Advancing electric vehicle range displays for enhanced user experience – the relevance of trust and adaptability

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ABSTRACT
Advancing range-information user interfaces towards enhanced usability is a continuous task in electric vehicle development. The objective of the present research was (1) to examine experienced trustworthiness of a typical range-information user interface, (2) to test a newly constructed trustworthiness scale, (3) to examine the relationship of experienced trustworthiness to individual usable range (i.e., comfortable range), and (4) to identify possibilities for further improvement of range-information user interfaces. Data from N = 74 participants of a large-scale electric vehicle field trial were analyzed. Results show that experienced trustworthiness of the range estimation system is related to a higher comfortable range. Moreover, users developed several suggestions on how to further improve the user interface. The results imply that perceived trustworthiness should be considered as a benchmark for evaluating range-information user interfaces and that users should have flexible options to adjust the parameters of the range estimation system.

Author Keywords
electric vehicle; range estimation; user interface; trust in automation; comfortable range; user experience

ACM Classification Keywords
H.5.2. [User Interfaces]: ergonomics, theory and methods, user-centered design

INTRODUCTION
A display of available range is an essential element in any electric vehicle user interface. Particularly in battery electric vehicles (BEVs) the distance-to-empty indicator is crucial for user-system interaction and user experience. It assists drivers in their task to gauge the available mobility resources in order to decide (1) which trips can be accomplished with a good user experience (i.e., with optimal range comfort, without range anxiety) or (2) whether a non-convenient charging opportunity can be safely dismissed. If drivers experience the range indicator as not perfectly reliable and trustworthy they will (1) make less efficient (i.e., more over-cautious) decisions or (2) experience more range stress [18] or range workload in their adaptive control of range resources. Hence, the range-information user interface is a key element for users’ adaptive control of mobility resources. It can enhance or deteriorate user experience.

Advancing indicators of available range towards enhanced usability and user experience is therefore an ongoing task in the development of electric vehicles. Given that BEVs start to increasingly enter the mass market with range still being the largest constraint (at least from the customer perspective [4,19]), this task becomes more and more important. Also for BEVs with longer range, which can be expected within the next years, this task will remain important because range variability can become more salient along with increased total range, and this can induce mistrust in displayed range.

Several previous works in the field of user-centered design have dealt with the evaluation and improvement of the user-friendliness of range-information user interfaces for electric vehicles [13,20], often focusing on how to best display range information. The present work focuses more on the question of what to display, meaning how to design the range estimation algorithm that lies behind an estimate of available range and how to best translate the available data into a numeric indicator of available range.

Yet, what should be the primary design criterion (i.e., benchmark) for a user-friendly range indicator? High precision and accuracy are certainly the most broadly discussed factors in the literature [2,14,20]. In this context many authors have argued for a data-fusion approach that focuses on forecasting the remaining range not only based on historical data obtained from the car but rather based on the state of as many variables as possible within the system and the environment (e.g., route profile, weather forecast, traffic conditions) to predict the range as accurately as possible [2,14]. However, reliability and trustworthiness are at least equally important as noted by some authors [2,20].
From a theoretical perspective, the range estimation system can be conceived as a kind of automated system which takes over the task of predicting the distance-to-empty based on the detected state of charge (i.e., energy in the battery) and different pieces of information that help to estimate future energy consumption. However, this prediction algorithm will never be completely accurate in every situation. This can induce uncertainty and mistrust.

There is a long line of research on user interaction with automated systems [10,15]. Trust in automation is an essential variable in this regard [10,12]. It can contribute to a better user experience [15]. Hence, trustworthiness is a relevant design criterion for automated systems and we argue here that it should also be considered as a benchmark variable for determining the user-friendliness of range-information user interfaces.

As argued above the experienced trustworthiness should have direct consequences for user-range interaction. Previous research has theorized that psychological range levels play a crucial role in users’ management of range resources, see adaptive control of range resources (ACOR) model [6,7,8]. Different psychological factors lead to the pattern that the actual usable range is typically below the technical range (i.e., objective range based on a certain standardized driving cycle). Particularly, each driver develops an individual range comfort zone, meaning that he/she prefers to keep certain range safety buffers. Research has shown that various factors can influence a user’s comfortable range [6,8]. A higher perceived trustworthiness of the range display should make it easier for drivers to adopt smaller range safety buffers and to more fully utilize available range (i.e., develop higher comfortable range). Testing this relationship could help to evaluate the real importance of trustworthiness as a design criterion for range-information user interfaces.

