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. The authors suggest the concept of comfortable range (i.e., the users’ range comfort zone or range safety buffer) as a benchmark variable for evaluating range-optimisation strategies. A methodology for assessing comfortable range was developed over the course of three BEV field trials. Here the final methodology is described and evaluated which consists of the comfortable range scenario task (CRST) which indirectly assesses comfortable range as well as several single-item indicators that directly ask respondents for comfortable trip distances or range safety buffers. Results show that the developed comfortable range indicators have good psychometric characteristics (internal consistency, factorial structure and test-retest reliability), are able to depict the known effect of behavioural adaptation to limited range, and correlate with actual range utilisation behaviour. The CRST performs more robust than the single-item indicators within this evaluation.

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1. Introduction

The improvement of battery electric vehicle (BEV) range is an essential task in advancing electric mobility systems. However, battery size is related to the ecological footprint and the cost-effectiveness of a BEV [1, 2, 3]. The production of a BEV with a battery that provides 150 km range consumes substantially more resources than the production of a conventional combustion vehicle [2, 4]. Owing to its lower environmental impact during usage such a BEV can compensate the initial disadvantage and turn out to be the more sustainable vehicle concept. Hence, simply doubling the battery size is not the optimal solution to the challenge of BEV range because it is difficult for BEVs with large batteries to compensate the initial environmental disadvantage of battery production during the period of vehicle usage (i.e., vehicle lifetime) [2, 4].

Consequently, 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., maximum usable range) based on a given battery capacity, while simultaneously safeguarding an optimal user experience (i.e., avoiding range anxiety). 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 to evaluate the utility of those strategies.

The objective of the present research was to examine 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. Understanding usable range

Every BEV can be characterised by its technical range (i.e., cycle range [5]), meaning the range of a BEV under certain standardised conditions. However, many psychological factors drive the interaction with range [5, 6, 7, 8]. This leads to a certain usable range of a BEV (i.e., the range that users can actually utilise with an optimal user experience) which typically is considerably smaller than technical range [5, 9, 10]. Yet, while there is an established objective method to assess technical range, namely standardised driving cycles (e.g., [11]), such a method is missing for the assessment of usable range.

The adaptive control of range resources (ACOR) model [5, 8, 9, 12, 13] proposes three psychological range levels that contribute to the disparity between technical and usable range (see Table 1). In the end, comfortable range (i.e., the users’ range comfort zone) most clearly defines the range resources that finally constitute actually usable range of a BEV (i.e., accessible mobility resources in an electric mobility system). Therefore, comfortable range should be seen as the central benchmark variable when evaluating range optimisation strategies.
Table 1: Psychological range levels that contribute to the disparity between technical and usable range according to the adaptive control of range resources (ACOR) model

<table>
<thead>
<tr>
<th>range level</th>
<th>definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>competent range</td>
<td>The range that a user can achieve based on… (a) his/her skills in dealing with the range (e.g., eco-driving knowledge) and/or (b) based on how easy the BEV makes it to extend the range (e.g., precise and informative feedback to monitor and control energy consumption, support of learning processes).</td>
</tr>
<tr>
<td>performant range</td>
<td>The range that a user usually obtains based on… (a) his/her driving motives and habits (e.g., driving style) and/or (b) based on the usability and enjoyability of energy conservation (e.g., inclusion of gamification elements in energy efficiency feedback [14, 15]).</td>
</tr>
<tr>
<td>comfortable range</td>
<td>The range a user really utilises with an optimal user experience (i.e., without range stress or range anxiety) based on… (a) his/her coping resources (e.g., certain personality traits such as internal control beliefs as well as subjective coping skills) and/or (b) the preciseness, accuracy, and traceability of the range resource prediction algorithm leading to a certain level of system trust and perceived reliability and/or (c) the elasticity of remaining range (i.e., can the range easily be extended). See also further definition in last paragraph of section 2.1.</td>
</tr>
</tbody>
</table>

2.1 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 [16] in which the notion of personal space (i.e., preferred distances) is most relevant. In the driving safety context, drivers’ safety margins (i.e., spatiotemporal distances between the drivers’ vehicle and other critical objects in the road environment) have been examined as a critical variable for a long time (e.g., see [17, 18]). More recently, safety margins have also been studied in research on highly automated driving functions (e.g., [19]) and will probably receive further attention in this area, because such driving functions essentially have to be designed to comply with drivers’ preferred safety margins to provide a comfortable driving experience [19]. Based on the notion of safety margins Summala [20] was the first to include the comfort zone concept in a comprehensive model of driver behaviour, the multiple comfort zone model. He theorised that drivers control to stay within their comfort zone by keeping certain accepted/preferred safety margins, and that being in the comfort zone corresponds to being in a “best feeling” state [20].

