Which factors can protect against range stress in everyday usage of battery electric vehicles? Towards enhancing sustainability of electric mobility systems

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Abstract

Objective: The objective of the present research was to advance understanding of factors that can protect against range anxiety, specifically range stress in everyday usage of battery electric vehicles (BEVs). Background: Range anxiety is a major barrier to the broad adoption of sustainable electric mobility systems. To develop strategies aimed at overcoming range anxiety, a clear understanding of this phenomenon and influencing factors is needed. Method: We examined range anxiety in the form of everyday range stress (ERS) in a field study setting. Seventy-two customers leased a battery electric vehicle for 3 months. The field study was specifically designed to enable examination of factors that can contribute to lower ERS. In particular, study design and sample recruitment were targeted at generating vehicle usage profiles that would lead to relatively frequent experience of situations requiring active management of range resources and thereby potentially leading to experienced range stress. Results: Less frequent encounter with critical range situations, higher practical experience, subjective range competence, tolerance of low range, and experienced trustworthiness of the range estimation system were related to lower ERS. Moreover, range stress was found to be related to range satisfaction and BEV acceptance. Conclusion: The results underline the importance of the human factors perspective to overcome range anxiety and enhance sustainability of electric mobility systems. Application: Trustworthiness should be employed as a key benchmark variable in the design of range estimation systems, and assistance systems should target increasing drivers’ adaptive capacity (i.e., resilience) to cope with critical range situations.

Keywords: range anxiety, field study, adaptive capacity, resilience

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1 INTRODUCTION

Electrification of road transport is one of the greatest transformations in the field of sustainable development (Capros, Tasios, De Vita, Mantzos, & Paroussos, 2012; McCollum, Krey, Kolp, Nagai, & Riahi, 2014), with the potential to address many sustainability challenges, such as decarbonization, global warming, and air pollution (e.g., Pietzcker et al., 2014; Hawkins, Gausen, & Strømman, 2012). Battery electric vehicles (BEVs) are particularly promising in these respects with the potential of zero emissions during their usage phase (i.e., in comparison to plug-in-hybrid electric vehicles) when operating with electricity from renewable sources. Further, BEVs are highly energy efficient (i.e., compared to fuel cell electric vehicles; Eaves & Eaves, 2004), which is essential for achieving a maximum sustainability effect.

However, a major challenge is the battery capacity (i.e., the range) of BEVs (e.g., Egbue & Long, 2012). Simply increasing battery size is not a sustainable solution, because of its link to the ecological footprint (McManus, 2012; Yuan, Li, Gou, & Dong, 2015) and cost-effectiveness (Neubauer, Brooker, & Wood, 2012) of a BEV. Hence, the larger the battery, the more difficult it becomes for a BEV to compensate for the initial resource cost of battery production during vehicle lifetime. Consequently, BEVs can only achieve maximum sustainability when battery size is tailored to actual mobility patterns. Thus, it is crucial to address human factor issues of the range-related user experience (i.e., under which conditions can users cope well with limited mobility resources).

One of the key issues in this regard is range anxiety, which is frequently considered a barrier to BEV usage (e.g., Birrell, McGordon, & Jennings, 2014; McIlroy, Stanton, & Harvey, 2014; Luettringhaus & Nilsson, 2012; Nilsson, 2011a). Hence, a comprehensive understanding of human factors that can protect against range anxiety in everyday usage of BEVs is needed.

However, despite considerable investment in BEV research projects around the world, scientific knowledge on range anxiety in everyday BEV usage is still lacking. A first reason might be, that range anxiety is not well defined in the literature and used with many meanings (see also Nilsson, 2011b). Hence, we previously suggested range stress as a more accurate psychological concept to account for the actual user experience in driving a BEV (Rauh, Franke, & Krems, 2015). We conceptualize range stress as a domain specific form of psychological stress occurring in a present or anticipated critical range situation (a situation where range resources and personal resources seem to be insufficient to successfully manage the situation). Herein, everyday range stress (ERS) specifically describes users’ range worries experienced within continued vehicle usage.
A second reason for the lack of scientific knowledge on range anxiety in everyday BEV usage might be that studying ERS in BEV usage is challenging, because range stress has been found to be a relatively rare event under the typical range demand conditions of average car drivers (Franke & Krems, 2013a). One approach is to consequently examine range stress in controlled field experiments (i.e., actively inducing range stress; e.g., Rauh et al., 2015; Jung, Sirkin, Gür, & Steinert, 2015). However, this approach is limited with regard to understanding range stress in everyday BEV usage. Hence, field study research that is specifically designed to allow for examination of dynamics in ERS is needed.

The objective of the present research was to advance understanding of factors that can protect against range stress in everyday BEV usage. To this end, a large-scale field study was conducted. Considerable effort was invested in the design of the present field study such that it enabled examination of ERS. In particular, study design and sample recruitment were targeted at generating vehicle usage profiles that would lead to frequent experience of situations requiring active management of range resources, and thereby increasing risk of experiencing ERS.

2 BACKGROUND

2.1 Addressing human factors in sustainable development

Sustainability means managing resources in such a way that present usage does not compromise future usage (World Commission on Environment and Development, 1987). Hence, wherever resource growth is not easily possible on a global level (e.g., energy or environmental resources), ensuring sustainability means establishing “low-resource systems” (Thatcher, 2013), i.e. systems that require fewer resources in production and usage. However, operating low-resource systems (e.g., monitoring and controlling resources) can cause workload and stress (Thatcher, 2013), making it difficult for users to fully exploit the sustainability potential of such systems (Franke & Krems, 2013a; Moore & Barnard, 2012). Hence, a decisive task for human factors research is to identify factors that support users’ stress-free interaction with low-resource systems by increasing users’ capacity to deal with stress-evoking situations (i.e., increasing resilience). One system that allows us to examine such factors are BEVs.

