User experience with electric vehicles while driving in a critical range situation – a qualitative approach

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Abstract:
A frequently discussed phenomenon within the context of battery electric vehicles (BEV) is range anxiety. Range anxiety is defined as a domain specific form of psychological stress, which can occur in a critical range situation. The objective of the present research is to better understand user experience in critical range situations (i.e., range anxiety). After driving a BEV in a critical range situation on an unaccompanied trip of 94 km length, 68 participants were asked about experienced stress-inducing and stress-reducing factors, as well as ideas for additional stress reducing strategies. The available range safety buffer and the uncertainty regarding the energy consumption of the BEV could be identified as central factors related to user experience in critical range situations. The obtained results can be utilized to formulate design recommendations to help future BEV users to better handle critical range situations. Installing displays which allow for accurate tracking of the range safety buffer, or providing knowledge to reduce uncertainty might be a good starting point for improving user experience.

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1. INTRODUCTION

One of the most important barriers to widespread acceptance of battery electric vehicles (BEV) is their limited range [1]. In this regard, range anxiety has been repeatedly discussed both in media coverage ([2], [3], [4]) and scientific literature ([5]) and was found to be negatively related to the efficient usage of BEV range resources (e.g., [6], [7]). We propose that range anxiety is best conceptualized as a domain-specific form of psychological stress, which can occur in a present or anticipated critical range situation [8]. There is some indication that relevant domain-specific knowledge regarding range and a better understanding of range dynamics while driving might help to alleviate range anxiety [6]. Hence, advanced driver assistance systems and an improved user interface design might represent fruitful approaches for reducing range anxiety. Especially regarding BEVs such systems and interfaces seem to be meaningful because one can assume that currently critical range situations are more likely while using BEVs than for combustion vehicles [8] due to a less dense charging network for BEVs, long charging durations and a limited range of typically around 150 km when fully charged. Hence, we assume that range anxiety and therefore the need for advanced driver assistance systems and an improved user interface design might be more important in BEV use than in combustion vehicles. However, in order to develop a user-centered system design, it is important to comprehensively understand the user experience in critical range situations (i.e., range anxiety). To our knowledge, published research that focuses specifically on user experience in critical range situations is currently lacking. Previous evidence suggests that managing BEV range in everyday use is typically not characterized by experience, but by avoidance of such situations [6]. Therefore, studies examining user experience in critical range situations as one of several variables within a field trial lasting several weeks (e.g., [9], [10]) might fail to produce much usable data. Additionally, users typically cannot be interviewed immediately after experiencing such situations, but only after a few days or weeks, which subjects the data to retrospective biases and memory degradation.

The objective of the present study is to examine user experience immediately after a critical range situation by using a qualitative approach. To this end we analyzed data from a field experiment. Our approach is exploratory, focusing on the identification of different stress-inducing and stress-reducing factors participants experienced in a critical range situation, as well as their additional ideas for reducing experienced stress.

2. METHOD

2.1 Participants

Participants were recruited via an online screening questionnaire. Due to insurance reasons
only members of the Technische Universität Chemnitz (employees and students) could be recruited. An invitation was sent by E-Mail which also contained the link to the online screening questionnaire. Additionally a short article about the study was posted on the internal news page of Technische Universität Chemnitz. Seventy-four drivers completed the experiment. For the analysis it was important that participants experienced a critical range situation. The criterion of driving in a critical range situation was defined as having a minimal experienced available range buffer during the trip that was smaller than the average preferred minimum range safety buffer (item: “Which range buffer do you set for yourself, below which you would not be willing to drive the BEV anymore (except in exceptional circumstances)?”). Six participants did not fulfill this criterion (the minimal experienced available range buffer was higher than the average preferred minimum range safety buffer) and were excluded from the analysis.

