

Examining User-Range Interaction in Battery Electric Vehicles – a Field Study Approach

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ABSTRACT

In order to provide users with an optimal range-related user experience, it is essential to develop a comprehensive understanding of everyday user-range interaction. For this to happen, it is important to sample a high amount of situations where battery-electric vehicle (BEV) users must actively interact with the range resources of their BEV. The present contribution presents the methodology (i.e., a toolbox to study user-range interaction) and preliminary results of a field study that was designed to reach this objective: The BMW ActiveE long-distance commuter field trial in the area of Leipzig, Germany. Within this study, a sample of 75 customers was given the opportunity to drive a BEV for three months. Applicants were recruited via an online screening questionnaire. In order to be selected, participants had to drive at least 90 km per day. A comprehensive data set was generated based on qualitative interviews, questionnaires, diary methods, and data loggers. Relevant constructs were identified and translated into items/scales or specific score definitions. Initial results show that even users who have high daily mobility needs can cope with the limited range of a BEV. However, results also point to the potential of strategies aimed at supporting users in adapting to BEV range to reach an optimal user experience even under conditions of high range demand.

Keywords: battery electric vehicles, field study, user experience, behavior, range, methodology

INTRODUCTION

Battery electric vehicles (BEVs) are a promising form of sustainable mobility because of their potential to reduce CO₂ emissions and air pollution (Holdway, Williams, Inderwildi, & King, 2010), as well as their potential to mitigate risks associated with peak oil (Hirsch, Bezdek, & Wendling, 2005). However, limited range can be a challenge for BEV users. Although substantial improvements in electric vehicle battery performance are likely within the coming years, smaller but suitable battery sizes will always constitute a more sustainable battery layout because battery size is strongly related to the ecological footprint of an electric vehicle (Hawkins, Gausen, & Strømman, 2012; McManus, 2012). Cost-effectiveness of a battery also plays a major role in buying decisions. Even with declining battery costs, it is likely that a large share of customers will not automatically opt for the largest possible battery, but will instead compromise between their daily driving needs and a suitable battery size. As a

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consequence, the following question will remain relevant in research and development: How can the maximum usable range for the customer be achieved given a certain nominal battery capacity?

Research has shown that it is challenging for users to interact with limited battery resources in an optimal way. For example, it has been shown that users tend to avoid situations that would lead to range stress (i.e., range anxiety) by reserving substantial range safety buffers (i.e., around 20% of real available range; Franke, Neumann, Bühler, Cocron, & Krems, 2012c; Franke & Krems, 2013a; Carroll, 2010). Their limited range comfort zone (i.e., comfortable range; Franke & Krems, 2013a) results in the usage pattern in which a certain share of the battery capacity is lost as a psychological safety buffer.

Obviously, it is difficult to study critical range situations systematically in everyday situations. Not only because users seek strategies to avoid these situations as described above, but also because most potential customers would simply not buy a vehicle that only marginally fits their mobility needs in the first place. Isolated laboratory experimental methods are also not suitable as user-range interaction takes substantial time to stabilize (Franke, Cocron, Bühler, Neumann, & Krems, 2012b; Pichelmann, Franke, & Krems, 2013; Burgess et al., 2013). Therefore, a field trial was established that recruited long-distance commuters interested in electric mobility.

The objective of the present contribution is to explicate key elements of the methodology developed to study user-range interaction (i.e., the interaction with limited resources in human-machine systems; Franke, 2014). The aim is to provide researchers with a toolbox for future studies in this area in terms of constructs and operationalizations. To this end, the range-related aspects of the methodology developed within the project “BMW ActiveE Leipzig – long-distance commuters” are described and discussed in the following sections along with a short description of preliminary results.

FIELD STUDY RESEARCH DESIGN

The project “BMW ActiveE Leipzig – long-distance commuters” was a field trial in the region around Leipzig, Germany. This field trial was set up by a consortium consisting of the BMW Group, the Stadtwerke Leipzig (SWL, Leipzig municipal utilities), and Technische Universität Chemnitz. It was funded by the German Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety (BMUB) as part of the e-mobility showcase region Bavaria-Saxony (“Electric Mobility Connects”). Major objectives of the study were to examine: (1) acceptance of having to charging once or even more than once a day (e.g., at work and at home), (2) interaction with range and range stress (i.e., range anxiety) in everyday BEV use, (3) adaptation and learning effects in driving a BEV (i.e., related to range management), (4) eco-driving and additional strategies to cope with range, (5) need for support and potential for optimizing user-system interaction, (6) user acceptance and behavior regarding different layouts of the regenerative braking systems (research topic is separate from user-range interaction, therefore it is not discussed in this contribution), and (7) phase effects (i.e., grid interferences) and charging curves (technical research topic of the SWL, therefore this area is also not documented).

