this question: *Do users/potential consumers perceive environmental friendliness, lower running costs, energy efficiency, low noise, smooth driving, fun, and home-charging as advantages and limited range, charging infrastructure and duration, battery issues, reliability, uncertainty with service availability, low noise as a safety problem, and other safety concerns as barriers? (Q1a).* Furthermore, we aim to answer the following questions: *Do reported advantages and barriers change when using an EV for a longer period of time? Are changes in reports more likely to be positive when advantages and barriers can be directly experienced? (Q1b)*

Apart from potential advantages and disadvantages, the reviewed literature (e.g., Carroll, 2010; Gärling & Johansson ,1999) indicates that experience has a positive influence on acceptance. Burgess, King, Harris, and Lewis (2013) also reported that experience is a crucial factor, because drivers reported that it has the potential to change peoples' perception of specific EV attributes (e.g., low noise).Yet, recent studies that directly perform pre-post comparisons regarding changes in EV acceptance over the process of gaining long-term experience are lacking. Older published research on long-term experience (Gärling & Johansson,1999; Gould & Golob, 1998) utilized an earlier generation of EVs with substantially lower performance capabilities. This study aims to bridge this gap and investigates the following questions: *How is the current state of EV technology perceived and is it acceptable to users/potential consumers? (Q2a) Does perception of EVs and acceptance change while testing an EV for a longer period of time? (Q2b)*

1.2.3 Defining perception and acceptance

In order to investigate the previously mentioned research questions, acceptance must be defined. In the scientific literature, different variables were assessed to make conclusions about acceptance or adoption of EVs. In several stated preference studies (e.g., Ziegler, 2012), individuals' preferences for different vehicle attributes (e.g., energy source, range, and price) were investigated. Based upon such data, conclusions can be drawn regarding the circumstances under which people would choose an EV and the potential market share of certain EVs. Other than this approach, attitudes (e.g., Gärling & Johansson, 1999) and direct questions regarding willingness to purchase (e.g., Gärling & Johansson, 1999) or use an EV (e.g., Carroll, 2010) were primarily used as indicators of acceptance. However, some authors investigated perceived advantages and barriers (e.g., Egbue & Long, 2012), perception of EVs (e.g., Burgess et al., 2013) and the willingness to recommend an EV (Jabeen et al., 2012).

According to Schade and Schlag (2003), acceptance is one's attitudinal and behavioral reaction after exposure to a product. Prior to exposure, only 'acceptability' can be assessed, which is a pure attitudinal construct. Schade and Schlag's (2003) definition of acceptance is the basis for our conceptual framework (Figure 1). Consistent with this definition, acceptance of EVs can only be assessed by measuring attitudes and behavior, which is assessed via behavioral intentions (e.g., purchase intentions, intention to recommend). In Schade and Schlag's (2003) study, attitudes are simply reflected in the degree to which a product or system is acceptable, but this does not reflect the various attitude assessments that were used in earlier research (e.g., Gärling & Johanssen, 1999). To expand the concept of attitudes in the present study, attitudes are defined as "predispositions to respond, or tendencies in terms of 'approach/avoidance' or 'favourable/unfavourable' " (p. 2, Van der Laan, Heino, & De Waard, 1997) with respect to EVs. Van der Laan et al. (1997) describes two dimensions (Satisfaction and Usefulness) that cover 'attitudinal' acceptance of technological innovations. This concept is often used in transportation research (e.g., Vlassenfort, Brookhuis, Marchau, & Witlox, 2010). More general opinions regarding, for instance, suitability for daily life or environmental benefit of EVs, are neither covered by the definition of Schade and Schlag (2003), nor by the definition of Van der Laan et al. (1997) and are therefore summarized in this study as 'general perception' of EVs. Given that general perception and different indicators are of interest in this study, a further research question is formulated: *How do general perception of EVs, attitudes towards EVs, as well as the intentions to recommend and purchase interact? (Q3)*

2 Summary of hypotheses

First, regarding Q1 (see section 1.2.2), several advantages and barriers when using an EV that were highlighted in section 1.2.1 and 1.2.2. were reported in studies with EV-experienced users and can be directly experienced when integrating an EV into the daily routine. They might be less salient for EV-inexperienced consumers. Consistent with results of pre-post-comparisons (e.g., Carroll, 2010) that suggest that experience with an EV influences the perception of EV attributes, we expect that:

H1: After experiencing an EV, the relevance of low noise as a benefit, high torque, smooth driving, fun, and home-charging as advantages and range and the need for planning as barriers will be higher than before.

Based on previous research, it is unclear if, and in which direction, the perception of the other hypothesized advantages and barriers will change. Therefore, we chose an exploratory approach.

Second, referring to Q2, findings from different studies (Carroll, 2010; Turrentine et al., 2011) indicate that opinions about EVs and purchase intentions are positively influenced by experience. This could be due to the fact that EVs are relatively new products and most people had little, if any, direct experience with such a vehicle by 2010. Many features like acceleration, sound or range are not comparable to a conventional vehicle, misconceptions regarding EVs exist in many consumers' minds (Burgess et al., 2013) and people in general are skeptical about emerging technology (Hacker, Harthan, Matthes, & Zimmer, 2009). When an EV is successfully integrated into a person's daily routine and is judged to be suitable for daily needs, the general perception of, and attitudes towards, EVs are expected to become more positive. In line with the findings reported above, attitude studies have found that direct experiences with a new product lead to more extreme attitudes (e.g., Smith & Swinyard, 1983). Regarding EVs, perceptions and attitudes seem to become more positive. Based on this argumentation, our hypotheses are:

H2: General perception will become more positive after experiencing an EV.

H3: Attitudes towards EVs will become more positive after experiencing an EV.

As reviewed in section 1.1.2 and 1.2.2, some previous studies showed that behavioral intentions seem to be positively influenced by experience (e.g., Turrentine et al., 2011). Thus, we propose the following hypotheses:

H4: Intention to recommend will increase after using an EV for some time.

H5: Purchase intentions will increase after using an EV for some time.

Third, referring to Q3 (section 1.2.3), longitudinal studies examining the associations between general EV perceptions, attitudes, intention to recommend, and purchase intentions do not exist. If an individual perceives general features of an EV (e.g., suitability for daily life) more positively, he will probably evaluate this kind of vehicle in a more positive (more satisfying and useful) way and vice versa. Therefore, we expect that:

H6: Before and after driving an EV, general perception of, and attitudes towards, EVs are positively correlated.

According to Kraus (1995), attitudes are one important predictor of behavior; however, the strength of the relationship depends on the kind of behavior and different moderating variables. Additionally, Jabeen et al. (2012) showed that the perception of EVs positively influences the intention to recommend and purchase EVs. Thus, people who have a more positive evaluation (perception, attitudes) of EVs should be more willing to recommend and purchase this kind of vehicle. Therefore, we hypothesize that:

H7: General perception and attitudes towards EVs predict the intention to recommend.

H8: General perception and attitudes towards EVs predict purchase intentions.

Furthermore, intention to recommend and purchase intentions are highly correlated in different studies (e.g., Jabeen et al., 2012). Reichheld (2006) argued that the intention to recommend is closely related to the consumer's own behavior in many areas. In accordance with this, we expect that:

H9: Intention to recommend and purchase intentions are positively correlated.

To provide a clearer picture of our conceptual framework, we summarized the different constructs and their relationships in Figure 1.

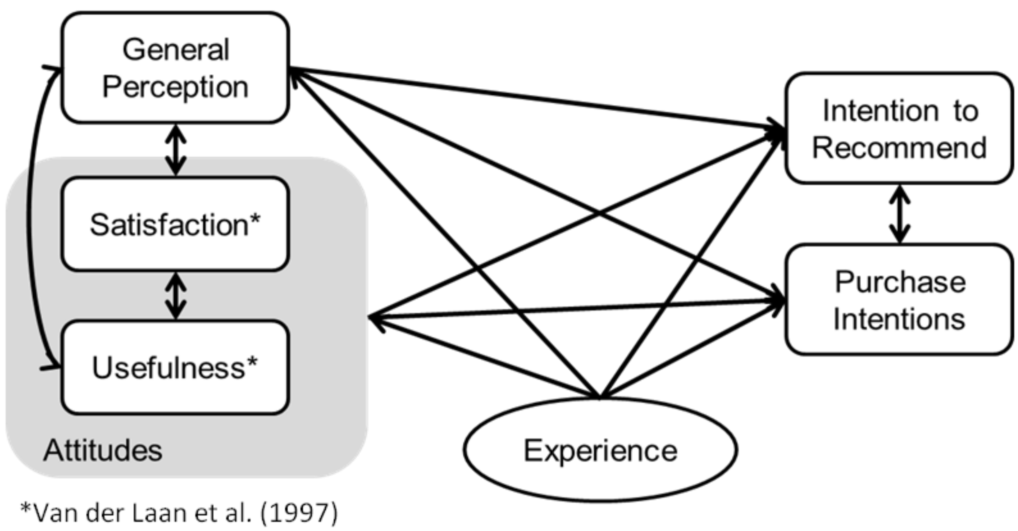

Figure 1 Conceptual framework of the relationships among the study's constructs

Note. All arrows represent assumed positive relationships

3 Methods

3.1 Study Design

The present paper presents the results of a large scale field study conducted in the Berlin metropolitan area, which was part of a series of international EV field trials (Krems, Weinmann, Weber, Westermann, & Albayrak, 2013; Vilimek, Keinath, & Schwalm, 2012). In two study periods, 80 participants (40 participants per study period) used an EV, the MINI E, either from the end of June 2009 to January 2010 or from February to August 2010 in their daily routine. Participants were assessed three times: before receiving their car (T_0), after 3 months of driving (T_1) and when returning the car after 6 months (T_2). Through the application of repeated measurements, changes in attitudes and behavior were observable.

3.2 Participants

More than 1200 people from the Berlin metropolitan area applied for the study via an online application form. Eighty households that fulfilled certain criteria (e.g., agreed to an installation of a home charging station, willingness to take part in scientific surveys and to pay the monthly leasing rate of 400€[1]) were selected. The recruitment and selection process is described in more detail in Cocron et al. (2011) and Neumann, Cocron, Franke, and Krems (2010). Data was only collected from the one person per household who was expected to be the primary EV user (main user approach). In the first period, one participant dropped out before T_1 and another withdrew from the study at a later time. In the second period, one participant did not complete all 6 months.

Seventy-nine participants (67 men, 12 women) completed T_0 and T_1. They were on average 49 (*SD* = 9.6) years old. Except for one, all participants lived in the city of Berlin; one lived in a suburb 25 km away of the city center. Most participants (70.1%) had no experience with any form of electric drive train in a vehicle. Three-quarters of participants were highly educated (75.6% held a university degree), 12.8% completed an apprenticeship, 9.0% finished vocational school and 2.6% reported graduation from high school as their highest degree. Most households (53.4%) consisted of three or more persons, two adults lived in 39.2% of the households and the sample included 7.6% single-households. Few participants (6.3%) did not own a car before the study and 26.6% reported that the

[1] The leasing rate is about the same as for a comparable gasoline model with similar leasing conditions. The leasing rate without participating in the scientific study was 650€.

EV would substitute for one of their vehicles. The majority of participants had a second car available during the study (one additional car: 48.1%; two: 31.6%; three or more: 10.1%). The household size and available vehicle fleet correlated significantly ($r = .31$, $p = .006$). The majority of participants (91.1%) endorsed using the EV for work trips that varied considerably in length ($M = 17.5$ km, $SD = 10.7$). German early adopters in other studies (e.g., Wietschel et al., 2012) showed similar distribution on sociodemographic variables. Compared to the population of early adopters, German car drivers in the representative large-scale survey "Mobility in Germany 2008" (Mobilität in Deutschland, MiD; infas and DLR, 2010) were younger ($M = 42$), included fewer men (51%), were not as highly educated (40% had at least a university of applied science entrance qualification) and had smaller household sizes (36% of households had three or more persons) (see Franke & Krems, 2013b).

3.3 Data collection

To investigate study hypotheses, portions of the conducted interviews and questionnaires were used.

3.3.1 Perceived advantages and barriers of EVs

In the first two interviews (T_0 & T_1), participants were asked the following open-ended questions: 1) "*In your opinion, what are the greatest advantages of electric vehicles like the MINI E?*" and 2) "*In your opinion, what are the greatest barriers to acceptance of electric vehicles?*" At T_1, users were asked to answer based on their experiences beforehand.

Recordings of the interviews were transcribed verbatim and coded using the qualitative data analysis software package MAXQDA 10. The qualitative content analysis by Mayring (2000), particularly the inductive category development, served as a guideline for coding. After coding all of the obtained interview data, reliability was checked, categories were interpreted and frequencies of assigned categories were analyzed. Because qualitative analysis might be biased or highly subjective due to the dependence on researchers' coding and interpretation of transcribed data, two different strategies to verify analyses were pursued, as suggested by Elliott, Fischer, and Rennie (1999). First, two researchers on the research team coded both the first 25% of the transcripts and continually discussed category development and text interpretation. For the overlapping 25% of the data, the interrater reliability using Cohen's κ proved to be very good ($\kappa = 0.81$, $p = .000$; Landis & Koch, 1977). This procedure was used to ensure that categories were shared between coders and that the interpretation was valid. Notably, only minimal interpretation was needed, because participants made mostly clear statements, at least in terms of the advantages and barriers they reported. While coding the rest of the material, researchers discussed more complex text passages. Second, some illustrative quotes were included in this paper to give the reader the opportunity to follow our interpretation. At the conclusion of content analysis, researchers subdivided the categorized advantages and barriers into “non-experiential”/not directly experienced or “experiential”/ directly experienced and frequencies were analyzed.

3.3.2 Perception, attitudes towards EVs and behavioral intentions

Regarding *General Perception* of EVs, five items (see Table 1) were consistently used at all points of data collection. These items were summarized to create the scale *General Perception* of EVs (.67 ≤ Cronbach’s α ≤ .70). A 6-point Likert Scale from 1 (*completely disagree*) to 6 (*completely agree*) was applied for all items, as well as for all intention items.

Furthermore, the *Van der Laan Acceptance Scale* (Van der Laan et al., 1997), an instrument for measuring acceptance that contains two dimensions (*Satisfaction* and *Usefulness*) was implemented. Only users who participated in the second study period were asked at all points of data collection to respond to the nine semantic differentials (ranging from -2 to 2) while evaluating the EV. Users participating in the first period were asked at T_1 and T_2, but not at T_0. Four of nine semantic differentials belong to the *Satisfaction* scale (e.g., *pleasant – unpleasant*, *nice – annoying*). The other five items represent the *Usefulness* scale (e.g., *useful – useless, bad – good*). The internal consistency of *Usefulness* (.64 ≤ Cronbach’s α ≤ .82) and *Satisfaction* (.70 ≤ Cronbach’s α ≤ .86) was satisfactory at all data collection points.

