Understanding the influence of state of health on the range anxiety of battery electric vehicle drivers

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1 INTRODUCTION

With the increasing public focus on environment protection, the past few years have witnessed a fast-growing market of battery electric vehicles (BEVs). Owing to their environmentally friendly features, BEVs have huge potential to reduce greenhouse gas emissions and control pollution in the transportation sector [1]. However, unlike drivers of traditional internal combustion engine vehicles, drivers of BEVs are more likely to face a new source of anxiety while driving, namely, range anxiety. Triggered by the limited available range of BEVs, range anxiety can negatively affect driving experience and safety, and is regarded as a huge obstacle to the usage and popularity of BEVs [2].

Range anxiety, as a specific form of psychological stress, can be described as a negative driving experience of the present or prospective range situation, whereby the remaining available range provided by BEV is considered to be inadequate to reach the destination [3]. Rauh et al. point out that range anxiety can influence BEV drivers on four levels, including cognitive, emotional, behavioural and physiological levels [4]. On the cognitive level, it may result in passive thoughts about not being able to complete the trip, and on the emotional level, it may make drivers feel nervous or even fear. On the behavioural level, some physiological activities, like frequently paying attention to the range gauge or finger knocking on the steering wheel, can be observed when range anxiety happens. Furthermore, range anxiety may speed up heartbeats or breathing on the physiological level. Seriously, high levels of range anxiety may largely possess the limited cognitive resources of BEV drivers, thus easily leading to distracted driving and causing unwanted severe consequences such as traffic accidents [5]. To ensure the driving experience and transportation safety, range anxiety is a significant factor to be focused on in recent research of BEVs’s operation.

One way to alleviate range anxiety of BEV drivers is to develop an optimized charging infrastructure network [6]. Therefore, the optimization of charging infrastructure
deployment becomes an issue to be studied. Yang et al. [7] proposed a BEV charging station network model considering the consumer satisfaction function associated with range anxiety and loss anxiety. Xie et al. [8] designed a flow-based multilevel chance-constrained random model to optimize the interurban BEV charging stations. To solve the deployment problem of fast charging stations, Xu et al. [9] presented a compact mixed-integer programming model considering user's range anxiety and path deviation. The above-mentioned research usually treats range anxiety as a constraint condition to be considered in dealing with the station location problem, but they do not explore the range anxiety deeply from the psychological perspectives of drivers. Since the range anxiety is a subjective feeling during the driving task, investigating the range anxiety psychologically seems to be a relatively targeted way to lessen anxiety and improve user experience.

Through performing various driving experiments, many research studies sought a psychologically based understanding of range anxiety of BEV drivers. Franke et al. [10] designed a round-trip driving experiment to investigate the relationships between several individual factors with the perceived range stress. They concluded that the higher the route familiarity, knowledge of BEV system, subjective capability to predict remaining range and control beliefs in handling technology are, the lower the range stress drivers feel. Moreover, Franke et al. [11] revealed that fewer encounters of critical range situation, higher endurance of low range situation and higher trust of BEV displayed range can lessen everyday range anxiety. Rauh et al. [4] emphasized the importance of BEV driving experience by a range-critical driving task. They found that when BEV driving experience increases, drivers are prone to report less range anxiety. Following this, they attributed this improvement to the enhancements of personal range competence and deeper comprehension of range dynamics [12].

Despite researching influential psychological factors, another useful solution to alleviating range-related anxiety is to provide appropriate information through in-vehicle information systems (IVISs) [13]. Useful and accurate information can lower the stressful feelings by diminishing the perceived uncertainties regarding whether the driver can reach the destination [14]. Therefore, it has been agreed that range anxiety can be alleviated if the in-vehicle interfaces are well designed in vehicular information provision [15]. For example, Eisel et al. [13] performed a BEV driving experiment and found that BEV equipped with the navigation system, offering electronic map, and locations of nearby charging stations, can mitigate drivers’ stressful feelings in range-critical situations. Particularly, as the main information source about the currently available range of BEV, range-related IVISs have been regarded as a crucial part in developing satisfactory human–vehicle interfaces with more positive driving experiences [11]. To promote the information reliability of range-related IVISs, many research studies are devoted to improving range estimation methods considering both internal and external features of BEV, such as battery state of charge (SOC), driving speed, road condition, or meteorological factors [16, 17].