The field trial was designed as a longitudinal study that involved three main points of data collection (see Table 1): Before users received their BEV (T0) including a short additional data collection event after users had gained their first experience with the BEV after approximately one week of BEV use (T0+1), after six weeks of BEV use (T1) and at the end of the trial after twelve weeks (T2). At each point of data collection, users completed a 2- to 3-hour face-to-face interview including questionnaires. Additionally, participants filled out diaries and data loggers automatically recorded several parameters. The general study design was based on structural elements that had already proven fruitful in earlier BEV field trials (Cocron et al., 2011; Franke, Bühler, Neumann, Cocron, & Krems, 2012a). To yield a high sample size with the given number of available cars (15), this study design was repeated five times (i.e., usage phases 1 to 5) resulting in a total number of 75 customers who got the chance to drive the BEV for three months.

The field trial used a person-based main user data collection approach, meaning that only data from the (prospective) primary (i.e., main) user of the BEV was collected and analyzed. The main user of the BEV was defined within the screening process based on an estimated usage share (i.e., primary drivers’ share of BEV vehicle miles travelled relative to the total miles driven by all drivers of the BEV) of greater than 70 percent. In terms of the logger data, personalized car keys were used to filter out data segments that were not generated by the main (i.e., primary) user of the BEV.

Several behavior-related variables (e.g., parameters of charging behavior, trip distances and other mobility parameters) were assessed with multiple methods (e.g., diaries and data loggers) for certain periods. This redundancy allowed for a comprehensive data triangulation (e.g., identification and quantification of weaknesses/biases of different methods), as well as data fusion (i.e., reduction of specific method biases through integrated multi-method assessment). As a result, for each variable the most accurate method(s) could be determined and/or several data sources could be combined to yield a more accurate estimate. Moreover, this aspect of the research design made it possible to derive data quality indicators (e.g., regarding participants' compliance or precision of subjective diaries).

Table 1: Sequence of data collection events within the user study.

Timeline (weeks)	Data collection event	Acronym
-12	<i>screening finalized</i>	
-3	first telephone interview	T0-3
-2-0	baseline trip diary (1 week) & baseline GPS logging (combustion vehicles)	T0
0	face-to-face appointment: questionnaire, interview, test drive <i>vehicle handover</i>	T0
1	questionnaire & telephone interview	T0+1
5-6	travel diary (1 week)	T1
6	face-to-face appointment: questionnaire, interview, test drive	T1
10-12	range and recharging diary (10 days)	T2
12	face-to-face appointment: questionnaire, interview, test drive <i>vehicle return</i>	T2
0-12	logger data collection (GPS & car data)	-
0-12	car diary (event-based diary)	-

RECRUITMENT AND SCREENING OF PARTICIPANTS

To recruit interested customers from the general public, information on the project was distributed via radio, local television, newspaper, online media, partner websites, public events, and informational stickers on the BEVs. People could apply by accessing a public website via one of several short links (e.g., www.bmw.de/testfahrer or www.tu-chemnitz.de/activee) and completing an online questionnaire on the linked website. More than 650 people applied for the three-month lease of the BMW ActiveE. Applicants were included in the final selection if they: (1) were willing to pay the monthly leasing rate of 450 € (reduced to 370 € as soon as the BMW i3 was available for sale) and the costs for electricity, (2) had at least one charging opportunity or the possibility of installing a charging station at home and/or work (dependent on the prospective daily distance driven with the BEV), (3) were willing to take part in data collection, (4) had a mobility profile that would be expected to result in a frequent active interaction with range (i.e., at least 90 km daily driving distance with the BEV), and (5) lived or worked in the area around Leipzig (max. 120 km away). Given that the average daily distance travelled in Germany is around 39 km (infas & DLR, 2010), 42 km for rural districts, a mobility profile resulting in a 90-km driving distance per day is relatively high (i.e., users with such a mobility profile can be readily labeled as daily long-distance commuters).

