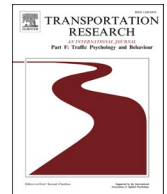




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The psychological, human factors and socio-technical contribution: A systematic review towards range anxiety of battery electric vehicles' drivers

Giuseppe Rainieri^{*}, Chiara Buizza, Alberto Ghilardi

Department of Clinical and Experimental Sciences, University of Brescia, Italy

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ABSTRACT

The use of Battery Electric Vehicles is one of the biggest transformations in the field of sustainable development, holding the potential to address many sustainability challenges. Despite their high energy efficiency, the utilisation of these vehicles remains largely underexplored due to several factors. One of the prominent factors is the phenomenon of range anxiety (RA). This review aims to provide an overview of the range anxiety phenomenon, identifying its primary influencing variables and strategies for mitigating it. The review places particular emphasis on the methodologies and tools employed for assessing range anxiety and related factors.

Following PRISMA guidelines, a systematic search was performed in PubMed, Scopus, and APA PsycInfo, using the following keywords: “range” AND (“stress” OR “anxiety”) AND ALL (“electric” AND “vehicle”). The protocol was registered with OSF, registration number is <https://doi.org/10.17605/OSF.IO/FN4VW>. The articles were selected by two independent authors. The methodological quality and risk of bias were assessed.

A total of 17 studies were included in the systematic review. Studies were analysed by sample size, conceptual framework, assessment method and results. The findings highlight that an approach grounded in Human-Factors principles and psychological metrics can significantly contribute to addressing range anxiety. More, individual (level of experience, self-efficacy, threatening perceptions, attitude, technology commitment and personality) and interface features (range estimation, State of Charge, adaptability, GPS, charging points map, road information) have a role in influencing the EV usage and the onset of RA. Among the commonly employed methods for assessing range anxiety were questionnaires (PASA), scenario-based analyses, and behavioral observations (including facial expression and gaze analysis).

This review shows that the best solution to reduce the range anxiety may be to design improvements that minimize alterations to lifestyle and behaviour in comparison to the traditional vehicle.

The most effective approach for mitigating range anxiety might involve designing improvements that minimise disruptions to lifestyle and behaviours when compared to traditional vehicles. As a novel contribution, this research presents a diagram illustrating the significant relationships between range anxiety and individual, socio-technical, and Human-Factors variables.

^{*} Corresponding author at: Department of Clinical and Experimental Sciences, University of Brescia, Viale Europa 11, 25123 Brescia, Italy.
E-mail address: giuseppe.rainieri@unibs.it (G. Rainieri).

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1. Introduction

The use of Battery Electric Vehicles (BEV) is one of the biggest transformations in the field of sustainable development with the potential to address many sustainability challenges. BEV demonstrate considerable benefits in terms of climate change mitigation, public health, fuel consumption and noise reduction. Although these vehicles are highly energy-efficient, their use is still largely underutilized, due to several factors that make it difficult to spread.

Recently, the interest regarding the barriers that block the BEV spread has grown, and generally it is found that those include price, range, charging infrastructure, consumer perceptions and institutional support (Sovacool & Hirsh, 2009). Transport economists report that price, range, and charging infrastructure/time are the most costly barriers (Schuitema, Anable, Skippon, & Kinnear, 2013). It can be included to them aesthetics, symbolic value and range span (Graham-Rowe et al., 2012). Thus, range appears in the literature as a prominent obstacle and one of the more substantial barriers to EV adoption.

Among these factors, there is the concern related to BEVs reduced span of autonomy, which in turn provokes stress in drivers (Hanifah, Toha, & Ahmad, 2015). This negative sensation is known as Range Anxiety (RA): the driver's fear of running out of electricity before reaching another available charging station (Neubauer & Wood, 2014). In this context, the terms RA or range stress are commonly used to describe concerns about being stranded with a BEV due to a discharged battery (Philipsen, Brell, Biermann, & Ziefle, 2019). RA is defined as a stressful experience of a present or anticipated range situation, whereby the range resources and personal resources available to effectively manage the situation are perceived to be insufficient (Rauh, Franke, & Krems, 2015).

RA is a complex phenomenon that involves many factors such as psychological characteristics of the driver, algorithms, interface features, BEV technical aspects, parking configurations, policies and governance (Bedogni, Bononi, D'Elia, Di Felice, Di Nicola, & Cinotti, 2014; Bonges & Lusk, 2016; Kester, 2019). RA, placed as a psychological factor, impacts on the BEV adoption lowering the perceived easy-of-use, pleasure while driving and safety. Consequently, these negative sensations increase the aversion to BEV's price, seen as excessive compared to the benefits, and reducing the general estimation of the vehicle's value.

