Interacting with limited mobility resources: Psychological range levels in electric vehicle use

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ABSTRACT

Limited driving range is an obstacle to adoption of electric vehicles (EVs). We examine from a self-regulation perspective the psychological dynamics underlying individual reference values for three different types of range constructs. In a 6-month field trial 40 EVs were leased to a sample of early adopter customers. In general, users were satisfied with range and stressful range situations rarely occurred. Results further suggested that users were comfortable with utilizing approximately 75–80% of their available range resources. Several personality traits (e.g., control beliefs, low impulsivity) and system competence variables (e.g., daily practice, subjective competence) were positively related to range level values and thus range utilization. Comfortable range was positively related to range satisfaction. We recommend that psychology-based strategies should be applied to enhance range optimization.

Keywords: Electric vehicle, Field trial, User experience, Self-regulation

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1 INTRODUCTION

Increasing concerns about the environmental impact of the current road transport system as well as the risks associated with peak oil (Hirsch et al., 2005) have stimulated interest in electric mobility systems[1] (EMSs). Battery performance and cost-effectiveness are still major barriers preventing the broad adoption of electric vehicles (EVs) (International Energy Agency, 2011).

Mobility resources in EMSs are more limited and precious compared to those of combustion-powered mobility systems (CMSs) and will likely remain so in the near future (Boston Consulting Group, 2010). Mobility data nevertheless reveal that the currently common 100-mile range of EVs would objectively satisfy the needs of many car drivers (Pearre et al., 2011). Nevertheless, car drivers typically perceive range as a barrier for considering EV use (Dimitropoulos et al., 2011). Research findings indicate that experience with an EV may reduce such range concerns and leads to higher range satisfaction (Franke et al., 2012b; Nilsson, 2011). This comes however at the expense of non-optimal range utilization, that is that users tend to avoid critical and potentially stressful range situations planning for substantial range buffers (Caroll, 2010; Franke et al., 2011). For example, users are only willing to utilize 80% of their available range (Franke et al., 2011). Range buffers are also likely present in conventional internal combustion engine (ICE) vehicles. Yet, range buffers are more relevant for EV use as each kWh of battery capacity should be translated into accessible range to enhance market potential and environmental utility of EVs.

Our research aims to increase understanding of factors that influence users’ range utilization behavior. We propose three range levels termed competent, performant, and comfortable range. They drive the transition from a technically maximum possible range to a practically usable range. We apply concepts of self-regulation and control theory (Carver and Scheier, 2001) to better understand inter-individual differences within these three range levels. We test the explanatory power of variables known to be important for self-regulation from related domains. To this end, we conducted a 6-month field trial with 40 EVs leased to volunteer drivers. During this trial, we examined: (1) range experience and indicators of range utilization, (2) the relation of personality traits and system competence variables to

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[1] With EMS/CMS we refer to a certain configuration of a vehicle (range and possible charging/refueling duration) and the available charging/refueling infrastructure (public vs. private, network density, usual available charging/refueling speed) as both parts together constitute the mobility resources available.

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range level values, (3) the relationships between the different types of range levels, and (4) the relation of range levels to range satisfaction.

1.1 The adaptive control of range resources framework

Fig. 1 illustrates how we conceptualize users' management of EV range resources as a control task aimed at maintaining certain preferred states (e.g., staying within personal range comfort zone) which translate into individual reference values (e.g., comfortable range level). These reference values are regulated by individual (e.g., range competence) as well as environmental factors (e.g., route profile). This dynamic interplay leads to an individual efficiency level of range utilization for each user.

Imagine the following example: for a trip an EV user chooses between the EV and another household vehicle. The available range (i.e., mobility resources) is estimated to be 60 km and the total journey distance (i.e., mobility needs) 50 km. That leads to a perceived range buffer of 20%. We propose that users' appraisal of such a situation depends on several factors, in particular their preferred range safety buffer (i.e., comfortable range). Range safety buffers in turn will be affected by coping skills, such as practice with EV range or self-concepts of competence in dealing with range, as well as by personality traits such as general control beliefs. This process may be fast and automatic if available and preferred range buffers differ considerably. Otherwise it may be deliberate such that users carefully evaluate their options for extending range, for example, by applying energy-efficient driving strategies. For this evaluation, users have to relate the currently available range to their average (i.e., performant) and maximum (i.e., competent) range values. Based on this appraisal (i.e., situation model), users will adapt their range-related behavior (i.e., coping strategies), for example, by adjusting trip decisions, planning for emergency charging spots and other fallback options, energy-efficient driving, adapting different driving and charging styles to increase future safety buffers or actively improving range management skills. Feedback from the environment (e.g., development of available range buffer during a trip) provides users with information on the success of their strategies, which in turn modifies the representation (i.e., the mental model) of the reference values.

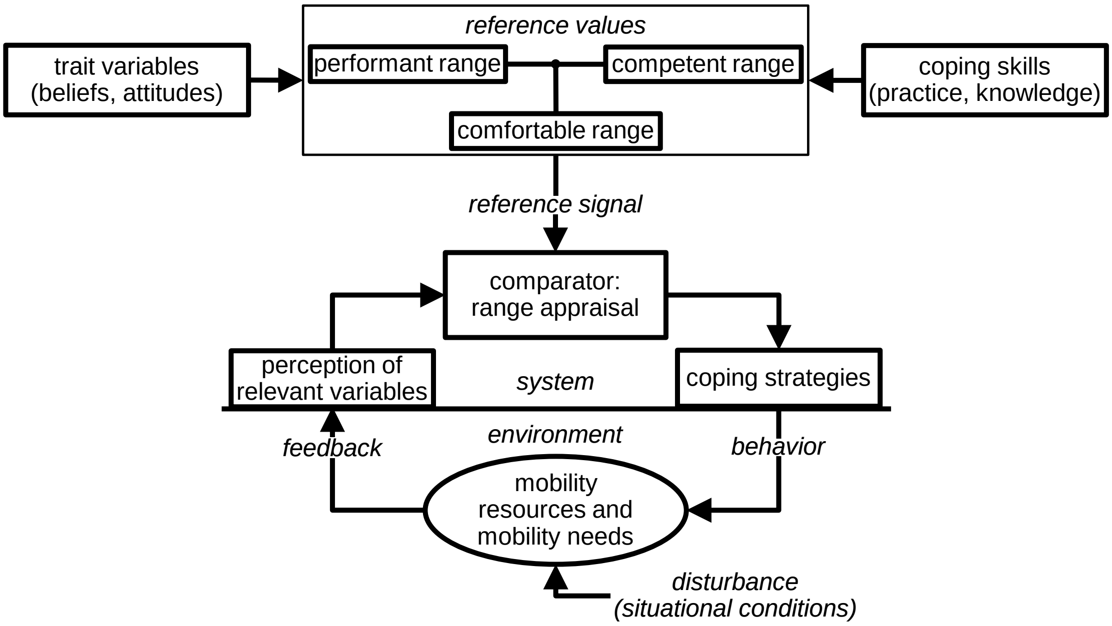

Figure 1. The adaptive control of range resources framework. Users compare the current range situation with their range level reference values. These are in turn driven by certain trait and coping skill variables. As a result of this comparison coping strategies are adapted (e.g., drive more economically, do not use EV). This leads to a certain efficiency of range utilization.