One item was administered to assess the *Willingness to Recommend* an EV (Table 1). It included the wording, “would recommend to my best friend”, which has been shown to reliably predict customers’ behavior in most contexts (Reichheld, 2003). Three items assessed purchase intentions (see Table 1). In particular, two items assessed the *Willingness to Pay*. These items were anchored on realistic leasing rates and purchase prices for EVs which would be comparable to the test vehicle in performance. The third item assessed the *Willingness to Purchase* an EV after the project, but it was only administered in the second study period at all three points of data collection (first period: T_1 & T_2).

Table 1 Overview of items assessing general perception of EVs, intentions to recommend and purchase an EV

Scales (Cronbach's alpha) and associated items
General Perception (.67 ≤ Cronbach's α ≤ .70)
Electric vehicles are a key solution to solving air pollution. (Gould & Golob, 1998)
Electric vehicles are the means of transport for the future.
Electric vehicles should play an important role in our transportation systems.
Electric vehicles provide driving pleasure.
Electric vehicles are suitable for everyday use.
Willingness to Recommend
I would recommend electric vehicles like the MINI E to my best friend.
Willingness to Pay (.57 ≤ Cronbach's α ≤ .62)
At the moment, I could imagine leasing an EV like the MINI E for a monthly rate of 650€.
I would pay one third more for an EV than for a comparable conventional vehicle.
Willingness to Purchase
I am seriously planning to purchase an EV after this study.

Note. For all three data collection points, internal reliability was calculated. 6-point Likert scale.

3.4 Test vehicle

The test vehicle was a converted standard MINI Cooper, commonly referred to as the MINI E (two-seater, 150 kW power, 220 Nm torque, top speed of 94 miles/h (≈150 km/h), without a sound generator), range of 104 miles (≈168 km) on a single charge under 'normal driving conditions'. A lithium ion battery pack that took up the rear seats and part of the trunk stored the power and was rechargeable using 32 and 12 Ampere. The regenerative braking system of the EV transferred kinetic energy from the momentum of braking back into the battery. Besides using the public charging stations that were available in Berlin, all users could recharge at home using a "wallbox". An empty battery took approximately four hours (32 Ampere) to charge.

4 Results

4.1 Perceived advantages of EVs and barriers to acceptance – Qualitative data (H1 & exploratory approach)

To investigate perceived advantages and barriers, frequencies of reported categories and the changes in participants' reports were analyzed. The McNemar test, with Yates correction for continuity, was performed to test if participants significantly changed their reports of perceived advantages and barriers. If preconditions of the McNemar test were violated, we used the binomial test. Because the experience effect was of interest, the effect size was calculated according to Green and Salkind (2003) (i.e., the proportions of participants that endorsed the particular advantage or barrier at T_0 was subtracted from the proportion of participants that endorsed the advantage or barrier at T_1). Although participants were asked to report general advantages and barriers, it became clear in the interviews that they often spoke in personal terms. It was not possible to distinguish between advantages/barriers that were perceived to be general or personal in most cases; therefore, this differentiation was not included in the analyses. However, some of the reported advantages and barriers could have been directly experienced while integrating the EV in daily life and others could not. This is addressed in the presentation of the results.

4.1.1 How perception of advantages changes with EV experience

Statistical results regarding perceived advantages are shown in Table 2. The most frequently reported experiential advantage was the *low noise emission* of the vehicle. After 3 months, participants were even more enthusiastic about the *low noise emission* and changes in reported frequencies were significant.

> "It might sound trivial, but I almost think that the greatest advantage is that [the EV] is silent. That's the best part about the whole thing." (T_1, *Participant 27*)

Table 2 Advantages that were reported at different data collection points

Advantage	Percentage of participants (%)		χ^2 (McNemar)	*p*	effect size[b]
	T_0	T_1			
Experiential advantage					
Low noise emission	38.5	56.4	4.97	.026	0.18
Driving experience	17.9	47.4	16.69	.000	0.29
Acceleration	14.1	23.1	-	.143[a]	0.09
Fun	6.4	20.5	-	.013[a]	0.14
Pleasant driving	3.8	20.5	-	.002[a]	0.17
Regenerative braking	3.8	11.5	-	.146[a]	0.08
Low refueling costs	11.5	28.2	5.33	.021	0.17
High energy efficiency / low consumption	10.3	11.5	-	1.000[a]	0.01
Home charging/ no need to go to gas stations	1.3	16.7	-	.002[a]	0.15
Less driving with a bad conscience (subcode of **environmental friendliness**)	0	12.8	-	.002[a]	0.13
Non-experiential advantage					
Environmental friendliness	85.9	57.7	13.78	.000	-0.28
Less/ no emissions (CO_2)	75.6	37.2	22.13	.000	-0.37
• Less local pollutant emissions (exhaust gases while driving)	29.5	10.3	-	.001[a]	-0.19
• Less local pollutant emissions if energy source is renewable/clean	29.5	6.4	-	.000[a]	-0.24
Usage of alternative energy sources for mobility	26.9	16.7	-	.134[a]	-0.10
Potential external storage	7.7	0	-	.031[a]	-0.08
Technology of the future	3.8	5.1	-	1.000[a]	0.01

Note. *N* = 78; categories were included if greater than or equal to 5% of the participants reported it, main categories are written in bold; [a] binomial distribution was used because precondition was violated; [b] effect size calculation according to Green and Salkind (2003).

Features related to the EV *driving experience* were reported as advantages by almost half of the participants, but only after experiencing the EV. Before the EV was delivered, some participants expected the very fast *acceleration* to be an advantage, but only a few participants reported *fun*, *pleasant driving* and/or *regenerative braking* as expected advantages. After 3 months, *fun* and *pleasant driving* was seen as an advantage by more participants and individual reported attitudes had changed significantly over time.

After 3 months, compared to prior to EV delivery, the number of participants who reported the *low 'refueling' costs* of an EV as an advantage more than doubled. After experiencing the EV, the perception of this feature changed significantly.

At both data collection points, around 10% of the participants perceived the *high energy efficiency,* and therefore *low consumption,* as one important advantage. There was no experience effect found for this feature.

Another category of advantages included that EVs could be *charged at home* if possible and participants do not need to make extra trips to gas stations. At T_0, just 1.3% reported this feature as an advantage, but after experience with the EV, 16.7% noted it as benefit. Participants' reports changed significantly.

The environmental friendliness per se is an advantage that could not have been directly experienced. However, driving with *less of a bad conscience* is a direct experience that the participants had. After 3 months, some drivers endorsed this quality because of perceived environmental friendliness. This change was significant.

Overall, *environmental friendliness* of the EV is the most frequently reported advantage. This category includes *less* CO_2*-emission* through EV usage, particularly lower inner-city air pollution. Some participants mentioned that this advantage would only appear if the energy used for charging was generated using low CO_2 technology (e.g., solar or wind power).

> "CO_2-neutral, on the condition that renewable energy is used, because if we use nuclear power or energy from coal-fired power plants, it wouldn't make much sense really" (T_0, *Participant 22*)

After using the EV for 3 months, *environmental friendliness* was mentioned less frequently when participants were asked to report advantages of EVs. There was a significant change in individuals' reports over time.

At T_0, another major non-experiential advantage was the *usage of alternative energy sources for mobility.* Although this category implies that electric vehicles are independent of fossil fuels, they depend on energy which could come from various sources. At T_1, it was mentioned less often, but the change in participants' reports between T_0 and T_1 was not significant.

> "I think the greatest advantage for the future is that energy can be generated or produced in many ways, using solar, wind, nuclear, coal or water energy. This energy can be used to operate vehicles. One is not tied to one specific kind of energy, oil, but has the opportunity to generate electricity from different sources." (T_1, *Participant 23*)

An EV as *potential external storage* was only reported as a relevant advantage at T_0; at T_1 none of the participants mentioned it. Participants' endorsement of this feature changed significantly after EV usage. Few participants reported *EVs are a technology of the future* as an advantage at either data collection point. No significant change was observed after experience with the EV.

In sum, as expected in Q1a, environmental friendliness, lower running costs, efficiency, low noise, fun, and home-charging were reported as advantages by participants. Furthermore, different driving characteristic such as acceleration and regenerative braking, usage of alternative energy sources for mobility and EVs as potential external storage were additionally reported. The hypothesized 'smooth driving' is most likely comparable to the reported 'pleasant driving'. Furthermore, different experiential features of the EV (e.g., low noise, pleasant driving) were more frequently reported after experience. However, perception of some features such as 'acceleration', which is likely comparable to 'high torque', were unaffected by experience. Other than that, we can conclude that perception of low noise, smooth driving, fun, and home-charging as advantages increased for the participants after gaining experience, and therefore, our data support hypothesis H1.

With two exceptions, the endorsement of most non-experiential advantages (e.g., environmental benefits) was negatively influenced by experience (i.e., these advantages were not mentioned as frequently anymore). In sum, the valence of the experience effect varied.

4.1.2 Barriers to acceptance and how perceptions change with EV experience

Reported barriers for acceptance and their statistical values are presented in Table 3. At T_0, the most frequently reported experiential barrier to widespread adoption of EVs was *limited range.* Although the percentage of participants who mentioned this barrier increased from 56.4% to 70.5%, the change in participant endorsement was not significant.

Compared to T_0, 20% more participants mentioned *limited space* due to the battery as a disadvantage at T_1. Experience had a significant effect. Participants partly distinguished between limited passenger and cargo space.

Regarding *charging*, different features were mentioned as barriers: *unsatisfying infrastructure, long charging duration*, or simply, the handling of the cable. In sum, every feature was reported less frequently as a barrier after 3 months of EV usage; however, only *charging duration* changed significantly. The *battery* (apart from size) as barrier was also mentioned more frequently at T_1. Participants evaluated the *battery* as heavy, and its battery life as unsatisfactory. Experience had a significant impact.

Especially in the beginning, participants mentioned *low noise* as a barrier. Many participants' reports changed significantly over time. Less than 3% mentioned the acoustics as a barrier after experience with the EV. Some participants were conflicted about this feature and simultaneously reported it as an advantage and a disadvantage. They were concerned about the safety consequences of low noise and missing important noise-related feedback, but were pleased with the silent driving. As a consequence, we analyzed the data differently, coding 3 groups: drivers who only endorse it as an advantage, only as barrier or as both. At T_0, 28.2% of the participants perceived the low sound level as an advantage, 10.3% felt ambivalent about it and 3.8% perceived the low noise exclusively as a barrier. One significant change was observed over time. At T_1, many more participants (53.8%) reported the low noise exclusively as an advantage ($p = .002$). After 3 months, 2.6% of the participants were conflicted ($p = .070$) and none of the participants reported this feature exclusively as a barrier ($p = .250$), but these latter changes were not significant.

Limited usability of an EV, which is closely related to other barriers (e.g., range, acquisition costs and unsatisfying infrastructure), was also reported as a barrier to acceptance. The percentage of participants who identified this feature as a barrier was higher at T_1; however, changes in reports between T_0 and T_1 were not significant.

"… and that [the EV] is not as functionally versatile, because you can't go on vacations with it or drive longer trips."(T_1, *Participant 74*)

At both data collection points, some participants reported that driving an EV requires more planning and organization than driving a conventional automobile, because EVs are less flexible (*limited flexibility / need for planning*). Experience did not significantly change perception of this barrier.

Table 3 Barriers to acceptance of EVs that were reported at different data collection points

Barrier	Percentage of participants (%)		χ^2 (McNemar)	p	effect size[b]
	T$_0$	T$_1$			
Experiential barrier					
Limited range	56.4	70.5	2.89	.091	0.14
Limited space / battery size	41.0	57.7	6.25	.037	0.17
Limited passenger space	11.5	21.8	1.89	.170	0.10
Limited cargo space	3.8	19.2	-	.008[a]	0.15
Charging	34.6	29.5	0.27	.607	-0.05
unsatisfying infrastructure	29.5	20.5	1.24	.265	-0.09
long charging duration	16.7	5.1	-	.035[a]	-0.12
Battery (except size)	32.1	14.1	-	.004[a]	-0.05
state of development of battery	14.1	3.8	-	.039[a]	-0.10
weight	11.5	2.6	-	.016[a]	-0.08
Low noise level as safety issue	14.1	2.6	-	.004[a]	-0.12
Limited usability	9.0	16.7	-	.210[a]	0.08
Limited flexibility / need for planning	9.0	7.7	-	1.000[a]	-0.01
Non-experiential barrier					
Acquisition costs	43.6	20.5	7.61	.006	-0.24
battery costs	9.0	6.4	-	.774[a]	-0.03
Societal resistance to change	19.2	5.1	-	.007[a]	-0.14
Availability of EVs on the market	5.1	3.8	-	1.000[a]	-0.01

Note. N = 78; categories were included if greater than or equal to 5% of the participants reported it; main categories are written in bold, [a] binomial distribution was used because precondition was violated; [b] effect size was calculated according to Green and Salkind (2003).

Although participants leased the EV, *acquisition costs* was a non-experiential barrier, because they paid a reduced leasing rate. At T_0, *acquisition costs,* including high *battery costs,* was the second most frequently endorsed barrier, but at T_1, only 19.2% reported this feature as a barrier. The McNemar test showed that the impact of experience was significant.

Another barrier that participants mentioned is best described as *societal resistance to change.* Some participants mentioned that the majority of the German population has a very specific conception of what a car should be and which characteristics and functions it must have. In addition, they reported that the population is skeptical about new products. Thus, this would be a barrier to widespread EV adoption. Participants' perceptions regarding this category changed significantly after experience with the EV. *Societal resistance to change* was perceived as much less of a barrier.

> "Well, I think that most people are somehow afraid of first losing mobility through the limited range and then they're scared of 'the unknown' " (T_0, *Participant 16*)

One barrier that was identified, that is probably not as valid today, is that the availability of EVs on the market is unknown or very limited.

As expected in Q1a, limited range, charging infrastructure and duration, battery issues, and low noise as a safety problem are perceived as barriers. Contrary to our expectation, reliability, uncertainty with service availability and other safety concerns were not reported by at least 5% of the participants. Additionally, barriers such as limited usability and societal resistance to change were identified. Participant endorsement of some barriers changed with experience. Some barriers became more relevant (e.g., limited space) and others were mentioned less frequently (e.g., low noise); thus, experience did not always positively influence perceptions. Our hypothesis (H1) that the salience of 'need for planning' and 'limited range' as barriers will increase after using an EV was not supported by our data.

4.2 Perception, attitudes, intention to recommend, and purchases intentions – Quantitative data

Regarding the questionnaire, all variables were tested for univariate outliers in accordance with the Grubbs (1969) procedure; 14 scores (*Usefulness*: 1, *Satisfaction*: 5, *Willingness to Recommend*: 4) were excluded. Experience effects for continuous variables were analyzed using paired samples t-tests and ANOVAs with repeated measures, depending on the number of data collection points. Relationships between the different variables as hypothesized in Figure 1 were analyzed using correlations and regression analyses. Assumptions for regression analyses were tested according to

Field (2013). Tests assessing multicollinearity, for instance, revealed that variance inflation factors (VIF) were below the critical value of 10 and tolerance values were above .25 (Urban & Mayerl, 2008) for all regression analyses. In Table 4, descriptive statistics of all analyzed variables are presented.