However, an important piece of information of BEV, state of health (SOH), is also closely related to the remaining range but is seldom being considered in the current research of range anxiety. SOH characterizes the level of battery performance degradation due to the irreversible inner electrochemical reaction, and it can be defined as the percentage of degraded available capacity and nominal capacity [18]. As shown in Figure 1, the battery SOH deteriorates with cyclic usage, which means that the vehicular capability to store energy becomes weaker and weaker. Obviously, the degraded SOH is bound to affect the range estimation of BEVs, thus reflecting in the driving experiences. For instance, even the same SOC of two same-type electric vehicles may correspond to different available ranges if they differ in the SOH. This inconsistency may lessen the trustworthiness of available range information, and aggravate the uncertainty and range anxiety when users are driving the old BEV. Hence, to relieve range anxiety, SOH is an essential factor to be acquired when range-related IVISs offer drivers range information.

Unfortunately, it is difficult to measure SOH directly in practice due to the strict measuring conditions [18]. Thereby, the key for SOH acquisition is to develop estimation algorithms based on the easily captured battery parameters. However, traditional SOH estimation methods restrict batteries to be discharged and charged completely, which can hardly be applicable because BEVs are seldom fully discharged during daily use [19]. Indeed, this irregularity raises huge difficulties in achieving accurate SOH-based range estimation online and may lead to potential exacerbation of range anxiety. To overcome this limitation, some novel methods have been presented to estimate SOH under the incompletely discharged conditions [19, 20]. Since the constant voltage (CV) charging phase of battery is relatively robust with the previously incomplete discharging process, our previous work has extracted a new health indicator from the CV charging current curve to achieve online SOH estimation during the daily use of BEV [20]. This makes it
technically possible to research the influence of vehicular SOH on the range anxiety of BEV drivers.

In summary, to the best of our knowledge, many research studies argue that range-related IVISs are significant to mitigate range-related concerns, but few research studies have been performed on how the information of vehicular SOH affects range anxiety through IVISs. Therefore, the research objective of this paper is to explore how SOH-influenced IVIS impacts the range anxiety of BEV drivers during the driving process. We have designed three types of range-related IVISs in a simulated experiment under the condition of degraded SOH. Three IVISs differ in the information content or information presentation. During the experiment, participants used their assigned BEV driving simulator (equipped with different IVISs) to finish a designated trip in a range-critical situation, and rated their perceived range anxiety during and after the trip. Data from the simulated experiment are compared and analysed by using statistical methods. On this basis, the results provide useful inspirations on the design of in-vehicle interface that the range anxiety can be reduced if the IVIS offers range information considering the battery SOH.

The remainder of this paper is organized as follows: In Section 2, the hypotheses of this research are presented and the recruited participants, measures and experiment settings are introduced in detail. Then, the experimental results are analysed statistically in Section 3 and discussed systematically in Section 4. Section 5 discusses the limitations and future works. Finally, Section 6 presents the conclusions of this research.

2 | MATERIALS AND METHOD

2.1 | Hypotheses development

According to the existing literature, range anxiety (i.e. range stress) can be illustrated as a field-specific psychological stress arisen from the underlying appraisal processes of drivers [21]. If drivers appraise that their possessed mobility resources i.e. the remaining available range displayed in IVIS, are difficult to meet the mobility requirements i.e. arrival to the scheduled destination on time, they will interpret the situation as a threat to their well-beings, and will be likely to feel stressed out.

The appraisal of range stress can be affected by the trust-worthiness of range-related information, especially the remaining range of BEV [3]. Nevertheless, range-critical situations are usually accompanied with high uncertainties regarding drivers’ possessed resources and abilities to reach the destination with currently available range, which may negatively affect the trustworthiness of information. A lack of trust in the obtained information will reinforce the feelings of uncertainties, thus increasing the psychological stress within the appraisal process. On the contrary, if BEV drivers have a trustworthy impression on the displayed range, they can construct a positive confidence about their abilities to cope with the range-critical situation. Researchers have also proven that people feel lower stress about range if they trust the estimated remaining range displayed in the IVIS [11].

