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Research Article

Investigation on Range Anxiety and Safety Buffer of Battery Electric Vehicle Drivers

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Drivers tend to have more range anxiety compared with driving traditional fuel vehicles if they are driving battery electric vehicle (BEV) with a long trip. Range anxiety could potentially have negative effect on driver's emotions and behaviors. In order to understand this behavior and improve the related safety issues, this paper will focus on BEV drivers' study in China. A survey on BEV drivers' actual range anxiety as well as the effect of range anxiety on drivers' behaviors is conducted in this research. Levels of feelings and attitudes of the interviewees are quantized with Likert scales using mathematical tools of the relationship. Safety buffer is defined as a measurement of the period given range anxiety starting to significantly intervene in driver's operation. The research reveals the proportional quotative relationship between BEV drivers' safety buffer and the mileage of trip. Factors, including driving experience, satisfactory level of recharge accessibility, and resistibility to emotions, are found to be significant contributing factors to influence the perceived range anxiety level of BEV drivers. This research will provide implications to the future study on the interface design of BEV.

1. Introduction

Battery electric vehicle (BEV) drivers typically tend to have more range anxiety compared to traditional fuel vehicle drivers. High levels of range anxiety can potentially lead to negative effects on BEV drivers' emotion and even cause dangerous driving behaviors. Due to this potential safety issue, several research projects ([1, 2]) have been developed in order to understand range anxiety including appraisal models and influential factors, and further, several solutions are proposed in the literature to reduce the range anxiety.

Nadine Rauh et al. [1] examined the assumption that range anxiety disturbs only inexperienced BEV drivers, and therefore it vanishes as driver gains more driving experience. In the experiment conducted in [1], drivers with different levels of driving experiences were given a critical range situation, where the range remaining in the BEV was less than the trip length. By measuring the range appraisal and range stress with different scales, researchers discovered that driving experience imposed strong effects on all measured variables. With more experience, BEV drivers tend to have less negative range appraisal and hence range anxiety. Therefore, it is important to increase efficiency and effectiveness of the learning process for BEV drivers.

To enhance the understanding of factors which can relieve range anxiety, Thomas Franke et al. [2] designed a field study setting to examine several factors that possibly contribute to lower everyday range stress (ERS). The study revealed the fact that variables such as less encounter with critical range situations, higher practical experience, subjective range competence, tolerance of low range, and experienced trustworthiness of the range estimation system were related to lower ERS, and range stress is found to be related to range satisfaction and battery electric vehicle acceptance.

Also, there are few studies on checking the influence of in-vehicle information systems (IVISs) on range anxiety. For example, Matthias Eisel et al. [3] performed a battery electric vehicle field experiment under a real traffic situation. The crew measured the participants' psychometric range appraisal and psychophysiological feedback and came to the conclusion that individuals perceived the critical range situation as less challenging and threatening with the provided IVISs. However, despite the fact that the IVISs led to a reduction of mean value of stress throughout the driving task, researchers found that participants with the IVISs had higher levels of stress perception. This result indicates that the IVISs can lead to an increased awareness of the depletion of range resources over time.

To gain insight in individual differences in range stress when BEV drivers are faced with a critical range situation for the first time, Thomas Franke et al. [4] designed a field experiment where participants were given a trip of which the range was tailored close to the BEV's range capacity. The results were helpful to formulate strategies aiming at reducing early experienced range stress.

There are many solutions proposed in the literature to reduce BEV drivers' range anxiety. Vincent R. Tannahill et al. [5] explored the future of range anxiety solutions. A driver alerting algorithm is proposed, which was able to reduce range anxiety. The key improvement of the algorithm is the advanced accuracy of BEV range estimation. No complex computations are involved in the algorithm. Hence the algorithm can be implemented on low-cost microcontrollers and still can achieve accurate results.

Mahmoud Faraj and Otman Basir [6] proposed a path arrangement model based on battery capability and energy cost analysis. The model compares the battery capacity of the BEV with the least energy cost of a round trip to the charging station. If the battery capability is less than the energy cost to the charging station, the model recommends the driver to recharge, preventing the driver from being stranded. An accurate estimation on the available range can also be given by the model to the BEV driver. This model is able to reduce range anxiety and further promotes the widespread use of BEVs.

Kaveh Sarrafan et al. [7] proposed an algorithm which makes real-time recommendations on BEV charging strategy. The algorithm is based on the combined calculation of an accurate state of charge (SoC) estimation method and GPS. With necessary initial data input, the algorithm can calculate and predict the BEV's remaining range at the trip destination. The function is realized through a real-time indicator system run by the algorithm. The user experience could potentially be improved by reduced range anxiety during the trip.

Vincent R. Tannahill et al. [8] came up with a new method of range estimation. Based on a state of charge (SoC) estimation method already proposed, the new method accounts for a wide range of environmental and behavioral factors. Hence, the estimation of range turns out to be more accurate than the results drawn by conventional methods which consider merely the SoC and vehicle efficiency. This new range estimation method can be used to notify the driver of the range capability of the BEV and can propose suggestions on whether the BEV needs recharge before reaching the destination.

Battery swapping system is an alternative way of reducing range anxiety. Properly allocating spare batteries will benefit the efficiency of the battery swapping network. Michael Dreyfuss and Yahel Giat [9] revealed the importance of estimating customers' tolerable battery swapping waiting time, which was considered negligible in previous research. Taking the waiting time into consideration, this research found out it will reduce the time of battery swapping. Some features of the optimal spare battery allocation were also found, which will help the design of future battery swapping system.

With regard to the current state of range anxiety research, this paper is intended to verify and forward several previously implemented researches. More specifically, this paper tests the safety buffer model and attempts to fit it into different occasions of trip mileage. In addition, broadened scope of factors are checked in this paper with potential influence on range anxiety. Behavioral effects of range anxiety are another topic discussed in this paper on range anxiety research.