2.2 The role of resilience in range stress

A framework that describes user interaction with a low-resource system is the adaptive control of range resources (ACOR) model (Franke, Günther, Trantow, Rauh, & Krems, 2015a; Franke & Krems, 2013a, Franke & Krems, 2013b), which draws from concepts of different control models (Lazarus & Folkman, 1984; Fuller, 2005; Summala, 2007; Hancock & Warm, 1989) to account for drivers’ interaction with limited BEV range (see Figure 1). The fundamental assumption of this model is that

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BEV drivers continuously manage (i.e., monitor and control) the fit of (1) available range resources (i.e., displayed range) to (2) their actual range resource needs (i.e., trip lengths) with the goal of keeping the available range resource buffer within their individual comfort zone (Franke et al., 2015a). The higher the discrepancy becomes between this available buffer and drivers’ preferred safety buffer (i.e., similar to safety margin concept of Summala, 2007), the more likely drivers will experience discomfort and, finally, stress (see also Hancock & Warm, 1989).

Hence, two basic assumptions underlie the model. First, there has to be an objective basis for range stress. The more often a BEV driver encounters critical range situations due to individual mobility patterns, the higher the extent of ERS should be. Second, objectively similar critical range situations can lead to a highly diverse subjective experience (i.e., range appraisal) because of individual coping skills and resources, resulting in different intensities of range stress.

However, everyday interaction with limited range resources of BEVs is typically not characterized by experience but rather by avoidance of range stress (Franke & Krems, 2013a), because drivers usually have various opportunities to cope with situational demands. Thus, drivers develop coping routines (e.g., charging styles; Franke & Krems, 2013b) that lead to an increase in resources before critical situations (i.e., coping necessities) may arise (i.e., routinized coping). Nevertheless, there tend to be fluctuations in situational demands, most of which can be easily anticipated such that drivers are able to adapt their behavior (i.e., break from their routines) before the situation becomes critical (i.e., anticipatory coping). Even if fluctuations are strong and/or unpredictable, drivers can often still compensate for an evolving critical situation (i.e., compensatory coping).

Range stress will only result if all kinds of coping fail. This likelihood of failure is dependent on the drivers’ adaptive capacity (i.e., drivers’ individual resilience against range stress), which can be assumed to be composed of several resilience factors that affect different components of the coping process. Hence, we essentially conceptualize resilience as the users’ adaptive capacity to handle critical situations in order to avoid negative outcomes (e.g., discomfort, stress). This definition acknowledges the fact that, while a well-established resilience definition is missing in the field, adaptive capacity is a core element of the resilience framework (Bergström, van Winsen, & Henriqson, 2015; Sheridan, 2008). We judge resilience as a relevant concept for the present research as the resilience framework has been discussed as particularly promising for developing sustainable systems (Folke, 2006).

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Figure 1. Simplified illustration of the ACOR model showing how different adaptation mechanisms (i.e., kinds of coping) can help to avoid range stress. There are two paths to coping behavior. First, convenient coping opportunities can directly initiate coping behavior (especially for routinized coping). Second, situational demands can lead to an anticipated or actual small available range buffer. If this buffer is smaller than the preferred range buffer this can lead to the appraisal of a coping necessity and therefore initiate increased coping efforts (i.e., anticipatory/compensatory coping). If all of these coping mechanisms fail, this can lead to experience of range stress.

2.3 Fostering resilience against range stress in everyday BEV usage.

In searching for factors that could contribute to increased adaptive capacity to cope with critical range situations, the first, and most basic factor within the ACOR model is practical experience (i.e., drivers develop routines and strategies to deal with situations over time) with the system (see also Luettringhaus & Nilsson, 2012). This factor can be assumed to be composed of different facets, foremost among which are (1) accumulated practice and (2) experience gathered from exploring relevant situations (Rauh et al., 2015; Pichelmann, Franke, & Krems, 2013; Franke, Cocron, Bühler, Neumann, & Krems, 2012a). In fact, practical experience has also been broadly discussed as a general resilience factor (e.g., Hollnagel, 2011).

Second, the extent of specific coping skills (e.g., facets like relevant knowledge, subjective range competence; Franke & Krems, 2013a) should also contribute to individual adaptive capacity against ERS. Such concepts have also been discussed in the general resilience literature (e.g., Morel, Amalberti, & Chauvin, 2008).

Third, the factor with the most direct effect on range appraisal (and therefore range stress), and found to show particularly high inter-individual variance, is individual tolerance of low-resource
situations (e.g., as signified by the individual range safety buffer, i.e. comfortable range; Franke et al., 2015a).

Finally, technical system characteristics also contribute to resilience (i.e., system coping support; e.g., Navarre, Palanque, Barboni, Ladry, & Martinie, 2011). As depicted in Figure 1, the available range buffer is the central variable that indicates range resources (i.e., external input signal for range appraisal). However, its assessment is dependent on one essential system element: the range estimation system of the BEV (i.e. range display and calculation algorithm). In any low-resource system, there will be a certain degree of uncertainty associated with the resource indicator leading to a certain degree of experienced trustworthiness. Users have to incorporate this in their appraisal process. Thus, higher trustworthiness (i.e., reliability, dependability, traceability) of the range estimation system can support users’ coping efforts, and thereby contribute to general resilience against range stress.

Together, these factors contribute to the rarity of range stress occurrences. Yet, the effect of range stress on general user experience should not be underestimated because also such rare but severe events may have adverse effects on user satisfaction and acceptance. Figure 2 summarizes the proposed predictors (situational demand indicator, facets of resilience factors, resilience factors) and outcomes of ERS including references to the hypotheses that are specified in Table 1.