**RESEARCH OBJECTIVE**

The objective of the present research was to examine experienced trustworthiness of a typical range estimation system as well as to identify possibilities to further improve such user interfaces towards increased trustworthiness. The term range estimation system is used in the following to accentuate that we examined user experience of both components of the range-information user interface, the range display and, in particular, the calculation algorithm behind it. The following research questions were addressed:

(Q1) How do users experience a typical range estimation system with regard to trustworthiness?

(Q2) Is our newly constructed trustworthiness scale a useful alternative to a more established scale?

(Q3) Is higher experienced trustworthiness of the range estimation system related to higher usable range (i.e., comfortable range)?

Regarding (Q3) the following hypothesis is tested (Q3H1): A higher experienced trustworthiness of the range estimation system is related to a higher comfortable range.

(Q4) What possibilities do users see for further improvement of the range estimation system?

Identifying possibilities for further improvement of an already quite sophisticated system is a challenging task. Yet, the present field trial was particularly suited to address these research questions because users drove comparatively large daily distances leading to a higher probability of uncovering problems (or limits) of the range estimation system.

**METHOD**

**Field trial setup**

The present research was part of a large-scale BEV field trial in the region surrounding Leipzig, Germany. This field trial was set up by a consortium consisting of the BMW Group, the Stadtwerke Leipzig, and Technische Universität Chemnitz and was funded by the German Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety (BMUB). A key objective was to comprehensively examine aspects of user-range interaction, including user interface topics (see also [9]). Within the field trial there were several points of data collection. For the present analysis, data from T1 (after six weeks of experience) and T2 (after three months) could be used. For further details on the methodology see [5].

**Participants**

The recruitment and selection process aimed at establishing a sample that represented typical electric vehicle customers with a focus on users who typically drove long daily distances and therefore needed to actively interact with range. To this end, information on the project was broadly distributed via diverse media channels. People from the general public could apply via an online screener questionnaire (673 applicants).

Requirements for participation included (1) the willingness to pay the monthly leasing rate of 450 € (finally reduced to 370 € when the BMW i3 became available for sale), (2) a charging opportunity or the possibility to install a charging station, and (3) a mobility profile that could be expected to result in a frequent active interaction with range. As restrictions for inclusion in the sample were similar to those for leasing a BEV, we expect the sample to represent a population of early BEV customers in Germany.

There were few dropouts during the field trial, therefore: \( N_{T0} = 75 \), \( N_{T1} = 74 \) and \( N_{T2} = 72 \). The 74 users who completed at least T1 had an average age of 43.4 years (SD = 9.3), 16% were female, and 58% had a university degree.

**Electric vehicle and range information user interface**

The BEV used in the trial was the BMW ActiveE with a maximum available driving range between 130 and 160 km in real terms, depending on driving style [17]. Remaining
range was displayed based on energy consumption over the last 30 km (as stated in the user manual), the state-of-charge was displayed (0-100%), and energy consumption was also displayed (including an energy consumption history display with averages given at 1-minute intervals).

**Scales and measures**

To examine trustworthiness of the range estimation system two approaches were pursued: First, a questionnaire scale was developed which assessed facets of trustworthiness that were assumed to be particularly relevant for the present context. The questionnaire scale was adapted to assess trust in the range estimation system also from a more theory-driven point of view as well as to validate the newly constructed scale (see Q2).

**Facets of system trustworthiness**

Five items assessed facets of trustworthiness of the range estimation system: “The range estimation of the ActiveE is reliable.” (i1-reliable); „The range estimation of the ActiveE is precise.“ (i2-precise); „The range estimation of the ActiveE is traceable.“ (i3-traceable); „I can trust the range estimation of the ActiveE.“ (i4-trustable); and „I cannot depend on the range estimation in the ActiveE.“ (i5 was inverted for the analysis, hence i5-dependable). Participants responded on a 6-point Likert scale (completely disagree, largely disagree, slightly disagree, slightly agree, largely agree, completely agree; coded as 1 to 6). The five items were preceded by the following instruction text: “How do you evaluate the range estimation system (i.e., the range display and the calculation algorithm behind it)?”