2. Data and Methods

2.1. Basic Assumptions. Range anxiety is described as the fear of being left in the middle of a trip due to a BEV's empty battery. Besides, there are other factors which contribute to the anxiety, such as the inadequate charging infrastructures and the trustworthiness of the vehicle's SoC display.

It is supposed that there is a minimum gap between vehicles' remaining mileage and trips' range which can protect a driver against range anxiety. In Thomas Franke's research [10], the gap was referred to as the safety buffer. In Franke's research, the safety buffer was measured from two aspects. First aspect is described as the difference between the values of vehicles' remaining mileage and the trips' range, and second aspect is depicted by the proportion of the trip's range. The analysis results indicated that the proportion was roughly around 80%.

The analysis results were derived from the study conducted in Germany, of which the authors were using conditions of BEVs which are greatly different from what it is utilized in China. The scenarios mentioned in [11] are fixed, where drivers are given a 168 km capable vehicle to drive from its full comfort range or given a 60 km-trip to select a specific range which makes them feel comfortable. Also, it is believed that range anxiety affects different modes in trips with different lengths [12]. Consequently, three trip scenarios with particular length are set up. The 10 km-trip represents short trip situations; the 30 km-trip represents middle trip situations; and the 60 km-trip represents long trip situations. Influential factors for each trip length is expected to be studied, which is helpful to formulate range anxiety reduction strategies in different circumstances. This paper provides the results based on Chinese BEV working condition, covering short-range, middle-range, and long-range trip conditions.

The factors that possibly have influences on range anxiety are also dug into the research. Information is collected from the interviewees. They include basic attributes: gender, age, defined figures, and degree of range anxiety. The defined figures cover two aspects including driver's satisfaction level towards vehicle and driving style. The two figures all consist of more than one measurement. Driver's satisfaction level is defined from three aspects: the driver's satisfaction level of vehicle range, the driver's satisfaction level of recharge accessibility, and the driver's trust level of range information displayed by the vehicle. In few previous works [13–15], better satisfaction towards vehicle range capacity leads to expansion of range comfort zone. The driver's driving style is defined from two dimensions: the driver's decisiveness and the driver's susceptibility. Factors are expected to be dug out that related to range anxiety and make solutions which can help with particular population against range anxiety.

When facing range anxiety, drivers would behave with the intention to reduce the risk of being stranded in the middle of a trip. The approaches to the reduction of risk are different including prolonging the remaining range of the vehicle or reaching a recharge infrastructure as soon as possible. Different approaches are reflected on the drivers as changes of driving behaviors. The changes of driving behaviors can bring additional stress to the driver and even can lead to dangerous behaviors. To help the drivers optimize their driving behaviors, the most common behaviors and the preferred behaviors differ for different types of drivers which is something needed to be studied. The results reveal some insights to advance the BEV human-machine interface.

2.2. Questionnaire. The questionnaire includes two major parts. The first part (Appendix Part I) is mainly about the driver's basic information, including gender, age, and driving age. Based on the previous reference [16], the second part (Appendix Part II) is designed with several 5-point Likert scales and multiple-choice questions on the range anxiety's influence. The Likert scales on the driver's satisfaction level towards vehicle and driving style are set with the intention that the higher score always refers to a better situation. For example, a 5-point answer may represent a situation where the driver shows the greatest trust towards the vehicle's range display, while the Likert scales on the safety buffer are set that the higher the score is, the more buffer is needed, which can make the results more straightforward.

The participants are all currently BEV drivers. Some of the recognized BEV owners were selected from the *Autohome* forum (which is the most visited auto website in the world). After an in-depth conversation, the recognized owners were asked to help spread the questionnaire to other BEV owners. Through the conversation, it was observed that the recognized owners did spread the questionnaire to authentic BEV owners. Besides, some particular measurements in the questionnaire were checked to filter the invalid questionnaires. For drivers with fuel vehicle driving experience, the *previous fuel vehicle fuel consumption per 100 km* was selected as a filter measurement. Only questionnaires with the value above 2 L and under 40 L passed the filter, taking drivers with hybrid power vehicle or luxury vehicle driving experience into consideration. For all participants, the *type of BEV currently driven* was examined to make sure that the interviewees are BEV drivers. Similarly, the *range of BEV currently driven* was selected as a filter. Questionnaires with a value between 50 km and 400 km would pass the filter. After the filter process, 208 questionnaires were considered valid for further research.

2.3. Statistical Method. To check the reliability of the questionnaire, particularly the Likert scales proposed in our approach, Cronbach's Alpha (α) was calculated and verified. All the Likert scales yield good internal reliability with $\alpha > 0.60$ ($\alpha = 0.758$).

The factors related to range anxiety are expected to be investigated qualitatively. Chi-square tests are conducted to examine the correlations between influential factors and safety buffer. Chi-square tests are also carried out for verifying the correlations between influential factors and driving behaviors. By checking the P values from the Chi-square tests of each combination of data, several factors are marked which are correlated with safety buffer or certain behaviors. Usually, data in combination with p value < 0.05 can be considered significantly correlated and data in combination with p value<0.01 can be considered very significantly correlated.

3. Results

3.1. Descriptive Statistics. Table 1 displays the characteristics of our research sample. Among the 208 interviewees, 156 interviewees are male (75% of all) and 52 interviewees are female (25% of all). The mean value of the interviewees' age is 32.99 (SD = 7.686), ranging from 19 to 67. The mean value of the interviewees' driving experience is 6.55 years (SD = 5.121), ranging from 0 to 22. Company personnel is the most occurred profession among all interviewees, appearing 78 times (78% of all). 169 interviewees have had fuel vehicle driving experience, with mean fuel consumption at 9.12 L/100 km (SD = 5.529). Geely Emgrand BEV appeared 65 times in the sample, which is the most among all types of BEV. The mean maximum range of the BEVs owned by the interviewees is 222.31 km (SD = 80.523), varying from 50 km to 400 km. Household charging-pile is the most commonly used recharge facility. The average recharge frequency of the interviewees is 3.33 times per week (SD = 3.045).