Hence, the task for human factors research is to examine (1) the impact of individual facets of the resilience factors (i.e., to understand individual variables that can be targeted in practical interventions), (2) the individual and relative impact of the four discussed resilience factors (see Figure 2), and (3) the total impact of all four resilience factors on ERS. Finally (4), it is crucial to examine the real impact of ERS on user satisfaction and acceptance.

Figure 2. Predictors and outcomes of ERS. The hypotheses numbers (e.g., H1) refer to our hypotheses as specified in Table 1.
3 PRESENT RESEARCH

The objective of the present research was to advance understanding of factors that can protect against ERS in BEV usage. The specific hypotheses are summarized in Table 1.

Table 1. Hypotheses tested in the present study

<table>
<thead>
<tr>
<th>Model component</th>
<th>Hypothesis</th>
<th>Specification of hypothesis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency of critical range situations</td>
<td>H1</td>
<td>Less frequent encounter with critical range situations (i.e., fewer situations per 1000 km) is related to lower ERS.</td>
</tr>
<tr>
<td>Practical experience</td>
<td>H2a</td>
<td>Practical experience with a BEV in general is related to lower ERS (i.e., range stress decreases when practical experience increases).</td>
</tr>
<tr>
<td></td>
<td>H2b</td>
<td>Higher accumulated practice with the BEV in terms of total distance driven is related to lower ERS.</td>
</tr>
<tr>
<td></td>
<td>H2c</td>
<td>A higher amount of specific experience from exploring low-range situations (i.e., having actively exhausted range) is related to lower ERS.</td>
</tr>
<tr>
<td>Coping Skills</td>
<td>H3a</td>
<td>Higher subjective range competence is related to lower ERS.</td>
</tr>
<tr>
<td></td>
<td>H3b</td>
<td>Higher technical system knowledge is related to lower ERS.</td>
</tr>
<tr>
<td>Tolerance of low range</td>
<td>H4a</td>
<td>Higher comfortable range (i.e., larger range comfort zone) is related to lower ERS.</td>
</tr>
<tr>
<td></td>
<td>H4b</td>
<td>Lower aversiveness of low-range situations is related to lower ERS.</td>
</tr>
<tr>
<td>Trustworthiness of range estimation</td>
<td>H5</td>
<td>Higher experienced trustworthiness of range estimation is related to lower ERS.</td>
</tr>
<tr>
<td>Collective adaptive capacity</td>
<td>H6</td>
<td>A collective higher adaptive capacity (i.e., all resilience factors together) is related to lower ERS.</td>
</tr>
<tr>
<td>Outcome variables</td>
<td>H7a</td>
<td>Lower ERS is related to higher range satisfaction.</td>
</tr>
<tr>
<td></td>
<td>H7b</td>
<td>Lower ERS is related to higher general BEV acceptance.</td>
</tr>
</tbody>
</table>

4 METHOD

4.1 Field study setup

The present research was part of a large-scale BEV field trial in Germany. A key objective was to comprehensively examine user-range interaction. Within the field trial, there were four main time points of data collection: before vehicle handover (T0), after the first week of BEV usage (T0+1), after six weeks (T1) and at vehicle return after 12 weeks (T2). At each point of data collection, users completed interviews and questionnaires. A person-based main user data collection approach was applied, i.e., only data from the main user of the BEV was analyzed. The BEV was the BMW ActiveE with a maximum available driving range of 130-160 km in real terms, depending on driving style.
Users had charging opportunities at home and/or work depending on their mobility patterns. Fifteen BEVs were available for the study. Five subsequent data collection phases allowed a sample of 75 drivers. For further methodological details see Franke et al. (2014).

### 4.2 Participants

Information on the project was broadly distributed via diverse media channels (e.g., radio, newspaper). People could apply via an online screener questionnaire (673 applicants). Requirements for participation included (1) the willingness to pay the monthly full service leasing rate of 450 € (reduced to 370 € when the BMW i3 entered the market), (2) a charging opportunity or the possibility to install a charging station, and (3) a mobility profile that could be expected to result in a frequent and active interaction with range (≥90 km daily driving distance with the BEV). As restrictions for inclusion in the sample were similar to those for leasing a BEV, we expect the sample to represent early BEV customers in Germany.

The N = 72 users who completed the study had an average age of 42.8 years (SD = 9.5), 17% were female, 57% had a university degree, and drove M = 87.9 km (SD = 25.2) with their BEV on an average day with BEV mobility (N = 68, see section 4.3.2).

### 4.3 Scales and measures

Questionnaire scale items are presented in the Appendix. Reliability was acceptable for all scales (see Table 2).

#### 4.3.1 Range stress

We queried a moderate degree of range stress (i.e., worry instead of anxiety) to obtain a normally distributed variable that still targeted a prototypic form of stress (i.e., worry instead of only having range in mind).

As the primary score for regression analyses, range stress was assessed at T2 with three items referring to the T1-T2 study period, i.e., best reflecting everyday range stress after the adaptation phase, which takes considerable time (Pichelmann et al., 2013). Further, to test H2a (decrease of range stress with experience) items were also administered at T0 (anticipated range stress), T0+1 and T1 (referring to the respective preceding study period).

#### 4.3.2 Logger data scores

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To assess variables for H1 (frequency of critical range situations) and H2b (accumulated practice with BEV), data loggers in the BEV recorded relevant parameters. Personalized car keys were used to filter out data segments that were not generated by the main user of the BEV. Before we computed the final scores there was an extended period of data validation where signals from the three different available data loggers were compared with regard to reliability and validity of data recording in order to identify the most accurate data source for each signal. The computed scores are described in sections 5.1 and 5.2.2. Because of missing logger data there were N = 68 users.

