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Inaccuracy versus volatility – Which is the lesser evil in battery electric vehicles?

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A B S T R A C T

Due to the limited range of battery electric vehicles, research has emphasized a frequently observed dimension of driver stress referred to as a concern of becoming stranded due to a depleted battery known as range stress. It has been suggested that the appropriate provision of range-related information through in-vehicle information systems constitutes a promising solution to overcome range stress. However, drivers often struggle to understand the influencing factors of the displayed range in battery electric vehicles and thus lose trust in the range estimation. Building on field experiments in real traffic situations, we aim to investigate the influence of two range gauges typically present in battery electric vehicles, which differ in terms of information accuracy and displayed volatility, on the perception of trust in the estimates and range stress. In addition, we aim to explore how trust in the range estimates influences the perception of range stress and how trust and range stress affect the acceptance of battery electric vehicles. We found that displaying accurate but volatile range information results in higher perception of range stress and a lower feeling of trust in comparison to the provision of less accurate but less volatile range information. In addition, we observed that higher levels of trust in range estimates leads to lower range stress and higher acceptance of battery electric vehicles. Finally, we showed that range stress is negatively related to battery electric vehicle acceptance.

1. Introduction

1.1. Background and related work

Given the considerable amount of environmental pollution caused by the transportation sector, battery electric vehicles (BEVs) are considered to be a promising solution to the reduction of carbon emissions by road transport (Capros, Tasios, De Vita, Mantzos, & Paroussos, 2012; McCollum, Krey, Kolp, Nagai, & Riahi, 2014; Thiel, Perujo, & Mercier, 2010). However, the widespread adoption of these vehicles is still low because of the high purchasing costs, the underdeveloped charging infrastructure and the limited driving range (Buehler, Cocron, Neumann, Franke, & Krems, 2014; Egbue & Long, 2012; Wallis & Lane, 2013; Zhang, Rao, Xie, & Liang, 2014).

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With regards to the BEVs limited range, research emphasizes on a widely observed phenomenon in which drivers of BEVs experience range stress due to the "*continual concern and fear of becoming stranded with a discharged battery in a limited* range" (Tate, Harpster, & Savagian, 2008, p. 158). The phenomenon of range stress can be seen as a specific form of psychological stress caused by the driver's perceived insufficient available range and personal resources to manage a present or an anticipated critical range situation whereby the user experience of the driver might be influenced negatively (Franke, Rauh, Günther, Trantow, & Krems, 2016). Following Rauh, Franke, & Krems (2015), range stress can be expressed on four different levels, as derived from the area of general anxiety and stress. On the cognitive level it can lead to negative thoughts about the range situation, e.g., not reaching the designated destination, while on the emotional level, changes in affect can result in nervousness or fear. Specific behavioural activities, e.g., frequently checking the range displays or finger tapping can occur on the behavioural level, whereas an increased heart rate or respiration is assumed to be caused by increased arousal on the physiological level. In addition, stress can result in numerous mental and physiological health problems (Richardson, et al., 2012) and increases the risk of traffic accidents (Matthews, et al., 1998).

From a psychological point of view, research has proposed a variety of factors suitable to mitigate range-related concerns, for example, knowledge of BEV technology, route familiarity, or control beliefs in dealing with technology (Franke, Rauh, and Krems, 2016b). Franke, Rauh, and, Günther, et al. (2016a) examine personal resilience factors, which may decrease range stress for everyday users of BEVs. Besides factors such as range-related personal tolerance, experience with BEVs is also assumed to decrease range stress. Rauh et al. (2015) arrived at similar results, emphasizing that experience with BEVs decreases range stress.