The results of the Likert scales on the driver's satisfaction level of the BEV are displayed in Table 2. The average point of the driver's satisfaction level towards the range is 3.41 (SD = 1.185), with 112 interviewees (53.9% of all) above average. The average point of the driver's satisfaction level towards the accessibility of recharge is 3.54 (SD = 1.100), with 121 interviewees (58.2% of all) above average. The average point of the driver's trust level towards the range information displayed by the BEV is 3.64 (SD = 1.135), with 133 interviewees (64.0% of all) above average. And the mean value of all 3 scales mentioned is 3.53 points (SD = 1.014). There are more interviewees with satisfaction level above the average than those with satisfaction level below the average. Based on the statistical data, the following conclusion can be reached that

Table 1: Sample characteristics (N = 208).

Variable	Mean	SD	Range	N	%
Gender					
Male				156	75.0
Female				52	25.0
Age	32.99	7.686	19-67		
Driving experience (years)	6.55	5.121	0-22		
Profession					
Job hunter				5	2.4
Civil servant				21	10.1
Teaching or scientific research personnel				21	10.1
Individual laborer				17	8.2
Retired				5	2.4
Production or service personnel				42	20.2
Company personnel				78	37.5
Student				5	2.4
Others				14	6.7
Fuel vehicle driving experience					
Yes				169	81.3
Fuel consumption (L/100 km)	9.12	5.529	2-30		
Refueling frequency (times/month)	3.27	3.289	1-20		
No				39	18.8
Type of BEV currently driven					
BJEV EV160				31	14.9
BJEV EV200				24	11.5
BYD E6				28	13.5
Geely Emgrand EV				65	31.3
JAC iEV5				8	3.9
Tesla Model S				11	5.3
Tesla Model X				4	1.9
Venucia e30				5	2.4
Denza				5	2.4
Others				27	13.0
Max range of currently driven BEV (km)	222.31	80.523	50-400		
Most commonly used method of recharge					
Public AC charging-pile				9	4.3
Public DC charging-pile				37	17.8
House hold charging-pile				116	55.8
Portable charger (220V AC)				39	18.8
Others				7	3.4
Recharging frequency (times/week)	3.33	3.045	0.5-25		
Use of BEV					
Official				8	3.8
Private				180	86.5
Rental				11	5.3
Service				6	2.9
Others				3	1.4

the interviewees were generally feeling contented with the BEVs they owned. Cronbach's Alpha for this group of Likert scales is 0.868.

The results of the Likert scales on the driver's driving style are displayed in Table 2. The average point of the driver's decisiveness is 3.87 (SD = 0.913), with 154 interviewees (74.1% of all) above the average. The average point of the driver's resistibility against emotions is 3.55 (SD = 0.989), with 123 interviewees (59.1% of all) above the average. Two drivers' driving style factors mentioned above are both believed to

Table 2: Statistics of driver's satisfaction level and driving style (StD: strongly disagree, D: disagree, Neither: neither agree or disagree, A: agree, StA: strongly agree; the same to the following tables).

Statement	StD (1 pts)	D (2 pts)	Neither (3 pts)	A (4 pts)	StA (5 pts)	Mean	SD
Satisfaction level							
I am contented with my BEV's range.	18 (8.7%)	29 (13.9%)	49 (23.6%)	74 (35.6%)	38 (18.3%)	3.41	1.185
It is convenient to recharge my BEV.	10 (4.8%)	29 (13.9%)	48 (23.1%)	80 (38.5%)	41 (19.7%)	3.54	1.100
I trust my BEV's range remain display.	12 (5.8%)	25 (12.0%)	38 (18.3%)	84 (40.4%)	49 (23.6%)	3.64	1.135
General satisfaction level						3.53	1.014
Driving style							
I behave decisively when driving.	6 (2.9%)	9 (4.3%)	39 (18.8%)	106 (51.0%)	48 (23.1%)	3.87	0.913
Emotions hardly affect me when I am driving.	8 (3.8%)	22 (10.6%)	55 (26.4%)	93 (44.7%)	30 (14.4%)	3.55	0.989

Table 3: Statistics of safety buffer.

Statement	**10 km**	**12.5 km**	**15 km**	**17.5 km**	**20 km**	**Mean**	**SD**
Minimum comfort range remaining in a 10 km trip	24 (11.5%)	24 (11.5%)	53 (25.5%)	23 (11.1%)	84 (40.4%)	3.57	1.406
Statement	**30 km**	**37.5 km**	**45 km**	**52.5 km**	**60 km**	**Mean**	**SD**
Minimum comfort range remaining in a 30 km trip	30 (14.4%)	43 (20.7%)	69 (33.2%)	31 (14.9%)	35 (16.8%)	2.99	1.267
Statement	**60 km**	**67.5 km**	**75 km**	**82.5 km**	**90 km**	**Mean**	**SD**
Minimum comfort range remaining in a 60 km trip	32 (15.4%)	28 (13.5%)	68 (32.7%)	35 (16.8%)	45 (21.6%)	3.16	1.326
General safety buffer						3.24	1.151

be positively related to better road safety performances. Cronbach's Alpha for this group of Likert scales is 0.706.