4.3.3 Active range exhaustion (H2c)

Two items assessed active range exhaustion at T1 and T2. To receive an indicator that represented the entire trial (see also Note below Table 2) a mean score was computed from combined T1 and T2 values.

4.3.4 Subjective range competence (H3a)

We extended the subjective range competence scale of Franke and Krems (2013a) in the present study (i.e., constructed two additional items resulting in a 6-item scale) to improve reliability. A mean score was computed from combined T1T2-values.

4.3.5 Technical system knowledge (H3b)

As an extension of our previous 3-item scale (Franke & Krems, 2013a), a 6-item scale assessed participants’ system knowledge regarding relevant aspects of BEV technology at T1. This scale was not assessed again at T2 as the values were expected to be stable between T1 and T2 and questionnaire space at T2 was particularly limited.

4.3.6 Comfortable range (H4a)

Comfortable range was assessed with the comfortable range scenario task (CRST, comprehensively described in Franke et al., 2015a) at T1 and T2. The CRST assesses a user’s individual range comfort zone based on a standardized scenario (60 km trip), asking participants to rate experienced range comfort on four items (e.g., “I am sure I will reach the destination with my BEV.”). This rating is done for 10 different range configurations (45-90 km range) per item. For each of the four items, the range configuration where users shift from optimal (completely agree) to sub-optimal range comfort is defined as the comfortable range threshold (e.g., 70 km) and a mean of the four item scores is computed (e.g., 67.5). Finally, by dividing 60 km / comfortable range threshold, the users’ proportional comfortable range utilization (e.g., 89%) is computed. The CRST has been successfully used in several studies (Franke et al., 2015a; Franke, Neumann, Bühler, Cocron, & Krems, 2012b; Franke & Krems, 2013a; Franke & Krems, 2013b). Again, a T1T2-score was computed. Single missing values and data sets where one item could not be scored resulted in N = 64.

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4.3.7 Low-range aversiveness (H4b)

Two items assessed low-range aversiveness at T1 and T2. Again, a combined T1T2-score was computed.

4.3.8 Experienced trustworthiness of range estimation system (H5)

First, the 5-item facets of trustworthiness scale (Franke et al., 2015b) was assessed at T1 and T2 which asked users to rate facets of trustworthiness (e.g., traceability, reliability) of the range estimation system (i.e., range display and calculation algorithm). Again, a combined T1T2-score was computed.

Second, the 12-item trust in automated systems scale (Jian, Bisantz, & Drury, 2000) was assessed. The scale had been translated to German within a previous research project (Beggiato, 2015). The instruction specified the system as the range estimation system. The scale was only assessed at T1 because of limited space in the T2 questionnaire and the scale being relatively long.

We used these two scales instead of just one because an additional methodological question of our study was to examine to what extent our newly developed economic scale would yield similar results to the established scale.

4.3.9 Range satisfaction (H7a)

Final range satisfaction was assessed at T2. The 6-item scale was an extension of an earlier scale (Franke & Krems, 2013a).

4.3.10 BEV acceptance (H7b)

The 9-item Van der Laan acceptance scale (Van der Laan, Heino, & De Waard, 1997), which assesses the acceptance facets satisfaction and usefulness, was used to assess acceptance of the BEV (under given usage profile) at T2. We computed one mean score because an exploratory factor analysis clearly suggested a one-factor solution.
Table 2. Reliability analysis and descriptive statistics for scores used in the regression analyses

<table>
<thead>
<tr>
<th>Scale</th>
<th>Cronbach’s alpha</th>
<th>$r_{T1T2}$</th>
<th>$M$</th>
<th>$SD$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Range stress</td>
<td>T2: .75</td>
<td>.72</td>
<td>3.21</td>
<td>1.06</td>
</tr>
<tr>
<td>Active range exhaustion</td>
<td>T1T2: .85 (T1: .89, T2: .71)</td>
<td>.70</td>
<td>3.59</td>
<td>1.36</td>
</tr>
<tr>
<td>Subjective range competence</td>
<td>T1T2: .85 (T1: .79, T2: .80)</td>
<td>.78</td>
<td>4.58</td>
<td>0.61</td>
</tr>
<tr>
<td>Technical system knowledge</td>
<td>T1: .81</td>
<td></td>
<td>4.47</td>
<td>0.71</td>
</tr>
<tr>
<td>Comfortable range</td>
<td>T1T2: .97 (T1: .96 , T2: .95)</td>
<td>.77</td>
<td>0.90</td>
<td>0.10</td>
</tr>
<tr>
<td>Low-range aversiveness</td>
<td>T1T2: .80 (T1: .73, T2: .73)</td>
<td>.72</td>
<td>3.89</td>
<td>1.17</td>
</tr>
<tr>
<td>Facets of system trustworthiness</td>
<td>T1T2: .92 (T1: .87, T2: .90)</td>
<td>.78</td>
<td>5.01</td>
<td>0.66</td>
</tr>
<tr>
<td>Trust in automated systems</td>
<td>T1: .88</td>
<td></td>
<td>5.36</td>
<td>0.72</td>
</tr>
<tr>
<td>Range satisfaction</td>
<td>T2: .89</td>
<td></td>
<td>3.80</td>
<td>1.08</td>
</tr>
<tr>
<td>Acceptance</td>
<td>T2: .88</td>
<td></td>
<td>4.48</td>
<td>0.51</td>
</tr>
</tbody>
</table>

Note. For range stress the T2 score (i.e., referring to T1T2-period) was the primary variable for the analysis (see section 4.3.1). Cronbach’s Alpha for other time points was also ≥.75. For all predictor variables we combined T1 and T2 scores to receive a variable that referred to the same T1T2-period (also supported by strong T1T2 correlations). Hence, Cronbach’s Alpha of averaged T1T2 item values is the main indicator of reliability. For the two scales, technical system knowledge and trust in automated systems, this was impossible as these were only available for T1 due to questionnaire length limitations at T2. The two final outcome variables were assessed at T2. The $M$ and $SD$ columns depict the final scores used in the regression analyses.