The 68 participants (50 male and 18 female) were on average 31 years old (MIN = 24, MAX = 61, SD = 6.70), possessed a driver license since M = 12 years (MIN = 7, MAX = 34, SD = 5.66), drove M = 1100 km (Min = 100; Max = 6000; SD = 922) per month with a conventional car and had M = 15.73 km BEV driving experience (MIN = 0, MAX = 200, SD = 39.74). Additionally, participants were asked for their system knowledge regarding relevant aspects of BEV technology with three different items (“I am familiar with typical units of electrical engineering (meaning of ampere, watt, kWh)”; “I am familiar with propulsion technology of electric vehicles (e.g., types and functionality of electric engines.)”; “I have knowledge about specific features of technical components, which are incorporated into the ActiveE (e.g., power electronics, dimensioning of the regenerative breaking system, displays, driving strategies,...”). All three items were answered on a 6-point Likert scale from (1) completely disagree to (6) completely agree. Cronbach’s Alpha for the three items was .79 and a mean score was computed. On average, participants rated their system knowledge as moderate (M = 4.00; SD = 1.15). Thirty-one percent of all participants estimated their knowledge as quite low (average values from 1 up to 3.5) and 69 % estimated their knowledge as quite high (average values from 3.5 up to 6).

2.2 Field experiment setup

We instructed participants to drive a round trip. They were informed that they will experience a critical range situation (i.e., remaining range was only marginally sufficient to complete the trip) due to BEV range in relation to trip length. They were briefed that the aim of the study was to examine user experience in a critical range situation.

The BEV used in this study was an ActiveE with a maximum available driving range

between 130 km and 160 km, depending on driving style [11]. The BEV had an ECO PRO mode that could be selected by pressing a button to automatically adjust the drive configuration and comfort functions to achieve a higher range. Range information was displayed via a digital remaining range display in km (range estimation based on charge level and energy consumption over the last 30 km, as stated in the user manual). Additionally, there was an onboard navigation system, which displayed the route and the remaining km the participants had to drive. This was the only information that participants had to estimate the criticality of the range situation.

At the beginning participants received a short briefing to the BEV including technical parameters, relevant displays (digital remaining range display, onboard navigation system, and speedometer) and explanation of specific functions like regenerative braking, followed by a short accompanied training track. Before the trip participants completed a questionnaire asking for the demographic variables, system knowledge regarding relevant aspects of BEV technology and questions regarding the range safety buffer including the preferred minimum range safety buffer.

With an average available driving range of 113 km ($\text{MIN} = 97; \text{MAX} = 137; \text{SD} = 7.5$), participants drove on a 94 km unaccompanied round-trip in a hilly rural area with small villages and country roads. In the last section of the route, there was a 17 km long section of a German Autobahn. The round trip was designed to lead to a critical range situation due to the energy consumption profile of the first sections (e.g., driving mostly uphill, which is positively correlated with a high consumption: participants started the trip at 298 m above sea level and drove up to 600 m above sea level after approximately 37 km). Participants stopped at several predefined locations during the trip and recorded their current remaining range and the remaining trip length. Over the whole trip, participants experienced a minimum available range safety buffer of $M = -2.45$ km ($\text{MIN} = -27.0$ km; $\text{MAX} = 11.0$ km; $\text{SD} = 9.14$; participants' preferred minimum range safety buffer was $M = 11.93$). At these locations participants also had to call the experimenter. During these calls the experimenter asked for problems during the trip and the ECO PRO mode was introduced to the participants.

### 2.3 Data collection

Participants reported their experience of the critical range situation immediately after the round trip in a structured interview (several interviewers). They were asked with open-ended questions (Q1) for stress-inducing factors (“What worried you during the test drive? Which situations led to increased stress?”), (Q2) for stress-reducing factors (“What calmed you down? Which situations decreased your stress level?”), and (Q3) for further strategies for reducing the stress level (“What would have helped you to be less stressed (e.g., which additional information before or while driving?)”). We conducted a pilot study with 8
participants to test the whole experiment and to examine if the interview questions were understandable and helped participants to concentrate on the topics of interest. Based on this we slightly reformulated the interview questions for the main study.