The results of the Likert scales on the driver's safety buffer are displayed in Table 3. For the situation where there is 10 km left in a trip, the average point of the safety buffer is 3.57 (SD = 1.406), which equals 16.43 km of BEV range remaining, 164.3% of the trip mileage. For the situation where there is 30 km left in a trip, the average point of the safety buffer is 2.99 (SD = 1.267), which equals 44.93 km of BEV range remaining, 149.8% of the trip mileage. For the situation where there is 60 km left in a trip, the average point of the safety buffer is 3.16 (SD = 1.326), which equals 76.20 km of BEV range remaining, 127.0% of the trip mileage. The comparison of net safety buffer and trip mileage under different trip scenarios is displayed in Figure 1. The net safety buffer for a 10 km-trip is 6.43 km in value and 64.3% in portion. The net safety buffer for a 30 km-trip is 14.93 km in value and 49.8% in portion. The net safety buffer for a 60 km-trip is 16.20 km in value and 27.0% in portion. For trips with longer mileages like 30 km or 60 km, the net safety buffer is close to 19.2 km as shown in the previous research. In addition, there seems to be stability with the buffer value; the gap between the values of 10 km-trip and 30 km-trip is huge whereas the gap between 30 km-trip and 60 km-trip is small. Also, the portion of the net buffer is higher when the trip is short and lower when the trip becomes longer and the buffer stays unchanged. Under 10 km-trip and 60 km-trip, the portion of interviewees choosing the longest safety range (40.4% under 10 km-trip, 21.6% under 60 km-trip) is much higher than that of the second longest range (11.1% under 10 km-trip, 16.8% under 60 km-trip). This may be due to the uncertainty the drivers have when the BEV range remaining is low or the trip mileage remaining is high. Cronbach's Alpha for this group of Likert scales is 0.829. For the convenience of further analysis, general safety buffer is defined as the mean value of the interviewee's safety buffer points under the three trip situations.

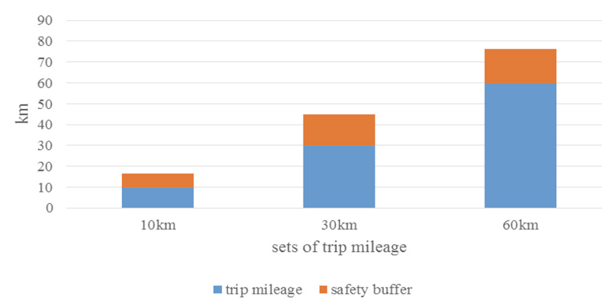

Figure 1: Trip mileage and safety buffer.

The statistics of the behaviors taken by drivers related to the range anxiety are displayed in Table 4. Among the 7 types of behaviors listed, *speed reduction* (97 interviewees, 46.6% of all), *change behaviors* (70 interviewees, 33.7% of all), and *seeking nearby charging-pile* (52 interviewees, 25.0% of all) are the three most frequently taken behaviors.

3.2. Correlation Analysis. Chi-square tests were conducted to find out factors related to driver's safety buffer and anxiety related behaviors. Results with P values less than 0.05 are considered as a sign that there is a significant difference between the observed frequency distribution and expected frequency distribution. The difference can be considered very significant in results with P values under 0.01. By checking the P value of each result, groups of figure combination can be discovered when the frequency distribution differs significantly from expected distribution. In groups where the involved figures

Table 4: Statistics of driver's behaviors taken related to range anxiety.

Behavior	Distracted by anxiety	Rearrange the route	Seeking nearby charging-pile	Change behaviors	Speed reduction	Get more disturbed	Grab lines
Number of interviewees taking the behaviors above.	26 (12.5%)	40 (19.2%)	52 (25.0%)	70 (33.7%)	97 (46.6%)	47 (22.6%)	26 (12.5%)

Table 5: Chi-square test results of factors that may be related to *general safety buffer* (factors with p value < 0.05 marked with ∗∗ and factors with p value < 0.01 marked with ∗ ∗ ∗, the same to the following tables).

Factor	Below average buffer	Above average buffer	p value
Driving experience∗∗			0.049
≤6.55 years	72	57	
	33	46	
Satisfaction level of recharge accessibility∗∗			0.018
Below average	45	60	
Above average	61	42	
Resistibility to emotions∗∗			0.045
Below average	50	35	
Above average	55	68	

Table 6: Chi-square test results of factors that may be related to safety buffer (10 km-trip).

Factor	Below average buffer	Above average buffer	p value
10 km-trip			
Driving experience∗∗			0.035
≤6.55 years	70	31	
>6.55	59	48	
Satisfaction level of max BEV range∗∗			0.020
Below average	55	41	
Above average	46	66	
Decisiveness when driving∗∗			0.014
Below average	34	20	
Above average	67	87	
60 km-trip			
Max range of BEV∗∗			0.028
≤222.31 km	76	35	
>222.31	52	45	
Resistibility to emotions∗ ∗ ∗			0.001
Below average	64	21	
Above average	64	59	

obey a frequency distribution different from the expected distribution, the two figures are closely related. Comparing the observed frequencies with the expected frequencies, the way in which one factor affects a driver's safety buffer or behaviors is found out.

To explore factors that may have influence on driver's safety buffer, Chi-square tests are conducted on different factors including driver characteristics, satisfaction level, and driving style. In order to dig out the difference of the time when each factor starts to work, the Chi-square P values of various factors under different trip mileage situations are examined. The results are shown in Tables 5, 6, and 7.

Among the drivers' characteristics on which Chi-square tests are conducted, *driving experience* (p value = 0.049) shows a significant relationship with *general safety buffer*. Comparing the results with the expected frequencies, the length of driving experience is found to have a positive relationship with the general safety index. This might be due to the difference between the driving mentalities of drivers with various driving experiences. Those with more driving experiences might be more cautious about leaving adequate safety buffer for a trip.

In the scales of driver's satisfaction level, the driver's *satisfaction level of recharge accessibility* (p value = 0.018)

Table 7: Chi-square test results of factors that may be related to grabbing lines behavior.