After screening for the inclusion criteria (see above), participants were primarily selected and prioritized based on their expected frequency of having to interact with range (i.e., combined analysis of daily driving distances and available charging opportunities). As restrictions for inclusion in the sample were similar to those for leasing a BEV (e.g., users paid an EV-adequate monthly leasing-rate, needed charging opportunity), we expect the sample to represent a population of early adopters (i.e., early customers) of BEVs in Germany.

BEV AND CHARGING INFRASTRUCTURE

The BEV used in this study was the BMW ActiveE, an electric conversion vehicle based on a BMW 1 Series Coupé with a maximum available driving range between 130 and 160 km in real terms, depending on driving style (Ramsbrock, Vilimek, & Weber, 2013). It took 4-5 hours to fully charge the battery using a 32 A charging station and 8-10 hours using a normal socket. Customers could access, amongst other data, information on battery charge level, range, energy consumption, and the charging process: The estimated remaining and full charge range were displayed based on energy consumption over the last 30 km (as stated in the user manual), the state-of-charge was displayed (0-100%), the current and average energy consumption were displayed (including an energy consumption history display with 1-minute averaging intervals for the current trip). Furthermore, during charging processes the estimated time until the vehicle was fully charged was displayed. In addition, users had access to advanced online vehicle functions including the “My BMW remote” smartphone app (see also Franke et al., 2014b) that could be used to remotely control certain functions (e.g., starting/stopping a charging process, preconditioning of the battery and passenger compartment) and monitor certain parameters (e.g., remaining range, remaining time until fully charged, charging status). Participants could install the app on their own smartphone or tablet (Android or iOS). For this field trial, the standard series version of the BMW ActiveE was slightly modified. The series version comes with an ECO PRO mode that can be selected to automatically adjust the drive configuration and comfort functions to achieve a higher range. For this field trial, the ECO PRO mode was deactivated, partly to maintain greater control over the available range for the users, but also to allow for testing of different layouts of the regenerative braking system.

Participants used different charging infrastructure configurations depending on their mobility profile. There were two different settings, determined by the commuting trip distance, i.e. the one-way trip distance between the place of residence (home) and the workplace (work): Setting 1 for participants using only *one* charging point (at work or at home) and setting 2 for those using *two* charging points (at work and at home). In the first case (setting 1), the distance should not be more than 60 km, in the second case (setting 2), it should not be more than 120 km. In terms of charging stations (work/home), there were different conditions possible: a 32 A charging station (or 16 A, depending on the capacity of the grid connection) or a normal socket. Sometimes, the 32 A charging station was already installed at the workplace. Moreover, there were participants using public charging stations as a charging point. It was considered important not to include the combination of two sockets (at work and at home) because charging duration could have been too long. Apart from that all participants received a “charging card” from the SWL that enabled them to use all public charging stations in the city of Leipzig (around 30).

PROTOCOL METHODS AND DATA LOGGERS

Travel Diary

The travel diary was a person-based, self-report diary. Before T0 (i.e., baseline mobility with combustion vehicle) and before T1 (i.e., mobility with BEV) the (prospective) main user of the BEV was asked to record all trips made with every means of transportation for 1-week (5 workdays, 2 weekend days – meaning non-working days as clarified in the T0-3 telephone interview with users who did not have a typical Mo-Fr workweek). The following trip definition was applied: Each discrete instance of travel outside of the home was defined as a trip (i.e., had to be recorded). If the trip was interrupted (e.g., for an errand) the section after this interruption was defined as a new trip (i.e., also outbound and inbound trips were counted as separate trips). Also trips by foot >100 m had to be recorded. For each trip, participants answered the following items at T0: (1) date and time at the beginning and at the end of the trip, (1) trip distance in km, (2) purpose of the trip (categories: more work-related vs. more leisure-related trip), (3) main mode of transportation used (defined as the mode of transportation with which the user traveled the most distance; categories included: car or other motorized private transportation, public transportation including taxi and plane, non-motorized transportation, other), and (4) if the trip was logged by the GPS logger (i.e., if the trip was taken in the vehicle that had the GPS logger installed). At T1, the additional category “BEV” was introduced as a mode of transportation and additional items assessed (5) remaining range, and (6) charging status at the beginning of the trip, as well as (7) reason for non-use of the BEV (if applicable; categories included: general limited range of the BEV, currently insufficient remaining range, non range-related reasons).