Table 4 Descriptive statistics for variables used in the analyses

Variables	Point of data collection								
	T_0			T_1			T_2		
	N	*M*	*SD*	*N*	*M*	*SD*	*N*	*M*	*SD*
General Perception [LS]	74	4.68	0.64	74	4.99	0.60	74	4.95	0.57
Satisfaction [SD]	38	1.65	0.36	75	1.66	0.39	75	1.45	0.54
Usefulness [SD]	39	1.40	0.43	77	1.35	0.45	76	1.23	0.55
Willingness to Recommend [LS]	75	4.93	0.79	76	5.38	0.80	74	5.34	0.73
Willingness to Pay [LS]	76	3.40	1.13	77	3.09	1.22	77	3.17	1.17
Willingness to Purchase [LS]	37	3.89	1.15	77	4.14	1.25	77	4.01	1.41

Note. The maximum available sample (*N*) is analyzed for each variable after outlier exclusion. *N* may be smaller when testing relationships between two variables in an analysis. Therefore key descriptive statistics are repeated for the final *N* used in the analyses (e.g., section 4.2.1). [LS] 6-point Likert Scale, [SD] Semantic Differential from -2 to 2 according to Van der Laan et al. (1997)

4.2.1 Perception and experience with an EV (H2)

Results of analyses of *General Perception* of EVs indicated that the evaluation of EVs was positive at all data collection points (Table 4). A repeated measures ANOVA revealed a significant experience effect for *General Perception*, $F(2, 134) = 10.85$, $p = .000$, $\eta^2_p = .14$. Post hoc tests (Bonferroni) showed that participants perceived EVs less positively before receiving the car than after 3 months of experience, $M = -.324$, $p < .001$, or 6 months, $M = -.279$, $p = .002$. The difference between *General Perception* of EVs at T_1 and T_2 was not significant. The results support hypothesis H2 which proposes that EV-experienced drivers perceived EVs in a more positive way.

4.2.2 Attitudes and experience with an EV (H3)

Data obtained from the Van der Laan Acceptance Scale (Van der Laan et al., 1997) showed that users judge the EV as satisfying and useful at all data collection points (Table 4). For the repeated measures ANOVA, only data from the second study period were analyzed, because the first study period data were not collected at all measurement points. Participants in the second study evaluated the test vehicle as satisfying, T_0: $M = 1.65$, $SD = 0.36$; T_1: $M = 1.62$, $SD = 0.37$; T_2: $M = 1.55$, $SD = 0.42$, and useful, T_0: $M = 1.40$, $SD = 0.43$; T_1: $M = 1.30$, $SD = 0.44$; T_2: $M = 1.30$, $SD = 0.50$, at all points of data collection, but *Usefulness* and *Satisfaction* slightly decreased. Results of a repeated measures ANOVA did not reveal a significant experience effect for *Satisfaction*, $F(2,74) = 1.31$, $p = .277$, $\eta^2_p = .03$, or *Usefulness*, $F(2,76) = 1.22$, $p = .300$, $\eta^2_p = .03$, and did not support hypothesis H3.

When analyzing the whole sample, *Satisfaction* and *Usefulness* correlated strongly with each other, T_0: $r = .55$, $p < .001$; T_1: $r = .62$, $p < .001$; T_2: $r = .82$, $p < .001$.

4.2.3 Intention to recommend and experience with an EV (H4)

Participants' willingness to recommend EVs like the MINI E to friends (WTrecommend) increased over time (Figure 2). A repeated measures ANOVA revealed a significant experience effect, $F(2, 142) = 15.38$, $p < .001$, $\eta^2_p = .18$. A post hoc test (Bonferroni) showed that the difference between T_0 and T_1 was significant, $M = -.486$, $p < .001$. Additionally, the increase in *Willingness to Recommend* an EV between T_0 and T_2 was significant, $M = -.403$, $p < .001$. No significant difference was observed between T_1 and T_2. These results support hypothesis H4.

4.2.4 Purchase intentions and experience with an EV (H5)

In addition to intention to recommend, purchase intentions were assessed. *Willingness to Pay* (WTpay) was relatively low and decreased somewhat over time (Figure 2). Participants more frequently endorsed the statement that they were willing to purchase (WTpurchase) an EV after the study (Figure 2). Forty percent (T_1) and 39% (T_2) of participants reported that they "agreed" or "completely agreed" with the statement, "I am seriously planning to purchase an EV after this study", after 3 and 6 months, respectively. A repeated measures ANOVA revealed that *Willingness to Pay* changed significantly over time, $F(1.883,141.238) = 3.49$, $p = .033$, $\eta^2_p = .04$ (Huynh-Feldt correction). A post hoc test (Bonferroni) showed no significant differences between T_0, T_1 and T_2. However, the direction of the obtained effect was the opposite of the direction that we hypothesized (H5).

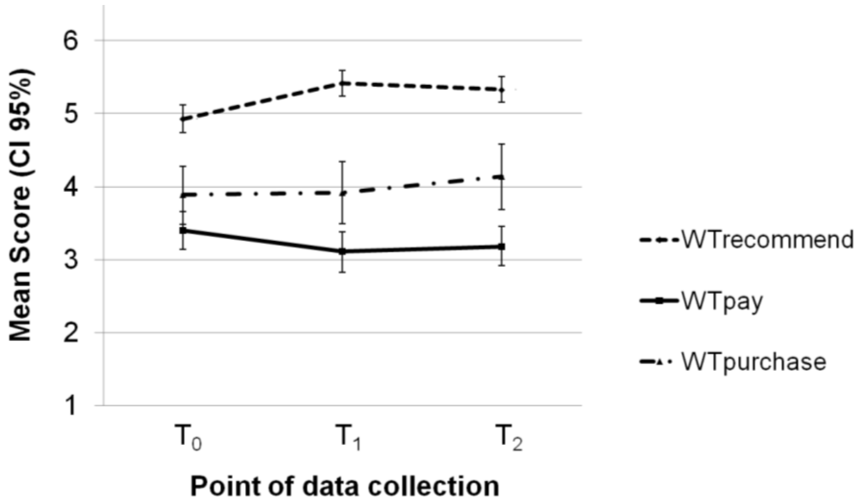

Figure 2. Results for intentions to recommend and purchase

Note. WTrecommend*:* $N = 72$, WTpay: $N = 76$. WTpurchase: $N = 37$. For WTpurchase, only data from the second study period were analyzed, because the first study period data were not collected at all measurement points. Results after outlier exclusion, 6-point Likert Scale

4.2.5 Relationship between general perceptions of EVs and attitudes towards EVs (H6)

Participants who evaluated the EV as more useful, viewed EVs more positively, T_0: $r = .47$, $p = .004$; T_1: $r = .55$, $p < .001$; T_2: $r = .61$, $p < .001$. Also, *Satisfaction* and *General Perception* of EVs showed medium to strong correlations, T_0: $r = .34$, $p = .047$; T_1: $r = .47$, $p < .001$; T_2: $r = .61$, $p < .001$. These results support hypothesis H6 (i.e., attitudes towards EVs are positively correlated with general perception).

4.2.6 Perception and attitudes predicting intention to recommend EVs (H7)

In multiple linear regression analyses, the predictive value of *General Perception, Satisfaction* and *Usefulness* on *Willingness to Recommend* was computed. The three predictors accounted for 16% (T_1) and 36% (T_2) of the variance in participants' intention to recommend an EV (Table 5). Only the predictor, *General Perception,* significantly predicted the criterion at T_2. In sum, our hypothesis (H7) that perception and attitudes predict the intention to recommend an EV is not supported by the reported findings.

Table 5 Perception and attitudes predicting *Willingness to Recommend* at all points of data collection

Point of data collection	Predictor	n	ß	*SE b*	*p*	Part correlation	Zero-order correlation
T_0	General Perception	34	.36	.20	.059	.33	.33
	Satisfaction	34	.02	.35	.916	.02	.16
	Usefulness	34	.03	.30	.904	.02	.19
	R^2_{adj} = .064, $F(3,31)$ = 1.78, p = .172						
T_1	General Perception	70	.21	.15	.119	.17	.38
	Satisfaction	70	.07	.28	.646	.05	.33
	Usefulness	70	.24	.23	.109	.18	.40
	R^2_{adj} = .163, $F(3,67)$ =5.54, p = .002						
T_2	General Perception	68	.25	.16	.042	.21	.48
	Satisfaction	68	.10	.25	.577	.06	.50
	Usefulness	68	.34	.26	.067	.19	.56
	R^2_{adj} = .360, $F(3,65)$ = 12.21, p = .000						

Note. Results after outlier exclusion

4.2.7 Perception and attitudes predicting purchase intentions (H8)

For the criterion *Willingness to Pay* 19% of the variance was explained by the model at T_0 and *General Perception* proved to be a significant predictor (Table 6). At T_1 and T_2, the regression models did not reach significance.

Multiple linear regression analyses for the criterion *Willingness to Purchase* only revealed significant results for data collected after experiencing the EV (T_1 & T_2), but not for data collected at T_0 (Table 7). These models explained 16% of the variance in the data. At T_1, *General Perception* significantly predicted *Willingness to Purchase*. In contrast, *Satisfaction* was the only significant predictor at T_2. In sum, our results do not support the hypothesis that perception and attitudes predict purchase intentions (H8).

Table 6 Perception and attitudes predicting *Willingness to Pay* at all points of data collection

Point of data collection	Predictor	n	ß	*SE b*	*p*	Part correlation	Zero-order correlation
T_0	General Perception	34	.41	.31	.023	.37	.46
	Satisfaction	34	-.18	.54	.350	-.15	.10
	Usefulness	34	.25	.47	.195	.21	.34
	R^2_{adj} = .186, $F(3,31)$ =3.28, p = .025						
T_1	General Perception	71	.16	.31	.289	.13	.10
	Satisfaction	71	-.01	.53	.933	-.01	.01
	Usefulness	71	-.09	.48	.568	-.07	-.02
	R^2_{adj} = -.026, $F(3,68)$ =.393, p = .758						
T_2	General Perception	71	.19	.30	.184	.16	.19
	Satisfaction	71	.27	.44	.208	.15	.17
	Usefulness	71	-.23	.48	.311	-.12	.10
	R^2_{adj} = .017, $F(3,68)$ = 1.41, p = .248						

Note. Results after outlier exclusion

Table 7 Perception and attitudes predicting *Willingness to Purchase* at all points of data collection

Point of data collection	Predictor	n	ß	*SE b*	*p*	Part correlation	Zero-order correlation
T_0	General Perception	33	.34	.33	.086	.31	.31
	Satisfaction	33	-.12	.58	.570	-.10	.02
	Usefulness	33	.02	.50	.916	.02	.11
	R^2_{adj} = .019, $F(3,30)$ = 1.21, p = .322						
T_1	General Perception	71	.47	.29	.001	.39	.36
	Satisfaction	71	.02	.49	.904	.01	.11
	Usefulness	71	-.21	.44	.159	-.16	.05
	R^2_{adj} = .160, $F(3,68)$ =4.30, p = .008						
T_2	General Perception	71	.25	.34	.067	.20	.33
	Satisfaction	71	.49	.50	.015	.27	.39
	Usefulness	71	-.26	.55	.224	-.13	.29
	R^2_{adj} = .164, $F(3,68)$ = 5.64, p = .002						

Note. Results after outlier exclusion

4.2.8 Relationship between intention to recommend and purchase intentions (H9)

At T_0 and T_2, participants who would recommend the EV are also more willing to pay for an EV, T_0: $r = .25$, $p = .032$, $N = 75$; T_2: $r = .28$, $p = .014$, $N = 74$. Only after experience with the EV did *Willingness to Purchase* an EV correlate with *Willingness to Recommend*, T_1: $r = .82$, $p < .001$, $N = 76$; T_2: $r = .43$, $p < .001$, $N = 74$, and *Willingness to Pay*, T_1: $r = .31$, $p = .007$, $N = 77$; T_2: $r = .37$, $p = .001$, $N = 77$. Thus, results largely support hypothesis H9 (i.e., intention to recommend is positively associated with purchase intentions).

5 Discussion

The present research aimed to investigate perception (including advantages and barriers) and acceptance of EVs. Additionally, it was of interest whether perception and acceptance change after intensive EV usage. These issues were addressed in a field study with drivers who lived in the Berlin metropolitan area and drove an EV for 6 months. Seventy-nine users who had the opportunity to experience an EV in their daily life for 6 months were studied.

5.1 Perceived Advantages of and Barriers to EV acceptance

A major aim of the present study was to examine which advantages and barriers EV users perceive (Q1a). Furthermore, it was of interest whether these perceptions change over time and if changes in reports of experiential advantages and barriers are more likely to be positive (Q1b). EV drivers perceive a variety of advantages. In sum, nine main categories (e.g., environmental friendliness, low noise) emerged through our analyses that partially reflect the expected advantages, as well as the perceived positive features (i.e., advantages) reported by Graham-Rowe et al. (2012). They could be categorized into experiential advantages (i.e., advantages that could be directly experienced) (e.g., low noise emission) and more abstract or non-experiential advantages (e.g., environmental friendliness). Most experiential advantages, including low noise emission, pleasant driving, fun, refueling costs, as well as the opportunity to 'refuel' at home were mentioned much more frequently after users gained experience using their EV.

Results revealed that after experiencing an EV, some non-experiential advantages became even less relevant. Thus, environmental benefits of EVs became less important over time, which is contrary to findings from Gould and Golob (1998). The decrease in the number of EV users reporting the usage of renewable energy sources as an advantage also became apparent. Still, compared to other countries, MINI E drivers in Germany were more likely to report that charging with renewable energy played an important role in their evaluation of the vehicle (Vilimek et al., 2012).

Regarding barriers, the ten identified main categories included most of the concerns reported in previous studies (e.g., Carroll, 2010; Graham-Rowe et al., 2012). Many EV users changed their opinion on experiential barriers after using the EV; charging duration and infrastructure, battery issues and low noise level were less frequently reported as barriers after experiencing the EV. Another experiential barrier that was quite specific to the test vehicle was limited space. It was perceived as a barrier by many more participants after experiencing the EV. However, in newer vehicles, batteries are integrated in ways that require less space; thus, this disadvantage is likely to become much less salient in the near future. However, several experiential barriers were not significantly influenced by experience. Limited range, for instance, remained a highly relevant barrier over the course of the study. Therefore, our data does not support the findings of Jensen et al. (2013), which showed that the importance of range increases after testing an EV, as our data suggest that it remains stable. Research indicates that daily range practice has a positive impact on the efficiency of users' interaction with range (Franke & Krems, 2013a), but this does not seem to influence the perception of range, as it remains a major barrier for acceptance even after gaining substantial experience with an EV. Still, it is unclear, for instance, how many EV users experienced range as a personal or general barrier. The results regarding space and range match with EV manufacturers' goals of reducing battery size, while simultaneously enlarging space and increasing range. Today, many EVs on the market have higher space capacity, and therefore, should already be more suitable for daily use. Alike Pearre, Kempton, Guensler, and Elango (2011) we expect that battery range is likely to improve in the future; thus, this barrier will become less significant than has been observed here. Additionally, one could argue, according to Franke, Neumann, Cocron, Bühler, and Krems (2012), that training drivers to achieve better utilization of limited mobility resources in EVs might help to bridge the gap until more advanced batteries become available. To overcome the 'range barrier' at the present time, EV manufacturers also offer free rental cars for a few days per year for long trips that exceed the EV range.