Factor	Grabbing lines	Not grabbing lines	p value
Gender**			0.029
Male	24	132	
Female	2	50	
Age**			0.040
≤32.99 years	19	94	
	7	88	
Fuel vehicle driving experience***			0.009
Yes	26	143	
No	0	39	
Max range of BEV**			0.040
≤222.31 km	9	102	
	17	80	
Decisiveness when driving**			0.023
Below average	2	52	
Above average	24	130	
Resistibility to emotions***			0.005
Below average	4	81	
Above average	22	101	

shows a significant relationship with *general safety buffer*. After comparing the results with the expectation, it turns out that with better recharge accessibility satisfaction comes less safety buffer. It is supposed that better recharge accessibility satisfaction reduces the driver's anticipation of the possibility for running out of energy in the middle of a trip. Therefore, less buffer is required by the driver to offset the anxiety.

In the scales of driver's driving style, the driver's *resistibility to emotions* (p value = 0.045) shows a significant relationship with *general safety buffer*. After comparing the results with the expectation, it is concluded that better *resistibility to emotions* results in more safety buffer. It is supposed that better *resistibility to emotions* yields from a series of driving habits and driver characteristics, which leads to the choice of bigger safety buffer. The *resistibility to emotions* and *general safety buffer* might be two related dependent variables to some other independent variables, which is left for further investigation in further research.

For the discussion of influential factors to different trip mileage situations, data are collected of driver's safety buffer for different trip mileage situations and Chi-square tests are conducted on the data, respectively. In the 10 km-trip situation, *driving experience* (p value = 0.035), *satisfaction level of max BEV range* (p value = 0.020), and *decisiveness when driving* (p value = 0.014) show a significant relationship with the safety buffer. Drivers with longer *driving experience* tend to have bigger safety buffer, which accords to the driving experience's influence on *general safety buffer*. Drivers with higher *satisfaction level of max BEV range* tend to have safety buffer of a smaller size. Drivers with greater *decisiveness when driving* tend to have smaller safety buffer. For the 30 km-trip situation, no factor is found to have a significant relationship with the safety buffer. In the 60 km-trip situation, *max range of BEV* (p value = 0.028) shows a significant relationship with the safety buffer and *resistibility to emotions* (p value = 0.001) shows a very significant relationship with the safety buffer. Drivers driving BEV with longer max range tend to have bigger safety buffer. Drivers with better *resistibility to emotions* tend to have bigger safety buffer.

To discover how potential factors can influence a driver's acts under range anxiety, Chi-square tests are conducted on each listed behavior. *Resistibility to emotions* (p value = 0.001) shows a very significant relationship with the behavior of *speed reduction*. Drivers with weaker *resistibility to emotions* tend to reduce driving speed under range anxiety. For the behavior of *getting more disturbed*, *general satisfaction level* (p value = 0.038) shows a significant relationship with it. Driver with lower *general satisfaction level* are more likely to get disturbed under range anxiety. For the behavior of *grabbing lines*, there are a series of factors that are linked to it. *Gender* (p value = 0.029) shows a significant relationship with the *grabbing lines*. Under range anxiety, male drivers are more likely to grab lines than female drivers. *Age* (p value = 0.040) shows a significant relationship with the *grabbing lines*. Younger drivers are more likely to grab lines under range anxiety. *Fuel vehicle driving experience* (p value = 0.009) shows a significant relationship with the *grabbing lines*. Drivers with *fuel vehicle driving experience* are more likely to grab lines. *Max BEV range* (p value = 0.040) shows a significant relationship with the *grabbing lines*. Drivers driving BEV with longer max range are more likely to grab lines. *Decisiveness when driving* (p value = 0.023) shows a significant relationship with the *grabbing lines*. Drivers with stronger decisiveness are more likely to grab lines. *Resistibility to emotions* (p value = 0.005) shows a significant relationship with the *grabbing lines*. Drivers with stronger resistibility are more likely to grab lines.

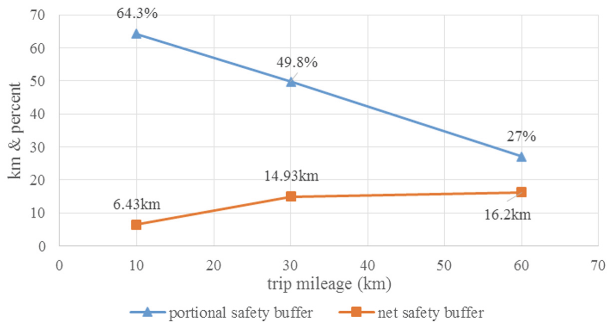

Figure 2: Net safety buffer and fractional safety buffer.

4. Discussions

4.1. Safety Buffer and Its Influential Factors. The safety buffer under different trip mileage circumstances is evaluated through the mean value of the Likert scale point. Data of net safety buffer and fractional safety buffer is shown in Figure 2. For 10 km-trip, the average net safety buffer is 6.43 km, which takes 64.3%. For 30 km-trip, the average net safety buffer is 14.93 km, which takes 49.8%. For 60 km-trip, the average net safety buffer is 16.20 km, which takes 27.0%. Research conducted by Thomas Franke et al. [9] finds that the average net safety buffer is 25.0% of the expected trip range. The data is collected from the field experiment in Germany. The safety buffer in this paper coincides well with the previous results in the 60 km-trip occasion, 27.0% comparing to 25.0%. However, the safety buffer portion in 30 km-trip is 49.8%, much greater than 25.0% assumed in [9]. In addition, the net values of safety buffer in 30 km-trip and 60 km-trip are close, 14.93 km and 16.20 km, respectively, which are very similar to each other. Regarding the portion of the net buffer in 10 km-trip, which is much bigger than that of 30 km-trip, 64.3% comparing 49.8%, the safety buffer portion is believed to increase as the actual trip range shortens, while in long-range trip, this paper confirms the reliability of the result from [9].