A score that was only derivable from this method was, for example, the number of trips driven with the BEV relative to the total number of trips (or relative to the total number of trips with motorized private transport). Human Aspects of Transportation II (2021)

Moreover, this method allowed for characterization of trip parameters (e.g., frequency, distance, mode of transport) that could not be taken with the BEV due to its limited range. Finally, by administering the diary in a similar layout before T0 and T1, comparisons of mobility profiles (i.e., BEV-related changes in general mobility patterns) became possible.

Range and Recharging Diary

The range and recharging diary was a car-based, self-report diary. Before T2, users were asked to record all trips and recharging events with their BEV over a period of at least 10 days of BEV usage within a diary (i.e., similar to a driver's logbook). The trip definition was: "Each instance of travel (i.e., distance driven) with the BEV is a trip." and "As soon as you step out of your car the trips ends and subsequently a new trip starts." For each trip, participants logged the following variables at the beginning and at the end of the trip: (1) time, (2) odometer reading, (3) information on remaining range and (4) full charge range, (5) charge level, (6) the availability- and (7) the use of a charging opportunity at the end of the trip, as well as (8) the user (main user of the BEV vs. secondary user). Data from secondary users was recorded to obtain a continuous (i.e., gap-free) record that allowed for more accurate plausibility checks and was more tolerant of single missing values (i.e., certain missing values could be reconstructed based on prior and subsequent data entries).

A score that was only derivable from this method was, for example, the *percentage of charging opportunities used* score (i.e., the amount of initiated recharging events divided by the amount of subjectively available recharging opportunities at the end of the trip). Together with information on trip length and available range, this also yielded a score for the *abundance of charging opportunities*, which is an important parameter when examining user-battery interaction (Franke & Krems, 2013b). Another score derived from this diary was the *time to charge* score. For each charging event, the available time in minutes until the next trip started was computed and divided by the amount of energy that had been discharged (i.e., 100 – the current state of charge). Results showed, for example, that there was a moderate negative relationship between this variable and the usage frequency of range-related remote access functions provided by the "My BMW remote" smartphone app (i.e., typically less time to charge = more intensive usage of remote access to range/charging status; Franke et al., 2014b).

Event-based Car Diary

The event-based car diary was used to record any events where the car behaved unexpected or car behavior was incomprehensible to the users. For each event, users were asked to record: (1) date, (2) time, (3) odometer reading, (4) how the car behaved (i.e., what was unexpected/abnormal), and (5) speculation as to what caused this car behavior.

Data Loggers

Different data loggers were used to record relevant parameters. First, a GPS logger recorded standard GPS variables (e.g., time, position, speed, height), trip distance (with map-matching algorithm correction), and information on the user (i.e., users were asked to press a button switch that changed a marker signal in the data logs from "main user" to "secondary user" and vice versa). The user-information was only collected for the GPS-logs before T0 (i.e., of the users' main combustion vehicle) because in this period no user-information was available from other logger data sources. For the BEV usage period (T0 to T2) it was deemed too burdensome and potentially error-prone to require users to operate the switch for the complete twelve weeks. By collecting GPS-information both before T0 and between T0 and T2 (i.e., for BEV usage), further analyses regarding BEV-related changes in mobility patterns were enabled (e.g., changes in activity space; Kurani, Turrentine, & Sperling, 1994).

The trip definition for the GPS logger and the other car-based data loggers was a function of turning the vehicle on/off (e.g., GPS logger received an on/off-signal from the cigarette lighter), and therefore, slightly differed from that of the diaries (see above). Hence, this resulted, in a tendency for more trips to be recorded via the loggers than through the diaries. However, such an on/off trip definition was not applicable for the diaries in most cases (e.g., given travel diary items) and would have resulted in too much burden on users, and therefore, potentially lower data quality.