Principles of control theory and self-regulation (Carver and Scheier, 2001) have been applied to a wide range of phenomena. Inter-individual differences in variables such as personality traits and competencies determine successful (adaptive) self-regulation (Boekaerts et al., 2005; Hoyle, 2010). Reference values (i.e., individual standards and goals) are central components in the control loop (Baumeister and Heatherton, 1996). We have introduced three psychological reference values that regulate the efficiency of range utilization: competent, performant, and comfortable range.

First, we assume that users differ in their self-set standards for developing competency for understanding range dynamics and extending range. These individual standards translate into their maximum achievable, and hence, competent range. This value will likely be lower than the maximum range technically possible because users face limits in their self-regulation capacity.

Second, achieving competent range requires considerable self-regulation resources (e.g., continuous monitoring of range dynamics in relation to implemented actions).

Moreover, energy efficiency is only one goal when driving a car. Thus, users will likely achieve lower range values in everyday use. We term this average range performant range.

Third, users hardly use the entire available range (e.g., competent or performant). Based on previous findings (Franke et al., 2011), we hypothesize that users adopt an individual range comfort zone that translates into a certain preferred range safety buffer, based on individual standards for avoiding stressful situations. We refer to this level as comfortable range. In sum, all three levels contribute to the gap between technically feasible and actually usable range.

Given the complexity of user–range interaction, we expect substantial variations in the reference values: (1) while adapting to limited range, (2) due to situational conditions, and (3) due to individual user differences. In this paper we focus on examining the third aspect, inter-individual differences between EV users that are already adapted to EV range. In our field trial we control for situational variation as far as possible in such a setting. In the following, we describe the three range levels and the factors explaining inter-individual differences in range level values in more detail.

1.1.1 Competent range

The impact of user behavior on EV energy consumption is more complex and characterized by different dynamics than those in ICE vehicles (e.g., concerning efficient use of regenerative braking, auxiliary consumers like heating, light etc.) (Romm and Frank, 2006). Achieving optimal energy efficiency requires substantial perceptual, cognitive, and motor resources (e.g., monitoring range dynamics, systematic test of range extension strategies). Operators have been found to experience difficulties performing similar control tasks in equally complex dynamic environments (Frensch and Funke, 1995; Osman, 2010). Furthermore, users differ in their achievement motivation or goal orientation (Pintrich, 2000). Both, competence beliefs as well as feedback on maximum performance contribute to the development of a self-concept of competence (Bandura, 1977; Boekaerts, 1991; Weinert, 1999). This in turn translates into a reference value of competent range**,** which is the maximum range a user is able to achieve. We thus operationalize competent range as the maximum range displayed after a full charge, given previous maximum range-optimizing efforts.

Among personality trait variables, internal control beliefs, that is the degree to which people believe that they can control events that affect them (Rotter, 1966), have been linked to more successful self-regulation (Bandura and Wood, 1989). Moreover, individuals with a higher need for cognition, that is the tendency to enjoy complex information processing demands (Cacioppo and Petty, 1982), are more efficient and successful in complex problem solving (Nair and Ramnarayan, 2000). Impulsivity, that is the tendency to control and plan insufficiently, is usually linked to low self-control and lack of persistence (Hoyle, 2010). High impulsivity interferes with reaching long-term goals (Carver, 2005) and problem-solving tasks that demand a high level of planning (Pietrzak et al., 2008). Tolerance of ambiguity, that is the tendency to experience ambiguous stimuli as desirable and challenging instead of threatening (Furnham and Ribchester, 1995), is an important factor for successful learning (e.g., Chapelle and Roberts, 1986) and self-regulation in creative problem solving tasks (Stoycheva, 2003). We expect internal control beliefs, need for cognition, low impulsiveness and tolerance of ambiguity to be positively related to competent range.

Among system competence variables, prior knowledge facilitates successful self-regulated learning (Moos and Azevedo, 2008) and affects performance in problem-solving environments positively (Lee and Chen, 2009). Subjective competence leads to more effort investment, and in turn, independent learning (Boekaerts, 1991). Moreover, the closely related concept of self-efficacy is important for gaining knowledge and setting challenging goals (e.g., Zimmerman et al., 1992). Finally, daily practice has been identified as key for promoting self-regulatory skills (Zimmerman and Kitsantas, 2005). Based on these findings, we expect prior knowledge of EV technology, subjective competence in dealing with range and daily range practice to be positively related to competent range.

1.1.2 Performant range

Optimizing vehicle range demands substantial self-regulation resources and is only one goal when driving a car besides a fast and comfortable journey and enjoying acceleration performance. Hence, in everyday driving most users will obtain range values below their competent range. We term this range performant range: the average or typical available range based on user’s driving motives and habits. Performant range is indicated by the displayed range when the EV is fully charged.

Among personality variables driving style is essential as it reflects relatively stable habits, general attitudes, needs, and values (Elander et al., 1993), as well as lifestyle attributes (Møller and Sigurdardóttir, 2009). Notably speedy and aggressive driving style should be linked to performant range because speed and acceleration are closely related to energy consumption in EVs. Furthermore, the willingness to take risks in driving is related to a higher probability of speeding and of reckless driving (Hatfield and Fernandes, 2009). Thus we expect speedy driving style and risk propensity in driving to be negatively associated with performant range.