Stress, or anxiety, occurs when people perceives a situation as exceeding their available resources and threatening their well-being (Lazarus & Folkman, 1984). The same stimulus may be stressful or not, depending on a person's evaluation of it. This evaluation is done by two appraisals, primary and secondary. In the primary appraisal, individuals assess the significance of the stressor, what it means to the individual, and what the potential outcomes of the demand are. Secondary appraisals address the individual's cognitive and behavioral options for coping with the stressor. Therefore, stress in turn leads to coping, wherein the individual attempts to manage the demand (Kruse, 2013). Considering a Range Anxiety scenario, the first appraisal determines whether the energy available is adequate for the intended destination. In the event of low energy, the second appraisal assesses alternative solutions such as the availability and locating a charging stations, adjusting the vehicle's air-conditioning, or decreasing speed. However, if these tactics are not perceived as satisfactory for meeting the energy requirements, RA is heightened.

Therefore, among the psychological features, coping strategies and individual resilience (such as active range exploration, experience with BEV, relevant knowledge, subjective range competence) seem to play an important role. People, who use adaptive coping strategies, seems to be more likely to be able to manage, reduce or tolerate RA by reorganizing both their behaviour and their emotions in the face of adverse situations (Kruse, 2013; Franke, Rauh, Günther, Trantow, & Krems, 2016b). As mentioned, experience in driving BEVs seems to be a variable that can affect RA. It was shown that practical driving experience of a few weeks was sufficient to lead to a decrease in drivers' experienced range stress and that this effect became even stronger with higher driving experience (Rauh et al., 2015). Nevertheless, it was found that driving in a critical range situation does not lead to an improvement in experienced BEV drivers' range appraisal (Rauh, Günther, & Krems, 2020).

The individual tolerance to low range, described as the range in which the driver feels comfort, was found to be negatively correlate with the RA (Franke et al., 2016b). On the other hand, a positive correlation was found for risk-taking behaviours and RA. This result appears to be in contrast with the classic resource-demand stress theory. The authors explain it advoking that low risk tolerance leads to the avoidance of situations where range stress might occur acutely, and the less risk-averse drivers tend to indicate higher SoC as critical (Philipsen et al., 2019). Moreover, the range buffer displayed was reported as a central variable. Its assessment depends on the interface calculation algorithm, and there is a certain degree of uncertainty associated with the resource indicator, that leads to a certain degree of experienced trustworthiness. The perceived trustworthiness of range estimation system was found to be negatively correlate with the RA (Franke et al., 2016b). Furthermore, regarding the in-vehicle interface, the range estimation system can take over the task of predicting distance-to-empty based on detected state of charge, which helps characterize past, present and future energy consumption. However, this prediction algorithm cannot guarantee complete accuracy for every situation. This may in turn induce uncertainty and mistrust (Franke, Rauh, & Krems, 2016a).

Some authors have shown that changing the driving style (from normal to the eco-driving) can also affect RA, because the eco-driving style represents a solution to possible stressful situations (Musabini, Nguyen, Rouyer, & Lilis, 2020). Attitudes and expectations that people has towards electric vehicles can also influence the experienced RA (Noel, de Rubens, Sovacool, & Kester, 2019).

Besides, the reduction of RA could benefit from improvements in infrastructure and technology (Sankaran, Venkatesan, & Prabhahar, 2020; Xu, Yang, & Wang, 2020). Basically RA can be reduced by setting additional charging stations and better location (Gorbunova & Anisimov, 2020). It should be mentioned also that an isolated public charging infrastructure program may have limited benefits of EV diffusion, because, as mentioned above, RA has strong rhetoric and socio-technical aspects (Noel et al., 2019). Moreover, charging time is a significant challenge for electric vehicles because it directly affects their usability and convenience for consumers. Unlike refuelling a conventional combustion-engine vehicle, which takes only a few minutes, recharging an electric vehicle's battery can take anywhere from several minutes to hours, depending on the charging technology and the battery capacity. This long charging

time is a problem because it limits the flexibility of electric vehicles. Drivers may need to plan their trips around charging opportunities or wait for extended periods for their vehicle to recharge, which can be inconvenient and time-consuming.

Because it is estimated that RA is one of the most important factors that influence new-vehicle buyers when deciding on whether to purchase a traditional Internal Combustion Engine (ICE) vehicle as opposed to a BEV (Adnan, Nordin, Rahman, Vasant, & Noor, 2017), the main aim of this review is to shed light on the RA phenomenon adopting a psychological and Human-Factors perspective, describing influencing factors, establishing a model and deriving insights to reduce RA.

The research question that motivate this work is the following: considering Battery Electric-Vehicle users, do the psychological characteristics, in-vehicle technologies and socio-technical context affect the Range Anxiety sensation?

Moreover, this work aims to cluster the selected articles in three frameworks: psychological, Human-Factors and Socio-Technical System. In order to discriminate those frameworks, their definition are given below. Psychology is the science that, observing and measuring human behaviours, explains the functioning of cognition (Gerrig, Zimbardo, Anolli, & Baldi, 2018). The Human-Factors framework encompass all the evidence useful for design, it was defined as the scientific discipline concerned with the understanding of interaction between human and other elements of a system, applying theory, principles, data and methods to design in order to optimise human well-being and overall system performance (Helander, 2005). This work seeks to incorporate the perceptions of non-EV users regarding EVs and RA issues within the context of the Socio-Technical System (Trist, 1978). Specifically, this framework emphasizes the relationships between users, the environment, and technology, adding a unique perspective to the other. Because of that, our approach is both innovative and supplementary to other reviews in the field.