The items were assessed at T1 and T2. Reliability was good to excellent (Cronbach’s Alpha T1 = .87 and T2 = .90, test-retest reliability \( r_{T1T2} = .78 \)). To receive a more comprehensive indicator of the experienced trustworthiness of the range estimation system over the trial and to enable a more condensed presentation of results, we averaged scale values of T1 and T2, which was also supported by the strong positive T1T2-correlation. The reliability of combined item values was also excellent (Cronbach’s Alpha = .92). Finally, we examined the factorial structure with principal-axis factor analysis. A clear single-factor solution resulted (eigenvalue of first factor = 3.84, second factor = 0.50) and all items loaded high on this factor (all factor loadings ≥ .75). The resulting score was labeled \( M_{FOT} \) (possible score values 1-6).

**Trust in automated systems**

The 12-item trust in automated systems scale [11] was used to assess trust in the range estimation system. The scale had been translated to German within a previous research project [1]. In the instruction the term system was specified as referring to the range estimation system using the instruction text as used for the facets of trustworthiness scale. Participants responded on a 7-point Likert scale. The scale was only assessed at T1. Reliability was good with Cronbach’s alpha = .87. The resulting score was labeled \( M_{TIA} \) (possible score values 1-7).

**Comfortable range**

The comfortable range scenario task (labeled CRST) was administered at T1 and T2 to assess the users’ individual comfortable range (i.e., users’ preferred range safety buffers). The CRST methodology, its reliability, and its validity have been comprehensively described in [6]. This kind of method has proven useful in several analyses (e.g., [7,8]).

The CRST consists of a scenario description and a special response grid. Scenario description (shortened; full scenario description see [6]): “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 6-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 have to 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, 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 utilization can be derived (e.g., 83%). The inverse of this percentage is the preferred range safety buffer (i.e., 17%).
Reliability of the CRST was excellent (Cronbach’s Alpha \( T1 = .96 \) and \( T2 = .95 \), test-retest reliability \( r_{T1T2} = .77 \)). To receive a more comprehensive indicator of users’ comfortable range over the trial and to enable a more condensed presentation of results, we averaged scale values of \( T1 \) and \( T2 \), which was also supported by the strong positive \( T1T2 \)-correlation. Reliability of combined item values was also excellent (Cronbach’s Alpha = .97). Because of single missing values and data sets where one item could not be scored there were \( N = 69 \) at \( T1 \), \( N = 65 \) at \( T2 \) and \( N = 64 \) for the final \( T1T2 \)-score. The proportional comfortable range utilization was computed as final score.

RESULTS

Experienced trustworthiness (Q1)

Users’ ratings for the five items of the facets of trustworthiness scale and the scale scores \( M_{FOT} \) and \( M_{TIA} \) are displayed in Table 1. As can be seen, the range estimation system was generally evaluated positively by the users regarding its trustworthiness, and all five facets (i.e., items) were at a similar level regarding the average ratings. Hence, the range estimation system in the present vehicle is certainly user-friendly for the average user.

However, there was also considerable variance in users’ evaluations (see \( \text{Min/Max} \) columns) and there was also a considerable share of users who did not largely agree or completely agree (i.e., item score <5). Hence, there is also still room for improvement of the range estimation system.

<table>
<thead>
<tr>
<th>Item</th>
<th>( M )</th>
<th>( SD )</th>
<th>( %&lt;5 )</th>
<th>( \text{Min} )</th>
<th>( \text{Max} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>i1</td>
<td>5.01</td>
<td>0.60</td>
<td>26%</td>
<td>3.0</td>
<td>6.0</td>
</tr>
<tr>
<td>i2</td>
<td>4.70</td>
<td>0.85</td>
<td>43%</td>
<td>2.0</td>
<td>6.0</td>
</tr>
<tr>
<td>i3</td>
<td>4.94</td>
<td>0.65</td>
<td>29%</td>
<td>3.5</td>
<td>6.0</td>
</tr>
<tr>
<td>i4</td>
<td>5.02</td>
<td>0.77</td>
<td>25%</td>
<td>2.0</td>
<td>6.0</td>
</tr>
<tr>
<td>i5</td>
<td>5.35</td>
<td>0.92</td>
<td>18%</td>
<td>1.5</td>
<td>6.0</td>
</tr>
</tbody>
</table>

