THE RANGE COMFORT ZONE OF ELECTRIC VEHICLE USERS – CONCEPT AND ASSESSMENT

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ABSTRACT:

Enhancing usable range and the range-related user experience in battery electric vehicle (BEV) use is an essential task in advancing electric mobility systems. We suggest the concept of comfortable range (i.e., the users' range comfort zone or range safety buffer) as a benchmark variable for evaluating range-optimization strategies. The methodology for assessing comfortable range is described and evaluated. Data from three BEV field trials are analyzed. Results show that the developed comfortable range indicators have good psychometric characteristics and are able to track the effects of behavioral adaptation.

1. INTRODUCTION

The improvement of battery electric vehicle (BEV) range is an essential task in advancing electric mobility systems. However, besides striving for improvements in battery capacity, research and development also must focus on strategies to provide users with the maximum mobility resources (i.e., usable range) based on a given battery capacity, while simultaneously safeguarding an optimal user experience. Driver information and assistance systems for range estimation and eco-driving, as well as training approaches can improve usable range and enhance range-related user experience. A key task for human factors research is the evaluation of the utility of those strategies.

Within the present contribution, we discuss the concept of comfortable range (i.e., a user's range comfort zone or preferred range safety buffer) as a potential benchmark variable for evaluating strategies that aim to improve usable range. We describe and evaluate the developed methodology for assessing comfortable range and give an overview regarding the magnitude of range safety buffers.

2. THE CONCEPT OF COMFORTABLE RANGE

The comfort zone concept has been used in different fields of psychology. An important theoretical foundation of this concept is derived from the proxemics approach [1] in which the notion of personal space (i.e., preferred distances) is most relevant. Based on this and further research, it has been theorized within the driving safety context that drivers have a certain comfort zone in terms of safety margins that they accept/prefer when controlling their vehicle so as to avoid collisions [2]. Somewhat similar concepts have been discussed in the adventure education literature [3], where the comfort zone metaphor is used to describe the learning process (e.g., learners can expand the limits of their comfort zone by moving outside of this zone).

Within the field of BEVs, range anxiety is a widely discussed topic and research has aimed to develop methods for reducing range anxiety in BEV drivers. However, research has shown that range anxiety is not the most salient qualitative experience when driving a BEV [4]. Stressful range situations seldom occur [4, 5, 6]. Rather, range interaction is characterized by the avoidance, not the experience, of range anxiety (i.e., range stress [7]). Consequently, the concept of comfortable range (i.e., a user's range comfort zone) represents a more reliable and valid indicator of users' everyday interaction with limited range. Therefore, we conclude that the increase in comfortable range is a more optimal benchmark variable for evaluating range-optimization strategies than the decrease in stressful range situations (i.e., range anxiety).

Comfortable range in the context of limited mobility resources is defined as users' preferred range safety buffer, which means a specific configuration of available range resources and range resource needs that does not yet impair the user experience (i.e., is still in line with a best feeling state [2]).

3. DESCRIPTION OF THE METHODOLOGY

The methodology for assessing comfortable range was continuously developed and refined over the course of three BEV field trials. The first version of the comfortable range scenario task (CRST), labeled "range game" (RG), has been described previously [4]. Here, we describe the final version of the CRST developed for the field trial “BMW ActiveE Leipzig – long-distance commuters”.

The CRST consists of a scenario description and a special response grid. Scenario description (shortened): Imagine you are on a trip with your BEV on a familiar road in a rural area (rather flat terrain, light traffic, good weather, 20°C). You have already driven 30 km and you still have 60 km to drive before reaching your destination. There are no charging possibilities en route. Yet, at the destination, there is both time and an opportunity to recharge the BEV.

Participants then receive four separate cards with one item on each (e.g., “I am sure I will reach the destination with my BEV”). There is a response grid for each item with a six-point Likert scale on the y-axis (*completely disagree* to *completely agree*, coded as 1 to 6) and 10 displayed remaining range values on the x-axis (45 km to 90 km, graded in 5 km intervals). Hence participants must answer the following question: Given that I still have to drive 60 km and I have 90 km range remaining in the battery – am I comfortable with this situation (e.g., am I sure I will reach the destination)? Participants rate this for each of the 10 remaining range values (i.e., 60 km with 85 km range, with 80 km range,…).

The comfortable range threshold is defined as the point of transition from (*a*) the *best-feeling state* [2], where users are still perfectly comfortable with the range resource situation (i.e., lowest remaining range down to which users still mark the response scale value 6 on the Likert scale) to (*b*) *decreased range comfort* (i.e., highest remaining range where participants mark a value <6). For scoring, we take the mean of these two remaining range values (e.g., a = 75 km, b = 70 km, score = 72.5 km). This is done for each of the four items. If a participant reports that he/she is already not in the best-feeling state with 90 km range, 95 km is set as the best-feeling-state range. Finally, a mean score is computed from the four item scores. By dividing 60 km (i.e., trip distance) by the mean score value (i.e., preferred range), the proportional comfortable range utilization can be derived (e.g., 83%). The inverse of this percentage is the preferred range safety buffer (i.e., 17%).