2.4 Data analysis

Interview data were analyzed using the inductive category development methodology according to Mayring [12]. First, all answers were recorded and transcribed question by question. After that, all of participants’ statements were coded by two independent coders and a system of categories was developed. Over the course of the coding process, including regularly discussions between the two coders, the system of categories was refined until a sufficiently condensed categorical structure was obtained for describing how participants experienced the critical range situation.

Following an exploratory approach, we were not primarily focused on the absolute number of participants in each category (i.e., the importance or relevance of, for example, a certain stressor in relation to another one). Rather, we focused on the identification of a wide range of categories describing participants’ experience in a critical range situation (i.e., which aspects caused stress and which aspects reduced stress). Still, in the following we report only those categories, which were mentioned by at least 10% of all participants (i.e., seven participants) for reasons of clarity.

3. RESULTS

In the following section, we present the extracted categories (labeled with C, e.g., C1; only categories reported by a minimum of 10% of all participants) of stress-inducing factors (Q1_StressInd), stress-reducing factors (Q2_StressRed), and additional stress reduction ideas (Q3_Idea). For a better understanding of the categories, and thereby, user experience in a critical range situation, we provide translated examples of actual participant statements, which are representative of the categories (alongside the participant number, e.g., P12). Thus, the actual wording of the statements was preserved as closely as possible given the necessary changes inherent to the translation process. Annotations by the authors for better clarification of some statements are written in brackets in italics. Table 1 gives an overview of interview questions, categories derived from participants’ answers and some examples to better describe the categories.

Table 1: Interview questions, categories derived from participants’ answers and examples for each category.

<table>
<thead>
<tr>
<th>question (Q)</th>
<th>categories (C)</th>
<th>examples</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Q1_StressInd</th>
<th>Q1C1</th>
<th>Q1C2</th>
</tr>
</thead>
<tbody>
<tr>
<td>stress-inducing factors</td>
<td>decreasing range</td>
<td>uncertainty</td>
</tr>
<tr>
<td>(&quot;What worried you during the test drive? Which situations led to increased stress?&quot;)</td>
<td>clearly noticeable decrease in range</td>
<td>uncertainty regarding BEV energy consumption</td>
</tr>
<tr>
<td></td>
<td>decreasing range safety buffer</td>
<td>anticipation of the potential for high consumption</td>
</tr>
<tr>
<td></td>
<td>range safety buffer became negative</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Q2_StressRed</th>
<th>Q2C1</th>
<th>Q2C2</th>
<th>Q2C3</th>
</tr>
</thead>
<tbody>
<tr>
<td>stress-reducing factors</td>
<td>sufficiency of / increase in range</td>
<td>enhance certainty</td>
<td>energy consumption assistance factors</td>
</tr>
<tr>
<td>(&quot;What calmed you down? Which situations decreased your stress level?&quot;)</td>
<td>enough remaining range</td>
<td>appropriate user interface</td>
<td>ECO PRO mode</td>
</tr>
<tr>
<td></td>
<td>sufficient range safety buffer</td>
<td>familiarity with the route</td>
<td>successful energy-efficient driving style</td>
</tr>
<tr>
<td></td>
<td>increase in range safety buffers</td>
<td></td>
<td>regenerative braking</td>
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</table>

<table>
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<tr>
<th>Q3_Ideas</th>
<th>Q3C1</th>
<th>Q3C2</th>
</tr>
</thead>
<tbody>
<tr>
<td>stress reduction ideas</td>
<td>more knowledge in general</td>
<td>more information while driving</td>
</tr>
<tr>
<td>(&quot;What would have helped you to be less stressed (e.g., which additional information before or while driving?)&quot;)</td>
<td>about energy-efficient driving style</td>
<td>feedback on individual driving style</td>
</tr>
<tr>
<td></td>
<td>about ECO PRO mode</td>
<td>about charging station network</td>
</tr>
<tr>
<td></td>
<td>about interpretation of display information</td>
<td>detailed consumption information</td>
</tr>
<tr>
<td></td>
<td>about consumption under different conditions</td>
<td></td>
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<tr>
<td></td>
<td>about elevation profile of the entire trip</td>
<td></td>
</tr>
<tr>
<td></td>
<td>about existence of a range reserve</td>
<td></td>
</tr>
</tbody>
</table>