Charging is closely related to range. One finding from our study is that under the present study's conditions (i.e., home charging station with 32 ampere fuse, 4-hour charging duration), charging duration became less of a barrier with increasing experience and home charging was even described as an advantage after the EV was integrated into daily life. These results are consistent with the findings of Turrentine et al. (2011). A sample of US drivers enjoyed charging at home and evaluated the charging time as adequate. In sum, we have observed that EV charging is suitable for daily life if drivers have access to personal (i.e., home-based) charging infrastructure. Still, under other circumstances, experience might have the opposite effect. For instance, experience might negatively influence EV users who do not have access to personal charging infrastructure, because of the inconvenience of relying on public recharging stations.

Perceptions of several reported barriers that could not have been directly experienced while driving an EV (referred to in this paper as 'non-experiential' barriers) were also investigated. For example, 'availability of EVs on the market' remained unchanged over the course of the study. In contrast, acquisition costs and perceived societal resistance to change were less frequently reported as barriers after experiencing an EV. Still, acquisition costs were an often reported barrier. In Norway, other benefits (e.g., no purchase tax, free parking, free ferry usage), in addition to cheaper running costs, are provided by the government to compensate for the high purchase price of EVs. At the same time, EVs are also more successful on the Norwegian market than in many other European markets.

Notably, low noise level is seen more as an advantage than as a barrier. Specifically, after driving an EV for a longer time, this particular EV characteristic was perceived very favorably. Additionally, none of the EV-experienced drivers described it exclusively as barrier; however, some participants were ambivalent and endorsed this special feature of EVs as both an advantage and a safety problem. This might be considered in the debate regarding sound generators for EVs. A detailed account of the advantages and disadvantages of driving a silent EV in urban traffic as well as the influence of experience on drivers' evaluation of low noise can be found in Cocron and Krems (2013). Although safety issues still need to be addressed, it should be taken into account that this feature could impact the market success of EVs.

Overall, in our study experience affects potential consumers' perception of the advantages and barriers of EVs; however, advantages do not become barriers or vice versa. Moreover, it seems to be the case that experiential advantages (e.g., low noise, fun) and barriers (e.g., charging duration) were of higher relevance and more positively evaluated respectively (i.e., advantages are strengthened, barriers are weakened) after gaining direct experience with an EV. These findings have several different implications. Providing EV experience could serve as a promising strategy for marketing EVs. This is consistent with Burgess et al. (2013), who argued that first-hand experience could change consumers' perception of EV performance. Notably, the test EV that we provided was quite agile relative to other available EV models. Thus, this result might not generalize to different EV models. However, even if positive perceptions of the EV driving experience do not generalize to other currently available EVs, this finding could have potential implications for the design and marketing of future EVs.

5.2 Perceptions, attitudes, intention to recommend, and purchase intentions

We evaluated how the current state of EV technology is perceived and accepted (Q2a) and whether perceptions and acceptance change after experiencing an EV (Q2b). At all data collection times, the general perception of EVs including, for instance, suitability for daily life, was quite positive. Consistent with Carroll (2010), experience had a favorable impact on user opinions; participants' general perception of EVs was *even more* positive after gaining experience.

Data obtained from the Van der Laan acceptance scale (Van der Laan et al., 1997) revealed that participants highly valued *Usefulness* and *Satisfaction* of the EV at all data collection points. Scores remained high throughout the study and no experience effects were detected. Given these results, it appears that current EV technology already meets the expectations of users, is judged to be satisfactory in everyday life, and experience does not influence these attitudes. Notably, it is very likely that our sample is more comparable to a population of early adopters, and therefore, might not be representative of the general population of potential consumers. Nevertheless, early adopters may be crucial for widespread acceptance of new technology, a topic that will be discussed in more detail later, and the positive evaluation observed here indicates that the development of EVs is trending in the right direction.

This research also examined several behavioral indicators of EV acceptance. As a whole, the sample was willing to recommend EVs and this intention even increased after experiencing the EV. Regarding purchase intentions, participants in this sample exhibited considerable variability, and EV experience had little impact on intentions. However, at all data collection points, between 13% and 27% of the sample were willing to spend more money for an EV than a conventional car. Even more participants (around 40%) endorsed that they were ready to purchase an EV. These results are comparable to those found in previous studies conducted with samples of EV-experienced drivers (e.g., Jabeen et al., 2012). Although the intention to recommend and purchase might be overestimated here because our sample most likely consisted of early adopters, these results are notable as they indicate that current EV technology is already acceptable for some potential consumers.

Another behavioral indicator of acceptance of EVs is the usage intensity after receiving an EV. In this study, considerable effort was made to collect usage data. However, for the present research, data quality was insufficient due to technical problems and multiple potential confounding factors that could not be controlled. Because we had to exclude many participants from analyses, it was not possible to make valid conclusions about usage intensity and changes over time. Thus, usage data are not reported here.

Regarding Q3, our results reveal that there is no association between general perception and the various indicators of acceptance investigated here, a finding that does not support our conceptual model (Figure 1). More positive perceptions of, and attitudes towards, EVs does not predict higher intention to recommend or purchase an EV. Several researchers (e.g., Ajzen, 1991) have shown that attitudes and behavioral intentions tend to be rather unreliable predictors of enacted behavior and that other factors (e.g., subjective norms and perceived behavioral control) might also influence the relationship. Furthermore, the possibility of a significant relationship is higher if attitudes and behavioral assessments correspond in their 'levels of specificity' (Kraus, 1995). Given that the major objective of the present research was to show how EVs are perceived and accepted, we required scales that assess more general EV evaluations and behavioral indicators. Investigation of the factors that influence EV purchase behavior was beyond the scope of the present research, but is of high interest for future investigations.

In sum, participants were given 6 months to experience many of the positive and negative aspects of living with and driving an EV. We were able to demonstrate that experience with EVs influences users' evaluation of EVs. Previous research has demonstrated the effect of experience on a variety of specific domains, including interaction with range (Franke & Krems, 2013a), usage of regenerative braking (Cocron et al., 2013), perception of acoustics (Cocron & Krems, 2013) and driver interface (Neumann, Franke, Cocron, Bühler, & Krems, 2013). The present study builds on this work by showing the effect of experience on a more global level—EV acceptance.

Although our sample is not representative of the population of German car owners and likely consists of a higher percentage of early adopters (Rogers, 2010), our findings have important implications for the potential widespread adoption of EVs. Satisfaction of early adopters seems to be an important pre-requisite for general acceptance of EVs. For instance, early adopters could influence others via word-of-mouth or incidentally promote emulation while using their EV (Rogers, 2010). If early adopters perceive barriers after experiencing the EV and are skeptical of the product, it is important to improve the characteristics of the product. According to Rogers (2010), a product will have a high probability of success when innovators and early adopters, approximately 16% of the potential market, accept the product.

5.3 Comparing qualitative and quantitative results

The combination of qualitative and quantitative results provides interesting information. When taking all perception results (i.e., advantages, barriers, general perception of EVs) into account, we can conclude that shortly after gaining experience with an EV, the perception of many EV features is positively influenced. Findings from Burgess et al. (2013) emphasize the importance of real-life experience. This supports our assertion in section 5.1 that giving potential EV consumers the opportunity to test an EV might be a promising means for supporting EV acceptance, and thereby, the expansion of the EV market. Direct experience can help to overcome consumers' misconceptions which may be based on older EV models (e.g., slow, strange design, embarrassing). Burgess et al. (2013) referred to these perceptions as the "traditional view".

When combining quantitative and qualitative data, another interesting point comes to light. The EV was perceived positively (e.g., suitable for daily life) and evaluated as useful and satisfying, even though several barriers like limited range were still reported. The negative evaluation of range and other barriers could be one potential explanation for the discrepancy between attitudes and intention to recommend or purchase.

5.4 Implications for future research

As stated earlier, our sample consists of urban residents with the opportunity to charge at home and who are early adopters of EVs. It would be interesting to determine if our results would generalize to a sample that is more representative of the population of German car owners. Early adopters' experiences, perceived barriers and suggestions for improvements serve as an important first step. The next step is to determine how users living under other circumstances (e.g., users who do not have access to private charging infrastructure) perceive and accept EVs, whether experience also affects them in similar ways, and what level of experience is necessary to change their EV-related perceptions.

Additionally, countries that have moved beyond the "early adopter stage" should be investigated. In Germany, encountering an EV on the road is still a noteworthy event. In comparison, in countries like Norway where the EV market is more mature, EVs are already highly integrated into the driving culture. According to Burgess et al. (2013), mere exposure to EVs can positively influence consumers' perceptions and attitudes. Thus, it is of interest whether direct EV experience for an extended period of time still has a positive effect on non-EV drivers' perceptions of EVs in such countries.

Furthermore, the 6-month test period offered in this study is relatively long and is likely not an economically viable business strategy. Realistically, potential consumers might be allowed to test an EV for approximately one day. It has not yet been investigated whether this relatively short test duration leads to changes in consumers' evaluation of EVs.

6 Conclusion

The present research explores EV drivers' acceptance of current EV technology and the impact that real-life experience has on perception and acceptance of EVs. Experience can significantly change perception of the EV's advantages and barriers in both positive and negative directions depending on the specific type of advantage or barrier. Our findings reveal that currently available EVs are already acceptable and suitable for daily life in urban areas, provided that a home charging station and a second car are available. However, for widespread market success, solutions are still needed to overcome important barriers such as limited range and acquisition costs. On the other hand, widespread adoption of EVs might be supported if features such as the 'fun factor' and low noise are retained in future EV designs. In addition to technological solutions, some new marketing strategies are required to demonstrate that EVs have favorable characteristics beyond the environmental benefits. These strategies could also target misconceptions related to EVs and societal resistance to change. Given these goals, first-hand experience seems to be a promising strategy.

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Paper IV:
Hazard detection in noise-related incidents – the role of driving experience with battery electric vehicles

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Hazard detection in noise-related incidents – the role of driving experience with battery electric vehicles

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The low noise emission of battery electric vehicles (BEVs) has led to discussions about how to address potential safety issues for other road users. Legislative actions have already been undertaken to implement artificial sounds. In previous research, BEV drivers reported that due to low noise emission they paid particular attention to pedestrians and bicyclists. For the current research, we developed a hazard detection task to test whether drivers with BEV experience respond faster to noise-related incidents than inexperienced drivers. The first study (N = 65) revealed that BEV experience only played a minor role in drivers' response to noise-related hazards. The tendency to respond, reaction times and hazard evaluations were similar among experienced and inexperienced BEV drivers; only small trends in the assumed direction were observed. Still, both groups clearly differentiated between critical and non-critical scenarios and responded accordingly. In the second study (N = 58), we investigated additionally if sensitization to low noise emission had an effect on noise-related hazard perception. Again, participants in all groups differentiated between critical and non-critical noise-related scenarios. Even though trends in response rates and latencies occurred, experience and sensitization to low noise seemed to only play a minor role in detecting noise-related hazards. The findings further suggest that even after a short test drive, the lack of BEV noise is perceived more as a comfort feature than a safety threat.

Key Words: Battery electric vehicles, low noise, hazard perception, experience, traffic safety

1 Introduction

In discussions regarding the strengths and weaknesses of vehicles with an electric power train (EVs), concerns related to their low noise emission have been raised (National Federation of the Blind, 2011; Rosenblum, 2009). Hybrid Electric Vehicles (HEVs) and Battery Electric Vehicles (BEVs) especially pose a potential threat to blind pedestrians, as these road users mainly rely on auditory cues when navigating in traffic (Wall Emerson, Naghshineh, Hapeman, & Wiener, 2011). Research on EV safety has mainly focused on the perceptibility of these vehicles, which means that pedestrians – in particular blind pedestrians – were tested to determine their ability to detect an approaching vehicle (e.g. Garay-Vega, Hastings, Pollard, Zuschlag, & Stearns, 2010; Robart & Rosenblum, 2009). In the present paper, we aim to address the issue from the driver's perspective utilizing a hazard perception (HP) approach (McKenna & Crick, 1994). During the transition phase, with only a few BEVs on the road, driver behavior is crucial in mitigating potential risks resulting from low noise emissions. Therefore, it is of vital interest to determine if and when drivers detect situations which might become dangerous due to the lack of engine noise. In particular, we wanted to investigate (1) at which point drivers with differing levels of practical BEV experience detect hazards in noise related situations in traffic, and (2) how they evaluate such incidents. In the second study, we wanted to investigate (3) if sensitization to low noise has an impact on hazard detection and evaluation, and (4) how drivers evaluate the low noise of BEVs in general. To address these issues, we conducted two experimental studies with drivers who had extensive BEV experience and others who did not.

2 Background

2.1 Accident and incident characteristics of HEVs and BEVs

A report by the National Highway Traffic Safety Administration (Hanna, 2009) revealed that HEVs had significantly higher incidence rates for accidents than vehicles with internal combustion engines (ICE). In turning maneuvers, the risk of a HEV colliding with a pedestrian was significantly higher; during slowing or stopping, backing up and entering or leaving a parking space, the risk of an accident involving a pedestrian and a HEV doubled. The latter maneuvers were grouped into one category as they most likely occurred at low speeds where the difference in noise emission between vehicle types is greatest. An increased likelihood was also reported for accidents with bicyclists (Hanna, 2009). Verheijen and Jabben (2010) questioned the NHTSA report, arguing that the report did not clarify whether low HEV noise was the cause of the accidents. In their analysis of Dutch accident data, Verheijen and Jabben (2010) found that HEVs did not have an increased incidence rate for accidents with pedestrians or bicyclists. The results mentioned above do not clearly indicate whether EVs in general pose a greater safety risk than ICE vehicles. Especially since the registration rates of electrically propelled vehicles are still low, these numbers need to be treated with caution.

More detailed descriptions of noise-related incidents were reported by Cocron and Krems (2013). When questioned after driving a BEV for three months in urban traffic, 67.5% of participants reported incidents which were related to noise emission; no accident was reported. Based on the drivers' feedback, a catalogue of noise-related incidents was compiled. The categories were labeled as follows: (1) <30km/h, (2) traffic light/turning, (3) overtaking/passing, (4) exit/parking lots, (5) straight ahead driving, and (6) other maneuvers. In general, noise-related incidents seldom occurred and the hazardous potential of the reported incidents was rated low to medium. The majority of the incidents occurred at speeds below 45 km/h and involved pedestrians or bicyclists. The categories reported by Cocron and Krems (2013) partially overlap with the maneuvers described by Hanna (2009). Together, they served as the empirical basis for the creation of the noise-related scenarios which were used for the hazard detection task in our studies.