In fact, trust comes from the cognition that the objective of trust is reliable [3]. In other words, the system reliability has a positive correlation with trust, because users can better comprehend and predict the system behaviour if the system is credible and dependable [22]. In this regard, it is easy to understand that systems are perceived as believable if they can offer necessary information with high accuracy. During the BEV driving, the provision of accurate remaining range undoubtedly contributes to reducing the subjective uncertainty and promoting the trustworthiness of the range estimation system. As mentioned before, the battery SOH is a significant parameter reflecting the current available maximum capacity of the battery i.e. the maximum available range of BEV. Hence, taking the accurate SOH value into the range estimation process is crucial for enhancing the estimation accuracy of range displayed on the IVIS. This may in turn reduce the improvement of users’ trust in the BEV, thereby relieving their range stress and allowing them to plan their trip with more ease.

However, traditional IVISs may be unable to acquire accurate SOH online due to the limitation of traditional SOH estimation methods, so they have to ignore the influence of SOH degradation (or just assume that the vehicular SOH remains at nominal value) for the range estimation, thereby leading to the deviation of estimation results more or less. Fortunately, by using the CV-based SOH estimation method of our earlier research (more details can be found in [20]), an accurate SOH estimation can be realized, and can thus improve the trustworthiness of IVIS with the SOH-based range estimation. This is considered to be able to reduce the range stress of drivers.

Following the aforementioned analysis, we propose the following hypothesis:

H1. Individuals perceive less range stress when using the improved IVIS with SOH-based range estimation compared to the normal IVIS without considering the influences of SOH.

In addition, we posit that the somewhat redundant display of range-related information may be beneficial to mitigate range anxiety. It has been found that with more sources of correlated information about the present task situation, the confidence in individual’s capabilities will be enhanced [23]. In other words, the extra provision of range-related information strengthens the driver’s perception of own abilities to manage a range-critical condition, thus simplifying the tasks associated with determining the vehicular status and formulating the following trip [13]. The vehicular SOH value characterizes the current aging status of BEV and is highly related to the remaining range. Even though the influence of SOH can be reflected in the estimation results of remaining range, the additional display of the SOH is believed to reduce the experienced uncertainties of the trip for drivers. Hence, we assume that the display of extra correlated information (current SOH value) results in a less stressful appraised situation:

H2. Individuals perceive less range stress when provided with the vehicular SOH value on the improved IVIS (equipped with SOH-based range estimation).
2.2 | Participants

In this work, we recruited participants by distributing leaflets and notices at local campus. The only requirement for recruited participants was the possession of a valid driving license. To achieve a snowball effect of recruitment, the initial participants were encouraged to invite their friends, schoolmates and acquaintances to join in our experiments. At last, the study had recruited 36 qualified participants ranging from 22 to 28 years old ($M = 24.83; SD = 1.75$), a quarter of which were female. All of the participants had already attained a bachelor or master degree, and had sufficient driving experience of traditional internal combustion engine powered vehicle, even though none of them had previous BEV driving experience. To compare the impacts of IVISs with/without considering the SOH, the study adopted a between-subjects design. Participants were randomly and averagely assigned to the three groups depending on the chronological receipt of recruitment and were gender balanced as far as possible across different groups.

2.3 | Measures

Since range anxiety can be expressed as a personal stressful feeling of battery running low and incapability to complete the desired trip, the term range stress is suggested to be suitable to represent the most typical aspect of range anxiety [21]. Therefore, inspired by the measuring methods in [4], we evaluated the range stress of participant cognitively and emotionally in this research.

During the course of the experiment, two items were asked periodically through pop-up windows on the IVIS. The items mainly addressed the real-time concern about the range situation (“Do you concern about the BEV remaining range?”) and the experienced stress level caused by the consumption of available driving range (“How stressed do you feel by the changes of range on the previous part of the trip?”). Participants responded to each item on an 11-point Likert scale ranging from “Not strong at all (1)” to “Extremely strong (11)” to describe their psychological anxious feelings, and a mean score of all rating points was computed.