In Likert scales of 10 km-trip and 60 km-trip, the portion of interviewees choosing the option with the largest buffer takes up much more in total samples than interviewees choosing the second largest buffer (40.4% to 11.1% in 10 km-trip, 21.6% to 16.8% in 60 km-trip). The distribution of the chosen option is quite biased from the normal distribution. The uncertainty of upcoming traffic and energy consumption are supposed to play a role in the abnormal frequency distribution. For 10 km-trip, the uncertainty of the energy consumption might play a bigger role. The SoC information display is usually less accurate when the SoC is low whereas the traffic condition is clearer to the driver when the trip mileage remaining is little as 10 km. The uncertainty of the energy consumption weights is more than the uncertainty of traffic to the driver in that circumstance. For 60 km-trip, the uncertainty of the upcoming traffic generates more anxiety than the uncertainty of the remaining energy, forcing some drivers to require more safety buffer.

Among the driver's characteristics correlating with general safety buffer, *driving experience* is found to be significantly correlated with safety buffer. The results show that drivers with more years of driving experience are more likely to have bigger safety buffer. Experienced drivers are supposed to be more cautious about sparing enough buffer for a trip. The difference between the driving mentality of fresh drivers and skilled drivers might cause the difference in safety buffer choice. The effect of driving experience on range anxiety is discussed in [1, 2], specifically on the driving experience of BEV. The results show that drivers with more experience of driving BEV are likely to have reduced range anxiety. Driving experience of BEV is not included in our research. However, assuming that the driver's driving experience of BEV is positively connected with the total driving experience and combining the results of [1, 2] with ours, the size of safety buffer can be found to be negatively connected to the level of range anxiety. That is currently a hypothesis and the connection between safety buffer and range anxiety level requires further investigation.

Among the defined factors, driver's satisfaction level and driving style are significantly correlated with *general safety buffer*. The *satisfaction level of recharge accessibility* is negatively connected with *general safety buffer*. It is assumed that better recharge accessibility comes up with less anticipated risk of being stranded in the middle of a trip due to an unavailable recharge. This result accords with [12] as well, which indicates that better satisfaction towards vehicle capacity expands the range comfort zone and reduces the safety buffer. The driver's *resistibility to emotions* is positively connected with *general safety buffer*. This result supports the claim made by [4] that emotional stability is partly related to the lower range stress. Drivers with better *resistibility to emotions* require more safety buffer. The *resistibility to emotions* and *general safety buffer* are assumed to be dependent variables to some other independent variables connected with driving and range anxiety level. Following the hypothesis above, it is possible that better *resistibility to emotions* leads to lower level of range anxiety and the safety buffer grows consequently.

Factors that work in situations of trips with different mileage are not the same. In a short trip, *driving experience*, *satisfaction level of max BEV range,* and *decisiveness when driving* show a significant relationship with safety buffer. Drivers with more *driving experience* require more safety buffer, which is according to the previous analysis. Drivers with higher *satisfaction level of max BEV range* require less safety buffer. Drivers with greater *decisiveness when driving* require less safety buffer. In a middle-range trip, no factor is found to be of great correlation with safety buffer. In a long trip, *max range of BEV* is positively related to safety buffer. Drivers who are driving BEVs with more max range require more safety buffer. These drivers are assumed to be more frequently driving with adequate remaining range, since the max range of their vehicles is higher. The advantage in max range makes drivers get used to driving with more buffer. Hence, they are less comfortable with low buffer situations and require more buffer. *Resistibility to emotions* is also correlated with the safety buffer. Drivers with better *resistibility to emotions* require more safety buffer, which accords to previous analysis.

4.2. Driver Behavior and Its Influential Factors. Among the 7 types of behavior listed, *speed reduction*, *change behaviors*, and *seeking nearby charging-pile* are the three most frequently taken behaviors. The factor of *change behaviors* represents the instability of behavior when drivers are under stress. *Speed reduction* and *seeking nearby charging-pile* represent two methods to reduce the risk of being stranded in the middle of a trip. To save energy and extend the range, drivers choose to reduce the speed. To recharge energy and substantially extend the range capacity, drivers choose to seek charging-pile. Other listed behaviors are also related to the two strategies, respectively, but not as featured as the two most chosen behaviors.

There are three of our listed behaviors showing co-relationship with one or more factors and there are rather many correlated factors with *grabbing lines*. For the behavior of *speed reduction*, *resistibility to emotions* is of significant correlation. Drivers with weaker *resistibility to emotions* tend to reduce driving speed under range anxiety. For the behavior of *getting more disturbed*, *general satisfaction level* shows a significant correlation. Drivers with lower *general satisfaction level* are more likely to get more disturbed in mind under range anxiety. The dissatisfaction of the BEV clearly worsens the stress of BEV driver under range anxiety.

For the behavior of *grabbing lines*, a series of factors are found. *Grabbing lines* is believed to be a behavior with the intention to approach recharge points quicker but it is a violation of traffic morality. So drivers are taking risks of getting involved in accidents by grabbing lines. Male drivers are more likely to grab lines, possibly because male drivers are more adventurous mentally. Younger drivers are more likely to grab lines than elder drivers, possibly for the similar reason that the young drivers are more adventurous. Drivers with *fuel vehicle driving experience* are more likely to grab lines, which is very interesting. No one in the total of 39 drivers without fuel vehicle experience reported grabbing lines. Grabbing lines might be too energy-risky for drivers who have no experience of driving fuel vehicles with great accessibility to energy. Considering the negative influence of grabbing lines and the potential risk of the drivers taking more hazardous driving behavior, the driving ethic of BEV drivers under range anxiety deserves further research. *Max BEV range* shows a significant relationship with *grabbing lines*. Drivers driving BEV with higher max range are more likely to grab lines. These drivers are considered to be used to their BEV's excellent range capacity and show more acceptance to more risky behaviors like grabbing lines. Drivers' *decisiveness when driving* and *resistibility to emotions* both show a positive connection with the possibility of grabbing lines under range anxiety. Drivers with stronger decisiveness are more likely to make quick decisions and thus more likely to take risky behaviors. Drivers with better resistibility to emotions are less sensitive to stress and thus take the risky behaviors like grabbing lines.