Additionally, the BMW Group recorded several signals with different data loggers. Exemplary variables derived from these signals that were used to study user-range interaction were: date, time, odometer reading, trip distance,

parameters of recharging processes, range, speed, and temperature. Moreover, the IDs of the personalized car keys were recorded along with trip, time, and odometer information to allow for filtering out all secondary user data segments from all the logger data. To identify user-related problems in using the car keys as instructed, users were asked in the interviews at T0+1, T1, and T2 to quantify and list events where they could not (or simply did not) use the car keys as instructed.

PSYCHOLOGICAL CONSTRUCTS AND OPERATIONALIZATION

The following sections will focus on the scales and items (i.e., scores) assessed within the questionnaires. As the aim of the development of the study methodology was to comprehensively examine user-range interaction, several steps were taken to ensure that the relevant psychological constructs were identified and operationalized appropriately.

First, in the *identification phase*, multiple strategies were employed to enable an anticipation of the everyday experience and behavior of users who have high range demands, thereby enhancing identification of constructs which could play a role in everyday user-range interaction: (1) literature research, (2) deduction of research questions and hypotheses from the adaptive control of range resources (ACOR) model (Franke et al., 2012c; Franke & Krems, 2013a; Franke & Krems, 2013b, Franke, 2014), as well as from results of the previous field trials with the MINI E and BMW ActiveE in Berlin (Franke, Cocron, Bühler, & Neumann, 2013; Vilimek & Keinath, 2014), (3) weekly meetings of the method development team, (4) consortium workshops, (5) extended trips with the BEV (i.e., by members of the method development team) to learn about range-related vehicle behavior (e.g., range dynamics) from a drivers' subjective perspective, and finally (6) a pre-study with more than 70 users who drove the BEV in a critical range situation (≈ 100 km trip with ≈ 120 km range in the beginning given challenging driving conditions) that provided comprehensive subjective data. The result of this process was a research topic list that contained relevant psychological constructs and topics that were then prioritized to create a final consolidated list of research topics.

Second, in the *operationalizations phase*, those constructs were assigned to appropriate methods and, where appropriate, questionnaire items and scales were developed (for a list of final scales see Figure 1). In this process, a first step was to search for existing (established) items and scales that could serve as a basis for item construction or that could be (directly) transferred/translated for usage in the present study. This included, for example, a literature search for properly developed short scales assessing psychological constructs related to task motivation, stress resistance and self efficacy, as well as the screening of questionnaires that had already been applied (and had proven to be useful) in the previous BEV field trials with the MINI E and the BMW ActiveE in Berlin (see above). In sum, most items needed to be newly constructed, yet at least structural item elements (e.g., certain response scale characteristics and item formats) could be transferred for most of the items. In terms of the response scale, most items were formulated so that a standard 6-point Likert scale that had proven to be useful in previous field trials (completely disagree, largely disagree, slightly disagree, slightly agree, largely agree, completely agree; coded as 1 to 6) could be used. This scale also had the advantage that it allowed for dichotomization of responses (i.e., % of users who rate the item with scale values of 4-6 = % of users who tend to agree with the item text). Additionally, for some items a more fine-grained scale with numerically indicated scale gradation (0, 1, ..., 9, 10) was used where only the end points of the scale were labeled (e.g., for a rating of confidence in one's retrospective estimation of average consumption: "not at all confident" vs. "absolutely confident"). Finally, frequency ratings were assessed with a 6-point scale (never, almost never, occasionally, often, almost always, always; coded as 1 to 6).

As the general psychological characteristics behind the specific BEV-related user-range interaction styles were of high interest (e.g., general interaction styles in managing limited resources), several scales and items were included that allowed for examination of: (1) the role of interaction style transfer from other human-machine systems and (2) the role of general personality characteristics (for the latter aspect see Figure 1). Regarding the role of cross-system transfer of certain key attributes/styles (e.g., user-battery interaction, range utilization, see Figure 1), additional items were constructed that were framed upon the non-BEV technical system (e.g., combustion vehicle and mobile phones), but formulated as similarly as possible to the BEV-related items. For example, the UBIS-1 and UBIS-8 scale (Franke & Krems, 2013b) were also assessed within the context of mobile phone charging. For instance, the BEV-related item of UBIS-8 "... I typically charge when I am below a specific buffer range that I always want to have in the battery." was translated to "... I typically charge when I am below a specific reserve capacity that I always want to have in the battery." Moreover, in terms of range-interaction in combustion vehicles, several items were administered to examine whether people who utilized the range of the BEV to a high extent (e.g., who