After the experiment, participants were further asked to assess their feelings about the range of the overall trip retrospectively by answering the following four items: “While driving, I was often worried about the range”; “While driving, I felt stressful by the range”; “While driving, I was concerned about completing the trip”; “While driving, the topic of range frequently bothered me”. Similarly, participants evaluated each item on an 11-point Likert scale. After their evaluations, a mean score was computed.

2.4 | Experiment settings

To achieve our research target, we designed a simulated experiment in which participants interacted with range-related IVISs to complete a prescribed trip. First of all, we adopted MATLAB GUI to develop digital IVISs as the experimental human–machine interactive prototype of real BEVs. Specifically, the information presented to participants was simplified to only what were needed to finish the experimental task—the current speed, the remaining available range and the remaining kilometres participants had to drive. Moreover, during the experiment, the vehicular information was updated dynamically based on the Lithium-ion battery powered car model provided by the commercial vehicle simulation software ADVISOR (Version 2002, National Renewable Energy Laboratory, Golden, CO, USA).

The simulation framework based on ADVISOR is shown in Figure 2. During the simulation experiment, ADVISOR was set as the main control platform to update vehicular information. On the one hand, the available capacity of Lithium-ion batteries in ADVISOR was adjusted at the beginning of each simulation on the basis of the current SOH value. The SOH was obtained based on the battery specifications provided by ADVISOR using our proposed CV-based SOH estimation method. On the other hand, ADVISOR sends relevant vehicular information for display (such as SOC, remaining range and SOH) to the experimental IVISs, and in turn, calculated the energy consumption in the next period according to different driving speeds corresponding to the driving mode users select.

Particularly, since the objective of this research was to explore the influence of vehicular SOH on the range anxiety theoretically, the parameters of the vehicle model used here were not completely equal to the actual BEV but reasonable enough to support the simulation experiment. Therefore, the default lithium-ion BEV model provided by ADVISOR was selected as the simulation model, and the constant-speed driving cycle under the plain highway and room temperature was selected as the simulating road conditions in this study. The relevant configuration screen of the vehicular parameters is shown in Figure 3.

According to the group assignment, the experimenter prepared three different IVISs, as shown in Figure 4. The IVIS of group 1 was normal IVIS with no adjustment of displayed remaining range based on the current SOH of BEV. In contrast, the displayed remaining range on the IVIS of group 2 was adjusted based on the current SOH of BEV (which was acquired by using the CV-based SOH estimation method proposed in our previous work [20]). By substituting the estimated SOH into the BEV simulation model in ADVISOR, the remaining available range can be corrected to a comparably real level. In other words, although the types of displayed information of the above two groups were the same, the accuracy of the information was totally different, thereby resulting in the difference of trust in the IVISs between two groups. The IVIS of group 3 had the same calculating process regarding the remaining range like that of group 2, but the estimated SOH values were also displayed on the dashboard interface.

Based on the developed experimental system, the flowchart of the entire experiment is shown schematically in Figure 5.

Once the participants of each group arrived at the experiment room, they were greeted and asked to sit in front of a computer in which the developed IVISs had been installed. They were told that the experimental system was a simulated...
FIGURE 2  The simulation framework of experiment

FIGURE 3  Parameter configuration of the BEV model
FIGURE 4 The experimental IVISs: (a) the IVIS of group 1 (normal IVIS without considering the degraded SOH); (b) the IVIS of group 2 (improved IVIS by adjusting range with the degraded SOH); and (c) the IVIS of group 3 (improved IVIS by adjusting range with the degraded SOH, and displaying extra SOH value on the dashboard).