The decision to categorise the results into three distinct frameworks is motivated by the varying variables and investigative techniques that each of these frameworks usually encompass. For instance, within the realm of psychology, the prevalent approach involves the utilization of questionnaires. In the context of Socio-Technical systems, observations and case-study analyses are commonly employed. Meanwhile, in the domain of Human-Factors, experiments featuring prototypes and simulators are frequently utilized.

Moreover, while these are not exhaustive, these frameworks demonstrate certain focal points. The Psychological framework primarily delves into cognitive aspects. The socio-technical framework concentrates on the interactive dynamics between users and their environment. Lastly, the Human-Factors framework scrutinizes the specific resources and behaviours that users might employ to accomplish a given task.

Starting from that, a model will be proposed in which all the relationships between RA and variables (psychological, Human-factors and Socio-Technical) will be represented. To the best of our knowledge, our contribution is the first that summarises the main psychological variables, the environmental conditions and the in-vehicle technologies affecting RA. Previous reviews were mainly concentrated on RA-related engineering aspects, such as lithium-battery capacity (Tomaszewska et al., 2019; Panwar, Singh, Garg, Gupta, & Gao, 2021; Karimi, Behi, Van Mierlo, & Bercibar, 2022; Liu, Sun, Zhang, Cheng, Li, Zeng, & Ci, 2022; Wassiliadis et al., 2021), supply chain barriers (Adegbohun, Von Jouanne, & Lee, 2019; Pandey & Nandan, 2022), range extension technologies (Tran et al., 2021; Lakshmi Prasad & Gudipalli, 2023), mathematical BEV operations management (Shen, Feng, Mao, & Ran, 2019), charging infrastructure (Afshar, Macedo, Mohamed, & Disfani, 2021; Ashfaq, Butt, Selvaraj, & Rahim, 2021; He, Sun, Wang, Lin, Zhang, Xiong, & Zhai, 2022; Cui, Song, & Wang, 2022; Aduama, Al-Sumaiti, & Al-Hosani, 2023), energy consumption model (Wang, Besselink, & Nijmeijer, 2018; Morlock, Rolle, Bauer, & Sawodny, 2019), grid's potential (Khalid, Khan, Hameed, Asghar, & Ro, 2021; Wang, Qin, Slangen, Bauer, & van Wijk, 2021; Gopinathan & Shanmugam, 2022), and conductive materials (Zhao, Wang, Chen, & He, 2019; Ke, Zhang, Wen, Huang, Ye, Tang, & Li, 2023; Alemu, Getie, & Worku, 2023). In a separate review, the focus was placed on user perceptions regarding range anxiety (Shrestha, Baral, Shah, Chitrakar, & Shrestha, 2022). However, the authors of that review limited their consideration of mitigating solutions to innovations related to extending the range of electric vehicles. These innovations encompassed the establishment of charging infrastructures, advancements in range estimation, optimization of energy consumption, and the implementation of car-sharing initiatives.

Additionally, this article wants to report methods, measures and tools to assess RA. Lastly, this review will highlight knowledge gaps, becoming a compass to orientate future research in the field.

2. Material and method

2.1. Protocol and registration

The study design adopted in this article is the Systematic Review, used to summarize the results of several primary research studies (Ranganathan & Aggarwal, 2020). In the following paragraphs, the criteria for the inclusion of studies are provided.

This systematic review was conducted according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement (Moher, Liberati, Tetzlaff, & Altman, 2009). It flourished from QUOROM Statement (Quality OfReporting Of Metaanalyses), in 2005. The PRISMA statement consists of a 27 item checklist and of a 4 phase flow diagram (identification, screening, eligibility, included). It was developed to focus on randomised trials, but it can also be used as a basis for reporting systematic reviews of other types of research, particularly evaluations of interventions.

The systematic review protocol was registered with Open Science Foundation (OSF) database. The registration number is <https://doi.org/10.17605/OSF.IO/FN4VW> (Date of registration: June 10, 2021).

2.2. Inclusion criteria

Articles were included if they satisfied the following criteria: a) being in English language; b) reporting original data; c) focusing on variables that affect the RA construct; d) papers that reported strategies aimed to reduce RA. We also included reviews that discuss case studies in order to better understand the RA phenomenon and its antecedents.

Those criteria were chosen to intercept the largest number of articles available on the international landscape, as air pollution and sustainable development are problems that affect several countries around the world. The decision to include original data was due to the need to be able to interpret the results in accordance with the social and temporal context in which the data were collected. In addition, the articles had to be useful in drawing a model that reported the greatest number of psychological and in-vehicle technology variables influencing RA. Lastly, it was decided that if the included papers belonged to the same dataset (two publications of different aspects of the same study) they would both be included, as they would add additional variables to the model, maintaining social-context consistency.

2.3. Search strategy and study selection

A systematic search was performed in PubMed, Scopus, and APA PsycInfo, using the following keywords: (“range” AND (“stress” OR “anxiety”) AND ALL (“electric” AND “vehicle”). Moreover, the reference lists of the systematic reviews were screened to identify further relevant articles. The literature search included all articles that were published until June 2021.