frequently experienced situations with low battery, assessed at T1 and T2) had already been among the people (at T0) who frequently encountered low-fuel situations in their combustion vehicle. This was, for example, assessed by asking users at T0 to report the frequency of encountering situations with: (1) less than 5 liters vs. (2) less than 10 liters in the fuel tank and asking at T1 for the frequency of encountering situations with the BEV with: (1) less than 20 km remaining range vs. (2) less than 40 km remaining range. Of course those values cannot be interpreted and compared in an absolute sense (i.e., comparison of means). Yet, testing for a correlation of the combustion vehicle items (T0) with the BEV items (T1) can give some indication regarding possible transfer effects from combustion mobility to electric mobility. However, to correctly analyze this relationship, it is also important to include mobility-related variables in the analysis. For example, some BEV drivers may simply not have the freedom to decide whether to charge the car before reaching 20 or 40 km remaining range because of their unique configuration of charging opportunities and commuting distance.

- Acceptance** – purchase intentions | satisfaction & usefulness¹ | overall satisfaction | suitability for everyday use | recommendation²
 - Mobility needs fit** – coverage of mobility needs by BEV | BEV-related barriers to optimal mobility needs fit | BEV-related flexibility loss | availability of alternative (combustion) car
 - Range evaluation** – range preferences | range satisfaction
 - Range experience** – range stress & range concerns (frequency & intensity) | annoyance of range interaction
 - Range levels** – comfortable range (absolute/relative safety buffer, distance with good feeling, comfortable range scenario task³) | performant range | competent range
 - Range competence** – subjective range competence (prediction & control) | mental model of range dynamics | general technical background knowledge
 - Range adaptation** – subjective adaptation duration | adaptation intensity | adaptation strategy | task motivation | subjective task difficulty | need for assistance | active practice with BEV
 - Range utilization** – frequency of low-battery situations | approach/avoidance of critical range situations | maximum distance per day & per charge | minimum displayed range/state-of-charge
 - Eco-driving** – interest & motivation | behavior (intensity & frequency) | range related adaptation of driving style | general driving style | competence/knowledge | general technical background knowledge
 - Display interaction** – interaction frequency with range & consumption displays | trust in range prediction | usage of remote access to range-related information & perceived support
 - User-battery interaction** – User-battery interaction (UBI) motivation | User-battery interaction style (UBIS-1 & UBIS-8⁴)
 - Charging** – appraisal of charging duration & reliability | charging locations | charging behavior (frequency & omission of opportunities)
 - Mobility** – daily distance estimates (average & weekly maximum) | confidence in daily distance estimates
 - Baseline mobility** – frequency & distance of long distance trips | yearly mileage | daily distances | affinity to plan trips | regularity/predictability of daily mobility patterns
 - Personality** – impulsivity (planning affinity)⁵ | control beliefs in dealing with technology (KUT)⁶ | self efficacy⁷ | need for cognition⁸ | affinity to technology | interaction with time buffers
- ¹ Van Der Laan et al., 1997 | ² Bühler et al., 2014 | ³ Franke et al., 2014 | ⁴ Franke & Krems, 2013b | ⁵ Meule et al., 2011 | ⁶ Beier, 1999 | ⁷ Schwarzer & Jerusalem, 1999 | ⁸ Bless et al., 1994

Figure 1. Scales and constructs assessed in the questionnaires.

Range Evaluation and Range Experience

Within this and the following sections some exemplary range-related scales will be discussed. One central research question of the field study was how users with high range demand experience, and consequently, evaluate BEV range. Furthermore, it was of high interest under which conditions (e.g., mobility and personality profile) range stress occurs with high frequency and intensity. In terms of range evaluation, for example, two open-ended, stated

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preference items were adopted from previous research (Franke & Krems, 2013c) to assess range preferences (e.g., "Which EV range would you consider to be quite short, but just acceptable?"). In terms of range stress and range concerns, items applied previously (Franke et al., 2012c; Franke & Krems, 2013a) were used and further developed (e.g., new item for range concern frequency "How often is a range situation unpleasant for you?").