5 RESULTS

We used partial correlation, contrast analysis, and regression analyses to test our hypotheses. We tested for univariate outliers according to Grubbs (1969), and none were identified. We interpreted effect sizes according to Cohen’s conventions (1992). A significance level of .05 and one-tailed tests (i.e., because of directional hypotheses, exception: F-test of $R^2$ in multiple regression) were used. Statistical results for H2b to H5 are presented in Table 3 (for H6 see Table 4; for H7 see Table 5). All other information regarding analyses and results are given in the text.

5.1 Frequency of critical range situations and range stress (H1)

To test H1 we assessed the number of critical range situations that participants encountered per km, based on logger data. We decided to use the most unambiguous and face-valid indicator – a situation where a user experiences a very low charge level. Therefore, we counted the total number of discharge cycles (i.e., period between two charging events) with a minimum state-of-charge <10% and divided this by the total driven distance of the user (i.e., finally scored as number of situations per 1000 km).

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We used a threshold of <10% because all comfortable range variables (CRST and other single-item measures, see Franke et al., 2015a) consistently indicated that drivers in the present sample were typically still comfortable with a range safety buffer of slightly >10%. While this rather conservative definition of a critical range situation was necessary, it resulted in 19 users with zero situations recorded by the data loggers, which created a problem for the correlation analysis (i.e., normality assumption). Hence, we could compute the analysis only with the N = 49 users who had >0 situations (i.e., for this sub-sample a log-transformation could correct normality problems).

The final challenge was that several critical range situations were attributable to users actively exhausting the BEV range limits (i.e., mostly in a “protected environment” with available safety options, as stated during interviews) that should not be related to more ERS. To control for this factor, we computed a partial correlation analysis with the variable active range exhaustion (see section 4.3.3) as control variable.

As expected for H1, the less frequently users encountered critical range situations the lower the ERS, as revealed in a moderate and significant effect ($r_{\text{partial}} = .34, p = .010$).

5.2 Practical experience and range stress (H2)

5.2.1 Decrease of range stress with experience (H2a)

To test H2a, we conducted a contrast analysis according to Furr and Rosenthal (2003). Because we expected a steady decrease of range stress with increasing practical experience, we used the contrast weights 19, 15, −5, −29 to map this hypothesis onto our four points of data collection (i.e., to account for different time intervals between data collection points following Furr, 2008). The results showed that the data fitted H2a, revealing a strong, significant relationship between hypothesis and data ($r_{\text{contrast}} = .56, t(71) = 5.80, p < .001$), indicating the above-mentioned negative relationship between time of measurement and ERS. In addition to this general trend, Figure 3 shows that the decrease in range stress was somewhat more pronounced over the first week of vehicle usage compared to subsequent weeks.
5.2.2 **Effect of total driven distance (H2b)**

To test H2b, we computed the total distance driven by the main user with the BEV until T2 based on logger data. For this and all following univariate regression analyses, assumptions (normality, linearity, no outliers) were tested according to Field (2009). Assumptions were satisfactorily met despite single outliers for some analyses that were detected via case-wise diagnostics (standardized residuals, Cook’s distance, leverage values, standardized DFBeta). Consequently, analyses were computed with and without these cases, as suggested by Urban and Mayerl (2008). All results are depicted in Table 3.

As expected for H2b, the higher the total distance driven with the BEV, the lower the ERS, as revealed in a significant yet relatively weak effect (see column β-weights in Table 3, for univariate regression β-weights are equivalent to r).

5.2.3 **Effect of actively exhausting range (H2c)**

As expected for H2c, the more specific experience that drivers had gathered with low-range situations (i.e., the more they had actively exhausted range), the lower the ERS (moderate and significant effect).

5.3 **Acquired coping skills and range stress (H3)**

As expected for H3a, the higher the subjective range competence, the lower the ERS, as revealed in a moderate and significant effect.
Regarding H3b, the effect was in the expected direction (i.e., higher technical system knowledge was related to lower range stress) but was weak and not clearly significant (i.e., only significant in analysis with outliers).

5.4 Tolerance of low-range situations and range stress (H4)

As expected for H4a, the higher the comfortable range the lower the ERS, as revealed in a moderate and significant effect (strong effect in analysis without outlier cases).

Also, as expected for H4b the lower the individual low-range aversiveness, the lower the ERS (moderate and significant effect).

5.5 Perceived trustworthiness of range estimation system and range stress (H5)

As expected for H5, the higher the experienced trustworthiness of the range estimation system the lower the ERS, as revealed in a moderate, significant effect for both indicators (i.e., scales). Indeed, both scales produced almost equal results giving some indication that our newly developed scale is useful to assess experienced trustworthiness (for further analyses see Franke et al., 2015b).