### 3.1 Stress-inducing factors (Q1_StressInd)

As one might expect, when asked for stress-inducing factors (Q1_StressInd), participants reported decreasing range (Q1C1), for instance limited available range safety buffers; and uncertainty (Q1C2), for instance uncertainty regarding consumption on different parts of the trip.

#### 3.1.1 StressInd: decreasing range (Q1C1)

Regarding the category decreasing range (Q1C1), one participant stated:

"[...] at the beginning the range display - the remaining range - decreased relatively fast." (P12)

For some participants, the clearly noticeable decrease in range was surprising:

"I think it was the first section when I left Chemnitz [Chemnitz was the starting point for the trip] - the remaining range display decreased relatively fast as I drove uphill, well, it was clearly noticeable - surprising." (P26)
More often they endorsed the decreasing range safety buffer (i.e., difference between displayed remaining range and remaining trip length) rather than the decrease of remaining range in general as stress-inducing:

"But it was just every time, when the buffer became a little bit small." (P11)

"[…] that there was temporarily just a 3 kilometers difference between the route I still had to drive and the total distance the car still was able to drive. Well, I really was temporarily very nervous." (P35)

The moment when the range safety buffer became negative (i.e., remaining range was smaller than remaining trip length) was especially stress provoking for participants:

"Well, every time when range fall below the remaining trip length." (P39)

3.1.2 StressInd: uncertainty (Q1C2)

Regarding the category uncertainty (Q1C2), for instance with respect to BEV energy consumption, participants stated:

"Well, actually only in the first section, because at this time I could not estimate how much I will consume and how much I can regain." (P43)

"Well, sometimes the unexpected fluctuation of range […] sometimes it decreased faster, sometimes slower […]. That irritated me a little bit. And then I was always wondering: will it decrease or increase?" (P53)

The uncertainty regarding consumption, particularly the anticipation of the potential for high consumption on the last part of the trip (i.e., on the Autobahn), stressed participants:

"And then the Autobahn - well, as I realized that we have to drive on the Autobahn, I was not sure anymore." (P57)

"[…] and I thought: Okay, the Autobahn is still ahead! […] the large distance […] I will not make it anymore." (P64)

3.2 Stress-reducing factors (Q2_StressRed)

Regarding stress-reducing factors (Q2_StressRed), the data indicated that sufficiency of / increase in range while driving (Q2C1), certainty enhancement factors (Q2C2), for instance an appropriate user-interface allowing for accurate tracking of the range buffer, familiarity with the route; and energy consumption assistance factors (Q2C3), for instance regenerative breaking and Eco-Pro mode would be helpful.
3.2.1 StressRed: sufficiency of / increase in range (Q2C1)

Regarding the category suffixiciency of / increase in range (Q2C1), participants reported:

"Simply that you had enough remaining range to reach the destination." (P17)

More frequently, they endorsed a sufficient range safety buffer (i.e., difference between displayed remaining range and remaining trip length) rather than the remaining range in general as stress-reducing:

"Well, as long as the remaining range was higher than the remaining trip length, everything was okay." (P36)

One additional interesting finding related to (Q2C1) was that users appraised an increase in range safety buffers as a stress-reducing factor, even if this buffer was still very small.

