USER EXPERIENCE WITH ELECTRIC VEHICLES WHILE DRIVING IN A CRITICAL RANGE SITUATION – A QUALITATIVE APPROACH

Nadine Rauh*, Thomas Franke, Josef F. Krems

Department of Psychology – Cognitive and Engineering Psychology

Wilhelm-Raabe-Str. 43, 09120 Chemnitz

*nadine.rauh@psychologie.tu-chemnitz.de

ABSTRACT: A frequently discussed phenomenon within the context of electric vehicles (BEV) is range anxiety, 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 a 94 km long unaccompanied trip, 68 participants were asked about experienced stressors and stress buffering factors, as well as additional strategies for reducing stress. The information obtained here can be utilized to inform design recommendations to help future BEV users better handle critical range situations.

Keywords: battery electric vehicle, range experience, range anxiety, field experiment

1 Introduction

One of the most important barriers to the widespread acceptance of battery electric vehicles (BEV) is their limited range [1]. Range anxiety has been repeatedly discussed in this regard and was found to be negatively related to efficient usage of BEV range resources (e.g., [2], [3]). We propose that range anxiety is best conceptualized as a domain-specific form of psychological stress, which can occur within a critical range situation [4].

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 [2]. Hence, advanced driver assistance systems and an improved user interface design might both represent fruitful approaches for reducing range anxiety. 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, there is currently a dearth of published research that focuses specifically on user experience in critical range situations. Previous evidence suggests that managing BEV range in everyday use is typically not characterized by experience with, but by avoidance of, such situations [2]. Therefore, studies examining user experience in critical range situations as one of several variables within a field trial lasting several weeks (e.g., [5], [6]) 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. Our approach is exploratory, focusing on the identification of different stress-inducing and stress buffering factors participants experienced in a critical range situation, as well as their additional ideas for reducing experienced stress.

2 Method

We conducted a field experiment in which participants were instructed to drive a round trip, on which they experienced a critical range situation (i.e., remaining range appeared only marginally sufficient to complete the trip). The BEV used in this study had a maximum available driving range between 130 and 160 km, depending on driving style [7]. The BEV had an ECO PRO mode that can be selected 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) and there was an onboard navigation system, which displayed the route and the remaining km the participants had to drive.

2.1 Participants

Participants were recruited via an online screening questionnaire. Seventy-four drivers completed the experiment. Six participants did not fulfill the criterion of driving in a critical range situation and were therefore excluded from the analysis. This criterion was defined as having a minimal experienced available range buffer throughout the trip that was smaller than 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)?”). The 68 participants (50 male and 18 female) were on average 31 years old, possessed a driver license since M = 12 years, drove M = 1300 km per month with a conventional car and had M = 15.73 km BEV driving experience.

2.2 Field experiment setup

With an average available driving range of 113 km (MIN = 97 ; MAX = 137 ; 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: start of the trip at 298 m above sea level, after approximately 37 km at 600 m over sea level). Over the whole trip, participants experienced a minimum available range safety buffer of M = -2.45 km (Min = -27.0 km; Max = 11.0 km; SD = 9.14; participants’ preferred minimum range safety buffer was M = 11.93; item assessed before the trip).

2.3 Data collection

Participants reported their experience of the critical range situation immediately after the round trip in a structured interview. They were asked with open-ended questions (Q1) for stressors (“What worried you during the test drive? Which situations led to increased stress?”), (Q2) for stress buffering factors (“What calmed you down? Which situations decreased your stress level?”), and (Q3) for further strategies for reducing stress level (“What would have helped you to be less stressed (e.g., which additional information before or while driving)?”).

2.4 Data analysis

Interview data were analyzed using the inductive category development methodology according to Mayring [8]. First, all answers were recorded and transcribed. After that, all relevant statements were coded and a system of categories was developed. Over the course of several coding processes, 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, certain stressors). 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, we report in the following only those categories, which were mentioned by at least 7 participants (i.e., approximately 10%).

3 Results

In the following section, we present the extracted categories (reported by a minimum of 7 participants; labeled with C, e.g., C1) of (Q1) stressors, (Q2) stress buffering factors, and (Q3) additional stress reduction ideas. 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 parentheses in italics.

As one might expect, when asked for (Q1) stressors during the trip, participants reported: (C1) decreasing range (e.g., limited available range safety buffers) and (C2) uncertainty (e.g., regarding consumption on different parts of the trip).

Regarding (C1) decreasing range, 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; annotation by the authors)* - 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)

Regarding (C2) uncertainty, for example 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?" (P73)

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." (P77)

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

Regarding (Q2) stress buffering factors, the data indicated that (C1) sufficiency of / increase in range while driving, (C2) certainty enhancement factors (e.g., appropriate user-interface allowing for accurate tracking of the range buffer, familiarity with the route), and (C3) energy consumption assistance factors (e.g., regenerative breaking, Eco-Pro mode) would be helpful.

Regarding (C1) sufficiency of / increase in range, 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 C1 was, that users endorsed an increase in range safety buffers as a stress buffering 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." (P83)

> "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." (P99)

Regarding (C2) factors that increase certainty and therefore reduce stress, 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 (C2), 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)

Regarding (C3) energy consumption assistance factors, participants mentioned, for example, existence of the Eco-Pro mode:

> "After finding the Eco-Pro mode - that calmed me, too." (P60)

Regarding (C3), participants also reported a successful energy-efficient driving style as a stress buffering 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." (P91)

Another point regarding (C3) 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)

Regarding (Q3), additional ideas for reducing stress, participants reported (C1) more knowledge in general (e.g., 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, existence of a range reserve), and (C2) more information while driving with a comprehensive user-interface (e.g., feedback on individual driving style, charging station network, detailed consumption information). A variety of statements, which provide an impression of participants' additional ideas for reducing stress, 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)

4 Discussion

Results show that participants endorsed 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) derive system design recommendations from these improvement suggestions that could help future BEV users better manage critical range situations.

Regarding (A), 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 within the critical range. Data shows 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 BEV's 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 the 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 the 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).

Regarding (B), a fruitful approach might be the incorporation of more detailed/domain-specific information management systems. 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 (e.g., about eco-driving, different driving modes, interpretation of display information, consumption under different conditions), with, for example, interactive manuals or trainings. And 2) provision of more information while driving (e.g., feedback and hints for individual energy-efficient driving style, information about the range safety buffer, detailed consumption information, 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.

Moreover, displays 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 would appear to be particularly helpful.

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