1.1.3 Comfortable range

We define comfortable range as the preferred range safety buffer of a user, that is the range buffer that is experienced as not stress-inducing (i.e., enough to avoid range anxiety). This range safety buffer can be expressed in absolute values (e.g., always keep a 10-km range reserve), relative values (e.g., 20% reserve), or minimum values (e.g., never go below 10 km remaining range). Range buffer values can be assessed directly by asking users to provide such values, or indirectly by assessing the experienced stressfulness of certain range buffers.

We assume that comfortable range is a function of performant and competent range, as well as individual characteristics relevant for coping with uncertain, demanding and stressful situations. Thus, comfortable range is most relevant for range appraisal as it reflects the perceived balance between mobility needs (e.g., journey distance, route profile, trip purpose) and mobility resources (e.g., remaining range, competent range, dispositional resources). Maintaining a certain comfortable range is similar to stress regulation which has also been described with control theoretic models (Edwards, 1992; Lazarus and Folkman, 1984). These models assume that stress is the result of a perceived imbalance between the demands that arise from a person's environment or his/her desires and the available resources that the person possesses. In a circular process people appraise and regulate this balance. These models also highlight the key role of individual differences in stress-buffering variables which moderate the appraisal process (Connor-Smith and Flachsbart, 2007).

Among personality traits, internal control beliefs have been addressed extensively as stress-buffering variables in the original work of Lazarus and Folkman (1984) and in research on driver stress (Holland et al., 2010). Ambiguity tolerance has been linked to less avoidance of uncertain (i.e., potentially stressful) situations and reduced experienced stress in ambiguous situations (Frone, 1990; Furnham & Ribchester, 1995; Lazarus & Folkman,1984). In contrast, high impulsiveness is related to a tendency to avoid unpleasant or difficult tasks (Carver and Connor-Smith, 2010). Lack of planning and low self-control as aspects of high impulsivity should also exert a negative effect on comfortable range. Accordingly, we expect internal control beliefs, ambiguity tolerance and low impulsivity to be positively related to comfortable range.

With regard to system competence variables, effective coping strategies promote stress resistance. Subjective competence and self-efficacy have been related to stress resistance (Bandura, 1977), notably the tendency to interpret demands as challenges rather than as threats (Zajacova et al., 2005). Also, practice with technical systems (Holland et al., 2010) results in less stress experience. Thus, we expect subjective competence in dealing with range and daily range practice to be positively related to comfortable range.

1.2 Research objectives

We argue that models of self-regulation and related research in problem-solving, learning, driving style, and stress, offer valuable perspectives on the psychological dynamics of EV range utilization. We propose that investigating individual differences in the reference values of comfortable, performant, and competent range will enhance our understanding of range utilization.

In the present research we first examine users' general range experience (e.g., range satisfaction, frequency of critical range situations), as well as comfortable range variables indicating range utilization. Second, we analyze individual differences in comfortable, performant, and competent range. For all three range levels we investigate the impact of several personality traits (control beliefs, need for cognition, ambiguity tolerance, impulsiveness, driving style, risk propensity in driving) and system competence variables (prior knowledge, daily practice, subjective competence) on users' reference values. We expect to find a positive relation of internal control beliefs, ambiguity tolerance, and low impulsiveness with comfortable and competent range; a positive relation of need for cognition to competent range; and a negative relation of speedy driving style and risk propensity in driving to performant range. We expect a positive relation of daily practice and subjective range competence to comfortable and competent range, and of prior knowledge to competent range. We also test the relation of performant and competent range to comfortable range, where we expect positive relationships for both variables to comfortable range. Third, we examine which range level variables are associated with the outcome measure of range satisfaction. We expect positive relationships between range levels and range satisfaction.

2 METHOD

2.1 Field trial setup

The present research was part of a large-scale EV field trial in the metropolitan area of Berlin, Germany. This trial was set up by the BMW Group and Vattenfall Europe, and funded by the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety. It was part of an international EV field trial (Vilimek et al., 2012). The EV was a converted MINI Cooper with a maximum cycle range of 250 km under ideal and 168 km under normal driving conditions (miniusa.com, 2012). It was equipped with a state-of-charge display and a remaining-range display (km), based on consumption over the last 30 km. Test drivers had access to a network of 50 public charging stations in the metropolitan area of Berlin, as well as to a private home-based charging station (4 h full charge duration). In the field trial two consecutive 6-month user studies were conducted. This paper incorporates data of the second study (n = 40). Participants used EVs between end of February and end of August 2010. For each user, data were collected prior to receiving the EV (T_0), after 3 months of driving (T_1), and upon returning the EV after 6 months (T_2). At each point of measurement, users filled out a 1-week travel diary, and took part in a 2- to 3-h face-to-face interview including completing several questionnaires. A wide range of topics was covered using a multi-method approach that allowed for data triangulation and data fusion. Logger data were recorded by the car manufacturer and were related to subjective data through personalized keys. Further details on the field trial methodology are reported elsewhere (Cocron et al., 2011; Franke et al., 2012a). This trial setup aimed at controlling situational variations (e.g., vehicle load, climate, terrain, traffic conditions) on user-range interaction.

2.2 Participants

Forty participants were selected from 489 applicants recruited via an online screening instrument that was announced in newsprint and online media. Requirements for participation were residence in the Berlin metropolitan area, willingness to pay a monthly leasing rate of 400 Euro (about the same as for an equivalent gasoline model with similar leasing conditions[2]), to take part in a scientific study, and to install a private home-based charging box. Further criteria aimed to ensure considerable variance in basic socio-demographic variables (e.g., age, gender, education) and mobility-related variables (e.g., mileage, vehicle fleet). Only the main EV user from each household was included in the data collection. As recruitment criteria were comparable to current EV leasing criteria (e.g., monthly leasing rate, access to charging facility), we expect the sample to be representative for early adopters of EVs in German urban areas. The 40 participants had a mean age of 50 years (*SD* = 10.2), 35 were male, and 29 had a university degree. All participants' households had access to at least one additional conventional car during the trial.