"[...] When I was successful, or alternatively it just happened that the difference became bigger – once it increased to 8 kilometers or so between the remaining range and remaining kilometers to drive." (P63)

"Well, first the fact that there is a negative buffer, well that... yes, that it was negative, because I realized that I calmed down when it, at the start, was at least plus/minus zero." (P49)

3.2.2 StressRed: certainty enhancement factors (Q2C2)

Regarding the category certainty enhancement factors (Q2C2), participants reported an appropriate user interface that allowed for accurate tracking of the range buffer:

"It calmed me that I could always see: How much remaining range I have and how many kilometers I still have to drive? And this difference was always positive." (P13)

"[...] the precise feedback of the range display. Well, you effectively always had the feeling that the range display really showed a value that is trustworthy. Because it changed frequently and adapted to the driving style." (P34)

Furthermore, also regarding (Q2C2), participants reported familiarity with the route:

"[...] that it goes downhill at the end and you can save some energy, that was relatively clear to me, because I know the route" (P09)

"I would say, because I know the route well […], that it will go into the mountains and then, on the way back, downhill – well, knowing that it will go downhill." (P68)

3.2.3 StressRed: energy consumption assistance factors (Q2C3)

Regarding the category energy consumption assistance factors (Q2C3), participants mentioned, for instance, existence of the Eco-Pro mode:

"After finding the Eco-Pro mode - that calmed me, too." (P60)
Regarding (Q2C3), participants also reported a successful energy-efficient driving style as a stress-reducing factor:

"And that you got experience with this special electric powertrain while driving. That you know you can calculate how much range remains. That you see, how much energy you can regain, that you reach the kilometers you need to drive. And then you got a feeling for the gas pedal to drive really efficiently." (P23)

"Well, that you learn, as time passed, that your own driving style can contribute to a slower decrease of range." (P69)

"On the one hand, certainly the range display. That you can see how through a special – well, through a predictive driving style - that you also add kilometers. That it is appreciated, I will say." (P41)

Another point regarding (Q2C3) is the regenerative braking, which was mentioned by participants:

"Well, also that kilometers were added through this recharge-thing. But that was actually the main reason, it was very calming." (P22)

"And also to see, when you are driving downhill, and two or three kilometers are regained through regenerative breaking – you see at least, that it is somehow of use and it does something." (P26)

### 3.3 Stress reduction ideas (Q3_Ideas)

Regarding additional ideas for reducing stress (Q3_Ideas), participants reported more knowledge in general (Q3C1) and more information while driving with a comprehensive user-interface (Q3C2).

#### 3.3.1 Ideas: more knowledge in general (Q3C1)

Regarding the category more knowledge in general (Q3C1), participants reported more knowledge about energy-efficient driving style, ECO PRO mode, interpretation of display information, consumption under different conditions such as Autobahn driving or using different electrical loads like heating or radio, elevation profile of the entire trip or about the existence of a range reserve. A selection of five statements, which provide an impression of participants’ additional ideas for reducing stress by providing more knowledge before driving, is shown below:

"Like I said, if I had had knowledge about the Eco-Pro mode right from the beginning, it wouldn’t have been so stressful at the beginning. […] And also the route profile. If I had had knowledge about it, I think I wouldn’t have been so stressed at the first sections […]" (P69)

"Basically, if the consumption is considerably higher on the German Autobahn or while driving with..."
high velocities. This means, the comparison between driving in the city with permanent stop and go, and continuous driving with high velocities. […] I mean, if I had known this before, I would have dealt a little bit more relaxed with the whole thing.” (P20)

"The relative amount of the air conditioning system and the radio, thus how much energy they usually consume. Thus, I simply thought it is just a little bit regarding the radio, but regarding the heating I simply didn’t know it, I had no idea. […] I didn’t know which effect it had.” (P51)

"I would have liked to know how the remaining range is calculated. Thus, which factors are responsible for the displayed remaining range. […] I have never driven an electric vehicle before and I have… thus, I know how a normal car works, a normal gasoline engine car, no matter if control gear or automatic. But I have absolutely no idea how an electric vehicle works. Thus, regarding a gasoline engine car I could imagine how the remaining range is calculated. And regarding my own car I can estimate it very very well, because I owned it for a very long time. But regarding an electric vehicle: no idea.” (P52)