2.2 Noise emission of EVs and its meaning for different road users

To date, various studies testing the perceptibility of EVs at low speeds have been conducted. In such studies, participants were typically either blindfolded or were visually impaired. EVs and ICE vehicles of a similar type and brand approached at different speeds or conducted various maneuvers, while the sound level and participants' reactions were recorded. The participants' task was to indicate when they detected the vehicle. The greatest difference between electrically propelled and ICE vehicles in noise emission is usually found at speeds up to 10 km/h (e.g. Gary-Vega et al., 2010; Morgan, Morris, Keigan, & Muirhead, 2010). These differences diminish at 20 km/h (Morgan et al., 2010), and at 32 km/h (Garay-Vega et al., 2010), no difference in noise levels between vehicle types can be detected. The fact that EVs are less perceptible at lower speeds has led to a debate about artificial sound as a countermeasure to address safety risks associated with quieter vehicles (Dudenhöffer & Hause, 2012; Sandberg, 2012; Sandberg, Goubert, & Mioduszewski, 2010). Steps toward legislative action have already been initiated, e.g., in the US (Pedestrian Safety Enhancement Act, 2009). Still, when approaching the issue from a different perspective, the lack of sound significantly benefits the road environment.

Gärling (2001) reported that low noise emission is part of the driving pleasure for BEV drivers. A study conducted in the UK revealed that drivers also appreciated the low noise emission in BEVs; however, these drivers additionally mentioned safety concerns (Carroll, 2010). Results from a German field trial with BEVs suggest that BEV drivers are aware of noise-related hazards, as they reported paying particular attention to pedestrians and bicyclists (Cocron, Bühler, Franke, Neumann, & Krems, 2011). Still, in this field study, the evaluation of low noise emission changed with experience. Although safety concerns existed before driving the vehicle for the first time, they decreased as drivers gained more experience with driving the BEV in urban traffic. The findings reported by Cocron, Bühler, Franke, et al. (2011) suggest that drivers seemed to be aware of noise-related risks (risk perception) and reported anticipating such incidents (HP). In this context, Deery's (1999) model of behavioral response to potential hazards provides a useful theoretical structure. According to the model, risk taking behavior as the behavioral outcome is dependent on the individual's risk threshold and driving skill. Further, the risk threshold is defined as the individual's risk perception, whereas driving skill is determined through self-assessment of one's ability to prevent hazards from resulting in an accident. Directly associated with the potential hazard is HP, which is defined as the detection of the hazard and the quantification of its hazardous potential. Cocron and Krems (2013) investigated the degree to which BEV drivers perceived risk associated with low noise. In our research, we aim to investigate response to low noise-related hazards in more detail. Therefore, HP is the focus of the present work and is discussed in more detail in the next section.

2.3 Hazard perception

The driver's notion of increased attention to vulnerable road users (VRUs) raises the question of whether drivers adapt their driving after utilizing a BEV over an extended period of time. Drivers reported that they were aware of the hazards due to low noise and accounted for this problem in their day-to-day driving (Cocron, Bühler, Franke, et al., 2011). Therefore, one could argue that anticipatory skills might be acquired over time to avoid noise-related collisions. In the literature on road safety, the awareness of potential hazards is usually referred to as hazard perception (McKenna & Crick, 1994). HP in the driving context usually refers to "the ability of individuals to anticipate potentially dangerous situations on the road ahead" (Horswill et al., 2008, p. 212). As the overlap with Endsley's (1995) concept of situation awareness (SA) is apparent, Horswill and McKenna (2004) described HP as "drivers' situation awareness for potentially dangerous incidents in the traffic environment" (p. 156). Focusing on driving, Baumann and Krems (2007) proposed a comprehension-based model on construction and maintenance of SA. Underwood, Crundall, and Chapman (2011) conceptualized the perception of the current environment and the knowledge about the origins of the present situation using the levels of Endsley's model of SA (1995), with the former corresponding to level 1 (perception of elements in current situation) and the latter to level 2 (comprehension of current situation). According to Underwood et al. (2011), anticipatory skills regarding how a situation might develop correspond to the third level of SA (projection of future status); HP tasks should ideally test skills at this level. In HP tests, drivers usually view a set of short videos showing traffic scenes and are asked to press a response button as soon as driver reactions such as braking or steering are required to avoid a collision. Reaction times and number of reactions in each video are usually recorded (for an overview see Horswill & McKenna, 2004).

Although several studies suggest that experienced drivers respond faster in HP tests (Horswill et al., 2008; McKenna & Crick, 1994; Sexton, 2000; Wallis & Horswill, 2007; Wetton et al., 2010), the empirical evidence is not consistent. Other studies found no differences between experienced and novice drivers in response latencies (Borowsky, Shinar, & Oron-Gilad, 2007; Chapman & Underwood, 1998; Crundall, Underwood, & Chapman, 2002; Crundall, Chapman, Phelps, & Underwood, 2003; Sagberg & Bjørnskau, 2006). Several explanations for the contradictory findings have been put forward. Horswill et al. (2008) questioned the validity of HP tests that failed to discriminate between novice and experienced drivers. Borowsky, Oron-Gilad, and Parmet (2009) argued that the conflicting empirical evidence might also result from differences in how hazard is operationalized, the instructions for the participants, and the definition of novice drivers. Additionally, Underwood et al. (2011) pointed out that the inconsistent results might stem from the nature of the hazards presented in the tests. The authors stated that some hazards directly capture the driver's attention. In such instances, novice and experienced drivers will most likely react similarly. If hazards develop gradually though, the skill of anticipation, which is learned through driving experience, is needed. Therefore, according to Underwood et al. (2011), the types of hazards selected for inclusion might be the reason why experience-related effects have not been observed in some studies.

Based on the assumption that HP skills are acquired through driving experience, several training approaches have been studied. Positive effects of training intended to increase hazard perception skills were reported by McKenna and Crick (1994) and Sexton (2000). McKenna, Horswill, and Alexander (2006) showed that anticipatory skills can be trained with short video-based interventions. An effect of computer-based training on the glancing behavior of learner drivers was reported by Petzoldt, Weiß, Franke, Krems, and Bannert (2013). Horswill, Taylor, Newnam, Wetton, and Hill (2013) reported that even highly experienced drivers can enhance their HP performance through a 20-minute video-based training.

The presented research on HP provides a foundation for the examination of whether BEV experience has an impact on the anticipation and detection of critical noise-related situations. The findings therefore serve as a theoretical and methodological framework for the present study's research objectives, which are described below.

3 Research objectives

Utilizing the hazard perception approach (for an overview see Horswill & McKenna, 2004), we studied (1) when drivers with different levels of BEV experience detect noise-related hazards. As mentioned above, some studies found that experienced drivers perform better on HP tests (Horswill et al., 2008; McKenna & Crick, 1994; Sexton, 2000; Wallis & Horswill, 2007; Wetton et al., 2010), while other studies did not find this effect (Borowsky, Shinar, & Oron-Gilad, 2007; Chapman & Underwood, 1998, Crundall et al., 2002; Crundall et al., 2003; Sagberg & Bjørnskau, 2006). Similar to other HP tasks, a reaction in our experiments is operationalized as a button press. In a German field study on BEVs (Cocron, Bühler, Franke, et al., 2011), drivers reported that they particularly learned to pay attention to VRUs. We argue that this experience should affect hazard perception, as it relates to drivers' ability to anticipate dangerous situations due to low vehicle noise. Therefore, we predict that this ability would be reflected in hazard detection performance tasks. This led to the following hypotheses:

H1.1 Experienced BEV drivers react more often in noise-related situations than novice BEV drivers (*reaction frequency = RF*).

H1.2: Experienced BEV drivers react faster in noise-related situations than novice BEV drivers (*reaction time = RT*).

When assessing drivers before driving a BEV for the first time and after three months, Cocron, Bühler, Franke, et al. (2011) found a decrease in noise-related concerns. We aimed to investigate (2) the evaluation of noise-related incidents under more controlled conditions and hypothesized the following regarding hazard evaluation:

H1.3: Experienced BEV drivers evaluate noise related situations as less hazardous than novice BEV drivers *(hazard evaluation = HAZ*).

Previous research has shown that performance on HP tests can be affected by training (McKenna et al., 2006; Horswill et al., 2013). Consequently, we further investigated in the second study (3) if prior sensitization to the low noise emission of BEVs has an effect on the reactions and evaluations of the drivers. Even if our implemented sensitization is not equivalent to a full HP training, we predicted the following effects in study 2.

H2.1 Experienced BEV drivers and participants with prior sensitization react more often in a hazard detection task than a control group (*RF*).

H2.2 Experienced BEV drivers and participants with prior sensitization react faster in a hazard detection task than a control group (*RT*).

H2.3 Experienced BEV drivers evaluate noise-related situations as less hazardous than both participants with prior sensitization and participants in a control group (*HAZ*).

Finally, as shown in German field studies on BEVs (Cocron, Bühler, Franke, et al., 2011; Cocron & Krems, 2013), drivers adjust their evaluation of low noise emission as soon as they gain experience driving such vehicles. After driving BEVs for an extended period of time, low noise is seen more as a comfort feature than a safety threat. In study 2, we wanted to investigate if this effect occurs after a short test drive in urban traffic.

H3.1 Even after briefly testing a BEV in urban traffic, participants in both the sensitized group and the control group regard low noise more as a comfort feature than as a safety threat.

To answer these hypotheses, we developed a noise-specific hazard detection task and tested drivers with differing levels of BEV experience. Both studies were nested in an international series of large-scale field trials on BEVs (Vilimek, Keinath, & Schwalm, 2012). The studies reported here were both conducted in Germany as part of the *MINI E Berlin* field trials investigating suitability for daily use and acceptance of BEVs (Krems, Weinmann, Weber, Westermann, & Albayrak, 2013; Krems et al., 2011). A more detailed account of the methodology of the *MINI E* field trials can be found elsewhere (Cocron, Bühler, Neumann, et al., 2011; Franke, Bühler, Cocron, Neumann, & Krems, 2012).

4 Study 1

4.1 Methods

4.1.1 Participants

The hazard detection performance of two groups with differing levels of BEV experience was assessed in study 1. For this purpose, participants from two BEV field studies were tested. Participants from the second usage period of the first *MINI E Berlin* field study (Krems et al., 2013) represented the group of drivers with extended BEV experience. For a period of six months, 40 drivers drove a standard MINI Cooper which was converted to a battery-powered vehicle and called MINI E. Due to technical difficulties and one dropout, data from only 35 participants (30 male, 5 female) could be used for the current analyses. These participants were an average 49 years (*SD* = 9.78) old. In the preceding year, 66 percent of the participants had driven 15,000 km (~9,300 miles) or more; the other participants drove less. The sample was selected from a pool of 498 applicants based on criteria such as current residence in the Berlin metropolitan area. Further details on the selection process are reported by Bühler et al. (2010) and Neumann, Cocron, Franke, and Krems (2010). The present quasi-experiment was conducted when the participants returned their vehicle after six months. By that time, drivers had gained considerable experience driving a BEV in everyday traffic, *M* = 4366 km (*SD* = 1819). In later sections of this paper, this group is labeled as *Experienced 1.0*.

The second group of participants was drawn from the second MINI E field trial in Berlin (*MINI E Berlin V2.0*, Krems et al., 2011). This group was comprised of drivers who had been selected for the second MINI E study but had not driven the test vehicle yet. In this study, 30 participants (26 males, 4 females) were selected from a pool of 1867 applicants. The selection criteria were comparable to the first MINI E trial. The test drivers were on average 46 years (*SD* = 11.69) old. Twenty percent had once tried a BEV, 37 percent had once tried a HEV before. In the preceding year, 47 percent of the participants had driven at least 15,000 km (~9,300 miles) with an ICE vehicle; the other participants drove less. This second group of participants will be labeled as *Inexperienced 2.0*.

4.1.2 Materials

During the course of the aforementioned first field study (i.e., *MINI E Berlin*), a catalogue of noise-related incidents was compiled based on driver-report (Cocron & Krems, 2013). This catalogue and the critical maneuvers identified by Hanna (2009) provided the empirical basis for the creation of video sequences which displayed noise-related incidents of differing criticality. In these staged videos, potential conflicts between a BEV driver and vulnerable road users such as pedestrians and bicyclists were shown from the driver’s perspective. In total 11 video scenarios were created by staging potential conflicts between a BEV and other road users. More details on the creation of the scenarios can be found in Bachl (2012). Together, the scenarios constitute set 1. An overview of the scenarios in set 1 is displayed in Table 1.

Each scenario lasted between 10 and 15 seconds. In the critical scenarios, the onset of the critical event varied across the scenarios. Additionally, we included scenarios in the task which were not related to BEV noise. One scenario (scenario #1) was integrated to familiarize the participants with the task, two other scenarios served as distractors (scenario #4, scenario #5). These scenarios were not incorporated in the analysis. Each critical scenario had an uncritical equivalent, however, scenario #3 was excluded as some participants misinterpreted the scene. In each scenario the BEV approached from behind. In the critical scenarios, the affected road users started to cross the BEV's path, e.g., without a shoulder check. In the uncritical scenarios, the affected road users showed no such hazardous maneuvers. All scenarios were presented on a laptop using the software E-Prime 2.0 (Psychology Software Tools, Pittsburgh, PA); an overview of the presented scenarios is displayed in table 1.

Table 1 Categorization of noise related scenarios (set 1)

Affected road users	Description	Criticality	
		critical	not critical
Pedestrians	Pedestrians walking at the road side.	Scenario #2	Scenario #3*
Jogger	Jogger running on the street.	Scenario #6	Scenario #7
Bicyclist (side street)	Bicyclist turning on a side street.	Scenario #8	Scenario #9
Bicyclist (major street)	Bicyclist riding on bike path.	Scenario #10	Scenario #11

Note: * = scene is not part of the analysis

Figure 1 Study 1: Illustration of scenario 8 (without hand signal) and 9 (with hand signal)

4.1.3 Design and procedure

The quasi-experiment featured a 2 x 2 mixed design with group (inexperienced vs. experienced) as a between-subjects factor and criticality (not critical vs. critical) as a within-subjects factor. Dependent variables were the reaction frequency (*RF*), the reaction time (*RT*) and, adapted from Groeger and Chapman (1996), the evaluation of the scenario's hazard potential on a 7-point Likert Scale (*HAZ*, *1 = not dangerous – 7 = extremely dangerous*). All participants were informed that they were about to see a set of videos depicting urban traffic and were asked to imagine that they were driving the test BEV. The experimenter informed the participants that some of the scenes contained critical situations in which a conflict with other road users would occur. Participants were asked to press a response key if they perceived that they needed to react in order to avoid a collision. Participants were also informed that the task was not to respond as quickly as possible, but to react as realistically as possible (i.e., as they would act under normal driving conditions). This instruction was given to discourage participants from pressing the button as fast as possible without evaluating whether a hazard occurred or not. If the participant hit the response key, the scenario was stopped and then the participant had to rate the degree of hazard in the scenario (*HAZ*). If drivers did not press the response key at all, the scenario was played until the end and participants rated the level of hazard afterwards. After the practice trial (scenario #1), the ten scenes shown above were presented to the participants in a randomized order. *HAZ, RF* and *RT* were recorded via E-Prime 2.0.