Despite these psychological factors, another promising solution to overcoming range stress is seen to be in the appropriate delivery of information by in-vehicle information systems. The general provision of range-related information about the status of the vehicle (e.g., the energy usage of internal electric consumers) or the trip (e.g., location of nearby charging stations or optimal route) can reduce range stress and increase the overall acceptance of using BEVs (Eisel & Schmidt, 2014; Eisel et al., 2014). In this context, the information provided through information systems diminishes range stress by reducing the feeling of uncertainty regarding the individual's ability to reach the final destination with the given driving range, and thus influences the overall affective evaluation of BEVs in a positive manner (Nastjuk & Kolbe, 2015).

However, research has also shown that the provision of range-related information is not always useful to reduce range stress. Nastjuk, Marrone, & Kolbe (2016), for example, revealed that the provision of unreliable and excessively detailed range-related information increases uncertainty in the driver and thus leads to range stress. The researchers emphasize that BEV users are not familiar with the factors that influence the calculation of the remaining range, which in turn, reduces the users' ability to estimate whether the intended destination is reachable within the given range. Thus, the range gauge represents the primary information source for the available driving range and mainly shapes the user experience with BEVs (Franke, et al., 2015). The range gauge in BEVs can be considered as an automated system (see also Franke et al., 2015) that "*actively selects data, transforms information, makes decisions, or controls processes*" (Lee & See, 2004, p. 50). Displayed inaccuracies of automated systems, for example, providing unreliable and fluctuating information, can adversely affect the trustworthiness and the related usage behaviour (Hoff & Bashir, 2015; Kantowitz, Hanowski, & Kantowitz, 1997). Sudden volatilities in the displayed range, up to 20 percent, are nothing out of the ordinary in BEVs (Lundstroem, 2014). Such volatilities stop the driver from understanding which factors influence the actual remaining range in BEVs and thus might elicit a general low trustworthiness and lower utilized range (Franke et al., 2015; Wellings, Binnersley, Robertson, & Khan, 2011). Hence, it is important to provide the user reliable information regarding the probabilities of inaccuracies in automated systems to increase trust and decision quality in certain situations (e.g. Beller, Heesen, & Vollrath, 2013; Kay, Kola, Hullmann, & Munson, 2016; Joslyn & LeClerc, 2012).

Moreover, certain design features, for example, appearance, ease of use, or transparency, can influence the trust towards these systems (Hoff & Bashir, 2015). In order to improve the understanding of the remaining range, Lundstroem (2014), for example, suggests an alternative display for the remaining range, based on different speed levels, to help the driver understand the correlation between speed and remaining range. Jung, Sirkin, Gür & Steinert (2015) suggest that it is useful to present error-prone range information in BEVs ambiguously. The researchers displayed the range information to the driver in the form of a diffuse colour band that varies in width directly with remaining range and showed that it might lead to a general higher trust in BEVs.

Research is additionally concerned with improvements in the range prediction algorithm, as the calculation of the distance to empty is considered as insufficient (Birrell, McGordon, & Jennings, 2014). In this context, a variety of factors can influence the remaining driving range in BEVs. Yuksel & Michalek (2015), for example, found a direct effect between energy consumption of BEVs and ambient temperature. The researchers revealed that BEVs consume more energy at the lower and upper ambient temperature boundaries of −26 and 43 °C, respectively. Karabasoglu & Michalek (2013) revealed that driving conditions also influence the driving range of electrified vehicles. The researchers showed, for example, that BEVs consume more energy in urban driving conditions (where frequent stops are required) compared to highway driving conditions. In addition, the researchers revealed that an aggressive driving style increases the energy consumption of BEVs. Faria, et al. (2013) and Mruzek, Gajdáč, Kučera, & Barta (2016) outline that big elevation differences heavily contribute to the overall energy consumption of BEVs. To predict the remaining driving range more accurately, research has begun to integrate these variables into the range estimation algorithm (e. g., Neaimeh, Hill, Hübner, & Blythe, 2013; Pichler & Riener, 2015; Rui & Lukic, 2011; Zhang, Wang, Kobayashi, & Shirai, 2012). However, such approaches are incapable of ensuring high prediction