4.3. Supposed Method of Helping with Range Anxiety. A more accurate and trustworthy in-vehicle information system is of great help to lower the total range anxiety level of drivers, according to [3, 5, 10]. Methods are proposed to estimate the battery SoC or vehicle range in [5, 8, 14]. However, the information system also reminds the driver of the depletion of the BEV's range, potentially raising the speed of the vehicle making drivers gaining anxiety. Hence, it is important to give the driver only the needed information and it must be on time, not earlier or later. Otherwise, the driver will suffer from unnecessary range anxiety gain. Necessary driving behavior guidance should also be given to drivers under stress. From the previous analysis, it can be concluded how range anxiety leads drivers to behave themselves. Changing existing driving habits could cause unfamiliarity of driving. Some of the behaviors are distractive and even dangerous, potentially leading to traffic accidents. So proper guidance is very important to driving safety.

If the BEV receives the destination of a trip, working with GPS, the BEV might be able to calculate the route and the mileage remaining in the current trip. When the detected BEV range remaining is close to the safety buffer range for the trip, the BEV should give guidance on solving the range anxiety. One solution has been proposed in [6] that helps the driver to follow the energy-optimized travelling route, which could relieve the range anxiety. By recording the personal attributes and behaviors, the BEV can generate a specific trip solution for each driver. The changeable part of the solution could include the safety buffer range when the guidance intervenes, the preferred strategy of the driver, and the content of the driver's guidance. Even charging behaviors can make a difference on driver's range anxiety, if one combines the charging behavior model in [13] with the charging strategy recommendation algorithm in [7] together. With the development of the Internet of vehicles (IOV), the analysis can be completed by big data technology. Moreover, when driving different BEVs connected to the IOV, drivers can download the individual setting of human-machine interface that precisely cuts down range anxiety according to the drivers' preference. An exclusive range anxiety solution for each driver of BEV will benefit from cutting range anxiety to the minimum and prevent unsafe behaviors from taking place.

4.4. Study Limitations and Further Research. In the research of safety buffer for different trip mileage, three mileage scenarios are given, roughly representing three different types of trips. But in reality, range anxiety can take place at any point of a trip. The limitation of the questionnaire research is that not all situations are covered precisely. The net safety buffer increases with mileage but starts to fluctuate around 15 km at some point between 10 km and 30 km. The exact mileage has not been found when the buffer stops to consistently grow. Further research might analyze the safety buffer with data collected from field experiments, where the trip mileage could vary more randomly.

The driving style measurements, including *decisiveness when driving* and *resistibility to emotions*, might not

Table 8

	Statement	Strongly disagree	Disagree	Neither agree or disagree	Agree	Strongly agree
1.	I am content with my BEV's range.	□	□	□	□	□
2.	It is convenient to recharge my BEV.	□	□	□	□	□
3.	I trust my BEV's range remain display.	□	□	□	□	□
4.	I behave decisively when driving.	□	□	□	□	□
5.	Emotions hardly affect me when I am driving.	□	□	□	□	□

be adequate to thoroughly describe a driver's driving style. Therefore, further research can expand the scope of drivers' factors that possibly have influence on the driving style.

During our conversation with a BEV driver, the interviewee mentioned the issue about the rapid energy consumption in winter when the heater is on. He never experienced range anxiety, except the range anxiety caused by the rapid drop of available energy due to the heater. But extensive contents were not added immediately to the questionnaire. The anxiety caused by heater in the winter should be a common and crucial issue to the BEV drivers. Future research might focus on the particular range anxiety under the working conditions in winter with the heater on.

The interviewees of our research are all BEV drivers. However, range anxiety might also be keeping some people from owning a BEV. If future research is conducted on the range anxiety of non-BEV-owners, some proposals might be developed for BEV manufacturers to relieve the stress of non-BEV-owners. Some optimizations could be made on the strategies for product development and marketing which will be beneficial for the industry.

5. Conclusions

The average net safety buffer for 10 km-trip is 6.43 km, 64.3% in portion. The average net safety buffer for 30 km-trip is 14.93 km, 49.8% in portion, while the average net safety buffer for 60 km-trip is 16.20 km, 27.0% in portion. The net safety for middle and long mileage trips are roughly around 15 km. To the general safety buffer without considering the trip mileage, *driving experience*, *satisfaction level of recharge accessibility,* and *resistibility to emotions* are significantly correlated. The influential factors are different for trips with different lengths.

Drivers' most chosen behaviors under range anxiety are *speed reduction*, *change behaviors,* and *seeking nearby charging-pile*. Three behaviors have correlations with the drivers' attributes. For the behavior of *speed reduction*, *resistibility to emotions* is significantly correlated with each other. For the behavior of *getting more disturbed*, *general satisfaction level* is of significant correlation. For the behavior of *grabbing lines*, six factors are correlated, including *gender*, *age*, *fuel vehicle driving experience*, *max BEV range*, *decisiveness when driving,* and *resistibility to emotions*.

Our research provides references for the solution of range anxiety. Through analyzing the attributes of a BEV driver, the driver's safety buffer for different trips and preferred behaviors under range anxiety can be anticipated. With this result, a solution to the range anxiety can be generated for a particular BEV driver. This will reduce the range anxiety level without causing extra stress to the driver and the risk of traffic accident can also be cut down.

Appendix

Questionnaire of Battery Electric Vehicle (BEV) Driver's Range Anxiety

This research is carried out with scientific research intention. Your privacy is privileged.

Range anxiety is defines as the anxiety or stress of BEV drivers when they concern about being stranded in the middle of a trip for running out energy.