Similar to Sagberg and Bjørnskau (2006), *RT* data were preprocessed for further analysis. First, if participants did not react in a critical scenario, the missing *RT* for those participants was replaced with the total duration of the scenario. This was only done for the critical scenarios, as those required reactions by the participants. If technical problems occurred or participants did not react because they misunderstood the task, *R* and *RT* data from such scenes were excluded from further analysis. Second, as the onset of the critical event varied between scenes, the *RTs* were transformed to *z*-scores and then averaged across situations. The resulting mean *RT* scores met the assumptions for parametric tests. Effect sizes were calculated with G-Power (Faul, Erdfelder, Lang, & Buchner, 2007) and interpreted according to Cohen (1992).

4.2 Results

As mentioned above, we expected that drivers with BEV experience would react more often (H1.1) and faster (H1.2) to noise-related situations. Furthermore, we predicted that drivers with BEV experience would evaluate noise-related situations as less hazardous (H1.3). The results of study 1 are presented below. Even though some data did not meet the requirements for parametric tests, we still used ANOVA as it is reported to be robust to violations of the normality assumption (Schmider, Ziegler, Danay, Beyer, & Bühner, 2010).

4.2.1 Reaction frequencies (*RF*)

A mixed ANOVA with *RF* as the dependent variable revealed a significant main effect of the criticality factor, $F(1, 59) = 145.54$, $p < .001$, $\eta^2_p = .71$. Table 2 shows that participants from both groups reacted more often in critical scenarios than in non-critical scenarios. These findings indicate that the criticality of the scenarios was apparent to the participants. Still, neither a significant main effect of group, $F(1, 59) = 0.53$, $p = .468$, $\eta^2_p = .01$, nor an interaction effect of criticality and group was observed, $F(1, 59) = 0.02$, $p = .895$, $\eta^2_p = .00$. Hence, although small trends in the expected direction can be seen in Table 2, our first hypothesis H1.1 must be rejected.

Table 2 Study 1: Reaction frequencies of participants to noise-related scenarios (set 1)

	Non-critical scenarios		Critical scenarios	
	Mean	*SD*	*Mean*	*SD*
Experienced 1.0	39.05	37.47	96.43	8.88
Inexperienced 2.0	33.33	35.14	93.52	14.86

Note:
Percentages of reacting participants are displayed.
Non-critical scenarios: N_{Exp} = 35, N_{Inexp} = 28
Critical scenarios: N_{Exp} = 35, N_{Inexp} = 27

4.2.2 Reaction times (*RT*)

Comparisons of *RT* were only conducted for the critical scenarios, since no responses were necessary in non-critical scenarios, and therefore, the response rates were generally low. As mentioned above, *RT* raw data were *z*-transformed and then averaged across critical scenarios. The resulting scores revealed no significant differences in *RTs* between experienced BEV drivers (N = 35) and novice BEV drivers (N = 26), $t(59) = -0.54$, $p = .295$; according to Cohen (1992) only a very small effect was observed, $d = 0.14$. On average, experienced BEV drivers tended to react slightly faster than inexperienced BEV drivers ($M_{Exp1.0} = -0.04$, $SD_{Exp1.0} = 0.64$; $M_{Inexp2.0} = 0.06$, $SD_{Inexp2.0} = 0.73$) in critical noise-related scenarios. Based on these data, hypothesis H1.2 must be rejected, despite the observation of a very small effect.

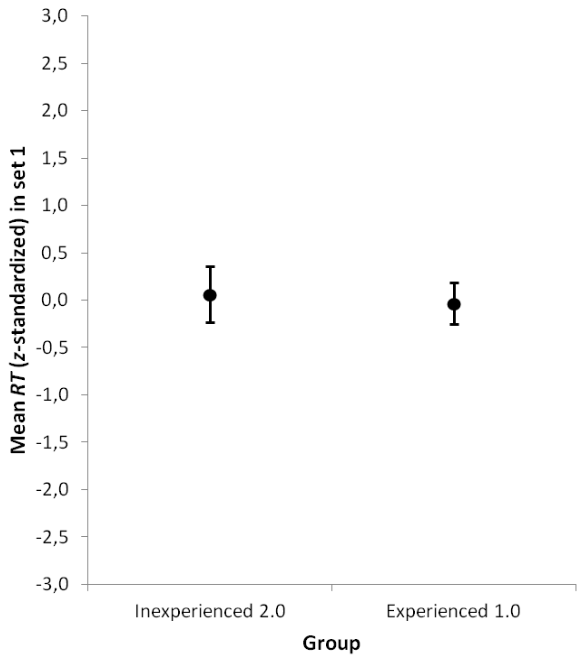

Figure 2 Study 1: Mean *RT* in critical scenarios (error bars represent 95% CI)

4.2.3 Hazard evaluation (*HAZ*)

A mixed ANOVA with hazard evaluation (*HAZ*) as the dependent variable revealed a significant main effect of criticality, $F(1, 59) = 196.82$, $p < .001$, $\eta^2_p = .77$. Participants in both groups rated the hazards depicted in the critical scenarios higher than the hazards depicted in non-critical scenarios (Table 2). As for the analysis of *RF*, neither a significant main effect for group, $F(1, 59) = 0.49$, $p = .488$, $\eta^2_p = .01$, nor a significant interaction effect (*group x criticality*) was observed, $F(1, 59) = 0.20$, $p = .654$, $\eta^2_p = .00$. When directly comparing the evaluation of critical scenarios, only a small, non-significant effect in the expected direction was observed ($p = .198$, one-tailed, $d = 0.22$). H1.3 must be rejected.

Table 3 Study 1: Hazard ratings (*HAZ*) of noise-related scenarios

	Non-critical scenarios		Critical scenarios	
	Mean	*SD*	*Mean*	*SD*
Experienced 1.0	2.30	1.23	4.59	1.00
Inexperienced 2.0	2.32	1.03	4.83	1.20

Note:
Hazard evaluation: *1(not dangerous) – 7(extremely dangerous)*
Non-critical scenarios: N_{Exp} = 35, N_{Inexp} = 28
Critical scenarios: N_{Exp} = 35, N_{Inexp} = 26

4.3 Discussion

The objective of Study 1 was to investigate whether experienced BEV drivers reacted more frequently (H1.1) and faster (H1.2) in noise-related scenarios than novice BEV drivers. Furthermore, we hypothesized that experienced BEV drivers evaluated such scenarios as less dangerous (H1.3). The findings of Study 1 revealed that although the criticality of the scenarios had an impact on the behavior and hazard evaluation of the participants, the level of experience did not have a significant effect. No group differences were observed in participants' tendency to respond in noise-related scenarios of varying criticality. This means that both groups interpreted both types of situations similarly and reacted accordingly. Regarding the subjective evaluation of hazard, similar results were observed. Criticality had an impact on participants' subjective evaluation, but BEV experience did not play a significant role. Although a small effect of group was observed in the evaluation of hazard, an interpretation that BEV experience significantly influences driver evaluation of noise-related situations was not supported.

Other studies with BEV drivers revealed that the perceived risk related to low noise decreases as experience increases (Cocron, Bühler, Franke, et al., 2011; Cocron & Krems, 2013). Regarding evaluation of hazard in specific scenarios, such an experience effect was not detected. A possible cause for this discrepancy might be the fact that drivers in other studies (Cocron, Bühler, Franke, et al., 2011; Cocron & Krems, 2013) evaluated the noise issue on a global level, whereas in the current study, noise was evaluated within the context of specific situations.

The analysis of response latency (*RT*) in critical scenarios also revealed no significant differences between groups. Both groups reacted equally fast in critical situations. This finding is consistent with previous studies which revealed no difference between experienced and novice drivers in HP performance (Borowsky et al., 2007; Chapman & Underwood, 1998; Crundall et al., 2002; Crundall et al., 2003; Sagberg & Bjørnskau, 2006).

Two features of the Study 1 methodology might have affected the findings. First, the tested situations might have been too obvious for the participants. This has also been discussed for conventional HP tests (Underwood et al., 2011). In reality, noise-related situations might be more complex and difficult to predict. In more complex noise-related situations, BEV experience might still make a difference. Second, although the participants in Study 1 differed in BEV experience, other characteristics of our groups might have played a role, too. In conventional HP tests, inexperienced drivers are typically compared to more experienced drivers, whereas in our study, both groups were similar on a variety of demographic characteristics, including age, gender and driven kilometers with ICE vehicles. One could argue that relevant knowledge and skills obtained driving ICE vehicles are transferable to BEVs and utilized to manage potential hazards associated with low vehicle noise.

5 Study 2

Study 2 was integrated into the project *MINI E Berlin V2.0* (Krems et al., 2011). Within this project, a field study was conducted in the Berlin metropolitan area and specific driving tests were carried out in Chemnitz. Study 2 investigated research objectives that are similar to Study 1, but additionally examined whether specific sensitization to low noise emission has an effect on driver reactions and evaluation of hazard (H2.1-2.3). Furthermore, in Study 2, we examined whether general evaluation of low noise emission changes after only one short test drive (H3.1). To address these objectives, a set of new scenarios (set 2) was included in the task and the effect of sensitization was examined.

5.1 Methods

5.1.1 Participants

In Study 2, participants were recruited from two cities. The first group of participants took part in the second MINI E field trial, *MINI E Berlin V2.0* (Krems et al., 2011). These participants were already assessed before they received their vehicles in Study 1 (as *Inexperienced 2.0*). For Study 2, these participants were assessed again after they gained experience driving a BEV for three months. Thus, the Berlin sample was familiar with set 1, but did not have exposure to set 2. Therefore, comparisons with other groups are mainly based on the new set 2 scenarios. Set 1 is only used for validation. The hazard detection task was incorporated into the midterm interview. At that time, participants had gained considerable BEV experience (*M* = 1563 km, *SD* = 928 km). These participants are labeled as *Experienced 2.0*.

The other groups of participants were recruited in Chemnitz as part of the *MINI E Berlin V2.0 test series* (Krems et al., 2011; Früh & Koch, 2011). More than 300 people applied to be part of the study. When signing up for the study, the participants were told that the study examined driver acceptance of BEVs and BEV-specific features. The selected sample was comprised of 29 participants (22 males, 7 females) with an average age of 39 years *(SD* = 12.73). Forty percent of these participants drove 15,000 km or more in the preceding year. The Chemnitz sample had no prior experience with BEVs, two participants had tested a HEV once. The group from Chemnitz was divided into two subgroups, neither of which differed significantly by age, sex or driven km during the previous year: a control group which did not receive any additional information (*Control 2.0*) and a group which was shown videos of approaching vehicles with differing sound emission (*Hearing 2.0*).

5.1.2 Materials

In Study 2, participants completed a questionnaire before and after driving the BEV. Drivers' evaluation of BEV noise was assessed with a rating scale created by Cocron and Krems (2013). The questionnaire included the subscales *Comfort* and *Safety Concerns* which were rated on a six point Likert scale (*1 = strongly disagree – 6 = strongly agree*). As in Study 1, videos of noise-related scenarios were shown to the participants. The hazard detection task in Study 2 was comprised of two sets of videos. Set 1 consisted of the same scenarios presented in Study 1. Additionally, new scenarios were created (set 2) to include more potential interactions with pedestrians in the task. Similarly to set 1, the videos in set 2 were shot from the driver perspective and depicted potential conflicts between a BEV and other road users. Each scenario lasted between 8 and 16 seconds, the onset of the critical event varied across the scenarios. In total, 17 scenarios were used for the analysis; 7 were part of set 1 and 10 were part of set 2. The scenarios were presented using the software E-Prime 2.0.

Table 4 Categorization of noise-related scenarios (set 2)

Affected road user	Description	Criticality	
		critical	not critical
Pedestrian	Pedestrian about to cross a side street.	Scenario #12	Scenario #13
	Pedestrian pushing a bike about to cross a street.	Scenario #14	Scenario #15
	Pedestrian appearing between parked cars.	Scenario #16	Scenario #17
	Pedestrian in a parking lot.	Scenario #18	Scenario #19
	Pedestrian unlocking car.	–	Scenario #21
Bicyclist	Bicyclist riding on the road.	–	Scenario #23

5.1.3 Design and procedure

Study 2 featured a 3 x 2 mixed design with group (*Experienced 2.0, Hearing 2.0, Control 2.0*) as a between-subjects variable and criticality (*critical vs. uncritical*) as a within-subjects variable. As in Study 1, dependent variables included reaction frequency (*RF*), reaction time (*RT*) and subjective rating of hazard (*HAZ*). Furthermore, *Comfort* and *Safety Concerns* were assessed prior to driving the BEV for the first time and immediately after the test-driving period. As mentioned above, the Berlin sample (*Experienced 2.0*) was tested after three months of BEV experience; *Hearing 2.0* and *Control 2.0* were tested after a test drive of 7.3 km through the city of Chemnitz. *Hearing 2.0* was sensitized to low noise emission prior to testing the BEV. Participants were shown videos of the test vehicle MINI E and a conventional MINI Cooper which passed by at 10 km/h, 15 km/h and 30 km/h. After each video, participants in the *Hearing 2.0* group were instructed to indicate on a semantic differential scale whether the car was *very easy (1)* or *very hard (10) to hear*. This item served as a manipulation check. The *Control 2.0* group completed the test drive, but did not receive any additional information. After finishing the test drive, the participants completed the hazard detection task on a computer. Upon completion of the hazard detection task, all participants were debriefed. As in Study 1, the data was recorded via E-Prime 2.0. Data was preprocessed and analyzed using procedures similar to those used in Study 1.

5.2 Results

As in Study 1, parametric tests were primarily utilized in Study 2. Data was preprocessed similarly to Study 1. Participants in the *Experienced 2.0* group already participated in Study 1 (as *Inexperienced 2.0)* and therefore had previous exposure to the set 1 scenarios. Thus, scenarios from both sets are analyzed separately. Set 2 is used for group comparisons; set 1 is used solely for validation. Before running the analyses, a manipulation check was conducted for *Hearing 2.0*. It revealed a significant main effect of vehicle type (MINI E vs. MINI Cooper), $F(1, 14) = 87.71$, $p < .001$, $\eta^2_p = .86$. Participants rated the conventional MINI Cooper as significantly more audible. Furthermore, participants' ratings also significantly depended on speed (10km/h, 15 km/h, 30 km/h), $F(1.43, 20.02) = 30.79$, $p < .001$, $\eta^2_p = .69$. Participants rated cars traveling at lower speeds as more difficult to hear. No significant interaction between vehicle type and approach speed was detected, $F(2, 28) = 2.53$, $p = .098$, $\eta^2_p = .15$. Due to the observed main effect of vehicle type, data from all participants ($N = 15$) in the *Hearing 2.0* group were used for the analyses.