Two authors independently (G.R. and C.B.) screened the article titles and abstracts for inclusion criteria and extracted data from all full-text articles selected. Any disagreements in data extraction process were negotiated among the two authors.

2.4. Data extraction

The final sample were analysed and the data were collected in a specific data extraction form, reporting the following items:

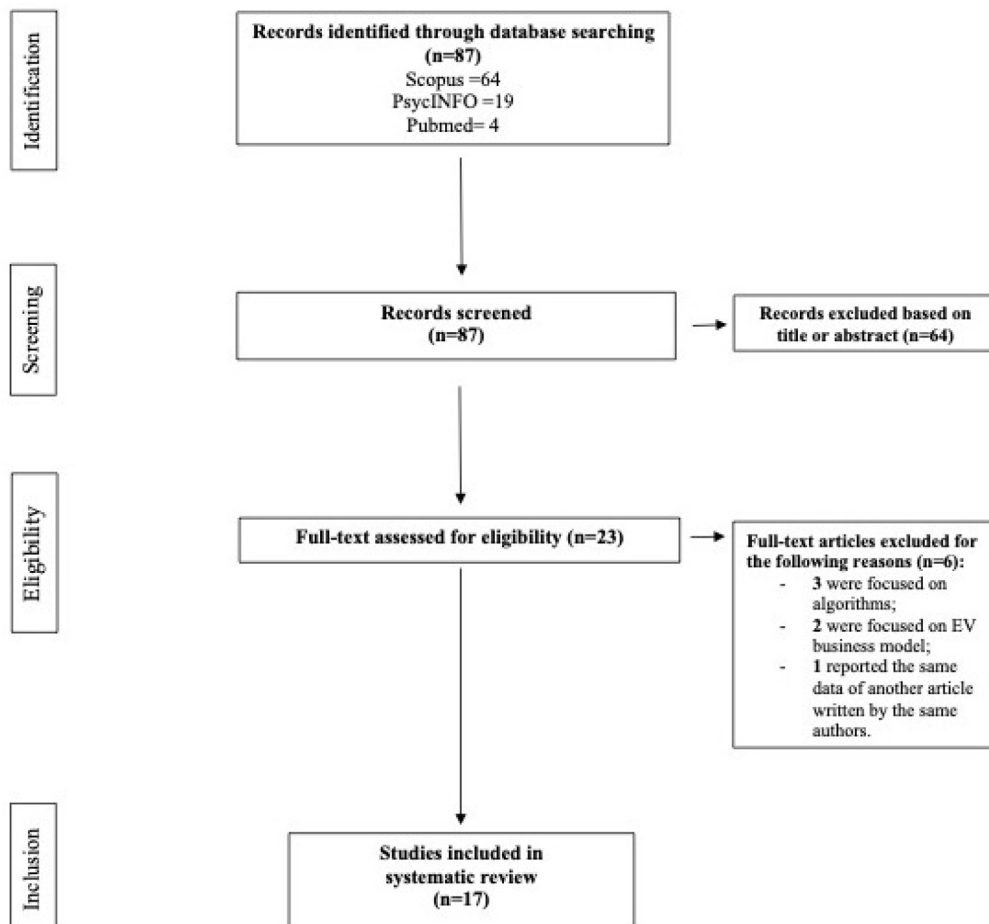


Fig. 1. Flow chart of the selection process; PRISMA Preferred Reporting Items for Systematic Reviews and Meta-Analyses.

authors and country of the study; sample characteristics (e.g., sex, average age, control and experimental group proportions); study design; RA framework; variables that affect RA; assessment tools; outcome and main study results. Two authors independently abstracted data and any discordance was resolved around consensus. Because the studies were different methodologically, a narrative synthesis was planned (Popay et al., 2006).

The narrative synthesis is an approach for the synthesis of findings from multiple studies, only to be used when statistical meta-analysis is not feasible. It adopts a textual approach to the process of synthesis to ‘tell the story’ of the findings from the included studies. It can be used in systematic reviews focusing on a wide range of questions, not only those relating to the effectiveness of a particular intervention.

2.5. Methodological quality assessment and risk of bias

The quality assessment of studies was done independently by two authors (G.R and C.B.) and confirmed by a third author (A.G.) by using the Mixed Methods Appraisal Tool (MMAT; Hong, Pluye, Fàbregues, Bartlett, Boardman, Cargo, Dagenais, Gagnon, Griffiths, Nicolau, O’Cathain, Rousseau, & Vedel, 2018).

The MMAT is a critical appraisal tool that is designed for the appraisal stage of systematic mixed studies reviews. It permits to appraise the methodological quality of five “Categories of study design”: 1 - Qualitative research, 2 - Quantitative randomized controlled trials (RCT), 3 - Quantitative non-randomized trials (non-RCT), 4 - quantitative descriptive, and 5 - mixed methods studies. All the categories have a specific set of items for a proper assessment, the “Methodological quality criteria”, that consists of 5 criteria concerning study design and method. Each criterion was scored answering yes, no, can’t tell. It is discouraged to calculate an overall score from the ratings of each criterion. Instead, it is advised to provide a more detailed presentation of the ratings of each criterion to better inform the quality of the included studies.