Somewhat similar concepts have also been discussed in the education literature [21], where the comfort zone metaphor has been used to describe the learning process (e.g., learners can expand the limits of their comfort zone by moving outside of this zone). Furthermore, in their stress model, Hancock and Warm [22] incorporated the comfort zone as the centre region in the continuum between hypostress and hyperstress where individual’s capability to adapt to environmental demands is highest and discomfort is lowest. According to their model, if environmental demands increase, first discomfort
starts to rise and then, second, psychological adaptability decreases. In summary, it can be said that being in the comfort zone is equitable with a best feeling state [20], characterised by a pleasant amount of (mental) workload, in which a person is fully able to meet changing environmental demands [22].

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 [5]. Stressful range situations seldom occur [5, 8, 23]. Rather, everyday range interaction is characterised by the avoidance, not the experience, of range anxiety [5, 7, 8, 10, 23], while it is in general also more appropriate to speak of range stress instead of range anxiety [24]. 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-optimisation strategies than the decrease in stressful range situations (i.e., range anxiety).

Comfortable range in the context of limited mobility resources is defined as the 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 [20], is large enough to definitively avoid range anxiety). This range safety buffer can be expressed in absolute values (e.g., always keep a 10-km range buffer), relative values (e.g., 20% buffer), or minimum values (e.g., never go below a 10 km remaining range reserve). Range buffer values can be assessed directly by asking users to provide such values (i.e., direct statement of numerical value, see single-item indicators in section 3.2), or indirectly by assessing the experienced comfortableness/stressfulness of certain range buffers (e.g., see CRST in section 3.1).

2.2 Previous findings on comfortable range

Previous findings have shown comfortable range as a central variable in users’ interaction with limited range resources. For example, comfortable range could explain the charge level (i.e., state of charge) at which users typically initiated a charging process [12]. Furthermore, comfortable range was related with actual range utilisation behaviour [13]. Moreover, comfortable range was found to be related to users’ range satisfaction while performant and competent range were not [8]. This reinforces that comfortable range is the central variable that defines the actual available mobility resources which the BEV provides. Finally, comfortable range and range utilisation were found to increase over the first weeks of BEV usage [25, 26, 27] which is in line with the parallel finding that substantial adaptation to BEV range happens over the first weeks of BEV usage [28].

The findings reported in [8, 12, 13, 25] were collected with a first version of the methodology to assess comfortable range. This first version was partly not easily transferrable to other study settings (i.e., those which aim to evaluate range optimisation strategies) and in parts relatively complex to administer. In the following section the current revised version of the methodology is described.
3. Description of the methodology

3.1 Comfortable range scenario task (CRST)

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), labelled “range game” (RG), has been described previously [5]. Here, we describe the final version of the CRST developed for the field trial “BMW ActiveE Leipzig – long-distance commuters” [23].

The CRST consists of a scenario description and a special response grid. Scenario description (shortened, full scenario description is included in the Appendix): 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 (“1. I am sure I will reach the destination with my BEV”, “2. I wish I had another car (combustion vehicle) to make this trip”, “3. I am concerned about reaching the destination”, “4. On this trip, I will not be worried about range”). 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). The response grid is depicted in Figure 1. 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., trip length of 60 km with 85 km range, with 80 km range,…).

![Figure 1: Response grid of the CRST.](image-url)
The comfortable range threshold is defined as the point of transition from (a) the best-feeling state [20], 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 for items 1./4., respectively value 1 for items 2./3.) to (b) decreased range comfort (i.e., highest remaining range where participants mark a value <6, respectively >1). 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 utilisation can be derived (e.g., 83%). The inverse of this percentage is the preferred range safety buffer (i.e., 17%).