Table 3. Relation of individual predictor variables to ERS

<table>
<thead>
<tr>
<th>Model component</th>
<th>Hypothesis: variable</th>
<th>N</th>
<th>β</th>
<th>p</th>
<th>$R^2_{adj}$</th>
<th>Outliers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Practical experience</td>
<td>H2b: distance driven</td>
<td>68 (66)</td>
<td>-.22 (-.25)</td>
<td>.034 (.022)</td>
<td>.04 (.05)</td>
<td>$L_{val} = .12$</td>
</tr>
<tr>
<td></td>
<td>H2c: active range exhaustion</td>
<td>72</td>
<td>-.36</td>
<td>.001</td>
<td>.12</td>
<td></td>
</tr>
<tr>
<td>Coping skills</td>
<td>H3a: subjective range competence</td>
<td>72 (70)</td>
<td>-.34 (-.28)</td>
<td>.002 (.009)</td>
<td>.10 (.07)</td>
<td>$L_{val} = .09$</td>
</tr>
<tr>
<td></td>
<td>H3b: technical system knowledge</td>
<td>72 (71)</td>
<td>-.21 (-.17)</td>
<td>.039 (.082)</td>
<td>.03 (.01)</td>
<td>$L_{val} = .11$</td>
</tr>
<tr>
<td>Tolerance of low range</td>
<td>H4a: comfortable range</td>
<td>64 (61)</td>
<td>-.47 (-.51)</td>
<td>&lt;.001 (&lt;.001)</td>
<td>.21 (.25)</td>
<td>$L_{val} = .13$</td>
</tr>
<tr>
<td></td>
<td>H4b: low-range aversiveness</td>
<td>72</td>
<td>.45</td>
<td>&lt;.001</td>
<td>.19</td>
<td></td>
</tr>
<tr>
<td>Trustworthiness of range estimation</td>
<td>H5: facets of trustworthiness</td>
<td>72</td>
<td>-.32</td>
<td>.003</td>
<td>.09</td>
<td></td>
</tr>
<tr>
<td></td>
<td>H5: trust in automation</td>
<td>72 (71)</td>
<td>-.33 (-.32)</td>
<td>.002 (.003)</td>
<td>.10 (.09)</td>
<td>$L_{val} = .09$</td>
</tr>
</tbody>
</table>

Note. P-values are one-tailed. Both variables of the facet trustworthiness of range estimation were cube-transformed to meet the assumption of normality. $L_{val} = $ Leverage value. $Z_{RE} = z$-standardized residual value. Outliers were identified and the analysis was repeated without these cases. Results after outlier exclusion are given in parentheses.

5.6 Total variance explained by examined resilience factors (H6)

Citation: Franke, T., Rauh, N., Günther, M., Trantow, M., & Krems, J. F. (in press). Which factors can protect against range stress in everyday usage of battery electric vehicles? Towards enhancing sustainability of electric mobility systems. Human Factors.

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To examine the amount of variance that the examined resilience factors can explain in total (H6), we computed an additional multiple regression analysis (method: forced entry). In accordance with our model (see Figure 2), we aggregated the eight variables into the four respective factors (practical experience, coping skills, tolerance of low range, trustworthiness of range estimation) by computing factor scores. Resulting factor loadings were acceptable for all but one variable (.25 for range competence, other factors .46 – .84). In the end, we decided to compute the factor scores in order to be able to examine the model. That is, we judged that the problems associated with testing eight predictors (i.e., multi-collinearity and too small sample size for testing so many predictors) far outweighed the problem of including a relatively heterogeneous factor score in the analysis. Assumptions (i.e., no multivariate outliers, normally distributed residuals, no multicollinearity, no heteroscedasticity) were tested according to Field (2009) and were satisfactorily met.

As depicted in Table 4, the model explained approximately 30% of variance in ERS. Inspecting zero-order correlations it can be seen that all factors were related to range stress (moderate to strong effects). Yet, as indicated by part correlations, these contributions to range stress were partially redundant. In particular, the effect of experience on ERS disappeared with the introduction of further factors (compare zero-order versus part correlations), indicating that this factor does not explain variance in ERS that cannot also be explained by the other factors. Tolerance of low range and trustworthiness of range estimation are significant predictors of ERS, and hence contribute particularly to lower range stress.

Table 4. Relation of aggregated model factors to ERS

<table>
<thead>
<tr>
<th>Predictor (model component)</th>
<th>$r_{zero\text{-}order}$</th>
<th>$r_{partial}$</th>
<th>$r_{part}$</th>
<th>$\beta$</th>
<th>$p$</th>
<th>$R^2_{adj}$ ($R^2$)</th>
<th>$p$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Practical experience</td>
<td>-.29</td>
<td>.00</td>
<td>.00</td>
<td>.00</td>
<td>.498</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coping skills</td>
<td>-.35</td>
<td>-.16</td>
<td>-.13</td>
<td>-.15</td>
<td>.112</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tolerance of low range</td>
<td>-.50</td>
<td>-.38</td>
<td>-.34</td>
<td>-.42</td>
<td>.002</td>
<td>.30 (.35)</td>
<td>&lt;.001</td>
</tr>
<tr>
<td>Trustworthiness of range estimation</td>
<td>-.37</td>
<td>-.25</td>
<td>-.21</td>
<td>-.23</td>
<td>.032</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note. $N = 60$ because of missing values. $p$-values for $\beta$-weights are one-tailed, $p$-value for the variance explained by the whole model ($R^2_{adj}$) is two-tailed (i.e., because of omnibus test).

Citation: Franke, T., Rauh, N., Günther, M., Trantow, M., & Krems, J. F. (in press). Which factors can protect against range stress in everyday usage of battery electric vehicles? Towards enhancing sustainability of electric mobility systems. Human Factors.

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5.7 Outcomes of range stress (H7)

As expected for H7a, the more ERS users experienced between T1 and T2, the lower their range satisfaction at T2 (significant effect, weak to moderate, see Table 5).

For H7b, also as expected, the higher the ERS the lower the general BEV acceptance in terms of perceived usefulness and satisfaction (significant, moderate effect).