\( M_{FOT} \) 5.01 0.66 - 2.9 6.0

\( M_{TIA} \) 5.37 0.72 - 2.7 6.5

Table 1. Users’ ratings of the trustworthiness of the range estimation system. The column “\( \%<5 \)” shows the percentage of users who did not largely or completely agree to this item. For \( M_{FOT} \) (and i1-i5) possible score values are 1-6, for \( M_{TIA} \) 1-7.

Usefulness of newly constructed trustworthiness scale (Q2)

Already in the method section (see above) it has become visible that the newly developed trustworthiness scale has good psychometric characteristics in terms of reliability (good internal consistency and test-retest reliability), and factor analysis indicated an unidimensional structure. As an additional test, we examined the convergent validity as an indicator of construct validity.

To this end, we computed the correlation between \( M_{FOT} \) and \( M_{TIA} \). As both variables could not be assumed to be normally distributed in our sample (\( p \)-value for Lilliefors test & Shapiro-Wilk test both < .05), we computed a Spearman-rank correlation coefficient (\( .69 \)) in addition to the parametric Pearson correlation coefficient (\( .77 \)). Furthermore, we applied a cube transformation [16] for both variables which led to \( p > .05 \) at least for the Shapiro-Wilk test. The Pearson correlation for these transformed variables was .71. All three correlations were highly significant (\( p < .001 \), two-tailed). Hence, all analyses revealed similar strong and significant relationships. Therefore we conclude that the newly constructed 5-item scale may be a useful alternative to the established 12-item scale of Jian et al. [11] at least for the present context. Further support for this conclusion is presented in the next section (Q3).

Relationship of experienced trustworthiness and comfortable range (Q3)

To test hypothesis H1, correlations between the trustworthiness indicators (\( M_{FOT}, M_{TIA} \)) and the proportional comfortable range utilization (as assessed by the CRST) were computed. Although the CRST scores were normally distributed we again faced the problems with the trust variables. Hence, we again computed the three different correlation coefficients as for Q2. For all analyses significant moderate effects were revealed (see Table 2). Thus, hypothesis H1 was clearly supported by the data.

In terms of practical significance, the moderate effect size might not seem much. However, it has to be considered that already increasing actual usable range by 5% solely by means of interface design (i.e., the effect of increasing trustworthiness by approx. 1 scale point) would be a significant improvement, particularly from the perspective that BEV battery resources should not be wasted [7]. This positive relationship between trust and usable range (comfortable range) emphasizes the relevance of trust as a benchmark variable in evaluating range-information user interfaces.

Furthermore, the results are also interesting from the perspective of Q2 because both scales (\( M_{FOT} \) and \( M_{TIA} \)) yielded very similar effect sizes (i.e., the newly developed scale is equally related to the external criterion as the established trustworthiness scale). This gives some indication that the criterion validity of the new trust scale is similar to the established trust in automated systems scale.

<table>
<thead>
<tr>
<th>Correlation coefficient</th>
<th>( M_{FOT} )</th>
<th>( M_{TIA} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Spearman</td>
<td>.35 (.002)</td>
<td>.29 (.011)</td>
</tr>
<tr>
<td>2 Pearson untransformed</td>
<td>.32 (.005)</td>
<td>.31 (.007)</td>
</tr>
<tr>
<td>3 Pearson transformed</td>
<td>.34 (.003)</td>
<td>.30 (.009)</td>
</tr>
</tbody>
</table>

Table 2. Correlations between the two trustworthiness indicators and comfortable range, \( p \)-values (displayed in parentheses) are one-tailed because of directional hypothesis.
Possibilities for further improvement (Q4)
To address Q4 we asked the following question in the T1 interview: “What needs to be done so that you could rely on the range prediction (range display) more strongly? In your opinion, what would have to be changed regarding the range display and/or the calculation algorithm?”