This appraisal was useful to make an idea regarding the quality of the selected studies’ results. It was decided that whenever the assessment results in a bad score, such as when an article received more than 3 negative answers in the 5 criteria, it would be excluded because judged as prone to inducing bias. The assessment is made upon the articles selected after the full-text check for eligibility.

3. Results

As reported in Fig. 1, out of the 87 articles generated by the preliminary search strategy, 64 were excluded based on title and abstract as they were irrelevant to the study criteria. Being precisely, many of them associated the term “stress” and/or “range” with “voltage”, other were mainly focused on infrastructures, microgrids, power converters, policies, battery innovations and power suppliers, others verified the hypothesis using simulation model to calculate the potentials and limits of BEV. Other were focused on medical science and, for example, “range” was connected with “life”, while “stress” was associated with “mindfulness” Moreover, 5 articles were in common between Scopus and PsycInfo; while all the articles from PubMed were reported also in Scopus and PsycInfo.

After reading the abstract or the full text, 6 more studies were excluded because: 3 were focused on algorithms ((i) a model takes into account traffic density on roadways to provide an accurate computation of energy consumption to charging (ii) based on queueing theory (iii) Substitution-Emergency-Detour); 2 focused on BEV business model ((i) security governance, (ii) combinations of battery owning/leasing with enhanced charging service); 1 reported the same data of another article written by the same authors (Pevce,

Table 1

Assessment of the studies quality through the Mixed Methods Appraisal Tool (MMAT). Study: it reports the article under appraisal. Screening questions: it reports the answers (“yes”, “no”, “can’t tell”) to the two questions S1: Are there clear research questions? and S2: Do the collected data allow to address the research questions? Category of study design: it reports the type of study. Methodological quality criteria: the five columns report the answers (“yes”, “no”, “can’t tell”) to the specific criteria associated with the category of study.

Study	Screening questions		Category of study design	Methodological quality criteria				
	S1	S2		1	2	3	4	5
Eisel et al., 2016	yes	yes	Quantitative non-RCT	no	yes	yes	no	yes
Franke et al., 2016 ^a	yes	yes	Quantitative non-RCT	yes	yes	yes	no	yes
Frank et al., 2016 ^b	yes	yes	Quantitative non-RCT	yes	yes	yes	no	yes
Jung et al., 2015	yes	yes	Quantitative RCT	yes	yes	yes	no	yes
Kawgan-Kagan & Daubitz, 2014	yes	can’t tell	Qualitative	yes	can’t tell	can’t tell	can’t tell	can’t tell
Khan et al., 2012	yes	can’t tell	Quantitative descriptive	no	no	yes	can’t tell	yes
Musabini et al., 2020	yes	yes	Quantitative descriptive	no	no	yes	yes	yes
Nastjuk et al., 2016	yes	yes	Quantitative RCT	yes	can’t tell	yes	no	yes
Noel & Sovacool, 2016	yes	yes	Qualitative	yes	yes	yes	can’t tell	can’t tell
Noel et al., 2019	yes	yes	Mixed methods	yes	yes	yes	yes	yes
Pevce et al. 2019	yes	yes	Quantitative descriptive	yes	yes	yes	yes	yes
Philipsen et al., 2019	yes	yes	Quantitative descriptive	yes	yes	yes	yes	yes
Rauh et al., 2015	yes	yes	Quantitative non-RCT	no	yes	yes	yes	yes
Rauh et al., 2020	yes	yes	Quantitative RCT	yes	can’t tell	yes	no	yes
Salah & Kama, 2016	yes	no	Qualitative	yes	can’t tell	no	can’t tell	no
Sankaran et al., 2020	yes	yes	Qualitative	yes	yes	yes	yes	yes
Yuan et al., 2018	yes	yes	Quantitative descriptive	yes	yes	yes	yes	yes

Table 2

Description of reviewed studies, by authors and country; Sample description in term of number of participants, divided in experimental groups (percentage of male), age average and standard deviation; study type as Quantitative non-Randomized Controlled Trials studies (non-RCT), Quantitative Randomized Controlled Trials studies (RCT), Qualitative, Quantitative descriptive, Mixed Methods; conceptual framework as psychological, Human-Factors, Socio-Technical System; Methodology as Setting of the study and Method; Assessment tools; Outcome and main results. BEV: Battery Electric Vehicle. NA: Not Available. HMI: Human Machine Interface. SoC: State of Charge.