5.2.1 Reaction frequency (*RF*)

Similar to Study 1, a mixed ANOVA using set 2 scenarios with reaction frequency (*RF*) as the dependent variable revealed a significant main effect of criticality, $F(1, 53) = 410.50$, $p < .001$, $\eta^2_p = .89$. Participants from all groups reacted more often to the critical scenes than the non-critical scenarios. Comparable to Study 1, neither a main effect for group, $F(2, 53) = 0.42$, $p = .658$, $\eta^2_p = .02$ nor for the interaction (group x criticality) occurred, $F(2, 53) = 0.76$, $p = .473$, $\eta^2_p = .03$. In set 2, Gabriel's post hoc tests revealed no significant differences between *Experienced 2.0* and *Control 2.0* ($p = .736$) or between *Hearing 2.0* and *Control 2.0* ($p = .972$). Similar results were detected in set 1. Criticality had an effect on reaction frequency, $F(1, 51) = 167.75$, $p < .001$, $\eta^2_p = .78$. No effect for group, $F(2, 51) = 1.72$, $p = .189$, $\eta^2_p = .06$ or the interaction (group x criticality) was detected, $F(2, 51) = 1.13$, $p = .331$, $\eta^2_p = .04$. Gabriel's post hoc tests revealed no significant differences between *Experienced 2.0* and *Control 2.0* ($p = .180$) or between *Hearing 2.0* and *Control 2.0* ($p = .587$). Neither experience, nor sensitization had a significant influence on reaction frequency; therefore H2.1 must be rejected. *RFs* are presented in table 5.

Table 5 Study 2: Reaction frequencies (*RF*) of participants in noise-related scenarios (percentage)

	Set 1				Set 2			
	Non-critical scenarios		Critical scenarios		Non-critical scenarios		Critical scenarios	
	Mean	*SD*	*Mean*	*SD*	*Mean*	*SD*	*Mean*	*SD*
Experienced 2.0	35.63	37.72	93.97	12.77	23.56	23.79	95.69	9.61
Hearing 2.0	25.00	37.94	97.92	7.22	19.23	19.06	95.51	11.08
Control 2.0	15.38	29.24	89.29	21.29	22.62	24.11	87.50	27.30

Note:
Percentages of reacting participants are displayed.
Set 1: Non-critical scenarios: $N_{Experienced2.0}$ = 29, $N_{Hearing2.0}$ = 12, $N_{Control2.0}$ = 13
Critical scenarios: $N_{Experienced2.0}$ = 29, $N_{Hearing2.0}$ = 12, $N_{Control2.0}$ = 14
Set 2: Non-critical scenarios: $N_{Experienced2.0}$ = 29, $N_{Hearing2.0}$ = 13, $N_{Control2.0}$ = 14
Critical scenarios: $N_{Experienced2.0}$ = 29, $N_{Hearing2.0}$ = 13, $N_{Control2.0}$ = 14

5.2.2 Reaction times (*RT*)

Similar to Study 1, only *RT* data from the critical scenarios were analyzed in Study 2. *RT* raw scores were also *z*-transformed and averaged across scenarios for both sets. In set 2, one outlier was excluded (mean *z*-score = -2.88). Similar to Study 1, a one-way ANOVA with *RT* as the dependent variable revealed no significant differences between groups in set 2, $F(2, 52) = 0.99$, $p = .375$, $\eta^2_p = .04$. In Figure 2, the *RTs* of the *Experienced 2.0* group demonstrate only marginally shorter response latencies than the other groups. Gabriel's post hoc tests revealed no significant difference between *Control 2.0* and *Hearing 2.0* ($p = .740$), *Control 2.0* and *Experienced 2.0* ($p = .396$), or between *Hearing 2.0* and *Experienced 2.0* ($p = .981$). The *RTs* of set 2 are depicted in Figure 3.

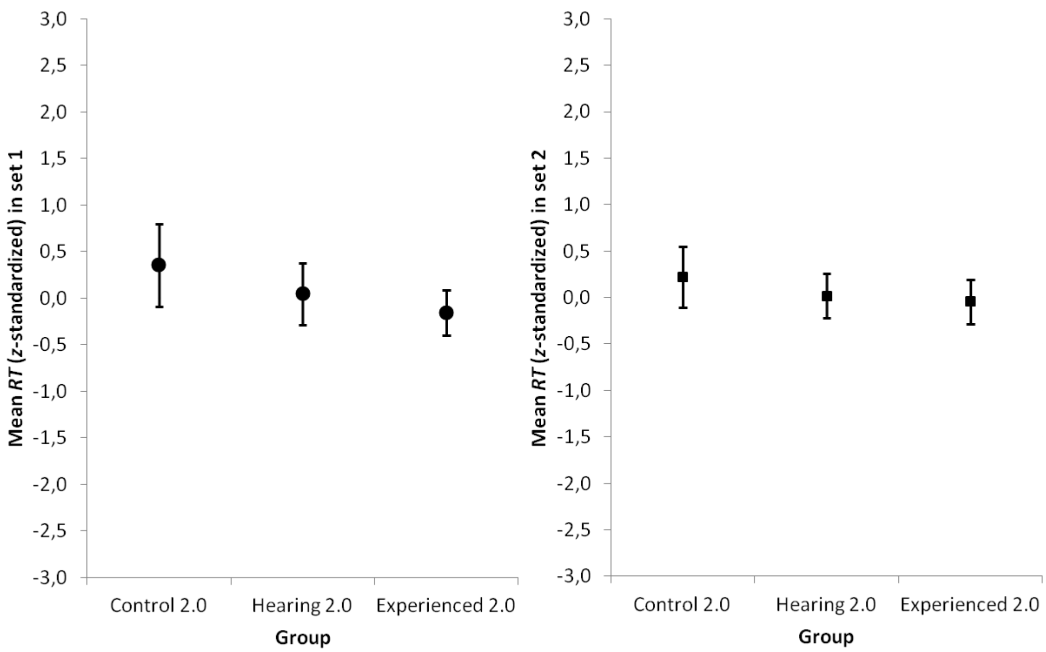

Figure 3 Study 2: Mean *RTs* in set 1 and set 2 (error bars represent 95% CI)

As mentioned above, *Experienced 2.0* was previously tested using set 1; therefore, *RTs* from set 1 only served as a validation of set 2. The results from set 1 are similar to set 2. No significant effect of group could be detected, $F(2, 52) = 2.87$, $p = .065$, $\eta^2_p = .10$. Gabriel's post hoc tests revealed no significant group difference between *Control 2.0* and *Hearing 2.0* ($p = .549$) or *Hearing 2.0* and *Experienced 2.0* ($p = .739$). Only the comparison between *Control 2.0* and *Experienced 2.0* approached significance ($p = .054$). The *RTs* from set 1 are also shown in Figure 3. Although trends towards shorter response latencies were observed for *Experienced 2.0* and *Hearing 2.0,* response latencies for both groups did not differ significantly from *Control 2.0*. Therefore, H2.2 must be rejected.

5.2.3 Hazard evaluation (*HAZ*)

In addition to responding to hazards in the scenarios, participants were also instructed to rate each scene in terms of its hazardous potential (*HAZ*). As before, each set was analyzed separately. In set 2, participants' hazard evaluations successfully distinguished between of critical and non-critical scenarios, $F(1, 53) = 106.88$, $p < .001$, $\eta^2_p = .67$. All groups evaluated critical scenarios in set 2 as more hazardous than non-critical scenarios. Again, a main effect of group was not observed, $F(2, 53) = 0.65$, $p = .528$, $\eta^2_p = .02$. Gabriel's post hoc test revealed no differences between *Control 2.0* and *Hearing 2.0* ($p = .628$), *Control 2.0* and *Experienced 2.0* ($p = .738$) or *Hearing 2.0* and *Experienced 2.0* ($p = .975$).

Still, a significant interaction between group and criticality was revealed, *F*(2, 53) = 3.46, *p* = .039, η^2_p = .12. Depending on criticality, groups rated the degree of hazard differently in set 2. Although all groups rated the hazards in non-critical scenarios as low, they differed in their ratings of critical scenarios. *Experienced 2.0* rated hazards in critical scenarios significantly lower than *Control 2.0* (*p* = .048, one-tailed) with a medium effect (*d* = 0.56). This partially supports H2.3. In addition, *Hearing 2.0* rated the hazards in critical scenarios lower than *Control 2.0,* although this difference did not reach significance (*p* = .064, one-tailed). This finding contradicts our assumed sensitization effect. Moreover, the hazard evaluations of *Experienced 2.0* and *Hearing 2.0* in critical scenarios of set 2 did not differ significantly from each other (*p* = .734), which also contradicts the sensitization effect.

Similar to set 2, the analysis of set 1 showed a significant effect of criticality, *F*(1, 51) = 96.36, *p* < .001, η^2_p=.65. Critical scenarios were rated as more hazardous. In set 1, there was no significant effect for group, *F*(2, 51) = 0.76, *p* = .475, η^2_p=.03 or the interaction (group x criticality), *F*(2, 51) = 2.16, *p* = .126, η^2_p=.08. Although the effects on hazard evaluation are similar in set 1, no significant interaction was observed. Therefore H2.3 is only partially supported insofar as the control group rated the critical scenarios of set 2 as more hazardous than the experienced group. With regard to sensitization, H2.3 must be rejected. All hazard evaluations are shown in table 6.

Table 6 Study 2: Hazard ratings (*HAZ*) of noise related scenes

	Set 1				Set 2			
	Non-critical scenarios		Critical scenarios		Non-critical scenarios		Critical scenarios	
	Mean	*SD*	*Mean*	*SD*	*Mean*	*SD*	*Mean*	*SD*
Experienced 2.0	2.25	0.77	3.72	1.35	1.78	0.62	3.11	1.23
Hearing 2.0	1.78	1.09	3.40	1.51	1.72	0.95	2.96	1.52
Control 2.0	1.74	0.65	4.06	1.25	1.62	0.45	3.79	1.21

Note:

Hazard ratings (*HAZ*): 1 (*not dangerous*) – 7 (*extremely dangerous*)

5.2.4 General evaluation of BEV noise

Before and after test-driving the BEV, participants from the Chemnitz sample were also asked to generally evaluate the noise emission of BEVs. Results regarding the general evaluation of noise emission obtained in the Berlin sample were already reported in Cocron and Krems (2013). Here, data from the Berlin sample was included as a reference to address H3.1, which stated that even after one short test drive, participants will evaluate low noise emission in BEVs more as a comfort feature than as a safety threat. The scale used to assess vehicle acoustics contained two subscales, *Safety Concerns* and *Comfort*.

A mixed ANOVA with group as the between-subjects factor and time as the within-subjects factor revealed a significant main effect of time on *Safety Concerns*, $F(1, 55) = 22.43$, $p < .001$, $\eta^2_p = .29$, but neither a main effect of group $F(2, 55) = 0.57$, $p = .571$, $\eta^2_p = .02$, nor an interaction between both factors, $F(2, 55) = 0.56$, $p = .578$, $\eta^2_p = .02$, was observed. Gabriel’s post hoc tests did not reveal significant differences between *Experienced 2.0* and *Control 2.0* ($p > .999$), *Experienced 2.0* and *Hearing 2.0* ($p = .667$), or *Hearing 2.0* and *Control 2.0* ($p = .789$). When assessed after the test period, all groups rated their safety concerns related to noise emission similarly. Compared to participants' assessments prior to driving the BEV for the first time, safety concerns were rated lower after gaining BEV experience.

As expected, an opposing trend was detected when examining *Comfort* with a mixed ANOVA. Again, the analysis revealed a significant main effect of time, $F(1, 55) = 21.10$, $p < .001$, $\eta^2_p = .28$, but neither the main effect of group $F(2, 55) = 2.84$, $p = .067$, $\eta^2_p = .09$, nor the interaction between both factors, $F(2, 55) = 1.64$, $p = .204$, $\eta^2_p = .06$, was significant. Gabriel's post hoc tests revealed no significant differences between *Experienced 2.0* and *Control 2.0* ($p = .176$), *Experienced 2.0* and *Hearing 2.0* ($p = .130$), or *Hearing 2.0* and *Control 2.0 ($p > .999$)*. All groups rated comfort resulting from low noise emission higher after driving the BEV than before driving the vehicle.

Thus, H3.1 is confirmed. It can be concluded that even after a brief test drive of 7.3 km, the drivers adjusted their evaluation of the BEV's low noise. That is, the BEVs low noise emission was regarded more as a feature that contributes to comfort than one that endangers other road users. Descriptive statistics are provided in Table 7. The results of drivers' evaluation of vehicle acoustics are displayed in Figure 4.

Table 7 Study: 2 Descriptive statistics of the driver evaluation of BEV noise

	Safety concerns				Comfort			
	T0 Before testing BEV		T1 After testing BEV		T0 Before testing BEV		T1 After testing BEV	
	Mean	*SD*	*Mean*	*SD*	*Mean*	*SD*	*Mean*	*SD*
(In)Experienced 2.0*	3.84	0.69	2.71	1.39	4.95	0.89	5.57	0.58
Hearing 2.0	3.87	0.93	3.18	0.82	4.57	1.08	4.80	0.92
Control 2.0	3.71	0.79	2.86	1.15	4.32	1.66	5.11	1.00

Note:
Evaluation of exterior BEV noise : 1 (*strongly disagree*) – 6 (*strongly agree*)
$N_{(In)Experienced\ 2.0} = 29$, $N_{Hearing2.0} = 15$, $N_{Control2.0} = 14$
*T1 = after testing BEV for three months

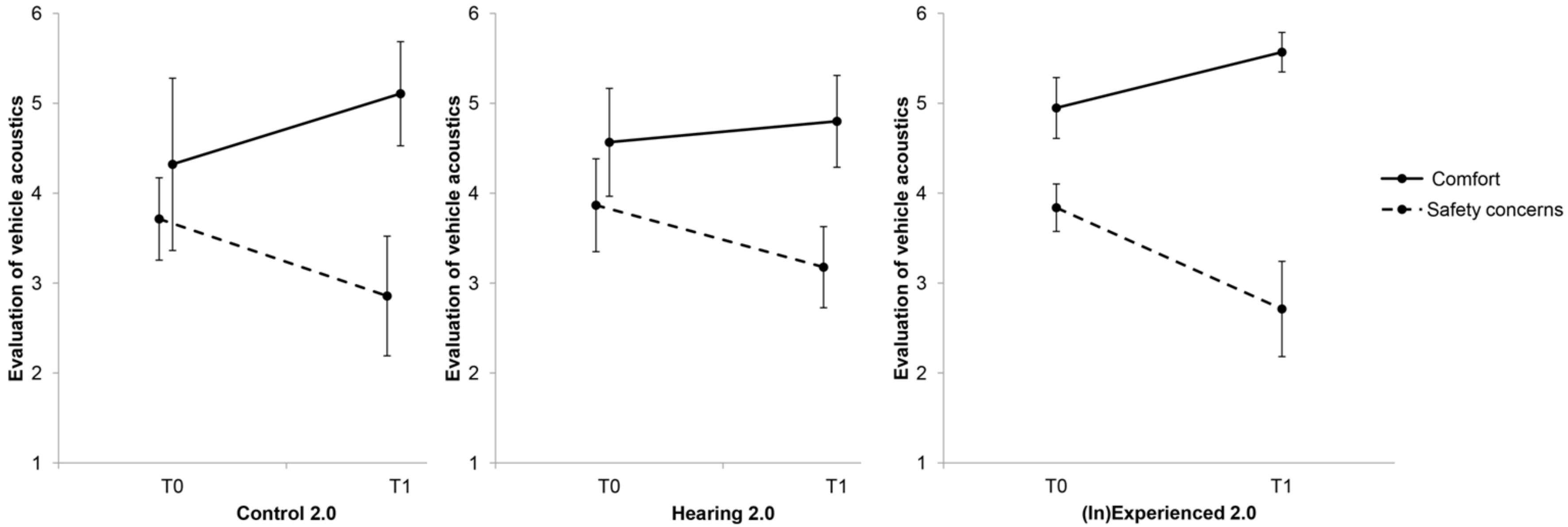

Figure 4 Study 2: Evaluation of BEV acoustics (Means, error bars represent 95% CI)

Note:
(In)Experienced 2.0: T1 = after three months
6-point Likert scale from 1 (*completely disagree*) to 6 (*completely agree*)

5.3 Discussion

The objective of Study 2 was to investigate whether BEV driving experience and specific sensitization to low vehicle noise had an impact on drivers' response to, and the evaluation of, noise-related situations. To test these assumptions, experienced BEV drivers, participants who were exposed to a sensitization procedure, and a control group without treatment were compared. We expected that experienced and sensitized drivers would react both more frequently (H2.1) and faster (H2.2) to our hazard detection task. Furthermore, we expected that experienced BEV drivers would rate noise-related incidents as less hazardous (H2.3) than the other groups.