2.3 Personality trait measures

Personality trait measurements used a 6-point Likert scale and response coding of 1-6 unless specified otherwise. We used the 8-item internal control beliefs in dealing with technology scale of Beier (1999), the 8-item ambiguity tolerance scale of Dalbert (1999), the "speed" scale of the driving style questionnaire (DSQ, French et al., 1993) with three items and a 6-point frequency scale, and the need for cognition scale (Bless et al., 1994) with 16 items and a 7-point Likert scale from –3 to +3. For risk propensity in driving and impulsivity we used two single-item measurements from the German socio-economic panel (Siedler et al., 2008). Both items employed an 11-point Likert scale (0–10). Due to missing values, there were between 37 and 39 valid cases per trait variable. We tested for univariate outliers according to the procedure and thresholds proposed by Grubbs (1969) for all variables. For personality traits, one outlier was detected for control beliefs (*z*-value = –3.17) and was therefore excluded. All multi-item measurements yielded a satisfactory reliability with Cronbach's alpha > .70.

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[2] The leasing rate of the EV without taking part in the scientific study was said to be 650 Euro.

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2.4 System competence measures

2.4.1 Subjective range competence

We assumed that subjective EV range competence would be driven by feelings of confidence in predicting remaining range as well as feelings of control over range-influencing factors. Accordingly, these two facets were addressed with two items each. For prediction "I know how far I can go on a full charge," and "I can precisely estimate the influence of different factors on range" and for control "The range of my EV is mostly affected by factors over which I have no influence," and "The range that I can reach with my EV is mostly dependent on factors that I can control“. A 6-point Likert scale ranging from 1 (completely disagree) to 6 (completely agree) was used for these and all other self-constructed agreement ratings. There were two cases with missing values and one outlier ($z = –3.75$, $n = 37$). Reliability was only partially satisfying with Cronbach's alpha $T_{1\text{all4}} = .50$, $T_{1\text{control2}} = .39$, $T_{1\text{prediction2}} = .50$, $T_{2\text{all4}} = .74$, $T_{2\text{control2}} = .67$, and $T_{2\text{prediction2}} = .49$. To increase reliability we averaged scale values at T_1 and T_2 supported by a strong correlation of values between T_1 and T_2 ($r_{\text{all4}} = .67$). The reliability for the combined item values was acceptable with Cronbach's alpha $T_{12\text{all4}} = .76$, $T_{12\text{control2}} = .67$, $T_{12\text{prediction2}} = .59$. In a factor analysis items loaded primarily on the control and prediction factor as expected although with some sizeable cross-loadings.

2.4.2 Prior knowledge of EV technology

At T_0 users were asked to rate their familiarity with three aspects of EV technology on a standard 6-point Likert agreement scale: EV drivetrain, units of electricity, and different types of batteries. There was one missing value and no outlier ($n = 39$, Cronbach's alpha = .85).

2.4.3 Daily range practice

We assumed that both frequency of range considerations before a trip (e.g., trip planning) and exposure to dealing with range during a trip (e.g., experiencing range dynamics, improving skills) constitute daily range practice. Therefore we combined in one indicator variable the mean daily number of trips ($M = 3.12$, $SD = 1.07$, no outlier) and the mean daily distance driven with the EV ($M = 41.46$ km, $SD = 18.86$, one outlier with $z = 3.24$)

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taken from T_1 travel diary (5 workdays only). There were seven cases with missing values in the combined daily range practice score (*n* = 32, Cronbach's alpha = .43).

2.5 Range measures

2.5.1 Competent range measures

For competent range a composite score was constructed consisting of subjective and objective subscores to provide comprehensive information on users' maximum achievable range. The objective subscore was defined as maximum displayed range when fully charged recorded by data loggers in the EV. The logger data recorded the range displayed at the beginning of each trip throughout the study period. Those values were included that could be related to the main user, that referred to periods with moderate temperatures of 5–25°C, and that did not refer to the first 2 months of use, as we were only interested in range level values of adapted drivers. Values that referred to situations with the battery not fully charged were extrapolated to full charge range. From these range values we extracted the maximum value as the objective subscore for competent range.

For the subjective subscore we asked participants about their maximum trip distance with four items: maximum accomplishable trip distance, maximum distance with all factors optimized, potential trip length in an urban area under optimal conditions, and perceived maximum range ever displayed. A factor score was computed from the first factor of a principal-axis factor analysis (eigenvalue = 2.38, second factor = .82, all factor loadings >.37). One outlier was detected (*z* = 3.10) on this subscore.

The subjective and objective subscore *z*-values yielded a Cronbach's alpha of .50 and were joined with a factor score to yield the final criterion variable for competent range. Because of missing values *n* = 35.

2.5.2 Performant range measures

For performant range we combined subjective and objective subscores to include information on users' average and typical available range. The objective subscore was defined as the mean displayed range of the fully charged EV, as recorded by data loggers in the car (scored in parallel to competent range).

The subjective subscore consisted of three items: “Which displayed range does the EV currently have for you when it is fully charged? (in normal daytime temperatures of approx. 10–20°C)” and “Please indicate, based on your experience, the range that was displayed after a full charge when daytime temperatures were (a) approx. 10°C and (b) approx. 20°C”. There was one outlier with values outside the plausible range of values (e.g., 10 km available range) that was excluded. A factor score was computed for the first factor (eigenvalue = 2.44, second factor = .41, all factor loadings >.70).

Objective and subjective subscore *z*-values yielded a Cronbach’s alpha of .58, and were combined to yield the final composite criterion variable for performant range (factor score). Because of missing values $n = 35$.

2.5.3 Comfortable range measures

The composite variable of comfortable range incorporated three subscores. First, the range game assessed the individual range comfort zone in a standardized, ecologically valid scenario (60-km trip in a mostly urban area). Four items asked participants to report their comfort level for embarking on a trip. This was done 10 times with displayed range values between 45 and 90 km in randomized order. The resulting score value represents the lowest range value which users still experience as perfectly comfortable (for further details, see Franke et al., 2011). Second, the 4-item threat scale of the primary appraisal secondary appraisal (PASA) questionnaire (Gaab, 2009) was used. This was framed for a situation where remaining range and remaining trip distance were equal. Third, the range safety buffer was assessed as the range level below which users were no longer willing to drive the EV. Users were asked to frame their responses to conditions of moderate daytime temperatures of 10–20°C. Variables were inverted so that high values indicated high comfortable range. We derived the composite criterion for comfortable range from the three subscores using the first factor from principal-axis factor analysis (eigenvalue = 1.53, second factor = 0.84). The three subscores yielded acceptable factor loadings: range threat appraisal = .37, range game comfort zone = .73, range safety buffer = .47. The resulting factor score had one missing value and no outlier ($n = 39$).

2.6 Range satisfaction measure

At T_1 four items were used to assess users' range satisfaction, specifically whether the range: (1) suited their daily needs, (2) was a usage barrier, (3) met their expectations, and (4) resulted in the feeling of a limited action radius. Item values were reversed so that high values indicated high satisfaction. Cronbach's alpha was .75 ($n = 40$, no outliers or missing values).

3 RESULTS

We analyzed our data using regression analyses. With the following exceptions the majority of assumptions were satisfactorily met (Stade et al., 2011). First, the internal consistency of range practice and competent range scores was unsatisfactory. Violating this assumption leads to an underestimation of R^2 and to a more conservative test of model fit (Stade et al., 2011). Such a result is not uncommon for scales combining only two subscores (Cortina, 1993). Moreover, internal consistency may underestimate reliability for heterogeneous measures of a construct (Yarkoni, 2010). Second, some cases were identified as outliers with residual z-values > $|1.96|$. Urban and Mayerl (2008) suggest to present results with and without these outliers. To aid readability, results after outlier exclusion are here only presented if their statistical significance or effect size magnitude differed importantly (e.g., change from a weak to a moderate effect). Third, available sample size was judged as sufficient for testing two predictors in one analysis assuming strong effects (R^2 ≥.26) and a desired statistical power of .80 (power calculation with G*Power; Faul et al., 2009).

The forced entry method was used for all analyses except the backward regression analysis in subsection 3.5. As we had directional hypotheses for the effects of the individual predictors we tested one-tailed hypotheses except for omnibus tests of whole-model fit R^2 and for predictors in one exploratory analysis in section 3.3.1. A significance level of .05 was used throughout. We tested the relationships of the predictor variables to every range level to examine if the range levels were indeed differentially related to the predictor variables as expected.

3.1 General range experience and range utilization

Based on the dichotomized 6-point scale, the majority of users (88%) agreed that the range offered by the EV was sufficient for everyday use, thus indicating high range satisfaction. Results also showed that stressful range situations occurred with only a mean frequency of 0.83 stressful events per month (*SD* = 1.28), and only 13% of users encountering more than one situation per month. The item asking participants to rate frequency of becoming nervous due to range received somewhat higher ratings, *M* = 1.13, *SD* = 1.24, 28% more than once per month.

Table 1 presents the score values for comfortable range variables. As the values of the upper and lower quartiles show, there were considerable inter-individual differences in comfortable range. In terms of average proportional range utilization, data from the range game suggested that users were comfortable utilizing 77% of available range resources, that is a 60-km trip distance with 78 km available range. A similar result was obtained when we related the comfortable trip distance value to the communicated range under daily conditions (71%, 120 of 168 km) or to the average value of the objective measure of performant range (77%, 120 of 156 km).

Table 1: *Descriptive statistics for comfortable range variables.*

Variable	*M*	*SD*	Q_{25}	Q_{75}
Safety buffer	19.23	13.02	10.00	25.00
Range comfort zone	78.27	10.11	71.25	86.25
Range threat appraisal	3.33	1.07	2.50	4.00
Comfortable trip distance	120.41	16.93	100.00	130.00

Note: All variables are in km except for range threat appraisal (scale value on a 6-point scale).

3.2 Personality traits and range levels

It is generally accepted that personality can be comprehensively described by five factors (Digman, 1990). Yet, to predict specific behavior and derive implications for interventions as well as to develop conceptual models, it has been that one should focus on specific facets of the five factors (e.g. Paunonen and Ashton, 2001). We follow this suggestion but also aim to test whether the examined specific personality variables may

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relate to the same superordinate personality dimension and thus may share similar variance in range level values. As sample size was only sufficient to test two predictors per analysis we grouped the personality variables based on their relatedness in a principal axis factor analysis (see Table 2). Although driving style is usually not treated as a personality trait, we included it in the analysis as we considered it a sufficiently stable personal characteristic. Three factors resulted according to both Kaiser-criterion and scree-plot, first factor eigenvalue = 1.83, second = 1.42, and third = 1.13. Each variable had a primary factor loading >.30 and all cross loadings were <.30. The first factor was related to the two variables assumed to assess facets of individual driving style. The second factor referred to the personality traits related to enjoyment and self confidence in dealing with complex or demanding situations (control beliefs, need for cognition). The third factor comprised ambiguity tolerance and impulsivity. These two variables may be linked to a similar dimension of self-regulation style, in the context of dealing with new or uncertain situations.

Table 2: *Factor loadings for principal axis factor analysis with varimax rotation of personality scales.*

	Factor		
	1	2	3
Risk propensity in driving	**.84**	-.08	.02
Speedy driving style	**.79**	.14	.16
Control beliefs	-.05	**.58**	-.22
Need for cognition	.06	**.64**	.18
Ambiguity tolerance	.16	.29	**.36**
Impulsivity	.03	-.08	**.58**

Note: Factor loadings > .30 are in boldface.

As expected, the two predictors internal control beliefs and need for cognition accounted for some of the variance in comfortable and competent range (see Table 3). For comfortable range, there was a significant model fit $R^2_{adj} = .13$, $F(2,32) = 3.59$, $p = .039$, that was stronger after outlier exclusion, $R^2_{adj} = .22$, $F(2,30) = 5.50$, $p = .009$. Yet, only control beliefs contributed significantly. The pattern was similar for competent range before, $R^2_{adj} = .16$, $F(2,28) = 3.84$, $p = .034$, and after outlier exclusion $R^2_{adj} = .30$, $F(2,27) = 7.30$, $p = .003$. As expected, there was a moderate positive zero-order correlation for need for cognition. Yet, the part correlation of need for cognition was weak, indicating that need for cognition was redundant to control beliefs in predicting competent range. Explained variance for performant range was small (all $F < 1$).

Table 3: *Internal control beliefs and need for cognition as predictors of range level values.*

	n		*B*		SE *B*		*p*		Part correlation		Zero-order correlation	
Comfortable Range												
Control beliefs	35	(33)	0.49	(0.49)	0.20	(0.18)	.010	(.005)	.39	(.43)	.43	.50
Need for cognition	35	(33)	0.05	(0.15)	0.19	(0.17)	.396	(.195)	.04	(.14)	.18	.29
Performant Range												
Control beliefs	31		0.10		0.24		.346		.08		.08	
Need for cognition	31		0.02		0.24		.471		.01		.03	
Competent Range												
Control beliefs	31	30	0.49	0.57	0.21	0.18	.014	(.002)	.39	(.48)	.45	.57
Need for cognition	31	30	0.12	0.18	0.19	0.17	.271	(.136)	.10	(.17)	.25	.34

Note: Results after outlier exclusion are given in parentheses; and *p*-values are one-tailed.

Some of the variance was explained by the model including the predictors ambiguity tolerance and impulsivity for all range levels (see Table 4). For comfortable range, $R^2_{adj} = .12$, $F(2,35) = 3.60$, $p = .038$, was obtained. Ambiguity tolerance had a weak and non-significant effect that was in the opposite direction than expected. The effect of impulsivity was moderate, significant and in the expected direction. Competent range yielded a significant model fit only after outlier exclusion, $R^2_{adj} = .20$, $F(2,30) = 4.99$, $p = .013$ (before $R^2_{adj} = .12$, $F(2,31) = 3.26$, $p = .052$). For both predictors, ambiguity tolerance and impulsivity, moderate relations in the expected directions resulted, but only the effect of ambiguity tolerance was significant. Results revealed an unexpected model fit for performant range after outlier exclusion $R^2_{adj} = .25$, $F(2,30) = 6.25$, $p = .005$ (before $R^2_{adj} = .10$, $F(2,31) = 2.76$, $p = .079$). It was driven by the moderate to strong positive relation of ambiguity tolerance to performant range.

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Table 4: *Ambiguity tolerance and impulsivity as predictors of range level values.*

	n		*B*		SE *B*		*p*		Part correlation		Zero-order correlation	
Comfortable Range												
Ambiguity tolerance	38		-0.16		0.19		.199		-.13		-.19	
Impulsivity	38		-0.15		0.06		.011		-.37		-.39	
Performant Range												
Ambiguity tolerance	34	(33)	0.48	(0.64)	0.21	(0.18)	.013	(.001)	.39	(.54)	.38	(.54)
Impulsivity	34		-0.04		0.07		.299		-.09		-.02	
Competent Range												
Ambiguity tolerance	34	(33)	0.39	(0.52)	0.20	(0.19)	.029	(.004)	.32	(.44)	.26	(.40)
Impulsivity	34		-0.12		0.06		.027		-.33		-.27	

Note: Results after outlier exclusion are given in parentheses; *p*-values are one-tailed.

For the two driving style variables the effect on performant range was weak before, $R^2_{adj} = .03$, $F(2,30) = 1.45$, $p = .250$, and after outlier exclusion $R^2_{adj} = .07$, $F(2,28) = 2.18$, $p = .132$ (see Table 5). However, the indicator for speedy driving style yielded a moderate part correlation in the expected direction after outlier exclusion. Explained variance for comfortable range and competent range was small (all $F < 1$).

Table 5: *Speedy driving style and risk propensity in driving as predictors of range level values.*

	n		*B*		SE *B*		*p*		Part correlation		Zero-order correlation	
Comfortable Range												
Speedy driving style	37		0.12		0.17		.240		.12		.11	
Risk propensity in driving	37		-0.03		0.08		.362		-.06		.02	
Performant Range												
Speedy driving style	33	(31)	-0.25	(-0.29)	0.18	(0.16)	.087	(.041)	-.24	(-.32)	-.30	(-.37)
Risk propensity in driving	33		-0.00		0.09		.496		-.00		-.17	
Competent Range												
Speedy driving style	34		-0.15		0.16		.179		-.17		-.24	
Risk propensity in driving	34		-0.03		0.08		.345		-.07		-.19	

Note: Results after outlier exclusion are given in parentheses; *p*-values are one-tailed.

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3.3 System competence and range levels

In analyzing the role of subjective range competence and in all of the following univariate regression analyses, the *p*-value for the *F*-test statistic is also given one-tailed. As expected, there was a positive effect of subjective range competence on comfortable range $R^2_{adj} = .09$, $F(1,35) = 4.48$, $p = .021$, that was even stronger after outlier exclusion $R^2_{adj} = .13$, $F(1,33) = 6.09$, $p = .009$ (see Table 6). However, the expected effect on competent range was not found ($F < 1$). Explained variance for performant range was also small ($F < 1$).

Table 6: *Subjective range competence as predictors of range level values.*

	n		*B*		SE *B*		*p*		Zero-order correlation	
Comfortable Range										
Subjective range competence	37	(35)	0.47	(0.48)	0.22	(0.20)	.021	(.009)	.34	(.40)
Performant Range										
Subjective range competence	33		-0.09		0.24		.348		-.07	
Competent Range										
Subjective range competence	33		0.08		0.22		.355		.07	

Note: Results after outlier exclusion are given in parentheses; *p*-values are one-tailed.

To examine this unexpected result further, we analyzed the two subscales of subjective competence (prediction versus control) as separate predictors (two-tailed exploratory tests, see Table 7). For competent range, a significant model fit resulted only after outlier exclusion, $R^2_{adj} = .20$, $F(2,28) = 4.80$, $p = .016$ (before $R^2_{adj} = .05$, $F(2,30) = 1.81$, $p = .181$). Control had a moderate negative effect and prediction a moderate positive effect. A similar pattern was obtained for performant range. Sizeable variance was explained before, $R^2_{adj} = .24$, $F(2,30) = 6.10$, $p = .006$, and even more after outlier exclusion, $R^2_{adj} = .38$, $F(2,29) = 10.61$, $p < .001$. Control had a strong negative effect and prediction had a strong positive effect. For comfortable range, model fit was not significant, $R^2_{adj} = .06$, $F(2,33) = 2.03$, $p = .148$. Only control had a moderate positive effect and prediction had no effect.

Table 7: *Subjective competence in predicting and controlling range as predictors of range level values.*

	n	*B*	SE *B*	*p*	Part correlation	Zero-order correlation
Comfortable Range						
Control	36	0.38	0.21	.085	.29	.33
Prediction	36	-0.08	0.33	.805	-.04	.16
Performant Range						
Control	33 (32)	-0.61 (-0.72)	0.19 (0.17)	.004 (<.001)	-.49 (-.61)	-.25 (-.35)
Prediction	33 (32)	0.95 (1.00)	0.30 (0.26)	.004 (.001)	.48 (.55)	.23 (.22)
Competent Range						
Control	33 (31)	-0.27 (-0.42)	0.20 (0.16)	.181 (.015)	-.24 (-.42)	-.05 (-.16)
Prediction	33 (31)	0.58 (0.74)	0.31 (0.25)	.069 (.006)	.32 (.48)	.23 (.28)

Note: Results after outlier exclusion are given in parentheses; *p*-values are two-tailed.

For prior knowledge, there was a significant effect on competent range as expected but only after outlier exclusion, $R^2_{\text{adj}} = .06$, $F(1,32) = 3.27$, $p = .040$ (before $R^2_{\text{adj}} = .05$, $F(1,33) = 2.81$, $p = .052$) (see Table 8). Only weak effects for comfortable and performant range were found ($F < 1.5$).

Table 8: *Prior knowledge as predictor of range level values.*

	n	*B*	SE *B*	*p*	Zero-order correlation
Comfortable Range					
EV technology knowledge	38	0.14	0.11	.117	.20
Performant Range					
EV technology knowledge	35	0.08	0.12	.262	.11
Competent Range					
EV technology knowledge	35 (34)	0.18 (0.18)	0.11 (0.10)	.052 (.040)	.28 (.30)

Note: Results after outlier exclusion are given in parentheses; *p*-values are one-tailed.

There was a moderate effect of daily range practice in the expected direction for competent range, $R^2_{\text{adj}} = .11$, $F(1,25) = 4.11$, $p = .027$, and comfortable range after outlier exclusion, $R^2_{\text{adj}} = .09$, $F(1,28) = 3.84$, $p = .030$, before ($F < 1$) (see Table 9). The effect for performant range was weak ($F < 1$).

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Table 9: *Daily practice as a predictor of range level values*

	n		*B*		SE *B*		*p*		Zero-order correlation	
Comfortable Range										
Range practice	32	(30)	0.11	(0.28)	0.18	(0.14)	.272	(.030)	.11	(.35)
Performant Range										
Range practice	27		0.18		0.19		.187		.18	
Competent Range										
Range practice	27		0.32		0.16		.027		.38	

Note: Results after outlier exclusion are given in parentheses: *p*-values are one-tailed.

3.4 Relation of performant and competent range to comfortable range

Performant and competent range levels predicted substantial variance in comfortable range, $R^2_{adj} = .27$, $F(2,30) = 6.94$, $p = .003$; no outlier (see Table 10). Competent range yielded a moderate positive effect as expected. Performant range had a strong negative effect. This last effect was counter to what we expected.

Table 10: *Performant and competent range as predictors of comfortable range.*

	n	*B*	SE *B*	*p*	Part correlation	Zero-order correlation
Performant Range	33	-0.84	0.23	<.001	-.56	-.39
Competent Range	33	0.71	0.26	.006	.41	-.01

Note: p-values are one-tailed.

3.5 Relation of range levels to range satisfaction

A backward regression analysis was conducted to identify the range levels that could explain variance in range satisfaction. Model fit with all three range levels was very weak and not significant ($F < 1$). Excluding the variable that explained the least variance (performant range) also did not result in a significant model fit, although explained variance increased, $R^2_{adj} = .03$, $F(2,32) = 1.59$, $p = .219$. Only the model with comfortable range could reliably explain variance in range satisfaction, and a moderate effect in the expected direction was obtained before, $R^2_{adj} = .05$, $F(1,37) = 2.86$, $p = .049$, and after outlier exclusion $R^2_{adj} = .08$, $F(1,36) = 4.40$, $p = .022$ (see Table 11).

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Table 11: *Comfortable range as predictor of range satisfaction.*

	n		*B*		SE *B*		*p*		Zero-order correlation	
Comfortable Range	39	(38)	0.30	(0.35)	0.18	(0.17)	.049	(.022)	.27	(.33)

Note: Results after outlier exclusion are given in parentheses; *p*-values are one-tailed.

4 DISCUSSION

The present research investigated the psychological dynamics of user–range interaction from a self-regulation perspective. In accordance with our previous study (Franke et al., 2011), range satisfaction of users with 3 months of EV experience was high, and situations where users felt stressed or nervous due to range seldom occurred. Comfortable range indicators suggested that the average user was comfortable utilizing 75–80% of available range resources.

Most hypotheses derived from our conceptual model were supported. First, there was indeed substantial variation in range level values supporting the proposed complexity of user–range interaction. Second, regarding personality traits, control beliefs and low impulsivity were positively linked to comfortable and competent range, ambiguity tolerance was positively linked to competent range whereas the link to comfortable range was not obtained. Need for cognition was related to competent range, but the observed correlation with control beliefs make conclusions uncertain. None of these variables, except for ambiguity tolerance, was linked to performant range, supporting our notion of distinct range levels. Likewise, speedy driving style was only negatively related to performant range. Yet, there was no link of risk propensity in driving to performant range. Third, regarding system competence variables (i.e., coping skills), daily practice was positively related to comfortable and competent range and prior knowledge to competent range. Again, performant range was not affected by these variables. The relationship of subjective range competence to range levels was more complicated than hypothesized. While the link to comfortable range was as expected, only the subscale “prediction” was positively related to competent range while the subscale “control” showed a negative relationship. Unexpectedly, there was a similar pattern for performant range. Fourth, regarding relationships among range levels, comfortable range was indeed partly explained by performant and competent range. Both predictors seemed to play different roles in this relationship. In the following, we first

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discuss the implication of the results for refining the model and for practical applications, then we discuss some limitations and needs for additional research.

The positive relationship of competent range to comfortable range implies that improvement of maximum performance may also lead to expansion of the range comfort zone. Conversely, a decrease in range safety buffers may lead to more ambitious trip planning, more experienced critical range situations with higher situational range awareness, and finally to better range management skills. This in turn could enhance competent range. Future research should clarify these possible causal chains for refining the conceptual model. In terms of practical implications, the relationships between the range levels indicate the potential of user information and training for extending the practically usable range. Notably, there was no zero-order correlation between comfortable and competent range. Only when performant range was partialled out, a moderate part correlation resulted. This means that essentially the gap between performant and competent range determines the range comfort zone.

Counter to our hypotheses, performant range was negatively associated with comfortable range. Perhaps a higher performant range reduces the need to expand the range comfort zone. Conversely, a higher comfortable range could make users reduce their efforts to optimize (increase) their available range in everyday driving. A tentative conclusion is that there are two ways to adapt to the limited range of an EV and safeguard a comfortable user experience. Either users expand their comfort zone (i.e., reduce range buffers), which will lead to a higher mileage traveled at lower remaining range levels, or they improve average range performance and thus travel with higher levels of remaining range (e.g., higher range buffers but larger absolute available range). In other words, users can maintain a level of desired risk or task difficulty by following one of these two strategies. Conceptions of task difficulty and risk homeostasis are well documented (Fuller, 2005) and fit into the control framework, which we posit is the basis for user–range interaction. For optimal range utilization it would be desirable to break through this homeostatic mechanism so that EV users strive for both increasing their range comfort zone and increasing their available range resources.

A powerful predictor for range utilization appears to be low internal control beliefs in dealing with technology. The second-best predictor seems to be high impulsivity. For the latter, it is especially noteworthy that it was obtained with a single-item measure. Such short scales would be useful for a practical screening tool. However, the effect of impulsivity needs further replication. For ambiguity tolerance, the positive effect on comfortable range found in our previous study (Franke et al., 2011) was not replicated. We have no explanation for this especially given the clear link of ambiguity tolerance to stress resistance generally found in the literature (e.g., Frone, 1990). However, there was a moderate positive association to competent range and, unexpectedly, to performant range. Ambiguity tolerance seems to facilitate average and maximum performance. We tentatively conclude that different styles of adapting to EV range may account for the differential effects for comfortable, performant, and competent range. Need for cognition seems to be redundant to internal control beliefs in accounting for variance in competent range given only a moderate zero-order and no part correlation. As expected, personality attributes related to driving style were only linked to performant range. However, this effect was weak and only driven by a moderate negative correlation of speedy driving style to performant range. Future research should aim for a more comprehensive assessment of driving style incorporating attitudes and personal values.

Regarding system competence variables we found all but one of the expected effects. First, prior knowledge was positively related to competent range. Consequently, users should be provided with sufficient background knowledge when purchasing an EV for ensuring successful self-regulated learning. Second, a positive effect of daily practice on comfortable range and competent range was obtained. Thus, actively promoting regular EV driving practice via user instructions and feedback may help users expand their range comfort zone and achieve maximum performance. Third, the effect of subjective competence was only present for comfortable range. Further explorations at the subscale level (predicting vs. controlling range) revealed that this was due to a negative relation of subjective range control competence and at the same time, a positive relation of subjective range prediction competence to competent range. We do not have an explanation for this. It could be that users with a strong belief in their range control abilities simply do not regard increasing their available range necessary because they are comfortable with lower remaining range situations. The similar pattern of results for performant and competent range supports this notion. Perhaps an illusion of control is beneficial for reaching a high level of comfortable range but not of competent range. This is further supported by the relation of range competence to comfortable range, which is mostly driven by the positive effect of subjective range control competency. Reaching a high level of maximum performance (e.g., competent range) may go hand in hand with obtaining a more balanced view of the controllability of range, which in turn produces a negative relation to subjective range control competency. This interpretation remains speculative and requires further empirical testing.

One question remains. Why is there a positive effect of trait control beliefs on competent range when there is a negative effect of more situation-specific subjective competence in controlling range? Research on the related concept of self-efficacy has also found general (trait) self-efficacy to be positively related to performance whereas more task-specific self-efficacy is negatively related to performance (e.g., Yeo and Neal, 2006). Trait control beliefs should more generally affect persistence and goal pursuit, whereas situational control beliefs can lead to decreased resource allocation to the task, thus preventing performance improvement (Vancouver and Kendall, 2006; Yeo and Neal, 2006).

Regarding the link of range levels to range satisfaction, only comfortable range accounted for considerable variance in range satisfaction scores. This reinforces that comfortable range is the most important determinant of range utilization. Although this effect is not very strong, it is noteworthy in terms of practical significance, especially if one considers that there are more proximate factors for range satisfaction, such as users' objective mobility needs or the share of mobility needs that users aim to assign to the EV. Comfortable range may account for a relatively small share of variance in range satisfaction, but this could represent the predominant one for inducing change.

Summarizing the discussion above, the results support our conceptual model. It thus seems fruitful to apply self-regulation and control theory and to distinguish three range levels to explain user–range interaction. The predictor variables were differentially linked to these different range level variables mostly in line with our hypotheses. However, further research is needed to better understand the relationships and interactions of range levels for range-related behavior. Also, easier-to-assess and less complex measures of range levels would render them more accessible in future research.

There are some limitations of the present study. Given the field trial design, inferences about causal relationships cannot be drawn. The causal chains of the conceptual model should therefore be examined in future studies. Moreover, significant effects may have not been discovered due to the small sample size, partly low reliability of measures (e.g., performant and competent range level measures), restriction of variance on some variables (e.g., personality), and the fact that experienced critical range situations were seldom encountered.

Furthermore, users had access to at least one additional conventional car besides the EV. This option may have caused less range stress and higher range satisfaction as well as different ways in adapting to EV range (e.g., less need to acquire a high competent range). Although such hybrid households may be common in the EV market (Kurani et al., 1996) future research should also examine user–range interaction in settings where the EV is the only car available to users.

Our results are based on a sample of early adopters of EVs. Early adopters accept more usage barriers than the average customer (Rodriguez and Page, 2004), for instance, a two-seater layout and minimal trunk space as in the present case. Time to adoption is related to certain personality characteristics (Rogers, 2003). Hence, an early adopter sample will be restricted in variance on personality variables, as we observed in our data (e.g., our users only scored in the upper half of possible scale values for internal control beliefs). Hence, the personality effects in this study likely underestimate the effect in the whole population of car buyers. In conclusion, although a finding of 75–80% average comfortable range utilization seems high, this may represent the upper limit of unsupported range utilization because early adopters are highly motivated and skilled and show favorable personality characteristics. Nevertheless, we believe that understanding this target group is important as it represents the wellspring for EV market penetration. Still, further research with mainstream drivers is needed, where more critical EV attitudes and less favorable interaction patterns are likely (Graham-Rowe et al., 2012). The same holds true for groups with more sporadic usage, such as car-sharing and company fleet settings, where, for example, intrinsic motivation for adapting to an EV might be lower (Burgess and Harris, 2011).

Finally, for accurate market predictions and policy decisions it is also critical to understand the nature of societal adaptation to EVs. Ideally, people may come to view EVs not as short-range combustion vehicles but as a new, distinct mode of transportation. Such adaptation would likely be best supported by EV concepts that shift from combustion conversions to vehicles that are innately electric.

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