Table 5. Relation of ERS to outcome variables

<table>
<thead>
<tr>
<th>Model component</th>
<th>Hypothesis: variable</th>
<th>N</th>
<th>$\beta$</th>
<th>$p$</th>
<th>$R^2_{adj}$</th>
<th>Outliers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outcome variables</td>
<td>H7a: range satisfaction</td>
<td>72 (71)</td>
<td>-22 (-.32)</td>
<td>.032 (.004)</td>
<td>.03 (.09)</td>
<td>$z_{RE} = -2.66$ $L_{val} = .08$</td>
</tr>
<tr>
<td></td>
<td>H7b: BEV acceptance</td>
<td>72 (70)</td>
<td>-.33 (-.40)</td>
<td>.003 (&lt;.001)</td>
<td>.09 (.15)</td>
<td>$z_{RE} = -2.43$ $L_{val} = 2.19$</td>
</tr>
</tbody>
</table>

Note. $P$-values are one-tailed. BEV acceptance was exponentially transformed (exponent: 4) to meet the assumption of normality. $L_{val} =$ Leverage value. $z_{RE} =$ $z$-standardized residual value. Outliers were identified and the analysis was repeated without these cases. Results after outlier exclusion are given in parentheses. For range satisfaction, the one outlier case was detected via two measures.

6 DISCUSSION

6.1 Summary of Results

The objective of the present research was to examine factors that can protect against range stress in everyday BEV usage. In general, our hypotheses were confirmed. Less frequent encounters with critical range situations (H1), experience in general (H2a), higher accumulated practice (H2b), higher gathered experience from exploring low-range situations (H2c), higher subjective range competence (H3a), higher comfortable range (H4a), lower aversiveness of low-range (H4b) and higher experienced trustworthiness of the range estimation system (H5) were all related to lower ERS. Only H3b, regarding higher technical knowledge, was not clearly confirmed. Moreover, together, the four examined resilience factors could account for a considerable share of the variance in ERS (H6). Particularly, tolerance of low range and trustworthiness of range estimation turned out to be key predictors of ERS (i.e., key resilience factors) and should therefore be considered as core concepts in further development of a general model of user interaction with low-resource systems. Finally, as expected, range stress was also found to be relevant for range satisfaction (H7a) and BEV acceptance (H7b).
6.2 Implications

The results of the present research show that there is an objective basis for ERS (see results of H1). Yet, the results also reveal the important impact of users’ individual adaptive capacity (at least factors such as practical experience, coping skills, tolerance of low-resource situations, system coping support) on ERS. This contribution of subjective factors to range stress reveals the great potential of green ergonomics interventions (Thatcher, 2013). This pattern of results is also in accordance with the ACOR model (see section 2.2).

Particularly based on the premise that wasting battery resources is not sustainable (see section 1 and Franke & Krems, 2013b), it becomes clear that improving user-friendliness of range management should be given high priority in further system development. This is especially true in view of the demonstrated relationship of ERS to user satisfaction and BEV acceptance, which clearly shows that counteracting even relatively infrequent instances of ERS could contribute considerably to increased adoption of sustainable system layouts.

With regard to methodological implications, the general field study approach of the present research proved promising for identifying resilience factors against ERS. However, this is only a first step towards improved system design. In further steps, experimental research should develop and test intervention strategies for the variables identified as increasing drivers’ adaptive capacity (e.g., increase resource indicator trustworthiness, help users gain experience with critical system states). Hence, to support sustainable development, human factors research must be based on an iterative interplay of different methodological approaches that build upon each other, with the ultimate goal of establishing a general theory of user interaction with sustainable systems.

Another implication concerns the effect of experienced trustworthiness of range estimation on ERS. This effect shows the importance of a well-designed human-machine interface (HMI) for resource information and implies that in further development of such interfaces, experienced trustworthiness should be a primary benchmark variable for system design and evaluation. In this regard, the self-constructed 5-item trustworthiness scale seems to be a good indicator to assess trustworthiness of range estimation, as it yielded comparable results to the established scale of Jian et al. (2000) and yet, is shorter and has higher face validity (i.e., is easier to relate to a display-based information system for respondents).
6.3 Limitations and further research

Several limitations and directions for further research have to be considered. First, the analyzed indicator for critical range situations was not exhaustive as it covered only one kind of critical range situation (i.e., very low resource state), and this led to several users having no such situations recorded. In our study, this was the only type of situation that could be identified unambiguously based on the available logger data. A more comprehensive indicator could be to continuously track the available range buffer and compute the relative share of kilometers driven under critical range conditions.

Second, in an ideal case it would have been possible to test all our hypotheses together in a structural equation model. However, our sample size was not sufficient to conduct a structural equation model analysis with so many variables. A possibility for future research could be to strive to simplify the research design to render it possible to examine the relevant constructs maybe even in an online questionnaire study with a large sample of early-adopter BEV customers.

Third, the present research only examined one aspect of technical system coping support (i.e., trustworthiness of range estimation system). In addition to supporting drivers in their range prediction (i.e., range assessment) further technical coping support systems (i.e., driver information and assistant systems) could be developed to increase drivers’ ability to control (i.e., extend) range, for example, systems that help to reduce cognitive workload in ecodriving.
7 KEY POINTS

- We examined the role of drivers’ adaptive capacity (i.e., resilience) in drivers’ everyday range stress (ERS) in battery electric vehicle (BEV) usage.
- The examined resilience factors (practical experience, coping skills, tolerance of low range, and trustworthiness of range estimation) have the potential to protect against range stress.
- Together the resilience factors explained approximately 30% of variance in ERS.
- Higher ERS was related to lower range satisfaction and lower BEV acceptance. This underlines the importance of developing strategies that protect against range stress.