Psychological range levels

At least within the context of relatively average mobility profiles in the German mobile population, user-range interaction is typically not characterized by the experience, but rather by the avoidance, of range stress (Franke et al., 2012c). This leads to the pattern in which there is a discrepancy between the maximum available range and the maximum range that the driver is comfortable using. As a consequence, the efficiency of user-range interaction (and therefore also the user experience) can be understood as a function of three psychological range levels (Franke & Krems, 2013a). In the present study a methodology was applied to assess range levels that is very similar to methodology utilized in previous research (Franke & Krems, 2013a). Yet, there were some further developments towards simpler scales to assess comfortable range (Franke, Günther, Trantow, Rauh, & Krems, 2014a).

Mobility and Mobility needs fit

Characteristics of the users' baseline mobility profile (i.e., resource demand profile) constitute a key variable set when studying user-range interaction. This is because mobility demand is strongly associated with the opportunities, challenges and the necessity of actively interacting with range. For example, drivers who have lower mobility needs will need to more actively search for critical range situations to push the limits of their range comfort zone while people with higher mobility needs will more often come into potentially critical range situations incidentally, in other words they will have a higher need to adapt their range comfort zone (i.e., a higher adaptational pressure).

However, not all parameters of the mobility profile are easily assessed with objective data like travel diaries (particularly not with a diary of only seven days). So we also targeted low-frequency events (e.g., long distance trips) and the regularity/predictability of daily mobility patterns (see Franke et al., 2014b) in the questionnaire.

Also, in terms of the mobility needs fit, there is more to evaluate than simply the percentage of mobility needs that can be covered with the BEV. For example, the need for planning and adjusting daily schedules (i.e., a loss in flexibility) is something that can go hand-in-hand with dealing with a more limited resource (i.e., resources that require substantial time to refill/recover). Hence, items like, "Planning car usage (trip planning, charging times) with the BEV is demanding" and "With the BEV, I am as flexible as with a combustion vehicle." were also included to study the subjective mobility needs fit of the BEV.

PRELIMINARY RESULTS

The following section shall give a preliminary impression of the pattern of results within the field study. For this purpose, only the data from the first two usage phases with 29 users who completed the whole study (one dropout before T1) could be analyzed. These had an average age of $M = 41.1$ years ($SD = 8.1$), 5 were female.

The aforementioned users estimated at T0 that their average daily car driving distance was around $M = 120$ km ($SD = 40$ km). Based on the travel diary at T1 it was found that people indeed drove, on average around $M = 109$ km a day with the BEV on days with BEV mobility including weekend days without commuting ($SD = 41$ km, $N = 28$ because one user had too few data points, additionally one user had an extremely low average daily distance of 2.5 km, without this user $M = 112$ km). Hence, users had, on average, even higher daily distances than what was required by the screening criterion. The longest driving distance with the BEV on one day that participants reported over the whole usage phase (the item was administered at T1 and T2; thus, the maximum of the two values of each user was taken) was on average $M = 176$ km ($Min = 90$, $Max = 265$).

In terms of general satisfaction (i.e., acceptance), the tendency to recommend the BEV to a friend with a similar mobility profile (item: "I would recommend electric vehicles like the BMW ActiveE to a friend with similar mobility demands", adapted from Bühler, Cocron, Neumann, Franke, and Krems, 2014) was very high throughout the study. While 90% of the 29 users agreed with the statement at T0 (dichotomization of 6-point Likert scale, see Human Aspects of Transportation II (2021)

above), this number was the same at T1 (90%) and T2 (90%). Also, in terms of the average rating of this item (scale values from 1-6, see above) there was nearly no difference between the data collection time points ($M_{T0} = 4.86$, $M_{T1} = 4.79$, $M_{T2} = 4.72$).

In terms of learning processes, participants reported that they increasingly had the feeling that they were able to predict the range of the BEV under different conditions (item: “I can precisely estimate the range of the BEV under different conditions”). While 76% of the users agreed at T0+1 ($M = 4.10$), this value increased to 100% at T2 ($M = 5.14$). A similar result was revealed with the item, “I can precisely estimate the influence of different factors on range” (T0+1: 69%, $M = 3.39$; T2: 100%, $M = 4.86$).