Authors, year of publication, country	Sample: N. of participants, divided between experimental groups (% male) Age average (sd)	Study type	RA framework	Methodology: Setting Method	Assessment tools	Outcome and main results
Eisel et al., 2016 Germany	12/12 (66.6) 26.1 (6.8)	Quantitative non-RCT	Human factors	Field trial Questionnaire and physiological measure	- Primary Appraisal Secondary Appraisal (PASA) (Gaab, 2009). - Technology affinity and recorded BEV experience (Edison & Geissler, 2003). - Skin conductance. - Five item based on the attitude construct from the well-established theory of planned behaviour (Ajzen, 1991).	In-vehicle information systems (IVISs) had a significant negative effect on both threat and challenge. No significant effect of the IVISs on locus of control and self-concept was found. Range Anxiety level led to a more negative attitude toward using the BEV. A medium to high effect size for the relation between attitude and range anxiety was identified.
Franke, Rauh, & Krems, 2016a Germany	74 (73) 31.0 (7.1)	Quantitative non-RCT	Psychological	Field trial Questionnaire	- General survey on route familiarity, system knowledge (Franke & Krems, 2013). - Trust in Automated Systems scale (Jian, Bisantz, & Drury, 2000). - Subjective Range Competence scale (Franke & Krems, 2013). - 2-item of the neuroticism scale of the Big Five Inventory (BFI-10) (Rammstedt & John, 2007). - Control beliefs in dealing with technology (Kontrollüberzeugug im Umgang mit Technik - KUT) (Beier, 1999). - Primary Appraisal Secondary Appraisal (PASA)	Higher route familiarity, trust in the range estimation system, system knowledge, subjective range competence and internal control beliefs were related to lower experienced range anxiety. The effect of emotional stability was not significant.
Franke, Rauh, Günther, Trantow, & Krems, 2016b Germany	72 (83) 42.8 (9.5)	Quantitative non-RCT	Psychological	Field trial Questionnaire	- General survey on range anxiety, active range exhaustion, subjective range competence, technical system knowledge. - Frequency of critical range situations and accumulated practice with BEV recorded by the data loggers in the BEV. - Comfortable Range Scenario Task.	Less frequent encounters with critical range situations, experience in general, higher accumulated practice, higher gathered experience from exploring low-range situations, higher subjective range competence, higher comfortable range, lower aversiveness of low range and higher experienced trustworthiness of the range estimation system were related to lower range anxiety.
Jung et al., 2015 Usa	57 (56.1) NA Group distribution:	Quantitative RCT	Human factors	Field trial Questionnaire and observations	- General survey on driving experience	Presenting information ambiguously could have advantages. Error-prone (continued on next page)

Table 2 (continued)

Authors, year of publication, country	Sample: N. of participants, divided between experimental groups (% male) Age average (sd)	Study type	RA framework	Methodology: Setting Method	Assessment tools	Outcome and main results
	Low Range Information Ambiguity: 11 (SOC Low) 17 (SOC High) High Range Information Ambiguity: 15 (SOC Low) 14 (SOC High)				- Trust towards vehicle (Jian, Bisantz, & Drury, 2000) - Driving behaviour assessed by starting to ending SoC.	information led to improvements in driving experience, behaviour and trust towards the car. The beneficial effects of presenting information ambiguously were even stronger in critical and highly stressful situations.
Kawgan-Kagan & Daubitz, 2014 Germany	20 NA	Qualitative	Psychological	Survey Standardized interview	- Grid based on personal construct Kelly's theory (Kelly, 1955).	Many respondents stated distrust regarding the environmental impact of BEVs. There was no discrete perception of BEVs. Range anxiety reduced with experience. Drivers developed strategies such as planning their journeys to ensure that they only undertook those that they were confident about having enough range to complete. Lack of trust in currently available BEV's range information was identified as a contributing factor towards range anxiety.
Khan et al., 2012 Usa, Uk	24/26 NA	Quantitative descriptive	Human factors	Lab study Mixed method	- Database analysis and benchmarking. - General survey on range anxiety. - Structured interview. - User Centred Design approach	An intelligent HMI could reduce the range anxiety of the driver by proposing adapted coping strategies (i.e., transmitting how to save energy when the vehicle approached a traffic light). An HMI and automated driving to a safe spot could reduce the stress of the driver when an emergency stop was necessary.
Musabini et al., 2020 France	28 (42.8) NA Groups distribution: 5 control. 22 experimental	Quantitative descriptive	Human factors	Field trial Physiological measures	- Near-infrared face-tracking cameras for facial expressions and gaze analysis (indicating anxiety). - Shotgun microphones collecting speech (indicating analysis). - Frequency Modulated Continuous Wave (FMCW) radar collecting heart rate and respiration rate (indicating anxiety).	The geo Information Systems (IS) led to a lower threat and challenge appraisal (less psychological range anxiety) and to a higher perception of being in control over the critical range situation, as well as an increased perception in one's own competencies to manage the situation. Participants perceived the range display to be unreliable. A separate provision of systems
Nastjuk et al., 2016 Germany	70 (57.7) 27.0 (5.6)	Quantitative RCT	Human factors	Field trial Survey	- Attitudes toward using the BEV (Ajzen 2002) - Affinity for technology (Edison and Geissler 2003) - System experience, experience with an in-vehicle Information Systems (Nastjuk & Kolbe, 2015). - Primary Appraisal Secondary Appraisal (PASA) (Gaab, 2009).	The geo Information Systems (IS) led to a lower threat and challenge appraisal (less psychological range anxiety) and to a higher perception of being in control over the critical range situation, as well as an increased perception in one's own competencies to manage the situation. Participants perceived the range display to be unreliable. A separate provision of systems