### 3.2 Single-item indicators

In addition to the CRST, other more economical single-item 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. Present research

The objective of the present research was to examine 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. For evaluating the methodology the following research questions were addressed:

[Q1]: Does the CRST show satisfactory internal consistency and is the factorial structure satisfactory?

[Q2]: Does the CRST show satisfactory test-retest reliability?

[Q3]: Can the CRST depict the known effect of behavioural adaptation (i.e., improvement in comfortable range with experience)? Consequently, we hypothesise [H1] that the CRST depicts an increase in comfortable range (decrease in preferred range safety buffer) over the first weeks of BEV experience.

[Q4]: Is there a relationship between CRST score values and actual range utilisation behaviour (i.e., indicator of criterion validity)? Consequently, we hypothesise [H2] that a higher comfortable range (a smaller preferred range safety buffer) as indicated by the CRST is related to a higher range utilisation.
Research questions [Q2] to [Q4] and hypotheses [H1] and [H2] were also addressed for the single-item indicators.

[Q5] Is the absolute indicated comfortable range utilisation (range buffer) similar between different methods?

5. Empirical evaluation of the methodology

5.1 CRST

5.1.1 Data basis

The primary data are derived from the field trial “BMW ActiveE Leipzig – long-distance commuters” (labelled LDC). Participants were recruited via a broadly publicised online screener questionnaire. They were primarily selected based on their mobility profile (i.e., prospective daily driving distance with the BEV at least 90 km). They paid a monthly rate of 450€ to lease a BMW ActiveE (around 130-160 km range under everyday conditions) for a usage phase of 3 months. They had a charging opportunity at home and/or work, dependent on their mobility profile. As restrictions for inclusion in the sample were similar to those for leasing a BEV, we expect the sample to represent early adopters of BEVs. For the present analysis a data set of 29 users was available (i.e. first two usage phases in the field trial). Sample characteristics are displayed in Table 2. Further details on the methodology are described in [23]. The CRST was assessed after an initial short test drive with the BEV (T0), after six weeks of BEV use (T1) and after twelve weeks (T2).

In addition, as comparative data we report findings from the previous field trials “MINI E Berlin powered by Vattenfall V1.0” and “V2.0” (labelled ME1 and ME2 here) to give an impression of findings in different studies. Both studies used a very similar methodology than the LDC study. Participants were also recruited via a broadly publicised online screener questionnaire. They had to pay a monthly rate of 400€ to lease a MINI E (around 168 km range under everyday conditions) for a usage phase of 6 months. However, in contrast to the LDC study ME1 and ME2 both rather focused on users with urban mobility profiles. In both studies the RG (i.e., previous version of CRST, see section 3.1) was assessed after an initial short test drive with the BEV (T0) and after 3 months of BEV use (T1).

Apart from the many similarities, there were also some notable differences between ME1 and ME2. In ME1, users had a charging opportunity at home. For the present analysis the data of 40 users were available (i.e., data from second usage phases in ME1, data from first usage phase have already been reported in [5, 25]). The RG in ME1 was mostly similar to the CRST in LDC (e.g., same four items were used, scenario description addressed same influencing factors). Yet, the scenario description in ME1 depicted a specific route in the Berlin area while the exact route was unspecified in LDC in favour of a more general description of the structural characteristics of the route (see section 3.1 and Appendix). Furthermore, the response grid was different in ME1 (for detailed description see [5]). In ME2, the sample of the 18 users examined here could only use public charging stations. The RG used the same scenario description as in ME1 but already had the revised response grid as in LDC. Further details on the methodology of ME1 are described in [29, 30], and regarding ME2 in [31].

Table 2: Sample characteristics in the three field trials.

<table>
<thead>
<tr>
<th>variable</th>
<th>field trial</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>LDC</td>
</tr>
<tr>
<td>N</td>
<td>29</td>
</tr>
<tr>
<td>age</td>
<td>$M = 41$ years ($SD = 8.1$)</td>
</tr>
<tr>
<td>gender</td>
<td>5 female (17%)</td>
</tr>
<tr>
<td>education</td>
<td>14 with university degree (48%)</td>
</tr>
<tr>
<td>daily BEV distance</td>
<td>109 km (see [23])</td>
</tr>
</tbody>
</table>

Note. “Daily BEV distance” is the typical driving distance per day with the BEV in the sample.