However, the increase in subjective ability to estimate (i.e., predict) the range under different conditions did not come automatically (i.e., without effort). Users who endorsed stronger agreement at T2 with the item, “I have tried to understand the factors that influence range” (i.e., a higher active exploration tendency), also reported a substantially higher increase in their subjective ability to predict range from T0+1 to T2. For this analysis, the difference between users’ ratings of the two aforementioned items at T0+1 and T2 was computed and a mean score of the two new difference variables was computed (high values = high increase in subjective range prediction ability). The correlation between active exploration tendency and subjective range prediction competence was significant ($r = .41$, $p = .026$). This suggests that assistance strategies which engage the user in active exploration of range dynamics might have the potential to enhance range-related learning processes (i.e., adaptation processes), thereby, resulting in a better user experience.

Parallel to the development in subjective range competences, active preoccupation with the range (item “While driving the BEV I am often preoccupied with the range”) continuously decreased with experience (T0: 90%, $M = 4.55$; T0+1: 83%, $M = 4.34$; T1: 79%, $M = 4.28$; T2: 76%, $M = 4.34$). Finally, we also examined the frequency of range-related stressful encounters (i.e., the frequency of range stress) with items that are similar to those used in previous research (Franke et al., 2012c; Franke & Krems, 2013a). Specifically, we administered the item, “How often do you feel stressed because of the range?” (exactly the same item as used in Franke et al., 2012c and Franke and Krems, 2013a) at T1 and T2. First, the correlation between range stress frequency assessed at T1 and T2 was strong. As normal distribution was not indicated for the frequency rating at T1 and T2 (p -values for Kolmogorow–Smirnov test $< .05$) Spearman’s rank correlation coefficient ($r_s = .88$, $p < .001$) and Kendals tau were computed ($\tau = .78$, $p < .001$) and, for completeness, also Pearson’s product-moment correlation coefficient ($r = .54$, $p = .003$). This finding indicates an acceptable test-retest reliability and that range experience had stabilized to a larger extent within the period between T1 and T2. This stabilization was also evidenced by the average values at T1 ($M = 2.40$, $Mdn = 0.50$) relative to T2 ($M = 2.34$, $Mdn = 0.50$). However, as suggested by the difference between the Mean and the Median values, there was a high degree of variance in users’ range stress frequency and there were also several users who never experienced range stress. In particular, at T1 45% of the users stated that they never experienced range stress in a typical month and 28% indicated more than one situation per month (same results at T2). These results are somewhat higher than what has been found previously in the MINI E Berlin field study, a study conducted in an urban region with a typical daily BEV driving distance of approximately 38 km; Franke & Krems, 2013b). Here the results at T2 were an average of approximately one stressful range situation per month (Franke et al., 2012c; Franke & Krems, 2013a). However, in this study only 34% of the users never experienced a stressful range situation and, similar to the present study, 24% experienced more than one situation per month (Franke et al., 2012c). Therefore, the story seems to be slightly more complicated than just “higher daily range demands lead to more range stress”.

DISCUSSION

The objective of the present contribution was to describe a methodology that was designed to better understand how users interact with the limited range resources in BEVs. An extensive package of methods was developed and applied within a field study setting. Based upon experience in utilizing these methods within the field trial, it can be concluded that the developed body of methods has proven to be fruitful and the developed questionnaire items and scales produce meaningful data and results. Moreover, preliminary results indicate that even users who have high daily mobility needs can cope with the limited range of a BEV. However, the results regarding the role that active range exploration plays in the increase in subjective range competence also suggests that strategies aimed at supporting users’ adaptation to BEV range have the potential to help users reach an optimal experience even under conditions of high range demand.

One final question may be whether we have learned something that is only specific to the examination of user-range interaction in BEVs based on the present research or if elements of this research methodology have broader applicability to other areas of human factors research. 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 behavior (e.g., Fuller, 2005). 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. This description of the resource situation structure fits with several battery-powered mobile devices to some degree. And indeed many of the psychological constructs and questionnaire items used in the present study can be translated, for example, also to the domain of user-battery interaction in smartphones. Consequently, we hope that the presented research methodology can inspire further studies that examine other human-machine systems where users have to deal with limited resources, particularly because the sustainable interaction with limited resources is a vital topic of our time.

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