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Table 2 (continued)

Authors, year of publication, country	Sample: N. of participants, divided between experimental groups (% male) Age average (sd)	Study type	RA framework	Methodology: Setting Method	Assessment tools	Outcome and main results
Noel & Sovacool, 2016 Denmark		Qualitative	Socio-technical system	Desk research Literature review and case-study analysis		from the geo IS category made the driving task less challenging and threatening as the navigation system decreased uncertainty. Drivers perceived more range anxiety when provided systems from the navigation device and a display of local charging stations. From a purely technical perspective, the range of most electric vehicles was already more than sufficient for the vast majority of trips taken by personal vehicles. Range anxiety may be an over-stated concern. Range anxiety may continue to be a post-hoc excuse for consumers to reject electric vehicles in order to avoid changing their behaviour or desires.
Noel et al., 2019 Denmark	227/61/5.067 NA	Mixed Methods	Socio-technical system	Desk research Survey and interview	- Semi-structured interviews. - Focus groups. - General survey.	Consumers and experts used and perpetuated the rhetoric of reaction, particularly the jeopardy thesis, and therefore the construction of range anxiety as a rhetorical excuse.
Pevec et., 2019 Croatia	134 (70) NA	Quantitative descriptive	Socio-technical system	Survey Questionnaire	- Demographic questions. - Questionnaire about the satisfaction with existing gas station infrastructure and a comparison with BEV charging infrastructure taking into consideration settlement hierarchies. - Five randomly generated scenarios based on which participants should provide opinion about their willingness to charge and about the range preferences in case they want to charge.	People were more influenced by the remaining driving range than the SoC when they had to decide how far they were willing to drive to reach another charging station. However, SoC was an important variable in the decision to charge, as people were uncomfortable when their SoC was below 30%.
Philipsen et al., 2019 Germany	134/70 (69.1) 41.2 (14.4)	Quantitative descriptive	Psychological	Survey Questionnaire	- General survey on demographics features and personality traits, mobility behaviour, range anxiety and trust. - Domain-specific risk-taking scale (DOSPRT) (Weber, Blais, & Betz, 2002). - Technology commitment: technology acceptance, technology self-efficacy, and	Drivers of conventional and electric drives differed less than expected in their perception of range. A significant negative correlation between technology commitment and range anxiety was determined. Increasing trust ensured

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Table 2 (continued)

Authors, year of publication, country	Sample: N. of participants, divided between experimental groups (% male) Age average (sd)	Study type	RA framework	Methodology: Setting Method	Assessment tools	Outcome and main results
Rauh et al., 2015 Germany	12/12 Age: Exp. 49 (7.50) * Inexp. 42(8.83)*	Quantitative non-RCT	Psychological	Field trial Mixed method	technology locus of control (Neyer et al., 2012). - General survey on emotional and cognitive level of range anxiety. - Glances toward the range display, as behavioural range anxiety appraisal. - Primary Appraisal Secondary Appraisal (PASA) assessing Range Appraisal (Gaab, 2009).	that the perceived range anxiety decreased. Experienced BEV drivers had less negative range appraisal (with the exception of challenge appraisal) and lower range anxiety than inexperienced BEV drivers. Experience seemed to have an effect on range anxiety at the cognitive, emotional, and behavioural levels.
Rauh et al., 2020 Germany	20/20/63 (87.3) 38 (9.5)	Quantitative RCT	Psychological	Field trial Survey	- General survey on subjective range competence (Franke & Krems, 2013), range anxiety (Franke, Cocron, Bühler, Neumann, & Krems, 2012; Rauh et al., 2015). - Primary Appraisal Secondary Appraisal (PASA) assessing Range Appraisal (Gaab, 2009).	Drivers benefited from the test drive (i.e., improvement of range experience), to a lesser extent even the experienced drivers. Providing relevant range related knowledge also improved range experience for inexperienced BEV drivers. Partly, they could reach the same stress level as experienced BEV drivers, who had the best range experience in a critical range situation.
Salah & Kama, 2016 Malaysia		Qualitative	Socio-technical system	Desk research Literature review		To reduce range anxiety, improvements in all areas were required. Even though an accurate SoC estimation and displaying the real SoC might help the BEV owners to adapt their driving style with the remaining power, and also choosing the most efficient route might extend the driving range, the BEV owners have to have access to charging stations whenever they need one.
Sankaran et al., 2020 India		Qualitative	Socio-technical system	Desk research Literature review		Authors suggested technology strategies to address RA: - high efficiency batteries with more energy density (wh/kg); - improved battery chemistry to manage temperature profile variation and safety; - fast charging facility; - BEV weight reduction; - optimisation of vehicle

(continued on next page)

Table 2 (continued)

Authors, year of publication, country	Sample: N. of participants, divided between experimental groups (% male) Age average (sd)	Study type	RA framework	Methodology: Setting Method	Assessment tools	Outcome and main results
Yuan et al., 2018 China	208 (75) 32.9 (7.6)	Quantitative descriptive	Psychological	Survey Questionnaire	- General survey on demographics features; minimum comfort range, possible behaviours under range anxiety (Zhang, Gu, Wang, Du, & Feng, 2016).	performance attributes; - lower the coefficient of drag during design phase; - lower rolling resistance tyres; - operation research based algorithms for charging sequence; - connected car technologies for SoC; - increased number of charging stations; - battery swapping techniques. The average net safety buffer for 10 km-trip was 6.43 km, 64.3% in portion. The average net safety buffer for 30 km-trip was 14.93 km, 49.8% in portion, while the average net safety buffer for 60 km-trip was 16.20 km, 27.0% in portion. Drivers' most chosen behaviours under range anxiety were speed reduction, change behaviours, and seeking nearby charging-pile.