In addition to the CRST, other more economical indicators were developed to assess the preferred range safety buffer. Four of these are: (1) *Minimum range safety buffer* (*MinBuff)*, item text: “Which range buffer do you set for yourself, below which you would not be willing to drive the BEV anymore (except in exceptional circumstances)?”; (2) *proportional range safety buffer* (*PropBuff)*, item text: “In general, I want to have a safety buffer of x% in the battery. That is: What percentage should the displayed range be above the total trip distance?” (item framed to overland trips); and (3+4) *comfortable trip distance* items (*ComfDist*). For these final indicators, participants are presented with a scenario description very similar to the CRST. Then participants are asked: “If the BEV shows a range of 100 km, I would still feel good about driving a total distance of up to x km” ($ComfDist_{100}$). For the second item, “100 km” is replaced with “50 km”($ComfDist_{50}$).

4. EMPIRICAL EVALUATION OF THE METHODOLOGY

The objective of this section is to examine the comfortable range indicators in terms of their psychometric properties and their ability to assess for the presence of expected behavioral adaptation patterns.

4.1 CRST

4.1.1 Data basis

The primary data are derived from the field trial “BMW ActiveE Leipzig – long-distance commuters” (labeled *LDC* here; methodology is described in [6]). Data from the first two usage phases are utilized here (*N* = 29). Additionally, we report findings from previous field trials, including “MINI E Berlin powered by Vattenfall V1.0” and “V2.0” (labeled *ME1* and *ME2* here) to give an impression of findings in different studies. From ME1 (methodology is described in [8, 9]; RG in [4]), only data from the second user study with *N* = 40 are reported (data from first user study have already been reported in [4, 10]). In ME1, users had a home-based charging opportunity and typically drove approximately 38 km with the BEV per day [11]. Instead, the *N* = 18 users in ME2 (methodology is described in [12]; RG with same scenario description as in ME1 but already with revised response scale, i.e., as in LDC) could only use public charging and typically drove around 25 km with the BEV per day [13]. For all studies, the RG/CRST was assessed after an initial short test drive with the BEV (T0) as well as after significant BEV driving experience (T1).

4.1.2 Results

Results are displayed in Table 1. Sample sizes were slightly lower than indicated above because of problems with data collection (single missing values, 1-2 data sets where one item could not be scored). In the LDC trial, the Cronbach's Alpha (α) of the four CRST item scores indicated excellent internal consistency, and test-retest reliability (r_{T0T1}) was acceptable. A similar pattern was found in the ME1 & ME2 data, yet, test-retest reliability was less satisfactory.

Table 1: Results based on the RG/CRST data

study	*time point*	*N*	*M*	$M_{\%}$	*α*	p_{T0T1}	d_{T0T1}	r_{T0T1}
LDC (CRST)	T0	27	71.6 km	84%	.93	.005	0.58	.70
	T1	27	67.2 km	89%	.97			
ME1 (RG)	T0	37	84.6 km	71%	.91	.019	0.40	.51
	T1	37	81.2 km	74%	.94			
ME2 (RG)	T0	17	81.8 km	73%	.91	.127	0.39	.43
	T1	17	79.1 km	76%	.93			

Note. $M_{\%}$ *is proportional comfortable range utilization, α is Cronbach's Alpha, p-values are two-tailed.*

In terms of indicated comfortable range utilization, data from ME1 & ME2 were similar, while LDC data exhibited smaller range safety buffers. As the same response grid was used in ME2 and LDC, this difference might have originated from a combination of: (1) the scenario description which provided more explicit specification of favorable scenario conditions in LDC than in ME2, (2) the sample of long distance commuters which may have had a higher "mobility competence" (i.e., were more adept at planning trips and judging trip distances), or (3) the BEV used in the LDC study which had a more precise range prediction algorithm than the BEV used in the ME1 & ME2 study. The only conclusion which the data allows is that the latter possibility (3) cannot fully account for the effect because the difference between ME1/ME2 and LDC was already high at T0 (i.e., before BEV users had extensive driving experience).

Furthermore, in all three studies, the RG/CRST was able to depict the known effect of behavioral adaption to limited range (i.e., improvement in comfortable range with experience [10, 14, 15, 16]). In ME2, the effect was likely not significant because of the very small sample size. The effect size in ME1 (i.e., second user study in ME1) and ME2 is also consistent with the effect size reported in the first user study in ME1 (d = 0.38, see [10]). Hence, the CRST should also be capable of assessing the effects of intervention strategies or changes in system design. The larger effect found in LDC, compared to ME1/ME2, is also consistent with the fact that users in LDC more often had to drive the BEV in more challenging range situations and had more daily range practice (i.e., had to interact more actively with the range). Such factors have been known to lead to better adaptation to BEV range [4, 5, 10].