Based on earlier studies of BEV drivers (Cocron, Bühler, Franke, et al., 2011), it was hypothesized that response sensitivity would increase as a result of BEV experience. Only trends for such an effect were found in Study 2. Drivers' responses to the critical scenarios revealed only a trend indicating that experienced and sensitized participants reacted more often than a control group. In non-critical scenarios, experienced BEV drivers also exhibited higher response rates. Still, H2.1 must be rejected, as no significant between-group differences in RFs emerged. The response rates further indicate that all drivers, regardless of group, similarly differentiated between critical and non-critical scenarios and reacted accordingly. In Study 2, drivers were presented with additional scenarios; nevertheless, results point in the same direction as Study 1. The tendency to react in noise-related situations seems to neither depend on BEV driving experience, nor on sensitization to low BEV vehicle noise.

In H2.2, we expected that drivers with BEV experience and sensitized participants would react faster than a control group to noise-related situations. Although small trends in the hypothesized direction were observed, this hypothesis had to be rejected. In both scenario sets, experienced BEV drivers exhibited the fastest response latencies, while the control group exhibited the slowest. For set 1, one could argue that the experienced group was familiar with the set, and therefore, performed slightly better than the other groups. A similar pattern occurred in the unknown set 2; therefore a practice effect seems to be an unlikely explanation for this finding. Similar to RFs, RTs were not enhanced through sensitization and do not seem to depend significantly on BEV driving experience. When considering these findings along with the results of previous reports of BEV drivers (Cocron, Bühler, Franke, et al., 2011), one could argue that BEV experience has no effect on the tendency to react and only a marginal effect on response latency in noise-related situations.

With respect to the evaluation of hazards (H2.3), it can be stated that sensitization did not have the expected effect on hazard evaluation. Indeed, data obtained from set 2 indicated that sensitized participants rated the hazard potential in critical scenarios lower than the control group. As a similar trend occurred in set 1, this might indicate that the sensitization procedure caused participants to rate critical scenarios as less hazardous. Thus, hearing an ICE and BEV approach at different speeds might therefore have led to desensitization. This is consistent with the change in hazard evaluations that was observed for drivers after they had gained BEV driving experience. The significant interaction in set 2 confirmed the hypothesized experience effect for critical scenarios. Experienced BEV drivers evaluated the critical scenarios as less hazardous than the control group. A possible explanation for this finding might be that such incidents are regarded as less dangerous as drivers repeatedly experience such incidents and learn how to handle even critical situations. This would support the adjustment of risk estimation discussed by Cocron, Bühler, Franke, et al. (2011) and Cocron and Krems (2013).

Regarding the final hypothesis in Study 2 (H3.1), it was expected, based on Cocron and Krems (2013), that even after briefly testing a BEV in urban traffic, drivers would regard the low noise more as a comfort feature than as a safety threat. The expected effect was observed even after one short test drive. Taken together with the findings reported by Cocron, Bühler, Franke, et al. (2011) as well as by Cocron and Krems (2013), drivers seem to adjust their evaluation of low noise emission in BEVs rapidly. Driving a BEV even for a short while resulted in an adjusted evaluation of exterior BEV noise, such that the perceived advantages quickly began to outweigh the disadvantages. Specifically, the low noise level was regarded more as an increase in comfort than as a decrease in traffic safety. A similar experience effect has also been reported with regard to BEV acceptance by Bühler, Cocron, Neumann, Franke, and Krems (in press).

6 General discussion and conclusion

In the present paper, we presented findings on hazard detection in driving scenarios that are potentially affected by the low noise emission of BEVs. With regard to the first objective of our paper (1) the findings suggest that BEV driving experience only played a minor role in noise-related hazard detection. The differences between groups, e.g. in response latencies, were very small. The criticality of the driving situations was more relevant for response frequency and latency. If one assumed that experienced drivers had prior exposure to such driving situations, and therefore, developed a thorough understanding of noise-related incidents, they could therefore serve as a reference for adequate responses in such situations. However, even without extensive prior BEV experience, drivers seem to be capable of responding adequately to noise-related driving situations.

There are several potential explanations for this finding. First and foremost, there is the question of whether our task was a valid and reliable assessment tool for noise-related hazard perception. As explained above, we created our scenarios based on empirical data regarding relevant situational characteristics reported by Hanna (2009) and Cocron and Krems (2013). As a consequence, the tested scenarios had an empirical basis, which supports the task's validity. To increase the reliability of our task, we increased the number of scenarios by incorporating a second set of scenarios. Other studies on HP have also found no substantial differences in reaction times between novice and experienced drivers of ICE vehicles (Borowsky et al., 2007; Chapman & Underwood, 1998; Crundall et al., 2002; Crundall et al., 2003; Sagberg & Bjørnskau, 2006). Sagberg and Bjørnskau (2006) argued that hazard perception might be only one among many factors which represent driving experience. This could also apply to our study. For instance, we used a hazard detection task, but other factors such as scanning patterns might play a more important role in how drivers respond to noise-related situations than recordable reactions. The importance of anticipation has also been suggested by McKenna and Crick (1994) and by Sagberg and Bjørnskau (2006).

In addition, the validity of previous HP tests which have failed to differentiate between novices and experts has been questioned (Horswill et al., 2008). This critique could also potentially apply to our hazard detection task; however, we propose alternative explanations. Although drivers who participated in our studies differed in their amount of BEV experience, they all had considerable driving experience with ICE vehicles and were similar in their demographic characteristics. One could therefore assume that drivers benefitted from their experience with ICE vehicles when completing the HP task. Thus, it is possible that noise-related hazards can be anticipated by experienced drivers, regardless of the type of vehicle with which they had previous experience. This notion is supported by the fact that the criticality of the scenarios had a much stronger influence on responses than group membership.

One could further note that the scenarios presented in our task might have been too obvious and the reality might be much more complex. In accordance with Underwood et al. (2011), we also propose integrating more ambiguous scenarios in which learned anticipatory skills of experienced BEV drivers might come into play. Furthermore, participants were able to devote their full attention to the hazard detection task. This is unlikely to be the case under normal driving conditions. Future studies should investigate BEV drivers while driving in real traffic so that actual driving behavior (e.g., steering, braking) can be analyzed in more detail. Ultimately, the skill tested in the present study might not be reflected in behavioral responses. One could argue that anticipatory behavior is a more valid skill in this context, which would suggest that experienced BEV drivers might shift their attention earlier to potentially critical areas. Investigating scanning behavior, as performed by Crundall et al. (2003), might help solve this issue.

As our second research objective (2) we wanted to investigate how drivers with differing levels of BEV experience evaluate noise-related incidents. Even though we only observed trends in Study 1 and set 1 of Study 2, findings from Study 2 (set 2) suggest that critical scenarios are evaluated as less hazardous by experienced BEV drivers. Thus, BEV experiences might cause an adjustment in drivers' subjective evaluations, but not in their behavior. In our view, this supports recent research (Cocron, Bühler, Franke, et al., 2011; Cocron & Krems, 2013) that noted an adjustment in noise-related risk estimation after obtaining BEV experience. Specifically, after drivers gain experience with these situations, they perceive them as less critical.

In the second study, we also investigated (3) if prior sensitization to low noise has an effect on hazard detection and evaluation. Only trends were observed, e.g., in response latency. It can be argued that our sensitization procedure was not strong enough to elicit different reactions to the task. In other studies, participants were trained to identify potential hazards, which then had an effect on their performance on the HP test (e.g. Horswill et al., 2013). We utilized a relatively short sensitization treatment condition and did not train specific HP skills; rather, we aimed to raise awareness of the noise issue. Therefore, the findings likely do not generalize to situations in which full hazard perception training is utilized. Nevertheless, we argue that some kind of sensitization is necessary to raise awareness to hazards due to low vehicle noise.

With respect to our last (4) research objective, Study 2 findings highlight an issue which has been reported previously by Cocron and Krems (2013). After testing a BEV, drivers' evaluation of low noise emission changes. Specifically, perceived comfort due to driving with low noise emission increases as concerns regarding the safety of other road users decreases. Our findings are noteworthy insofar as these opposing trends are already observable after only one short test drive through the city. In this context, Vilimek and Keinath (2014) reported similar results for other European countries, but also mentioned a different evaluation in Asian countries. Here, arguably due to different traffic conditions, safety concerns were rated higher.

In sum, the results of our studies suggest that drivers with differing levels of BEV experience can differentiate well between critical and non-critical noise-related situations and react accordingly. Drivers who drove a BEV only once exhibited the same performance as experienced BEV drivers, suggesting that BEV driving experience seems to play only a minor role in noise-specific hazard detection. It is possible that the necessary skills are transferable from ICE vehicle driving experience. Even after briefly testing a BEV, drivers perceive the lack of noise more as a comfort feature than as a safety threat. These findings should be considered in the discussion about acoustic vehicle alerting systems (AVAS) as potential countermeasures for the noise-related hazards of quiet vehicles.

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2013 – 2014	DECOMOBIL (http://decomobil.humanist-vce.eu/)
2013 – 2016	Freiluftlabor 'Neue Mobilität' am Sachsenring
2014 – 2016	COST TU 1105 (http://www.tu1105.ulg.ac.be/index.html)

Teaching

2011 – 2012	Winter semester: Empirical and experimental practical course
2012	Summer semester: Empirical and experimental practical course
2012– 2013	Winter semester: Empirical and experimental practical course
2013	Summer semester: Industrial psychology ("Job analysis")
2013 – 2014	Winter semester: Empirical and experimental practical course

Award

2013 IET Intelligent Transport Systems Premium Award for the paper on research methods of the MINI E work group: Cocron, P., Bühler, F., Neumann, I., Franke, T., Krems, J.F., Schwalm, M., & Keinath, A. (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. doi: 10.1049/iet-its.2010.0126

Publications

Articles in journals (peer-reviewed)

Bühler, F., Cocron, P., Neumann, I., Franke, T., & Krems, J.F. (2014). Is EV experience related to EV acceptance? Results from a German field study. *Transportation Research Part F: Traffic Psychology and Behaviour, 25*(A), 85-90. doi:10.1016/j.trf.2014.05.002

Cocron, P., Bachl, V., Früh, L., Koch, I., & Krems, J.F. (2014). Hazard detection in noise-related incidents - the role of driving experience with battery electric vehicles. *Accident Analysis and Prevention, 73*, 380-391. dx.doi.org/10.1016/j.aap.2014.09.016

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Cocron, P., Bühler, F., Neumann, I., Franke, T., Krems, J.F., Schwalm, M., & Keinath, A. (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. doi: 10.1049/iet-its.2010.0126

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Franke, T., Neumann, I., Bühler, F., Cocron, P., & Krems, J. F. (2012). Experiencing range in an electric vehicle: Understanding psychological barriers. *Applied Psychology*, *61*(3), 368-391. doi: 10.1111/j.1464-0597.2011.00474.x

Book chapters and conference proceedings

Bühler, F., Franke, T., Schleinitz, K., Cocron, P., Neumann, I., Ischebeck, M., & Krems, J. F. (2013). Driving an EV with no opportunity to charge at home - is this acceptable? In D. De Waard et al. (Eds.), *Proceedings of the Human Factors and Ergonomics Society Europe Chapter 2013 Annual Conference.* Retrieved from http://www.hfes-europe.org/books/proceedings2013/Buehler.pdf

Bühler, F., Neumann, I., Cocron, P., Franke, T., & Krems, J. F. (2011). Usage patterns of electric vehicles: A reliable indicator of acceptance? Findings from a German field study.

Proceedings of the 90th Annual Meeting of the Transportation Research Board. Retrieved from http://amonline.trb.org/12jj41/1

Bühler, F., Neumann, I., Cocron, P., Franke, T., Krems, J. F., Schwalm, M., & Keinath, A. (2010). Die Nutzerstudie im Rahmen des Flottenversuchs MINI E Berlin – Methodisches Vorgehen und erste Erfahrungen im Rahmen der wissenschaftlichen Begleitforschung. In T. J. Mager (Ed.), *Mobilitätsmanagement – Beiträge zur Verkehrspraxis* (pp. 81-96). Köln, Deutschland: ksv-verlag.

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Franke, T., Bühler, F., Cocron, P., Neumann, I., & Krems, J. F. (2012). Enhancing sustainability of electric vehicles: A field study approach to understanding user acceptance and behavior. In M. Sullman & L. Dorn. (Eds.), *Advances in traffic psychology* (pp. 295-306). Farnham, UK: Ashgate.

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Presentations and posters

Cocron, P. (2009). Anpassungsprozesse im Fahrverhalten bei der Nutzung von Elektrofahrzeugen. *Beitrag auf dem 3. Nachwuchsworkshop der Fachgruppe Verkehrspsychologie in der Deutschen Gesellschaft für Psychologie*, Leipzig, Germany, 24. September.

Cocron, P., Bachl, V., Neumann, I., Franke, T., Bühler, F., & Krems, J. F. (2011). Die geringe Geräuschkulisse von Elektrofahrzeugen: Viel Lärm um nichts? In K. Bittrich, S. Blankenberger & J. Lukas (Eds.), *Beiträge zur 53. Tagung experimentell arbeitender Psychologen* (p. 33). Lengerich, Germany: Pabst Science Publishers.

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Eidesstattliche Erklärung

Hiermit erkläre ich, dass ich die vorliegende Arbeit selbstständig verfasst und keine anderen als die angegebenen Hilfsmittel verwendet habe.

Peter Cocron

Chemnitz, 28.05.2014