"If you had known before that there is a certain buffer available. Thus, when the range [remaining range of the vehicle] is zero, you know that there are definitely fifteen, twenty or ten kilometers more available. Thus, such a certain buffer would have calmed me down definitely.” (P62)

3.3.2 Ideas: more information while driving (Q3C2)

Furthermore regarding the category more information while driving with a comprehensive user-interface (Q3C2), participants reported for instance feedback on individual driving style, information about charging station network and detailed consumption information. Again a selection of five statements, which provide an impression of participants’ additional ideas for reducing stress by providing knowledge while driving, is shown below:

"But I don’t know if it is possible: that by entering this route profile into the navigation system […]. That you just say, when it goes a bit uphill that it [the navigation system] calculated how much [range] you need on the basis of the route profile.” (P12)

"What would help me is such a head-up-display, so that you don’t always have to look down, because you have on the one hand the display where you can see the charging or discharging status, the remaining range, and from the navigation system, the remaining distance you still have to drive. It [the head-up-display] projected this data on the inside of windshield. So you can concentrate fully on the road and have all of the important information in the field of view.” (P23)

"That there is a display that shows how efficiently I drive. That means, I know that my battery, my engine, my complete energy consumption inside [the vehicle] worked optimally.” (P28)

"Well, maybe hints, how you can drive… well, from the car. […] Yes, energy-efficient driving style. Or, I also think that the pedal is very, very sensitive. You have to habituate to it so that you may find somewhere the right millimeter when the use of power and the [energy consumption?] are lowest.” (P40)

"Information regarding charging stations nearby. […] Maybe on the map, that it will not only be
displayed when you need it, but rather all the time, as a hint." (P63)

4. DISCUSSION

The present study was conducted to better understand user experience in critical range situations. Therefore a qualitative approach was used to examine different stress-inducing and stress-reducing factors participants experienced in a critical range situation, as well as their additional ideas for reducing experienced stress.

Results show that participants generated a variety of different responses to the interview questions (Q1-Q3). Out of these responses, (A) critical factors related to user experience could be extracted which might provide a starting point for improving the user experience, and (B) system design recommendations from these improvement suggestions could be derived that could help future BEV users to better manage critical range situations.

4.1 Critical factors related to user experience

Regarding (A) critical factors related to user experience, one relevant factor is the available range safety buffer. Results indicate that the difference between displayed remaining range and remaining trip length is very important for users (i.e., it is the primary variable that determines user experience). When this buffer decreases, usage comfort also decreases. In particular, the moment in which the range buffer becomes negative marks a substantial change in the quality of the user experience (i.e., it represents the tipping point for range stress). When the buffer increases, users calm down, even if the range buffer is still very small or still negative. Data indicates that in a critical range situation, participants used the available range buffer, rather than the absolute remaining range values when evaluating the situation. Therefore, it is essential to provide users with the information needed to accurately evaluate this buffer (e.g., remaining range, remaining trip length) in an easily accessible way. Another major critical factor is uncertainty with respect to BEV energy consumption. When users are unsure about the BEVs’ consumption due to individual factors (e.g., driving style), environmental factors (e.g., route profile, Autobahn) or BEV-related factors (e.g., different driving modes, effects of regenerative braking), the quality of user experience is reduced. On the other hand, familiarity with the route (e.g., route profile, shortcuts) and “getting a feeling” for the BEV (e.g., regarding the drive pedal, consumption and regeneration of energy under different conditions) improve user experience. Therefore, in order to feel comfortable even in a critical range situation, it is important to provide relevant knowledge for reducing uncertainty (e.g., help users to understand BEV energy consumption and development of BEV range under different conditions affected by various individual, environmental and BEV-related factors; provide information about route profile).