FIGURE 5 Flowchart of the experiment

prototype of real IVIS installed in current BEVs, which could provide all necessary vehicular information to finish a range study. Experimenters then introduced the experimental procedure and the functions of participants’ assigned IVISs with a special focus on the theory of vehicular SOH. The experiment simulated a situation that the participant drove a BEV on the plain highway (without traffic jam) to accomplish an intended trip. Participants were also told that the BEV was not newly purchased and had been used for a period of time. To create a range anxiety prone situation, the initial available range was set to be enough to finish the trip, but without sufficient margin. Moreover, to measure the anxiety level conveniently, the trip had been divided into several consecutive intervals of equal length. For every trip interval, participants could choose their driving modes, including the fast-driving mode (driving with a constant speed of 60 miles/h) and eco-driving mode (driving with a constant speed of 45 miles/h) by clicking the
corresponding buttons. Different driving modes corresponded to different energy consumptions. To avoid over-conservatism, experimenters explained that the experiment simulated an urgent trip needed to be finished as soon as possible. However, choosing fast-driving mode too frequently may also lead to the task failure due to the over-rapid consumption of limited range. Therefore, participants should make their choice holistically based on multiple factors, including the authenticity of the remaining range, the health status of BEV and the task requirement, just like in real driving.

Following the experiment introduction, participants had to implement test drives to become familiar with the experimental procedure and their allocated IVISs. The displayed SOH value in the test drives was different from that used in the formal drive, aiming to avoid the participants being over-familiar with the changing rule of the available range when performing the formal experiment. After the test drives, participants received a demographic questionnaire including gender, age, educational level, driving experience and so on. Then, they were asked to perform the formal experiment in which they were assigned a task of driving a fully charged BEV for a trip of 33 km. Since the lithium-ion battery was recognized to reach the end-of-life when the SOH degenerated to 80% [24], consequently, we set the SOH of experimental BEV as 90% to simulate one of the degraded states of BEV, and modified relative parameters of the BEV model in ADVISOR. Therefore, participants of group 1 started with a BEV which displayed a remaining range of 40 km with no SOH-based correction, while BEVs of groups 2 and 3 had been charged the same amount of electric energy but their displayed driving range had already been adjusted to a real level based on the vehicular SOH. Afterwards, participants were asked to begin the driving task. Throughout the experiment, questions about the anxiety measurement were asked to the participant through pop-up windows after finishing every trip interval of 5 km. Under this condition, the number of interruptions was relatively small, while the amount of measuring data was still enough to support the subsequent analysis. When the participants completed the trip, they would receive another questionnaire to further evaluate their feelings about the range condition of the entire trip. Finally, the experimenter showed up and informed participants that the experiment has ended.

3 RESULTS

Before the data analysis, we had checked whether participants comprehended the intended differences of IVISs by asking them questions about certain aspects of the provided IVISs (e.g. “Were the IVIS provided helpful to complete your trip?” or “Do you believe that the displayed available range reflects the real remaining range of the BEV currently?”). All participants of groups 2 and 3 claimed that their IVISs were very useful for lessening range concerns to different degrees. In addition, we inquired participants whether any other troubles happened with their IVISs, but no problems were mentioned. Accordingly, collected data of all participants were recognized qualified for the further analyses.

We applied the software IBM SPSS Statistics 25 to analyse the obtained data. Firstly, to examine the reliability of the questionnaires used in this work, Cronbach’s alpha (α) was computed and verified. The results are shown in Table 1. It can be found that all scales yield satisfactory internal reliability with α > 0.8, which means that the quality of the adopted questionnaires is high. To select a suitable test method for evaluating the difference between groups, the normality of the collected data was then tested and the analysis results are also listed in Table 1. Since the sample size was relatively small, the Shapiro–Wilk test was applied to test the normality. The results demonstrate that both of two variables were statistically significant among all three groups, indicating that two variables (range stress while/after driving) were regarded as being normally distributed. Furthermore, the homoscedasticity of collected data is also tested by using the Levene’s test. As listed in Table 2, the Levene’s test shows non-significant results for all variables, implying homoscedasticity.

As the collected data were confirmed to be normally distributed and homoscedastic, the independent samples t-test was picked out to evaluate the differences between experimental groups. The results for testing H1 and H2 are presented in Tables 3 and 4, respectively. Results with p value less than 0.05 stand for a sign that two samples are significantly different in a statistical sense. Cohen’s d value was computed as a measure of

\[ d = \frac{M_1 - M_2}{SD} \]

where \( M_1 \) and \( M_2 \) are the means of two groups, and SD is the standard deviation of their combined data.