DRIVER CHARACTERISTICS

GENDER——AGE——DRIVEING EXPERIENCE——YEARS

PROFESSION:

Job hunter/Civil servant/Teaching or scientific research personnel/Individual laborer/Retired/Production or service personnel/Company personnel/Student/Others

FUEL VEHICLE DRIVING EXPERIENCE? Yes/ No

If yes, the fuel consumption of previous fuel vehicle——L/100km

Refueling frequency——times/month

TYPE OF BEV CURRENTLY DRIVEN

BJEV EV160/BJEV EV200/BYD E6/Geely Emgrand EV/JAC iEV5/Tesla Model S/Tesla Model X/ Venucia e30/Denza/Others———(write down the type)

MAX RANGE OF CURRENTLY DRIVEN BEV——km

MOST COMMONLY USED METHOD OF RECHARGE

Public AC charging-pile/Public DC charging-pile/House hold charging-pile/Portable charger (220V AC)/ Others

RECHARGING FREQUENCY——TIMES/WEEK

USE OF BEV

Official/Private/Rental/Service/Others

PART I

See Table 8

PART II

See Table 9

PART II

See Table 10

Thank you for your precious time spent on the questionnaire!

Table 9

	Statement	10 km	12.5 km	15 km	17.5 km	20 km
6.	Minimum comfort range remaining in a 10 km trip	□	□	□	□	□
	Statement	**30 km**	**37.5 km**	**45 km**	**52.5 km**	**60 km**
7.	Minimum comfort range remaining in a 30 km trip	□	□	□	□	□
	Statement	**60 km**	**67.5 km**	**75 km**	**82.5 km**	**90 km**
8.	Minimum comfort range remaining in a 60 km trip	□	□	□	□	□

Table 10

	Statement	Distracted by anxiety	Rearrange the route	Seeking nearby charging-pile	Change behaviors	Speed reduction	Get more disturbed	Grab lines
9.	Under range anxiety	□	□	□	□	□	□	□

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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References

[1] N. Rauh, T. Franke, and J. F. Krems, “Understanding the impact of electric vehicle driving experience on range anxiety,” *Human Factors*, vol. 57, pp. 177–187, 2015.

[2] T. Franke, N. Rauh, M. Günther, M. Trantow, and J. F. Krems, “Which Factors Can Protect Against Range Stress in Everyday Usage of Battery Electric Vehicles? Toward Enhancing Sustainability of Electric Mobility Systems,” *Human Factors: The Journal of the Human Factors and Ergonomics Society*, vol. 58, no. 1, pp. 13–26, 2016.

[3] M. Eisel, I. Nastjuk, and L. M. Kolbe, “Understanding the influence of in-vehicle information systems on range stress – Insights from an electric vehicle field experiment,” *Transportation Research Part F: Traffic Psychology and Behaviour*, vol. 43, pp. 199–211, 2016.

[4] T. Franke, N. Rauh, and J. F. Krems, “Individual differences in BEV drivers’ range stress during first encounter of a critical range situation,” *Applied Ergonomics*, vol. 57, pp. 28–35, 2016.

[5] V. R. Tannahill, D. Sutanto, K. M. Muttaqi, and A. Masrur, “Future vision for reduction of range anxiety by using an improved state of charge estimation algorithm for electric vehicle batteries implemented with low-cost microcontrollers,” *IET Electrical Systems in Transportation*, vol. 5, no. 1, pp. 24–32, 2015.

[6] M. Faraj and O. Basir, “Range anxiety reduction in battery-powered vehicles,” in *Proceedings of the IEEE Transportation Electrification Conference and Expo, ITEC ’16*, USA, June 2016.

[7] K. Sarrafan, K. M. Muttaqi, D. Sutanto, and G. Town, “An intelligent driver alerting system for real-time range indicator embedded in electric vehicles,” in *Proceedings of the 52nd Annual Meeting on IEEE Industry Application Society, IAS ’16*, USA, October 2016.

[8] V. R. Tannahill, K. M. Muttaqi, and D. Sutanto, “Driver alerting system using range estimation of electric vehicles in real time under dynamically varying environmental conditions,” *IET Electrical Systems in Transportation*, vol. 6, no. 2, pp. 107–116, 2016.

[9] M. Dreyfuss and Y. Giat, “Optimizing Spare Battery Allocation in an Electric Vehicle Battery Swapping System,” in *Proceedings of the 6th International Conference on Operations Research and Enterprise Systems*, pp. 38–46, Porto, Portugal, Feburary 2017.

[10] T. Franke, I. Neumann, F. Bühler, P. Cocron, and J. F. Krems, “Experiencing range in an electric vehicle: understanding psychological barriers,” *Applied Psychology*, vol. 61, no. 3, pp. 368–391, 2012.

[11] M. F. Jung, D. Sirkin, T. M. Gür, and M. Steinert, “Displayed uncertainty improves driving experience and behavior: The case of range anxiety in an electric car,” in *Proceedings of the 33rd Annual CHI Conference on Human Factors in Computing Systems, CHI ’15*, pp. 2201–2210, Seoul, Korea, April 2015.

[12] N. S. Pearre, W. Kempton, R. L. Guensler, and V. V. Elango, “Electric vehicles: How much range is required for a day’s driving?” *Transportation Research Part C: Emerging Technologies*, vol. 19, no. 6, pp. 1171–1184, 2011.

[13] T. Franke and J. F. Krems, “Interacting with limited mobility resources: Psychological range levels in electric vehicle use,” *Transportation Research Part A: Policy and Practice*, vol. 48, pp. 109–122, 2013.

[14] T. Franke and J. F. Krems, “Understanding charging behaviour of electric vehicle users,” *Transportation Research Part F: Traffic Psychology and Behaviour*, vol. 21, pp. 75–89, 2013.

[15] G. Liu, M. Ouyang, L. Lu, J. Li, and X. Han, “Online estimation of lithium-ion battery remaining discharge capacity through differential voltage analysis,” *Journal of Power Sources*, vol. 274, pp. 971–989, 2015.

[16] W. Zhang, J. Gu, K. Wang, Y. Du, and Z. Feng, “Drivers’ willingness to drive in old age: a case study on young and mid-aged drivers in China,” *Cognition, Technology & Work*, vol. 18, no. 4, pp. 733–743, 2016.