All answers were recorded and transcribed verbatim. The statements were analyzed with thematic analysis [3]. After familiarizing with the statements and reviewing the material several times while noting ideas for possible themes (i.e., areas for improvement), a system of codes was developed and finally condensed into a set of themes. For providing some kind of minimal quantitative information on relevance of themes, all statements were finally again reviewed and assigned to a theme where appropriate.

Before presenting the identified areas for improvement it has to be highlighted that participants typically expressed their general satisfaction with the range estimation system in the first place. Still, 34 of the 74 users (46%) expressed specific ideas for further improvements of the range estimation system. This subsample constitutes the basis for the further analysis.

Four major areas of possible improvements (A1-A4) were identified. These areas are explicated in the four following sections. Each of these sections follows the same structure: (1) A description of the area of improvement together with a numeric indicator of relevance (i.e., how many % of users named this topic), (2) a prototypic user statement that reflects this topic, and (3) further sub-topics and specific crowd-sourced solutions (i.e., to comprehensively characterize the results regarding the specific area of improvement). After these for sections a short description of some further user ideas (A5) that did not clearly fit to the main subject areas A1-A4 is given.

Accounting for driver changes (A1)
The first major subject area that was identified was the possible improvement to better account for situations where drivers change (26%, i.e., 9 of 34; for simplicity only percentages are given in the following). Users described situations where the range estimation system displayed an inaccurate/uninformative value because a different driver had driven the vehicle before:

“Probably it really needs some time to adjust to another driver. And if you, like me, get in the car and your husband has driven before and there are just 120 km left and you know: you still have 115 or 110 to go, it would be a comforting feeling if it would adapt earlier to my driving style.” (U27)

Consequently, users suggested that the vehicle should identify who is driving (e.g., with the help of the individual car key) and then adapt the range estimation accordingly:

“If different people use the vehicle, e.g., in a family or in a company, I would prefer if you could save your individual settings like for example the memory-function for the seat. […] So I would say: ‘I am the driver’, perhaps it could be realized with different keys, and then it [the BEV] would say, now I calculate your data based on your last…” (U7)

Users also mentioned larger intra-individual changes in driving style (or driving habits), which can occur on a day-to-day basis that would make it useful to store certain “driving habit settings”:

“There it would eventually make sense if you could store certain driving habits and you retrieve them, so that you say, ‘Today if I want to drive like this, how far will I get like this?’” (U2)

Adjustment of the reference period (A2)
The second major subject area that was identified was the users’ suggestion to change the reference period of the range estimation system (41%). For example, users stated that the relatively long reference period led the displayed range value to be less trustable especially at the beginning of trips:

“This way you have to say now that when I am starting to drive, I cannot rely on it [the range value] anyway and therefore I wait for a while and watch how the range value develops.” (P35)

Yet, there were both: drivers who suggested significantly decreasing the reference period (26%) and others who suggested increasing it significantly (12%, for 3% this specification was not possible based on the data).

The participants suggesting an increase of the reference period typically mentioned that they would prefer a long-term average or a value from typical trips to be displayed, maybe as an additional display:

“And then there should maybe be an alternative range, like a second display that shows either the value of a typical trip or another average value. Then you would have an opportunity to compare.” (U65)

On the other hand the participants suggesting a decrease of the reference period mentioned that it would be good to have a reference period of, for example, 5 km or 5 minutes:

“If I now suddenly change my driving style, for example if I want to drive at a higher speed than I did so far, then I would still have to go 30 km and observe it [the range value], […] Maybe that would be a small addition that you can say, ‘Okay please calculate only based on the last 5km.’” (P28)

Few of the “decreasers” also referred to the energy consumption history display and stated that it would be helpful for them to change this to a “range history display” to see how range changes in quite a short time span:

“I think it would be more interesting to display how the range value actually changed in the last 5 km or the last minute - not the energy consumption. Whether it decreased disproportionately high in the last few minutes or it decreased rather low.” (U21)

Predicting route profile & variable environmental factors (A3)
The third major subject area that was identified concerned the change of the range estimation system to be a predictive system (as opposed to being based only on historical data).

For example, users experienced difficulties when driving in hilly areas:

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“For example if you go to the mountains, I have experienced when travelling to [city name deleted]. It all went uphill, from the plain to the mountains, and there the display was not reliable which made me sweat a little bit.” (U4)

Consequently, several users saw a possible improvement in the inclusion of information on the oncoming route profile (24%) for example via using information from the navigation system (18%):

“The oncoming route profile would somehow have to be considered. And if this would require the navigation system to be turned on, no problem.” (U16)

Second, several users suggested incorporating variable environmental factors more closely (21%) like rain, wind, or temperature:

“The only situations when range really decreased disproportionately [...] were when temperatures were particular low or when even rain or wind came on top. Then more auxiliary consumers were needed. [...] That only could be incorporated if an intelligent weather forecast would be used. So, really updated short-term and constantly. Similar to the TMC traffic control system. [...]” (U2)

**Transparency/Self-Explanation (A4)**

Finally, several of the users (26%) stated that it would be important to increase the transparency of the range estimation system. For example, they reported that they were not sure about the reference period in the beginning:

“At the beginning I was not able to deal with the range estimation because I did not know the logic behind it. Now I trust the estimation actually quite well because I know that the display is based on previous routes or speeds and the corresponding energy consumption.” (U4)

Or they added that an automatic algorithm would be fine yet they also wanted to have a possibility to regulate the range estimation in addition to that:

“Certainly it would be useful if there would be an option of having an automatic system that optimizes based on algorithms but allows to see the information and then to regulate it manually.” (U16)

And finally, users mentioned that a more fine-grained information on the influence of different consumers in the vehicle on range could be helpful:

„Maybe, to make it transparent, […] the current consumption of different functions of the car could be presented. Hence, how much energy is used for propulsion, how much for heating, so that you get a sense for that […] how much percent that constitutes. If that could be visualized as a percentage, one could work more with that.” (U35)

**Further ideas (A5)**

Regarding further ideas, individual users discussed aspects of range warnings. For example, one user suggested visualizing a “point of no return”, i.e., to warn drivers before they reach a situation where they cannot go back to their preferred charging opportunity with the remaining range. Another user stated that it would be helpful to be able to set range warnings individually. And finally one user suggested clearly informing drivers about the safety reserve when they have driven the vehicle to “official” 0% state of charge (i.e., inform drivers whether they can still go 1 km or 5 km before the vehicle really stops).

**DISCUSSION**

The objective of the present research was to examine experienced trustworthiness of a typical range estimation system as well as to identify possibilities to further improve range-information user interfaces. The results regarding the four research questions showed that (Q1) the examined user interface was experienced as trustworthy by the average user, yet there was still room for further improvements. (Q2) The newly developed scale can be concluded to be a useful alternative to the established trust scale. (Q3) Experienced trustworthiness was indeed found to be a relevant variable given its relationship to the actual usable range (comfortable range). (Q4) Finally, users developed several suggestions about how to further improve the user interface. Many comments related to the fact that the interface should be more adaptable to individual needs and circumstances of the driving situation. In the following the methodological and design implications of these findings are discussed.

**Methodological implications**

The present research has shown that trustworthiness of range-information user interfaces plays a relevant role in user-interaction with mobility resources of an electric vehicle. In fact, it can be assumed to be directly related to a larger or smaller usable range. This gives empirical support to the arguments in previous research that a well-designed human-machine interface (HMI) of an electric vehicle can contribute considerably to overcoming the psychological barrier of limited range [8]. In this regard, our newly developed 5-item trustworthiness scale seems to be a good indicator to assess trustworthiness of range-information user interfaces. It yields comparable results to the established scale of Jian et al. [11]. Yet, it is shorter (5 vs. 12 items), has higher face validity for respondents and is potentially easier to answer because the statements are less abstract and more directly relatable to a display-based users interface than the scale of Jian et al. [11]. Hence, a somewhat higher acceptance by study participants can be assumed, especially if participants complete this scale for several layouts of a range estimation system.

**Design implications**

Although the drivers were in general highly satisfied with the range estimation system of the BEV (i.e., a range estimation based on historic energy consumption data with a fixed reference period of 30 km), there were still several situations where this system reached its limits and appeared unreliable and less trustable.

The typical problematic situations from the users’ perspective seem to be those where substantial changes occur in the range-influencing conditions, either induced by the driver or by changes of environmental conditions (i.e.,

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driver change or change of driving habits, route profile, or weather conditions).

Some of these issues might be overcome by a range-estimation system that incorporates all possible range-influencing factors, integrating data from various sources (i.e., sensors). However, some users expressed their skepticism regarding the viability of such an approach. Moreover, the more complex the range prediction algorithm becomes, the more difficult it will be for drivers to understand (i.e., trace) changes in displayed range and this will, at least, become a problem if there is any situation remaining where the algorithm has a weakness and this leads to untraceable variations of displayed range. Yet, traceability (i.e., system transparency) seems to be relevant. Drivers’ statements made clear that being able to understand the dynamics in displayed range is of crucial importance.

Indeed, many ideas for improvement echoed that drivers wish to have a highly predictable and controllable range-estimation system. Hence, it appears crucial to consider some kind of adaptability as a fundamental element of any range estimation system for BEVs, i.e., in the sense of cooperative automation (as a cooperative assistance system). The goal of such an approach would be that the driver receives some kind of control over the parameters of the range estimation system, i.e., that he/she can influence which information the range estimation takes into account.

In this respect, it appears useful to include an option to shorten the reference period of the range estimation system, for example for situations where drivers consider that the newly started trip will be substantially different than the last trip and they want the range estimation system to adapt faster (i.e., without needing to wait a considerable distance). Another solution to this problem (as also suggested by a user) might be to add a “reset” option that starts a new reference period (i.e., similar to the reset option that is already available for average consumption displays in electric and conventional vehicles). As users are both interested in shorter and longer reference periods it might also be useful to give users two possible range estimators that could for example indicate a “current range” versus a “long-time-drivers’-average”, or to provide two range displays that can be reset separately (i.e., like trip A vs. trip B in an odometer display).

Related to this, the issue of driver change should be considered in such an interface design because participants frequently noted this as a situation that led to particularly reduced trustworthiness of displayed range (at least subjectively). Individual car keys would be a simple and transparent mode to detect driver change. Yet, misses and false alarms can occur (i.e., no consequent person-key allocation). Hence, it might only be useful to offer users a recalculation of the range estimation if a driver change is detected instead of forcing this recalculation. Furthermore, new problems might arise with such an automation (e.g., traceability of how the “driver factor” is incorporated in the range estimation, question if driver data is still predictive if only older data of a driver is available or data collected in a different environment).

Giving users a high level of control over the range-estimation period also acknowledges the fact that, in the end, the user will likely remain the best predictor of larger changes in energy consumption and, at the same time, the user is the most difficult factor to predict.

Such a user-controlled approach could also be coupled with an automatic range prediction system (i.e., inclusion of oncoming range-influencing factors) by adding an option to activate or deactivate predictive information input.

Yet, it has to be highlighted that all these suggestions are, at this stage, purely formulated from a user perspective (i.e., a perspective of user-centered design). For realizing such system layouts many additional factors have to be taken into account (e.g., do new usability problems arise?). Such options could be a challenge for ease of use of the range prediction system. As users are mostly satisfied with the historic range estimation system with quite a long reference period, it may be best to keep such a highly transparent and simple range estimation as a default option and only give the adaptability options in an extra menu in the HMI. A very flexible option in this regard may also be to use the already available remote vehicle information systems (RVIS) and display a highly flexible range-information user interface only within a smartphone app.

CONCLUSION

The present research has shown that trustworthiness of range-information user interfaces plays a relevant role for a positive user experience and user interaction with mobility resources of an electric vehicle. In fact, trustworthiness is related to a higher usable range. The trustworthiness of the examined typical range-information user interface was found to be already good. Yet, users still generated a considerable list of further possible improvements. The results imply that subjective trust should be considered as a benchmark for evaluating range-information user interfaces and that users should have flexible options to adjust the parameters of the range estimation system (i.e., adapt system settings). Hence, trust and adaptability are two relevant variables for the advancement of range-information user interfaces in BEVs.

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