5.1.2 Results

Results are displayed in Table 3. 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).

Regarding research question [Q1], the Cronbach’s Alpha ($\alpha$) of the four CRST item scores indicated excellent internal consistency in LDC. Moreover, a principal-axis factor analysis indicated a clear single factor solution at all time points (eigenvalue of first factor > 3.0, second factor < 0.5, all factor loadings > .7). A similar pattern was found for the comparative data from ME1 and ME2, both, in terms of internal consistency as well as factorial structure (eigenvalue of first factor > 3.0, second factor < 0.6, all factor loadings > .7).

Regarding research question [Q2], test-retest reliability was acceptable for the CRST and particular good for $r_{T1T2}$ (i.e., the critical test for test-retest reliability for period where interaction with range was relatively stable after adaptation, see [Q3]). In contrast, the RG in ME1 and ME2 yielded less satisfactory values.

Table 3: Results based on the RG/CRST data

<table>
<thead>
<tr>
<th>study</th>
<th>time point</th>
<th>N</th>
<th>M</th>
<th>$M%$</th>
<th>$\alpha$</th>
<th>$p$</th>
<th>$d$</th>
<th>$r$</th>
</tr>
</thead>
<tbody>
<tr>
<td>LDC (CRST)</td>
<td>T0</td>
<td>27</td>
<td>71.6 km</td>
<td>84%</td>
<td>.93</td>
<td>T0T1</td>
<td>.005</td>
<td>.58</td>
</tr>
<tr>
<td></td>
<td>T1</td>
<td>27</td>
<td>67.2 km</td>
<td>89%</td>
<td>.97</td>
<td>T0T2</td>
<td>.015</td>
<td>.51</td>
</tr>
<tr>
<td></td>
<td>T2</td>
<td>26</td>
<td>67.8 km</td>
<td>89%</td>
<td>.96</td>
<td>T1T2</td>
<td>.418</td>
<td>.16</td>
</tr>
<tr>
<td>ME1 (RG)</td>
<td>T0</td>
<td>37</td>
<td>84.6 km</td>
<td>71%</td>
<td>.91</td>
<td>T0T1</td>
<td>.019</td>
<td>.40</td>
</tr>
<tr>
<td></td>
<td>T1</td>
<td>37</td>
<td>81.2 km</td>
<td>74%</td>
<td>.94</td>
<td>T0T1</td>
<td>.127</td>
<td>.39</td>
</tr>
<tr>
<td>ME2 (RG)</td>
<td>T0</td>
<td>17</td>
<td>81.8 km</td>
<td>73%</td>
<td>.91</td>
<td>T0T1</td>
<td>.127</td>
<td>.39</td>
</tr>
<tr>
<td></td>
<td>T1</td>
<td>17</td>
<td>79.1 km</td>
<td>76%</td>
<td>.93</td>
<td>T0T1</td>
<td>.127</td>
<td>.39</td>
</tr>
</tbody>
</table>

Note. $M\%$ is proportional comfortable range utilisation, $\alpha$ is Cronbach’s Alpha, $p$-values are two-tailed.
Regarding research question [Q3], the CRST was able to depict the known effect of behavioural adaption to limited range in LDC (comparison T0/T1 and T0/T2). Consequently [H1] was supported by the results. Hence, the CRST should also be capable of assessing the effects of intervention strategies or changes in system design. Importantly, there was no difference in CRST score values between T1 and T2. Hence, as also indicated by the good test-retest reliability between T1 and T2 the CRST should also be able to accurately track if a range optimisation strategy has no effect on comfortable range. A similar pattern was found for the comparative data from ME1 and ME2. 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 [25]). The larger effect found in LDC, compared to ME1 and 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 [5, 8, 25].

Regarding research question [Q4], the CRST scores were found to correlate with actual range utilisation behaviour: The correlation between the indicated proportional comfortable range utilisation derived from the CRST and the lowest displayed state-of-charge value that a user experienced over the course of the entire trial (i.e., users were asked after approximately one week of BEV use (T0+1)), at T1 and at T2 for the minimum state-of-charge value that they had experienced, from these three values the minimum was taken as a score) was significant (correlation with score values of CRST at T0: $r = -.46, p = .017, N = 27$; T1: $r = -.43, p = .027, N = 27$; T2: $r = -.42, p = .032, N = 26$). Hence, it was even possible to predict range utilization behaviour during the trial period already based on the CRST scores at T0. Consequently [H2] was supported by the results. Similar results have also been found using data from ME1 [12, 13]. Hence, the CRST indeed seems to be a valid indicator of preferred range utilisation (i.e., preferred range safety buffer).