8 ACKNOWLEDGEMENTS

This research is based on a field trial that was set up by a consortium of the BMW Group, Stadtwerke Leipzig, and Technische Universität Chemnitz and was funded by the German Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety (16SBS014B). Statements in this paper reflect the authors’ views and do not necessarily reflect those of the funding body or of the project partners. We are grateful for the support of our consortium partners, the BMW Group (particularly Dr. Roman Vilimek, Viktoria Zott, Dr. Andreas Keinath, Dr. Jens Ramsbrock) and Stadtwerke Leipzig, who made our research possible. We also gratefully thank Torsten Müller, Dr. Johann Prenninger and Oliver Angermaier for collecting and pre-processing logger data, and Matthias Arend and Christiane Attig for fruitful discussions and supporting manuscript preparation.


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Landry, G. Di Bucchianico, & A. Vallicelli (Eds.), *Advances in Human Aspects of Transportation Part II. AHFE Conference* (pp. 334-344). AHFE Conference.


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**Citation:** Franke, T., Rauh, N., Günther, M., Trantow, M., & Krems, J. F. (in press). Which factors can protect against range stress in everyday usage of battery electric vehicles? Towards enhancing sustainability of electric mobility systems. *Human Factors.*

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### 10 APPENDIX

Translated item texts of all newly constructed or revised scales (original German item wording can be obtained from the authors).

<table>
<thead>
<tr>
<th>Scale label</th>
<th>Item text</th>
</tr>
</thead>
<tbody>
<tr>
<td>Range stress</td>
<td>While driving with the BEV...</td>
</tr>
<tr>
<td>i1: ...I am more worried about the range than I would be in a combustion vehicle.</td>
<td></td>
</tr>
<tr>
<td>i2: ...I am often worried about the range.</td>
<td></td>
</tr>
<tr>
<td>i3r: ...I seldom have worries about the remaining range.</td>
<td></td>
</tr>
<tr>
<td>Active range exhaustion</td>
<td>i1: I have repeatedly exhausted the range of the ActiveE.</td>
</tr>
<tr>
<td>i2r: I have deliberately avoided driving at the range limit of the BEV.</td>
<td></td>
</tr>
<tr>
<td>Subjective range competence</td>
<td>i1: I can precisely estimate the range of my BEV under various conditions.</td>
</tr>
<tr>
<td>i2: I know how far I can go on a full charge.</td>
<td></td>
</tr>
<tr>
<td>i3: I can precisely estimate the influence of different factors on the range of my BEV.</td>
<td></td>
</tr>
<tr>
<td>i4r: The range of my BEV is mostly affected by factors over which I have no influence.</td>
<td></td>
</tr>
<tr>
<td>i5: How far I can go with my BEV (which range I obtain) essentially depends upon me.</td>
<td></td>
</tr>
<tr>
<td>i6: The range I can reach with my BEV is mostly dependent on factors that I can control.</td>
<td></td>
</tr>
<tr>
<td>Technical system knowledge</td>
<td>i1: I am familiar with the propulsion technology of electric vehicles (e.g., types and functionality of electric engines).</td>
</tr>
<tr>
<td>i2: I am familiar with conventional units of electricity (e.g., meaning of watt, ampere, kWh).</td>
<td></td>
</tr>
<tr>
<td>i3: I know different characteristics of various battery chemicals/materials.</td>
<td></td>
</tr>
<tr>
<td>i4: I have an idea about how recuperation technically works.</td>
<td></td>
</tr>
<tr>
<td>i5: I am able to explain why an electric vehicle is more efficient than an internal combustion vehicle, especially in urban areas.</td>
<td></td>
</tr>
<tr>
<td>i6: I am familiar with concepts like energy density and energy conversion efficiency.</td>
<td></td>
</tr>
<tr>
<td>Low-range aversiveness</td>
<td>i1r: I am still rather relaxed when the battery is almost empty.</td>
</tr>
<tr>
<td>i2: I always want to have an energy reserve in the battery.</td>
<td></td>
</tr>
<tr>
<td>Facets of system trustworthiness</td>
<td>i1: The range estimation of the BEV is reliable.</td>
</tr>
<tr>
<td>i2: The range estimation of the BEV is precise.</td>
<td></td>
</tr>
<tr>
<td>i3: The range estimation of the BEV is traceable.</td>
<td></td>
</tr>
<tr>
<td>i4: I can trust the range estimation of the BEV.</td>
<td></td>
</tr>
<tr>
<td>i5r: I cannot depend on the range estimation in the BEV.</td>
<td></td>
</tr>
<tr>
<td>Range satisfaction</td>
<td>i1: I am satisfied with the range of the BEV.</td>
</tr>
<tr>
<td>i2: The range of the BEV meets my expectations.</td>
<td></td>
</tr>
<tr>
<td>i3: The range of the BEV is sufficient for accomplishing my trips.</td>
<td></td>
</tr>
<tr>
<td>i4: The range of the BEV is sufficient for everyday use.</td>
<td></td>
</tr>
<tr>
<td>i5r: I feel constrained in my action radius due to the range of the BEV.</td>
<td></td>
</tr>
<tr>
<td>i6r: The range of the BEV is a major barrier for its usage as a normal vehicle.</td>
<td></td>
</tr>
</tbody>
</table>

**Note.** Items with an “r” were reversed before computing a mean score. Items of scales that have already been published are omitted (references are included in the Method section). Participants answered all items displayed here on a 6-point Likert scale from *completely disagree* to *completely agree*, coded as 1 to 6.

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**Citation:** Franke, T., Rauh, N., Günther, M., Trantow, M., & Krems, J. F. (in press). Which factors can protect against range stress in everyday usage of battery electric vehicles? Towards enhancing sustainability of electric mobility systems. *Human Factors.*  
**Date:** 06.10.2015
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