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4.2 System design recommendations

Regarding (B) system design recommendations, a fruitful approach might be the incorporation of displays that should allow for accurate tracking of the range buffer (i.e., matching of remaining range and remaining trip length), which means that the relevant information is optimally displayed (e.g., information visible simultaneously or perhaps the range safety buffer could be automatically computed by the BEV’s information management system and shown as a percentage or in total kilometers). As continuous information on this variable appears to be important in critical range situations, a head-up display or a similarly visible display location appears to be particularly helpful.

Moreover, more detailed/domain-specific information management systems seem to be meaningful. This approach would be especially helpful in reducing uncertainty as a stress-inducing factor. Here, two approaches appear important: 1) provision of information about the BEV, for instance information about eco-driving, different driving modes, interpretation of display information and consumption under different conditions, with, for instance, interactive manuals or trainings. One possibility is to implement this information at an early stage (e.g., within driving school training). As BEVs become more and more relevant in modern mobility, information about BEVs should be provided to novice drivers to reduce uncertainty in dealing with this new technology. And 2) provision of more information while driving, for instance feedback and hints for individual energy-efficient driving style, information about the range safety buffer, detailed consumption information and trip elevation profile through a comprehensive user interface. Therefore, effective displays (i.e., precise, dynamic, reliable) are needed. Individualized feedback regarding the success of users’ efforts to reduce energy consumption and recommendations for additional range enhancement strategies seem to be important issues.

Another interesting point emerging from participants’ answers is the importance of practical BEV driving experience to reduce stress experience in critical range situations. Participants stated that a better understanding of, for instance, displays, functionality of the electric engine and especially the different factors influencing range development while driving would be helpful to reduce stress. They mentioned that they got more familiar with all these specific issues of electric driving during the trip. This learning effect and its potential to reduce range anxiety are supposed to even increase with a longer period of driving experience with a BEV. Literature shows that practical driving experience with BEVs (defined as absolute km driven with a BEV) had the potential to reduce stress appraisal and stress experience in a critical range situation [8]. In [8] it was suggested that the effectiveness and efficiency of the learning process should be increased in order to reduce range anxiety of BEV drivers. However, data shows that this effect was higher for a driving experience of $M =$
89 months in comparison to three months. This implicates that the adaptation and learning process consumes a longer time period. Therefore it seems also fruitful to help BEV drivers to speed up this learning process, for instance with special tutor systems supporting the driver during each trip, advanced driver assistant systems that involve concepts from the field of gamification or with special accompanied BEV trainings. Strategies aimed at decreasing range anxiety should ideally be designed to be in effect for more than just the first three months.

4.3 Limitations and further research

It is possible that the results of the current study did not cover all relevant aspects which are important in critical range situations (especially regarding stress-inducing factors) due to the experimental setting. Participants might have been less stressed while driving in the field experiment context compared to driving under everyday conditions (e.g., they might have felt less anxious about negative consequences, because of the fact that the university had the ultimately responsibility). In future research, experience in critical range situations should also be examined under everyday conditions, for instance a naturalistic driving study with focus on critical range situations with participants who are predestinated for experiencing critical range situations (e.g., long distance commuters).

Additionally the current research took place in winter under harsh conditions (snow, ice, sparse light) which are stressful conditions themselves for some participants. It is possible that this had an influence on the stress experience in that way that participants were more focused on the weather conditions than on the critical range situation and therefore could not explore the critical range situation in detail. In future research the experiment should be repeated under more standard weather conditions to examine if more, less or other stress-inducing and stress-reducing factors will be mentioned by the participants.

Further investigations are needed to examine which additional variables have an influence on range anxiety (i.e., experience of a critical range) like individual differences (e.g., personality traits), system features (e.g., availability of charging stations enroute, charging time) and environmental factors like daytime or regional structure [8].

One should also keep in mind that in the current study we focused on experiences of participants who are driving in a critical range situation. In future research it might be fruitful to additionally examine in detail, what concerns drivers have before starting the trip. To identify stressors which are relevant before the trip might provide further or more detailed design recommendations regarding information or assistance systems.

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