Regarding research question [Q5], LDC data exhibited smaller range safety buffers than data from ME1 and ME2. 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 favourable 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 and 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).

### 5.2 Single-item indicators

#### 5.2.1 Data basis

For the additional indicators of comfortable range, data from all four points of data collection in LDC were available ($N = 29$ for all items): T0, T0+1 (approximately 1 week of BEV use), T1, and T2.

5.2.2 Results

Results are displayed in Table 4.

Regarding research question [Q2] the critical test of $r_{T1T2}$ indicated good test-retest reliability for all but the MinBuff indicator, very similar to the CRST. Yet, the $r_{T0T1}$ was much weaker for all single-item indicators compared to the CRST. This could indicate that the single-item indicators have particular problems in assessing comfortable range in inexperienced BEV users. For such groups of respondents a comprehensive scenario description and an indirect assessment of comfortable range like in the CRST may be necessary to assess effects of range optimisation strategies.

Regarding research question [Q3] the four indicators performed differently (i.e. in general less reliable) in assessing the effect of behavioural adaptation to BEV range. Consequently [H1] was not supported for all single-item indicators. Interestingly, the average item values in Table 2 show that T0-T1 comparisons may even underestimate the effect of behavioural adaptation, because range safety buffers first increased during the period from T0 to T0+1 before they again decreased.

Regarding research question [Q4], all indicators were found to correlate with actual range utilisation behaviour. The $M$-values of the four indicators (values at T1, similar results for T2) correlated with lowest ever displayed state-of-charge, with a magnitude comparable to that observed between this variable and the CRST: (1) MinBuff $r = .44$, $p = .017$; (2) PropBuff $r = .37$, $p = .046$; (3) ComfDist$_{100}$ $r = -.54$, $p = .003$; (4) ComfDist$_{50}$ $r = -.62$, $p < .001$. Furthermore, again similar to the CRST results, also the T0-values of the four indicator variables could predict range utilization during the trial (all $r > .40$, except only $r = .26$ for PropBuff). Consequently [H2] was generally supported for the single-item indicators.

Regarding research question [Q5], interestingly the mean score of the last three indicators (PropBuff, ComfDist$_{100}$, ComfDist$_{50}$) in terms of indicated comfortable range utilisation was equal to the CRST score (84% at T0, 89% at T1 and T2). Yet, the individual indicator scores varied considerably around this value.

Table 4: Results based on the additional comfortable range indicators

<table>
<thead>
<tr>
<th>indicator variable</th>
<th>$T0$</th>
<th>$T0+1$</th>
<th>$T1$</th>
<th>$T2$</th>
<th>$T0T1$</th>
<th>$T0T2$</th>
<th>$T1T2$</th>
<th>$r_{T0T1}$</th>
<th>$r_{T0T2}$</th>
<th>$r_{T1T2}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>MinBuff</td>
<td>$M$</td>
<td>13.8 km</td>
<td>14.3 km</td>
<td>7.4 km</td>
<td>6.9 km</td>
<td>$p$ .001</td>
<td>.589</td>
<td>0.36</td>
<td>0.31</td>
<td>0.49</td>
</tr>
<tr>
<td></td>
<td>$M%$</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>$d$ 0.74</td>
<td>0.77</td>
<td>0.10</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PropBuff</td>
<td>$M$</td>
<td>12.4%</td>
<td>15.0%</td>
<td>11.1%</td>
<td>9.9%</td>
<td>$p$ .227</td>
<td>.073</td>
<td>0.13</td>
<td>0.57</td>
<td>0.44</td>
</tr>
<tr>
<td></td>
<td>$M%$</td>
<td>88%</td>
<td>85%</td>
<td>89%</td>
<td>90%</td>
<td>$d$ 0.23</td>
<td>0.35</td>
<td>0.28</td>
<td>0.35</td>
<td>0.38</td>
</tr>
<tr>
<td>ComfDist$_{100}$</td>
<td>$M$</td>
<td>85.0 km</td>
<td>80.9 km</td>
<td>92.1 km</td>
<td>93.9 km</td>
<td>$p$ .002</td>
<td>&lt;.001</td>
<td>.175</td>
<td>0.35</td>
<td>0.38</td>
</tr>
<tr>
<td></td>
<td>$M%$</td>
<td>85%</td>
<td>81%</td>
<td>92%</td>
<td>94%</td>
<td>$d$ 0.63</td>
<td>0.82</td>
<td>0.26</td>
<td>0.41</td>
<td>0.38</td>
</tr>
<tr>
<td>ComfDist$_{50}$</td>
<td>$M$</td>
<td>39.1 km</td>
<td>37.2 km</td>
<td>43.2 km</td>
<td>44.7 km</td>
<td>$p$ .089</td>
<td>.023</td>
<td>.117</td>
<td>0.41</td>
<td>0.38</td>
</tr>
<tr>
<td></td>
<td>$M%$</td>
<td>78%</td>
<td>74%</td>
<td>86%</td>
<td>89%</td>
<td>$d$ 0.33</td>
<td>0.45</td>
<td>0.30</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note. $M$ is in original item units, $M\%$ is proportional comfortable range utilisation, $p$-values are two-tailed. $N = 29$. 