Finally, the CRST scores were also found to correlate with actual range utilization behavior: The correlation between the indicated proportional comfortable range utilization derived from the CRST (at T1) and the lowest displayed state-of-charge value that a user experienced over the course of the entire trial was significant, r = -.43, p = .027, N = 27. Similar results have also been found using data from ME1 [17, 11]. Hence, the CRST indeed seems to be a valid indicator of preferred range utilization (i.e., preferred range safety buffer).

4.2 Additional comfortable range indicators

4.2.1 Data basis

For the additional indicators of comfortable range, data from all four points of data collection in LDC (see [6]) were available (N = 29 for all items): T0, T0+1 (approximately 1 week after T0), T1 (after 6 weeks), and T2 (after 12 weeks).

4.2.2 Results

Results are displayed in Table 2. Regarding indicated comfortable range utilization, the mean score of the last three indicators (PropBuff, $ComfDist_{100}$, $ComfDist_{50}$) was equal to the CRST score (84% at T0, 89% at T1). Yet, the individual indicator scores varied considerably around this value. Moreover, the four indicators performed differently in assessing the effect of behavioral adaptation.

Furthermore, the results of the CRST in Table 2 show that T0-T1 comparisons underestimate the effect of behavioral adaptation, because range safety buffers first increase during the period from T0 to T0+1 before they again decrease.

Finally, the *M*-values of the four indicators (values at T1) correlated with lowest ever displayed state-of-charge, with a magnitude comparable to that observed between this variable and CRST: (1) MinBuff $r = .44$, $p = .017$; (2) PropBuff $r = .37$, $p = .046$; (3) $ComfDist_{100}$ $r = -.54$, $p = .003$; (4) $ComfDist_{50}$ $r = -.62$, $p < .001$.

Table 2: Results based on the additional comfortable range indicators

item		*T0*	*T0+1*	*T1*	*T2*	p_{T0T1}	d_{T0T1}
MinBuff	*M*	13.8 km	14.3 km	7.4 km	6.9 km	<.001	0.74
	$M_{\%}$	-	-	-	-		
PropBuff	*M*	12.4%	15.0%	11.1%	9.9%	.227	0.23
	$M_{\%}$	88%	85%	89%	90%		
$ComfDist_{100}$	*M*	85.0 km	80.9 km	92.1 km	93.9 km	.002	0.63
	$M_{\%}$	85%	81%	92%	94%		
$ComfDist_{50}$	*M*	39.1 km	37.2 km	43.2 km	44.7 km	.089	0.33
	$M_{\%}$	78%	74%	86%	89%		

Note. M is in original item units, $M_{\%}$ is proportional comfortable range utilization, p-values are two-tailed.

5. GENERAL DISCUSSION

Overall, the results indicate that the developed methodology for assessing comfortable range may provide a valuable tool for quantifying the effect of range-optimization strategies or behavioral adaptation on usable range.

However, there is also some potential for further improvement of the methodology. For example, it might be advantageous to include remaining range values >90 km (e.g., up to 100 km) to reduce the likelihood of ceiling effects (i.e., data sets where participants were already outside of their best-feeling state at 90 km of range) which might be especially relevant under less favorable conditions.

Furthermore, although the *average* comfortable range values were the focus of our analysis, it should be acknowledged that there was a high degree of variability among individual scores. Consequently, if one wants to interpret, for example, the score values from the CRST in an absolute sense (i.e., the extent to which we have already reduced the problem of range resource losses due to psychological range safety buffers), it may be more advisable to consider other statistical parameters (e.g., the 80th percentile of range safety buffers). In the end, a design-for-all approach should not only provide the average user, but ideally all users, with an optimal range-related user experience.

Moreover, it must be noted that comfortable range is only one of three psychological range levels in the adaptive control of range resources model [17, 11, 5, 4], the others being competent (maximum achievable) and performant (average available) range. Given that all three drive the discrepancy between technically available range and actual usable range, all three psychological range levels must be optimized. In order for this to occur, range optimization strategies must provide users with the capability to substantially extend the available range, if needed. This consideration is also partly addressed in the methods described above: If available range of a certain BEV is “elastic” for the user, the preferred range safety buffer can become very small. That is, users do not have to plan for a safety reserve if they can extend the range when needed. Still, it may be necessary to use additional variables that explicitly target the assessment of experienced range elasticity to more comprehensively evaluate this facet of usable range.

Finally, given that the interaction with limited resources is a vital topic of our time in many fields, a critical question may be: To what extent can the concept and methods discussed in the present contribution be generalized to other areas in which people have to interact with limited resources (e.g., energy resources)? We suppose that the existence and extent of comfort zones within the context of interaction with limited energy resources is essentially dependent on the specific features of the resource situation. Comfort zones may exist in all resource interaction situations in which the outcome of suboptimal resource management can be severe (e.g., can result in a significant loss in other resources like time, health or information) and decisions have to be made under conditions of uncertainty (e.g., uncertainty regarding the predictability and controllability of resource dynamics, uncertainty regarding balance of resource needs and available resources).

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