### Table 1: Results of internal reliability and distribution normality test

| Range stress | Internal reliability Cronbach’s α | Group | W-statistics | Significance |
|--------------|-----------------------------------|-------|-------------|--------------|
| While driving | 0.82 | 1 | 0.94 | 0.17 |
| | 2 | 0.93 | 0.08 |
| | 3 | 0.96 | 0.53 |
| After driving | 0.91 | 1 | 0.93 | 0.36 |
| | 2 | 0.91 | 0.23 |
| | 3 | 0.86 | 0.05 |

### Table 2: Results of Homoscedasticity test

| Range stress | Homoscedasticity (Levene’s test) |
|--------------|----------------------------------|
| While driving | F-statistics | 0.72 | 0.49 |
| After driving | 0.16 | 0.86 |

### Table 3: Group comparisons based on H1

| Range stress | Group | Number | Mean | SD | t | df | p | d |
|--------------|-------|--------|------|----|---|----|---|---|
| While driving | 1 | 12 | 6.73 | 1.18 | 2.41 | 46 | 0.02 | 0.70 |
| | 2 | 12 | 5.94 | 1.07 | | | | |
| After driving | 1 | 12 | 7.02 | 0.99 | 2.36 | 22 | 0.03 | 0.96 |
| | 2 | 12 | 5.94 | 1.24 | | | | |
TABLE 4  Group comparisons based on H2

| Range stress  | Group | Number | Mean | SD  | t   | df | p     | d   |
|---------------|-------|--------|------|-----|-----|----|-------|-----|
| While driving | 2     | 12     | 5.94 | 1.07| 2.96| 46 | 0.01  | 0.85|
|               | 3     | 12     | 5.04 | 1.04|     |    |       |     |
| After driving | 2     | 12     | 5.94 | 1.24| 2.67| 22 | 0.01  | 1.09|
|               | 3     | 12     | 4.63 | 1.16|     |    |       |     |

FIGURE 6  The comparison of average range stress ratings between group 1 and group 2

FIGURE 7  The comparison of average range stress ratings between group 2 and group 3

effect size with $d = 0.20$ as a weak effect, $d = 0.20$ as a moderate effect and $d = 0.80$ as a strong effect [25]. Hence, in support of H1, there is a statistically significant difference ($p$ value = 0.02, $d = 0.70$) between group 1 and group 2 about the range stress while driving. Compared with participants of group 1, participants of group 2 had less range stress on cognitive and emotional levels during the driving experiment. A similar conclusion can be drawn regarding the perceived range stress after the driving of group 1 and group 2 ($p$ value = 0.03, $d = 0.96$). To be more intuitive, the comparison of range stress between group 1 and group 2 is shown in Figure 6. Compared with group 1, there are obvious decreases in both two measures of range stress of group 2. As expected for H2, the results shown in Table 4 reveal that the differences of self-evaluated stress while driving and after driving between group 2 and group 3 are both very significant with $p$ values equal to 0.01. The statistically significant differences can be also seen from the large effect sizes with $d = 0.85$ for the range stress while driving and $d = 1.09$ for the range stress after driving. Similarly, Figure 7 illustrates the comparison of average range stress ratings between group 2 and group 3. It can found that participants of group 3 gave lower rating points about the provided scales and, therefore, experienced lower range stress than the participants of group 2, indicating that the provision of extra range-related information (the battery SOH) was fruitful to mitigate the range anxiety of BEV drivers. In addition, it can be seen from Figures 6 and 7 that the changing trend of range stress of group 1 and of group 3 was different. The reason was that the range stress after driving was measured by asking the participants to recall and self-evaluate their experienced stress of the whole task. The participants of group 1 experienced more task failures, thereby leading to a negative and higher stress evaluation after driving. On the contrary, most participants of group 3 had completed the driving task successfully, thus leading to a positive and lower stress evaluation after driving.

Moreover, to make the data analysis more comprehensive, the Analysis Of Variance (ANOVA) was performed to compare the three groups at the same time. To be specific, one factorial ANOVA for mixed designs was used, with range stress as repeated measures (with two levels—during and after driving), and gender (male–female) and experimental groups (group 1–group 2–group 3) as between subject factors. Moreover, we interpreted effect sizes according to Cohen [25] with $\eta^2_p = 0.01$ as a weak effect, $\eta^2_p = 0.06$ as a moderate effect and $\eta^2_p = 0.14$ as a strong effect.