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6. 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-optimisation strategies or behavioural 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 range) which might be especially relevant under less favourable conditions. In addition, there were some problems with the second item in the CRST because some single users stated that they would never want to take a different vehicle (combustion vehicle) for the trip (i.e., indicated lowest possible item value for all range displays). Although it was considered important within item design to also have clearly behaviour-oriented items, it may be advisable to revise this specific item in further studies.

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 because of 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 [13, 12, 8, 5], the others being competent and performant range. Given that all three drive the discrepancy between technically available range and actual usable range, all three psychological range levels must be optimised. In order for this to occur, range optimisation 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, the interaction with limited resources is a vital topic of our time in many fields. Hence, a critical question may be: To what extent can the concept and methods discussed in the present contribution be generalised to other areas in which people have to interact with limited resources (e.g., energy resources)?

We think that transferability is ultimately dependent upon the similarity of the resource situation. In BEVs, the interaction with range resources essentially has the following structure: Sustaining mobility (i.e., reaching the trip destination, avoiding breakdown of resources) is the primary goal of users, as is the case with many other facets of driving behaviour [33]. Resources are continuously consumed

while the system is in use. The resource storage capacity is limited and resources can only be refilled through the investment of other resources (e.g., time resources). Within the resource consumption phase, there are only periodically convenient opportunities to replenish the resources. In such contexts, comfort zones may probably exist in all 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).

This description of the resource situation structure fits with several battery-powered mobile devices to some degree. Indeed, we have presented first results that indicate similarities between user-energy interaction in BEVs and in smartphones [12]. Moreover, as explicated in section 2.1 assessing the comfort zone has relevance for several fields of driving behaviour research, particularly for the prospering field of highly automated driving [19]. Thus, we hope that this study can inspire further research in the field of human-machine interaction.

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Appendix: Scenario description of the CRST

Imagine you are on a trip with your BEV alone on a Saturday; you drive on a familiar road in a rural area (country road/villages). The terrain is rather flat. There is hardly any traffic. The weather is good (sunny, around 20°C). You have already driven 30 km with your average driving style under these conditions on the way to your destination. You still have 60 km to drive before reaching your destination. There are definitely no charging possibilities en route. Yet, at the destination, there is a free usable charging opportunity and you also have enough time to completely recharge the BEV.

Please try to immerse yourself as good as possible into this scenario.

You will now be presented four cards. On each card we assume that you experience this situation in 10 different variants. The total distance until the next charging possibility is always the same (60 km). However, the displayed remaining range of the BEV is varied (45 to 90 km).

Hence, the question is: “If I have 90 km in the battery and I have to drive 60 km – am I then sure I will reach the destination? And how is it when I have 85 km in the battery and I have to drive 60 km?”

Important: For the calculation of remaining range in your BEV the charging status of the battery and the energy consumption over the last 30 km is used. We assume that you have driven the last 30 km with your average driving style (see above).
References:


