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# Displayed Uncertainty Improves Driving Experience and Behavior: The Case of Range Anxiety in an Electric Car

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## ABSTRACT

We explore the impact of the displayed precision of instrumentation estimates of range and state-of-charge on drivers' attitudes towards an all-electric vehicle (EV), on their driving experience, and driving behavior under varying conditions of resource availability. Participants (N=73) completed a 19-mile long drive through highway, rural town and mountain road conditions in an EV that displayed high vs. low remaining range, and gave estimates of that range with high and low information ambiguity. We found that an ambiguous display of range preserved drivers' feelings of trust towards the vehicle, despite encountering situations intended to induce severe range anxiety. Furthermore, compared to drivers facing an unambiguous display of range, drivers presented with an ambiguous range display reported improved driving experience, and exhibited driving behavior better adapted to road and remaining range conditions.

## Author Keywords

Range anxiety; information display; progress bar; trust in automated systems; car; electric vehicle; ambiguity.

## ACM Classification Keywords

H.1.2; H.5.2; J.4; J.7

## INTRODUCTION

Have you ever been startled by your laptop's warning that "you only have a few minutes of battery power left" even though only moments earlier it had indicated closer to an hour of resources? Maybe you have also waited in front of

your washing machine staring at the "one minute left" display only to find out that the washing machine's one minute was closer to 15? Have you ever been anxious about not having enough fuel in your car as you go up a hill and you suddenly notice that those "100 miles until your fuel tank is empty" of the range display shrank to 20 miles?

We encounter displays of estimates almost every time we interact with technical systems, and we hardly ever question the veracity of the displayed information, yet the outcomes of our decisions and actions are often highly dependent upon our understanding the system's actual state. Unbeknownst to the ordinary observer, these displays may appear highly precise, while in fact, they are merely estimates, or predictions, based on assumptions that the user can neither observe nor verify.

For example, remaining battery life is often displayed at a level of accuracy (e.g. minutes for mobile devices, and single digit miles for automobiles) that is at least one order of magnitude higher than it should be. As a consequence, many systems create user expectations that cannot be met. This becomes particularly important when resources such as power for transportation, navigation or life support are rapidly depleting, or when there is utmost urgency to take drastic corrective action. Therefore the implications of how uncertainty is made salient to a user go far beyond the examples at the beginning of the paper. A case in point is the example of the Royal Majesty, a cruise ship that ran ashore miles off course. When the GPS system aboard failed, the navigation system switched to dead reckoning mode and displayed an estimate to the crew without making this switch salient. Deviating from its programmed course due to winds and currents, the system indicated a precise—although no longer accurate—numerical position to the crew [19]. Similar situations can occur in many system control scenarios, including nuclear power plants, or large experiment or mission control centers..

Signaling accuracy when in fact, there is none, can also have important consequences for drivers of electric vehicles (EVs), as charging stations are not nearly as pervasive (yet)

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as gas stations. Drivers build expectations about available power resources and, through often unforeseeable changes in conditions, will encounter situations in which these expectations are disappointed [3, 16]. Being surprised by what may come as a sudden lack of available range can cause anxiety and stress, and can lead to potentially hazardous situations. This concern stemming from limited range is often referred to as *range anxiety*, “an anxiety or fear that one may not reach a target before the battery is empty, which can occur while driving or prior to driving as the user worries about later planned trips [9, p. 202].”

We have thus focused on the range display in electric vehicles, with the guiding question for our study being: How do expectations about available energy resources affect drivers’ attitudes towards the vehicle, the driving experience—with an emphasis on range anxiety—and driving behavior?

We focused on the format of the range display in an electric car, in particular, for three reasons: First, the range display is a central instrument in electric vehicles. While rarely more than a gimmick in standard combustion engine vehicles, the range display is a central instrument for drivers of electric vehicles and it influences driving experience to a large degree [1, 20]. This focus is reflected in the public discourse that has shifted from emphasizing efficiency and miles per gallon typical for internal combustion engine vehicles to range in miles when

referring to EVs. Perceptions of range even influence EV purchasing decisions [1]. Second, drivers of EVs and especially novice EV drivers are likely to rely more on the range display than drivers of combustion engine vehicles [20]. Drivers of standard cars have a sense about the best and worst case of fuel consumption and have developed a feel for the available range based on the indicated fuel level. As mileage is not a measure typically discussed with EVs it is much harder to translate a 30% battery charge into an available range. Third, EVs are a suitable test case because over-reliance on the information display can have severe consequences for the consumer of that information. Misjudging the battery life of a laptop might prevent one from sending an important email, but misjudging the battery life of a car might leave a driver stranded on a busy highway or remote mountain road.

## BACKGROUND AND APPROACH

### Trust and Range Displays

How a device, process, or system displays information has consequences for attitudes that users and operators develop towards that system. Situations in which expectations are set up based on a high level of presumed precision and authority, which are subsequently not met, can affect trust not only towards the information displayed, but also towards the system as a whole [10].

The main challenge with current range displays is that they

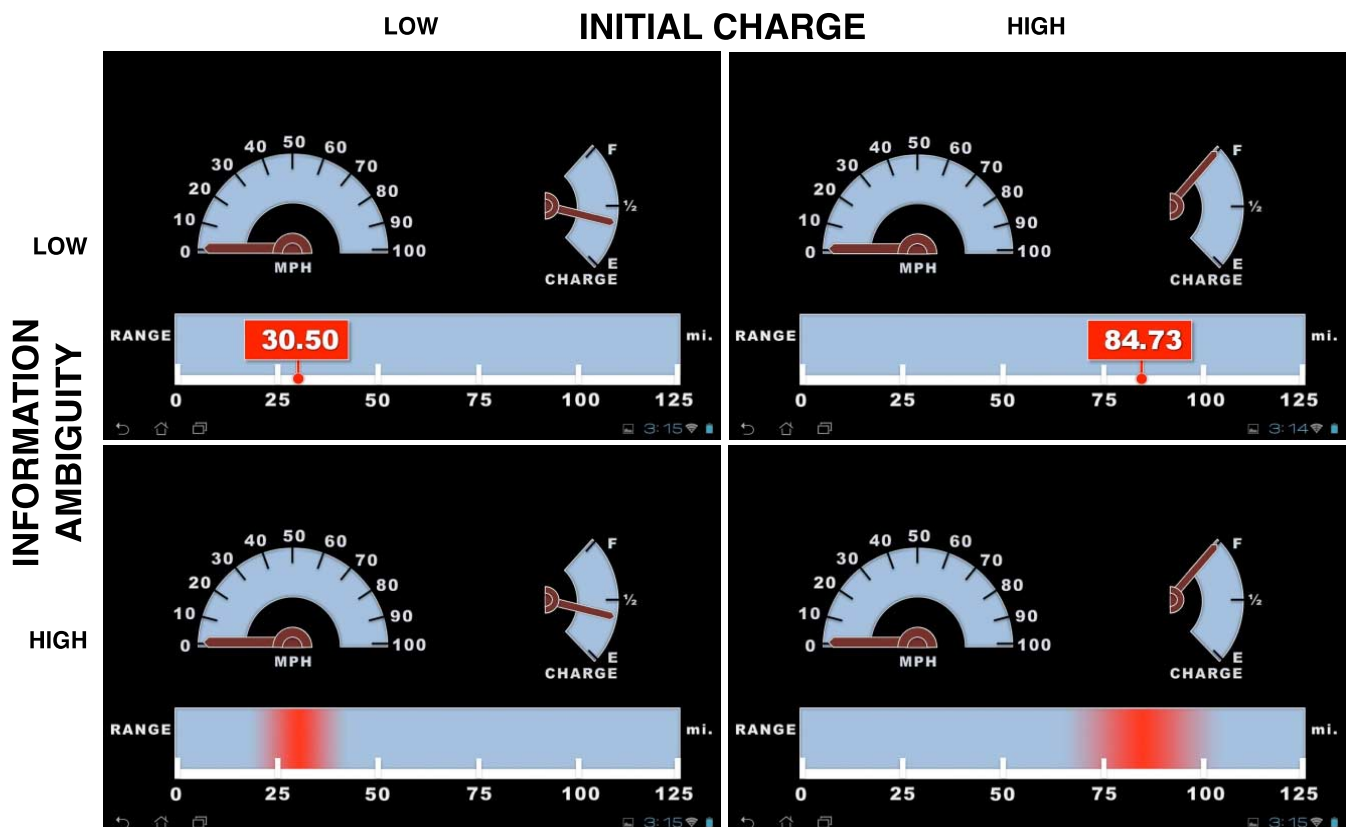


Figure 1. The four study conditions. Each panel shows the dashboard as participants saw it when entering the vehicle. Remaining range was displayed as either highly precise values (top row) or a diffuse color band that varied in width directly with remaining range (bottom row).

represent an estimate. Remaining range is inferred based on factors that include battery capacity, vehicle dynamics, environmental conditions and driving style, and this estimate often leads to inaccurate predictions. An inaccurate prediction can have several implications for reducing a driver's trust in the vehicle. For example, there might be a situation where the vehicle displays a remaining range of 30 miles on a level road, and the driver wants to reach a destination just 15 miles away on top of a hill. Even though the original estimate suggests sufficient reserve to reach the destination, the driver might not reach the top, as the steep incline leads to a fast decline in battery charge, resulting in an effective range of just 10 miles. Sudden drops of range are particularly frustrating for EV drivers [7], and whenever a prediction doesn't meet the actual range, the car can be perceived as having misled, or even *lied*, to the driver. Due to these instances it is understandable that EV drivers and especially experienced drivers lose trust in the information presented by the vehicle [20] and often refer to the range meter as a "Guess-O-Meter" [7]. A large body of research, built upon the Computers Are Social Actors paradigm [17], supports the idea that people perceive and treat machines in much the same way as they do other people. In that context, with cars that effectively, and repeatedly, "lie" to drivers, it seems reasonable that drivers might lose trust in their vehicles.

Having the car make clear that the range display is just a *guess*, drivers might feel a higher level of responsibility towards their ability to reach a destination. Even when running out of battery, drivers with an ambiguous range display might consequently not lose trust in their vehicle, as the car had not lied to them in the first place.

### Predicting Resources

Other researchers have been aware of the problems arising from inaccurate predictions of resources in cars and other battery-dependent technologies. However, most of this prior work has focused on designing algorithms that improve prediction accuracy by increasing the number of parameters that the system takes into account.

In their exploration of mobile phone battery charging behavior patterns, charge level indicators and user knowledge and reactions, Rahmati and colleagues [15] found that inaccurate predictions of remaining battery life affected users' sense of trust towards the phone, and suggest that improving the accuracy and resolution of predictions could make charging more convenient. In the context of implantable or wearable medical devices, where lives depend on predictable power, designers have improved estimates of remaining battery life by including ongoing operating parameters, such as pulse counters, along with known device electrical characteristics [12]. In the case of electric vehicles, Lundström et al. [9] suggest including temperature into range prediction algorithms to improve accuracy, while Zhang and colleagues [21] present an algorithm that includes the vehicle's immediate status

regarding energy capacity and usage, mass and coefficient of drag, road topography, atmospheric conditions and driving behavior. The problem with these approaches to increase prediction accuracy through improved algorithms is that, no matter how sophisticated, they cannot avoid situations of unmet expectations: there will always be situations in which predictions will suddenly be unmet due to a change in driving context, such as the decision to take a mountain road instead of the highway.

Exceptions to the efforts of prior research to improve range prediction accuracy are the work of Lundström and colleagues. For example Lundström and Bogdan investigated "coping strategies" used by highly experienced EV drivers to down-regulate stress when driving in limited resource conditions in order to inform the design of range information display to help less experienced drivers cope with similar situations [8]. Additionally, Lundström and colleagues investigated alternative ways of displaying driving range, such as special visualizations of range on maps [9], or visualizing factors that influence the available range into the display [7]. While these approaches depart from the design strategy to increase accuracy of range algorithms, they do not question the utility of a specific range number displayed to the driver.

### Reflecting Uncertainty

To deal with situations of unmet or missed expectations, we took an alternative strategy that has generally been overlooked by researchers concerned with energy source displays of mobile devices and cars. Rather than exploring new algorithms that expand on the parameter space to increase prediction accuracy, we explored how a display can not only make the nature of an estimate more salient, but also reflect the considerable amount of uncertainty associated with that estimate. Following the idea that ambiguity can be a valuable resource for designers, and particularly the guidance to use imprecise visualizations to emphasize the uncertainty of information [22], we designed a range display that highlights prediction uncertainty. We were particularly interested in the question of how the ambiguous display of range information can mitigate negative effects of missed expectations on attitudes, driving experience, and driving behavior.

### THE STUDY

We explored how the display of ambiguous range information affects EV driving experience and behavior through a 2 x 2 (state of charge (SOC) at start: low vs. high) x (range information ambiguity: low vs. high) factorial study design. Participants were asked to complete a specific 19-mile long route to a predefined location driving a fully electric vehicle. Half of the drivers started out with what appeared to be a 35% battery charge (about 30 miles) while the other half started out with what appeared to be a 100% battery charge (about 85 miles). Additionally, half of the drivers were presented with range information that



suggested precision (2 significant digits), whereas the other half of the drivers were presented with ambiguous range information (see Fig. 1). This setup was designed to provide insight into how participants react to the range display in situations when expectations are not met in everyday and anxiety provoking situations.

### The display

The car used for the study was a Honda Fit fully electric pre-production prototype that was further modified by Honda engineers to allow for the integration of our display setup. In order to manipulate the apparent level of battery charge (low versus high) and the mode of range display (low and high range information ambiguity), we developed a dashboard interface on the basis of an android tablet that could be placed in front of the actual dashboard of our study vehicle (see Fig. 2).



Figure 2 Photo of the in-car display setup.

The tablet was directly connected to the car's CAN-bus via a CAN-bus reader, which allowed one-way access to data about current battery charge, vehicle speed, and remaining range. The tablet was fastened with Velcro in front of the dashboard in such a way that it fully covered the original instruments but also such that it was easily removable in case the software crashed during the drive. Additionally, a frame was constructed around the tablet to prevent light reflections that might inhibit the readability of the display. Participants were specifically instructed to remove the tablet in case something seemed wrong with the display.

The display itself was designed with several parameters in mind—in particular: content, layout and color. Regarding content, we reduced the information presented to drivers to only what was needed to safely navigate on the road and to experience the study manipulations: current speed, current state of charge and remaining range. Regarding layout, we arranged the indicators so that range was most prominent, and they were all visible through the inner rim of the steering wheel. Regarding color, we chose light blue on a black background for high readability under various

lighting conditions, and bright red for the range indicator to make it particularly prominent in the overall design.

### Participants

We recruited 73 participants for the study. All participants had a valid US driver's license, were students, were a minimum 21 years of age, had no previous EV driving experience, but sufficient general driving experience. General driving experience was required so that any stress and cognitive load induced through the display changes would not get confounded with stress and cognitive load from standard driving scenarios. Participants were recruited via email announcements and were asked to sign up on an online scheduling system. Participants were randomly assigned to one of the four study conditions and were gender balanced as much as possible across conditions. We also scheduled all study runs outside of rush hours, and all runs were conducted under similar weather conditions to minimize potential influence from traffic and weather on our measures. Each participant received a \$50 Amazon gift card in exchange for his or her participation.

### Procedure

Upon arrival at the lab, participants were greeted and asked to take a seat in front of a laptop that displayed a survey. Participants were told that their help was needed to explore the experience of driving an electric vehicle with a newly designed display. After asking for their informed consent, participants signed in on a log sheet that determined the experimental condition for the participant. Participants were then asked to enter their participant id into an online survey tool, and to follow the instructions given on the screen. The survey tool introduced the participants to the following specifics of the task:

*Your task will be to take a short drive with our Electric Vehicle to Alice's Restaurant and park the car in the parking lot (see picture below). The drive to Alice's restaurant should take about 30 minutes.*

*We have programmed this route into the car's navigation system. Please follow the directions as stated by the navigation system. As soon as you arrive at Alice's Restaurant and safely parked the car, please call the study administrator to let him or her know that you have arrived. He or she will give you his phone number before the drive.*

*While parked at Alice's Restaurant you will be asked to fill out a short survey about your driving experience. As soon as the survey is completed, please drive the car back to the starting location. The route will be already programmed into the navigation system of the car. In case of any problems with the car, please stop the car somewhere safe, and give the study administrator a call.*

As part of the task description, participants were shown a map of the roughly 19 mile long route they were asked to drive, as well as a picture of the destination. Participants were told to park the car the car safely in front of the

restaurant shown on the picture and then call the experimenter for further instructions. At the beginning of the study participants were not made aware that the driving task would be over once they reached Alice's restaurant.

Before starting the drive, participants were asked to wear a skin conductivity sensor (affective Q sensor) measuring electro dermal activity on their wrist, as well as a heart rate, body movement and respiration monitor on their upper torso (Zephyr Bioharness BT). Both sensors were calibrated by asking the participant to relax for 5 minutes while their vitals are being recorded. This paper will however not report on data collected from these sensors.

As soon as finished with the online survey, participants were introduced to the vehicle and instructed to drive according to the directions from the GPS navigation system. Everything the experimenter said and did was carefully scripted and the experimenter was instructed to respond to possible questions about remaining range with a standard answer and not to make any additional explanations: "If there is any problem, just give me a call." This evasive answer was to prevent the experimenter from inadvertently making participants feel psychologically safe when encountering doubts about available range. However none of the participants mentioned experiencing stress greater than what they had previously encountered when nearing an empty gas tank. The research was IRB approved and all drivers were fully insured for the study. Additionally the vehicle could be stopped safely along the road at any time during the study and the experimenter made sure that each participant had a working cell-phone and gave his or her cell phone number to the participant before the drive.

Upon arrival at Alice's Restaurant, participants called the experimenter who instructed them to first fill out a prescribed questionnaire package to reflect on their main driving experience, and then call again. Afterwards participants were debriefed over the phone at which point the study was formally over. In the debriefing, participants were told that the car had been fully charged with plenty of resources to return to the starting location. Upon arrival at the start location each participant was then asked to complete an exit survey about participant demographics after completion of which each participant received the \$50 gift certificate.

### The Route

The route was carefully designed to fulfill a set of specific characteristics. First, the drive was about 30 minutes and long enough to create an immersive driving experience. We chose a route that would ask people to drive up a long and winding road to give drivers a sense that they are on their own. This was also amplified by choosing a destination away from the starting location rather than a circular route. We hoped that any sense of range anxiety would be amplified by this setting. Second, the route featured different road conditions and terrains encountered in

everyday driving: suburban streets, highway, mountain and countryside. Third, and most importantly we designed the route to have an elevation profile that would remain flat for the first 3/4<sup>th</sup> of the drive and then suddenly increase in slope going up the mountain road (see Fig. 4). As the range estimation of the vehicle is calculated by extrapolating from current driving conditions, this profile was intended to set expectations of sufficient range during the initial phases of the drive and then disappoint those expectations when driving up the hill which lead to a rapid decline in range due to increased energy consumption.

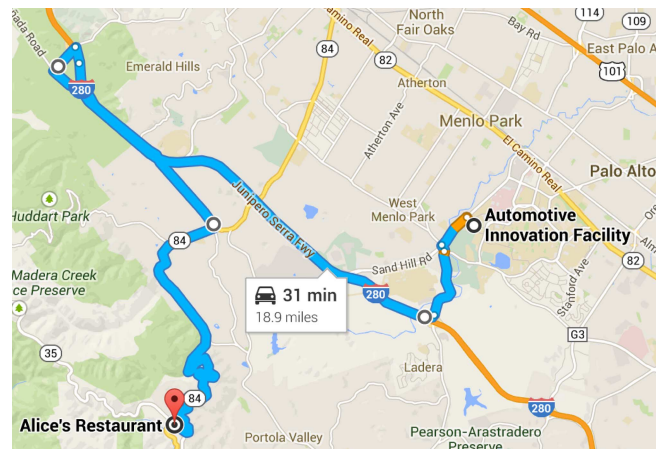


Figure 3. Map of the 19 miles test route

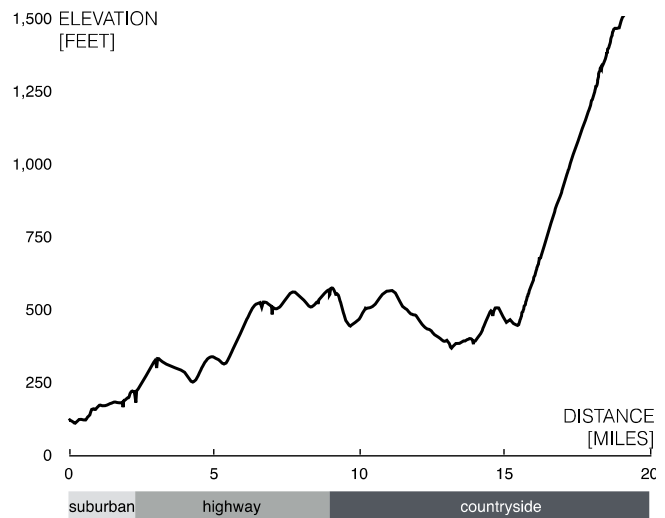


Figure 4. Elevation and road/driving context of the 9 miles test route

### Manipulating SOC and Range Information Ambiguity

#### Initial Values

We manipulated the apparent level of initial battery charge by simulating a state of battery charge at the beginning of the drive (SOC at start) to read 100% in the "high" condition and 35% in the "low" condition. Unbeknownst to participants, and independent of what level of charge was displayed in the vehicle, the experimenters always ensured that the actual level of charge was high enough to allow

safe completion of the course for all participants. The initial low charge state of 35% was carefully determined such that when driving in “eco” mode (the default economic setting as participants entered the car), the display indicated 32 miles of remaining range at the start of the drive, and (typically) indicated 2.17 miles of remaining range upon reaching the destination. Given that the driving course was only 19 miles long, we expected participants to be comfortable starting a drive with this level of charge.

For participants in the 100% condition, the displayed state of charge and range decreased as they ordinarily would over time, given current driving and road conditions. For participants in the 35% condition, the displayed state of charge and range decreased at a lower, scaled rate, to ensure that they would never reach negative values.

### Warnings

To increase participants’ awareness of a low state of charge we programmed the tablet to issue warnings at specific levels or SOC. These low range warnings were displayed in all conditions when the remaining range reached certain thresholds; however, only the participants in the low charge conditions reached an SOC low enough to trigger the warnings. The intensity of the warning messages increased in three stages: First, a yellow battery warning symbol (in between the speed and range indicators) lit up. Second, the battery symbol started to blink with a frequency of 1 Hz. Third, a spoken range warning was issued twice informing the driver about insufficient range to reach the destination. The range warnings were carefully adjusted so that they appeared only after the participants had started to enter the road with the steep incline. The late triggering of the range warnings was intended to heighten range awareness but prevent participants from aborting the drive before driving up hill on a road section that would make it difficult to turn around.

### Information Ambiguity

We manipulated the level of information ambiguity of the range display by modifying how range was displayed to the driver. In the low ambiguity condition, the remaining range was displayed with two digits after the decimal point, signaling precision and a high level of confidence in an accurate prediction. The range value was set within a red box along the range indicator, which moved leftward as participants drove (since range values decreased to the left).

In the high ambiguity condition, the remaining range was displayed without showing a number, but instead by displaying a kind of uncertainty interval around the calculated range—represented visually as a colored gradient, fading to the background on either side. The interval also moved leftward as participants drove, mirroring the position of the range value box in the low ambiguity condition. The width of the uncertainty interval was determined as a percentage of the estimated range, so that its horizontal width shrank as the remaining range

decreased. The width of the interval was designed so that it still signaled uncertainty even when approaching zero.

Both low and high ambiguity display conditions were carefully designed such that the only difference between them was in the level of ambiguity around the range prediction. Therefore both displays were equal in size and layout. Even the red box showing the remaining range value was roughly equal in size to the red uncertainty interval. In addition to changing the display we also modified the spoken limited range warning from “The battery charge *is not* sufficient to reach the destination” in the low ambiguity condition to “The battery charge *might not be* sufficient to reach the destination” in the high ambiguity condition.

### Measures

The main measures of interest were Driving Experience, Trust towards Vehicle, and Driving Behavior. As controls, we measured age, gender and driving experience. However we did not include these variables in our final analyses as they did not significantly change our results.

### Driving Experience

Driving experience was measured by assessing i) range anxiety, ii) driving pleasure, and iii) level of calmness. The range anxiety measure was operationalized through the following four items: “I sometimes felt frightened while driving the car,” “I often felt anxious while driving the car,” “Driving the vehicle often made me nervous,” and “I got totally scared during the drive.” The items deliberately did not refer explicitly to “range anxiety” as we did not want to tap into lay theories about range anxiety that people are likely to have and therefore assessed directly the experience of anxiety. Additionally, we did not want to make participants aware that the study was about range. Due to the randomized assignment of the participants to study conditions, and since nothing but SOC and display were changed between conditions, differences in anxiety can be attributed to differences in the experience of range anxiety. Participants rated for each statement from “Not at all (1)” to “Totally (10)” how much they agreed with each statement on a 10-point scale. The scale was reliable ( $\alpha = .89$ ). Driving pleasure was measured by taking the pleasure rating from the affect grid, a validated and widely used measure of pleasure and arousal [18]. Level of calmness was measured by asking people on a 10-point scale ranging from “not at all” to “extremely” how much they agreed with the statement “I was calm while driving.”

### Trust towards the vehicle

Trust towards the vehicle was operationalized by adapting and combining two items from a widely used survey tool originally designed to measure trust towards automated systems [5]. We asked participants to rate on a 10-point scale ranging from “not at all” to “extremely” to what extent they agreed with the following two statements: “I am confident in the vehicle,” and “I am familiar with the



vehicle,” ( $\alpha = .74$ ). We deliberately framed the questions to refer to the vehicle rather than the display, as we were interested in how changes affect the overall perception of the car.

### Driving Behavior

Driving behavior was measured by assessing how efficient participants drove. The measure of efficiency was operationalized by calculating the difference between the battery state of charge level (SOC) before and after completing the main driving task.

## RESULTS

Analysis of Variance (ANOVA) was used for data analysis. Data from 57 out of 73 participants contributed to the final data analysis. 10 participants had to be excluded because they called the experimenter before reaching the final destination and therefore had a driving experience that was not comparable to the other participants. An additional 6 participants had to be excluded due lack of adherence to the study protocol and due to technical errors. Table 1 shows the final participant distribution across conditions.

		SOC	
		Low	High
Range Information	low	11 (6m/5f)	17 (8m/9f)
Ambiguity	high	15 (11m/4f)	14 (7m/7f)

**Table 1. Participants' distribution across conditions and by gender (male/female)**

### Manipulation Checks

Two measures served as manipulation checks. To assess whether we successfully manipulated range information ambiguity we used a 3-item scale. Participants were asked to rate on a 10-point Likert-type scales ranging from “Not at all (1)” to “Totally (10)” how much they agreed with statements such as “The range display was very precise in providing the remaining number of miles given the battery charge.” The scale was reliable ( $\alpha = .73$ ). To assess whether we successfully manipulated beliefs of sufficient resources we created a 3-item scale including questions such as “The car had plenty of battery charge for the route I was given.” Participants rated on a 10 item scale from “Not at all” to “Totally” how much they agreed with each statement. The scale was reliable as well ( $\alpha = .91$ ). We found a significant main effect of our range information ambiguity

manipulation on how ambiguous the range information was perceived,  $F(3,54) = 42.92, p < .0001$ . When the range information was displayed unambiguously ( $M = 7.29$ ) people on average perceived the displayed information almost twice as ambiguous than when the information was displayed ambiguously ( $M = 4.18$ ) (Figure 5).

We also found a significant main effect of our SOC manipulation on perceptions of sufficiency of resources,  $F(3,54) = 85.05, p < .0001$ . When the car was fully charged at the beginning of the drive ( $M = 8.21$ ), participants on average were more than twice likely to report that the charge was sufficient than when the car was only partially charged ( $M = 3.80$ ) (Figure 6).

Therefore we found strong evidence that our manipulations had the intended effects. We were able to create a situation in which people believed that their resources were barely sufficient for the course given and we were successful in designing a display that communicates ambiguity when presenting an estimate.

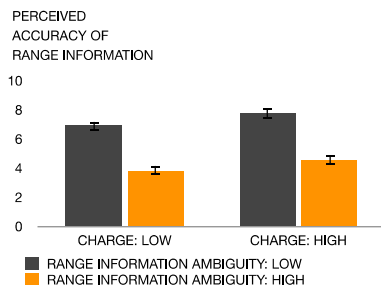
### Driving Experience

#### Range anxiety

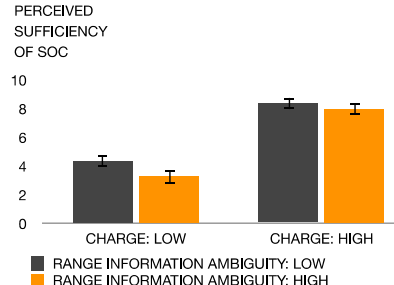
We found a significant main effect of the starting SOC on range anxiety (Figure 7). Range anxiety was significantly higher when the SOC at start was low ( $M = 3.68, SE = .29$ ) in comparison to when the SOC at start was high ( $M = 2.36, SE = .29$ ),  $F(3,54) = 8.6, p < .01$ .

#### Calmness

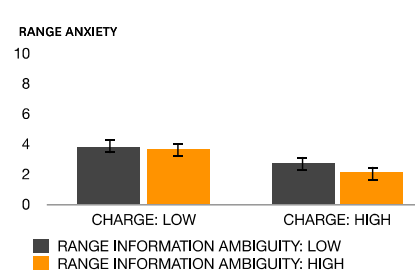
We also found a significant main effect of the range information ambiguity on participants' perceptions of how calm they felt during the drive (Figure 9). Participants felt significantly more calm in the “Range Ambiguity: high” condition ( $M = 7.20; SE = .39$ ) than in the “Range Information Ambiguity: low” condition ( $M = 6.04, SE = .41$ ),  $F(3,54) = 4.42, p < .05$ . Participants also felt marginally significantly more calm in the SOC high condition ( $M = 7.10; SE = .38$ ) than in the SOC low condition ( $M = 6.14, SE = .42$ ),  $F(3,54) = 2.88, p = .10$ . Interestingly the display type seemed to be able to compensate for the SOC differences: Even though not statistically significant it is interesting to see that people felt on average more calm when driving with a low SOC and high range information ambiguity display than when driving with a high SOC and low ambiguity display.



**Figure 5: Impact on display changes on perceived accuracy of range information.**



**Figure 6: Impact of charge at the beginning on perceived sufficiency of charge (SOC).**



**Figure 7: Range Anxiety was increased when participants started the drive with a low battery charge.**



### Driving Pleasure

We found a marginally significant effect of the SOC level on driving pleasure (Figure 10). Participants on average felt better when driving in the “SOC: high” conditions ( $M = 6.44$ ;  $SE = .39$ ) than when driving in the “SOC: low” conditions ( $M = 5.36$ ;  $SE = .44$ )  $F(3,54) = 4.18$ ,  $p < .05$ . The type of display did not have any significant effect on participants overall emotional state when driving.

### Trust towards Vehicle

We found a significant main effect of the SOC of the car on trust towards the car (Figure 11). On average, participants trusted the car significantly more if they were driving with a full battery ( $M = 6.62$ ,  $SE = .36$ ) than with an almost empty one ( $M = 5.21$ ;  $SE = .41$ ),  $F(3,54) = 6.70$ ,  $p < .05$ . There was also a marginally significant main effect of the range information ambiguity on trust, as participants on average trusted the car more when it displayed range ambiguously ( $M = 6.43$ ;  $SE = .37$ ) rather than unambiguously ( $M = 5.39$ ;  $SE = .40$ ),  $F(3,54) = 3.64$ ,  $p = .06$ .

### Driving Behavior

We found a significant interaction between range information ambiguity and SOC on driving efficiency  $F(3,54) = 4.28$ ,  $p < .05$  (Figure 8). When participants drove in the “SOC: high” conditions, they used on average more energy when driving with the ambiguous range display ( $M = 34.37$ ;  $SE = 3.38$ ) than when driving with the unambiguous range display ( $M = 32.16$ ;  $SE = 2.79$ ). However this trend was reversed in the “SOC: low” conditions: Here drivers drove almost 10% more efficiently when driving with the ambiguous range display ( $M = 31.65$ ;  $SE = 6.66$ ) than when driving with the precise range display ( $M = 34.60$ ;  $SE = 5.00$ ).

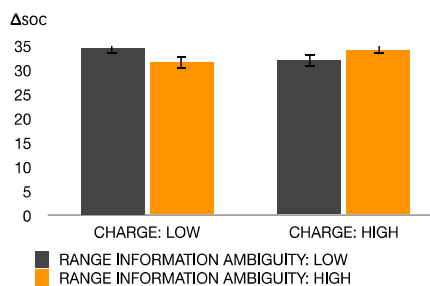


Figure 8: Effects of charge and range information ambiguity on energy consumption.

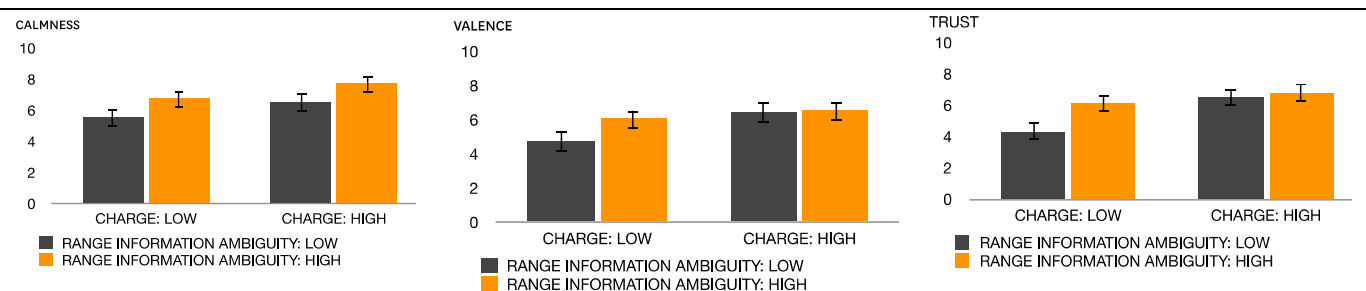


Figure 9: Participants felt calmer with the ambiguous range information.

Figure 10: Participants had a more pleasurable driving experience when the car was fully charged.

Figure 11: Effects of charge and range information ambiguity on trust towards the vehicle.

### Limitations

Several limitations should be noted. First, the complex study setup made it difficult to obtain data from large numbers of participants. However, given that research around on interactive systems in the car is often conducted in simulators to ease data collection, our research provides findings that have higher ecological validity and therefore provide insights that we might not have been able to gather if we had run the study in a simulator. Second, we did not include conditions in which drivers did not encounter a large discrepancy between expected and actual range. For example we could have asked additional participants to drive a 19 mile route on a flat terrain. While additional study conditions might have given additional insights we believe that the conditions in which participants drove with a full charge can be taken as a sufficient baseline. In fact, every time people drive a car there is a, however small, discrepancy between expected and actual range. Since the high-SOC conditions did not cause situations in which people had to be concerned about running out of fuel, those conditions can be taken as a “control.” While more amplified, the high SOC conditions were not fundamentally different from everyday driving situations as they did not create an experience of severe range anxiety. Finally, our research only included participants who had no prior EV driving experience. Previous research has shown that range anxiety is particularly a phenomenon experienced by novice drivers [2]. It might therefore be possible that some effects would be weakened with more experienced drivers of electric vehicles. However, Strömberg and colleagues [20] argued that even experienced drivers experience concerns over range during unplanned trips.

### DISCUSSION

Current range information systems are designed to take incomplete information and present it as trustworthy to the driver. Based on findings from a study about use of GPS navigation systems, Leshed and colleagues suggested that it might be advantageous to present error-prone information ambiguously [11]. We explored this suggestion and, in fact, found that presenting information ambiguously can have advantages. Revealing, rather than hiding, error-prone information led to improvements in driving experience, behavior and trust towards the car.

Surprisingly, the beneficial effects of presenting information ambiguously were even stronger in critical and highly stressful situations.

Maybe our most exciting finding is that the ambiguous range display supported a driving style that was more adaptive to the available resources: People with the imprecise display drove more agile when having enough resources but drove more carefully when driving with limited resources. In contrast people with the precise display took less useful driving strategies: They drove economically when having plenty of resources and more aggressively when driving with limited resources. This finding, that the adaptiveness of driving style improved when information was presented ambiguously, is in line with Langer and Piper's research on mindfulness [6]. In several studies, the authors showed that participants, who were presented with new information in a way that did not communicate certainty, were subsequently more able to use that information more adaptively. Our ambiguous display in combination with the ambiguous range warnings might have promoted a more "mindful" and adaptive driving style in the participants.

Our study contributes to research on range anxiety. To our knowledge this study is the first to employ an experimental research paradigm to elicit and study this phenomenon under controlled conditions. We found that driving with limited resources does create increased levels of anxiety and significantly impairs the overall driving experience. People not only felt more range anxiety when driving with limited resources, they also experienced driving as less pleasurable and less calm. An encouraging finding was that the ambiguous range display had a tendency to make people feel calmer when driving. This finding is particularly interesting since most drivers had told us in earlier prototypes evaluations of our display that they did not like seeing the range information presented in an ambiguous display. Our findings about range anxiety are also interesting as prior work on range anxiety has relied predominantly on survey research methods and not explored whether this phenomenon can be experimentally stimulated [3, 16]. Therefore our test protocol provides a useful starting point for other researchers to study range anxiety and to evaluate novel designs to counteract it.

Our study also contributes to research on progress bars [13]. Progress bars indicate that an operation is proceeding successfully but also make predictions about completion time. Similar to range predictions, these completion time predictions are often unreliable due to non-linear progressions of the tracked processes [4] and are therefore prone to elicit user frustrations. While previous research has predominantly focused reducing perceived durations to improve user experience, displaying progress information ambiguously might be an alternative strategy to improve user experience.

Finally, our findings contribute to research on interactions between humans and automated systems in general. The premise of our research was that automated systems, like people who do not keep a promise, might be perceived as untrustworthy if set expectations are subsequently not met. Parasuraman and Miller [14] demonstrated that following social rules of etiquette in presenting errors to a user not only improved trust towards the system but overall system reliability. Our finding extends this work by demonstrating that systems that are more careful in how they make promises not only improve user experience but also overall system performance (in this case driving behavior).

An open question for future research remains whether high and low information ambiguity display styles can be combined to promote more sustainable driving behavior. It might be possible that transitioning from an unambiguous to an ambiguous display design at an appropriate SOC level might lead drivers to use less overall resources. Presenting an imprecise display, particularly when the battery depletes, may also serve the purpose of avoiding serious system consequences such as deep discharge of a battery, which is undesirable and shortens battery life. Future research could therefore explore the transitioning effect itself and how switching between different range displays might affect driving experience and behavior. Another avenue for future research is to explore possible long-term learning effects of ambiguous range information displays. Our findings stemmed from observations of novice EV drivers and it is unclear how experienced drivers react to range information that is displayed ambiguously and how drivers interpret ambiguously visualized information over the long term. Interestingly, past research found that while experienced drivers develop an explicit understanding of the unreliability of the predicted range, experiences of discrepancies between range prediction and actual range still lead to considerable frustration [7]. This suggests that displaying range information ambiguously might help even more experienced drivers cope with frustrations stemming from unreliable predictions.

## Conclusion

Our study demonstrates that it can be advantageous to highlight the uncertainty associated with a measure rather than to hide it. While presenting a single number can be fast to read and easy to apprehend, designers have to carefully consider the implications that disguised uncertainty may have on user experience and behavior especially in critical situations. Although tested on drivers of electric vehicles only, the findings of the present study may not be limited to EV applications alone, but may potentially be considered for other applications that require solemn decision-making in the face of unreliable information during rapidly depleting battery power sources, including critical function portable medical, communication and electronic devices.

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