According to the results of ANOVA, it can be found that there was a statistically significant difference among the three experimental groups with a strong effect size ($F(2, 30) = 12.39, p < 0.001, \eta^2_p = 0.45$), while the male participants and female participants in this research did not differ significantly in the perceived range stress ($F(1, 30) = 12.39, p = 0.56, \eta^2_p = 0.11$). In brief, the results of ANOVA revealed the difference of perceived stress among the three groups and confirmed the effectiveness to reduce the range anxiety by using the improved IVIS.

4 | DISCUSSIONS

The present research was performed to better comprehend the phenomenon of range anxiety and to explore the underlying influence of battery SOH on range anxiety. Generally, the proposed hypotheses were confirmed. Experimental
results demonstrated that compared with participants equipped with the normal IVISs without considering the degraded SOH, participants felt less stressful about range when the IVIS provided corrected range based on the degraded SOH. In addition, the perceived psychological stress was further reduced with the provision of current SOH value on the dashboard.

The experimental results can be interpreted from the perspective of perceived uncertainties during the driving and trust towards IVISs. Since the range-related IVIS established a critical information resource in evaluating the difference between the remaining available range and trip range, the inaccuracy of estimated range will lead to an increased uncertainty of the trip, affecting the appraisal process of range stress in a negative way [5]. During the test drive, participants of group 1 often failed their driving tasks due to the credulity of unreliable range information, thus resulting in decreased trustworthiness of the system and increased uncertainties about completing the designated trip with the given range when they performed the formal experiment. Such untrustworthiness and uncertainties inevitably caused a certain degree of tension and anxiety of participants in group 1. Furthermore, although the participants of both groups did not know in advance if corrections are being applied in the range shown or not, the participants of group 1 had to face with the over-rapid consumption of displayed range due to the unreliable range information, thus resulting in a more stressful experience. By contrast, depending on the accurate correction of remaining range based on the degraded SOH, participants of group 2 and group 3 were less faced with unreliable estimated range, thereby promoting their trust towards systems and making the smooth arrival at the planned destination less uncertain. Accordingly, participants of group 2 and group 3 appraised the range situation as less anxious. Furthermore, the redundant display of range-related information (the vehicular SOH value) on the IVISs of group 3 further enhances participants’ confidence in the range estimation system to counteract uncertainties in the range-critical scenario, which influences the stress appraisal positively.

There are significant implications regarding the design and development of BEV which can be summarized from this research. In brief, the range anxiety can be reduced if the range-related IVIS is well designed in both information content and presentation considering the vehicular SOH.

For one thing, the research results emphasize that an accurate SOH-based range estimation provided by the IVIS is of great importance to lessen the range anxiety of BEV drivers. In this context, the BEV manufacturers are suggested to concern more about how the range-related IVIS associated with its influential factors, for example, the degraded vehicular SOH, affect the personal evaluation process of range anxiety, because range anxiety has been investigated to be negatively connected with range satisfaction, the desire of purchasing a BEV and the efficient usage of BEV range resources [21]. To prevent the adverse effects caused by range anxiety, it is recommended for the BEV manufacturers to adopt effective SOH estimation methods suitable for daily use into the battery management system, and offer more credible range information to drivers in real time. However, owing to the complex environmental conditions, it is difficult for the battery management system to totally avoid the disturbances of measured errors from the monitoring process in the actual driving context. Fortunately, with the development of measuring techniques like the high-fidelity current sensor systems [26], the uncertainties of the monitoring processes can be reduced gradually to an acceptable level, and it is possible to timely display the accurate SOH-based range information during the driving process of BEV drivers.

For another, to further relieve range anxiety, the design of the in-vehicle information interface can be improved by somewhat redundant display of range-related information, such as appropriately presenting remaining range and vehicular SOH value at the same time. As the experimental results showed, even though remaining available range and vehicular SOH value are highly correlated, the drivers take both types of information seriously while driving. This is consistent with the so-called “principle of redundancy gain” [27], which indicates that the appropriate redundancy of key vehicular parameters helps BEV users with both the verification of information source and the correct comprehension of information, increasing their own confidence in arriving at the destination. Therefore, the layout of redundant display of range-related information may be of particular significance to the BEV designers. In this regard, the proximity compatibility principle commonly used in the design process of human–machine interface may also be applicable [28]. Since the remaining range and the vehicular SOH are correlated, such parameters should not be arranged too far from each other, which help the BEV users combine the range-related information pieces together to reduce perceived uncertainties of the displayed figures [29].

Moreover, the effect of range-related information on road safety is a noteworthy issue. In this study, the information presented on the interface is apparent and convenient to be captured and understood, making it unlikely to cause heavy distractions and cognitive load. Furthermore, by offering reliable range-related information, the range stress of BEV drivers can be alleviated. In this context, the human error probability of drivers can be reduced, thereby being beneficial to the driving safety to some extent. However, if the range-related information of group 3 becomes unreliable and is displayed redundantly at the same time, with no doubt, it will distract the drivers from the driving process most heavily, thus affecting the road safety negatively. Hence, considering the importance of remaining range and vehicular SOH in driving safety, they should be displayed continually and signally on the dashboard of BEV, thus minimizing the cost of information acquisition as possible during the driving process.

Finally, another interesting issue needed to be focused on is to investigate the relationships between the driving mode and the range anxiety. In this work, the driving task was set as a relatively urgent trip needed to be finished as soon as possible, so it can be inferred from common sense that the participants would tend to select the fast-driving mode when completing the trip if they did not feel obvious range anxiety. The BEV designers are expected to further study and test this relationship to help the drivers use the available driving range as efficiently as possible.
5 | LIMITATIONS AND FUTURE WORKS

The following limitations and future works should be considered whilst accounting for this study. First, to minimize the influence of external interferential factors, we have performed our simulation experiments under the controlled external environment (plain highway with no traffic jam and no extreme weather). So for now, the findings of this study can be extrapolated to a real situation under similarly external conditions. However, the road and environment conditions are usually uncertain in real driving contexts. In future works, we suggest that more driving experiments can be carried out to test the external validity of our findings under more diverse and complicated driving environments (e.g. urban roads).

Second, the experimental results indicated the positive effect of SOH on range anxiety, but the quantitative influence of different SOH levels on the range anxiety was not further explored. Empirically, the more seriously the SOH degrades, the higher range anxiety the driver feels. Therefore, we suggest that future works should manipulate the SOH as the key variable during the experiment to reveal and verify the severity of range anxiety under different levels of degraded SOH.

Third, we assessed the perception of range stress based on questionnaires related to the stress appraisal. However, the measurement methods can be more comprehensive, because research has also shown that stress is also accompanied by arousals, typically relating to a change in physiology [30]. Therefore, some physiological measurements, such as eye glance [31] and heart rate [13] of participants, should be applied in future works to achieve a more objective evaluation of range stress.

Fourth, to further research the effect of range-related information on road safety, we call for future works to focus more on exploring the distracting behaviours of drivers under unreliable information environments.

The last limitation is the young participant sample without sufficient BEV experience, which could have influenced the results. It has been found that inexperienced BEV drivers are prone to experience more range anxiety than experienced drivers [4]. Therefore, future works are suggested to extend the sampling range to improve the generalization of our research.

6 | CONCLUSIONS

The objective of this research was to better understand the impacts of the vehicular SOH on the range anxiety of BEV drivers. Under the condition of SOH degradation, 36 participants used simplified BEV driving simulators equipped with different IVISs to finish a designated trip in a range-critical situation. Results indicate that the improved IVIS with corrected range based on the SOH leads to a lower level of range anxiety compared with that without considering the effect of the degraded SOH. In addition, the perceived psychological stress was further reduced when the IVIS displayed the current SOH value on the dashboard.

In recent years, the flourishing development of BEV is regarded as an effective measure to deal with the challenges of decreasing the greenhouse gas emissions and controlling air pollution caused by urban cars, but their broad application, up to now, is still low. In the context of limited available range of BEVs, this research reveals the significance of displaying accurate remaining range and related information (the battery SOH) to enhance the trustworthiness and acceptability of BEVs, which is expected to be referable and useful for the design and refinement of BEV interfaces.

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