Babic, Carvalho, Ghiassi-Farrokhfal, Ketter, & Podobnik, 2019).

3.1. Methodological quality of the included studies

The quality assessment, based on the MMAT tool, is reported in Table 1. The first two screening questions (S1 and S2) require to assess if there are clear research questions and if the collected data allow to address the research questions. Three studies (Kawgan-Kagan & Daubitz, 2014; Khan, Williams, Wellings, Robertson, & Binersley, 2012; Salah & Kama, 2016.) received a neutral or negative score at question S2. This result should not encourage to exclude them, but, according to the MMAT authors, this may lead to perform a sensitivity analysis, considering the quality of studies by contrasting their results. In particular, the contribution made by Kawgan-Kagan and Daubitz (2014) was deemed valid due to its emphasis on potential user perceptions and attitudes toward BEVs. Although the methodology wasn't extensively described, this study's inclusion was justified given its relevance to the Psychological framework. Similarly, the articles authored by Khan et al. (2012) and Salah and Kama (2016) were accepted despite not presenting exhaustive experimental evidence to address all of their research questions. This decision was based on the comprehensive insights they provided regarding the issue of range estimation.

The other Methodological quality criteria (from 1 to 5) depend on the category of study designs, and inquire the quality of the methods, for example asking if the data were adequately to address the research question, or if the findings were adequately derived from the data. For the complete description of the criteria, that change according to the category of study design, it is recommended to see the original MMAT source (Hong et al., 2018).

As it is depicted, the majority of the studies had received a positive evaluation, therefore these studies had been accepted as quality information materials. Moreover, there were 3 articles reporting randomized controlled studies (Jung, Sirkin, Gür, & Steinert, 2015; Nastjuk, Marrone, & Kolbe, 2016; Rauh et al., 2020), and 10 non-randomized studies (Philipsen et al., 2019; Rauh et al., 2015; Franke et al., 2016b; Franke et al., 2016a; Musabini et al., 2020; Pevec, Babic, Carvalho, Ghiassi-Farrokhfal, Ketter, & Podobnik, 2019; Kawgan-Kagan & Daubitz, 2014; Eisel, Nastjuk, & Kolbe, 2016; Khan et al., 2012; Yuan, Hao, Su, Bing, Gui, & Safikhani, 2018). The remaining 4 articles report reviews and case studies (Noel et al., 2019; Sankaran et al., 2020; Noel & Sovacool, 2016; Salah & Kama, 2016).

According to our method, since none of the articles received a negative score of more than three on these criteria, all of the articles

were deemed suitable for inclusion.

3.2. Studies and sample characteristics

Table 2 shows the characteristics of the included studies. Eight studies were conducted in Germany (Eisel et al., 2016; Franke et al., 2016a; Franke et al., 2016b; Kawgan-Kagan & Daubitz, 2014; Nastjuk et al., 2016; Philipsen et al., 2019; Rauh et al., 2015; Rauh et al., 2020), two in Denmark (Noel & Sovacool, 2016; Noel et al., 2019), one in Croatia (Pevce et al., 2019), one in France (Musabini et al., 2020), one in India (Sankaran et al., 2020), one in China (Yuan et al., 2018) one in Malaysia (Salah & Kama, 2016), one in the USA (Jung et al., 2015) and one reported data from the USA and the UK (Khan et al., 2012).

Studies varied in their sample sizes (from a low 22 up to 5,067 participants) and included a total of 6,440 subjects, most commonly male.

The studies were categorised in three frameworks, 7 belong to the psychological framework (the main focus was on the process of expiring a BEV, cognitions, beliefs), 5 to the Human-Factors framework (focus on interaction with interface and purposed to enhancing in-vehicle technology), and 5 to the Socio-Technical System framework (focus on how people can interact with the whole system). If an article addressed multiple frameworks, we primarily focused on the topics covered in the article to determine which framework it should be classified under. If we still encountered difficulty in making a decision, we took into account the journal in which the article was published.

Most of the studies regarded the user experience, studied through a critical-range situation in a real traffic environment. Authors manipulated the perception of the State of Charge (SoC) in BEV's users: e.g., the participants were told that the BEV was not fully charged due to unexpected technical problems, the quality/amount of coping information and the available range safety buffer. Other studies used the Human-Factors framework (Interface and in-vehicle features). Authors manipulated the information shown by the in-vehicle system (e.g., providing an interface that reports maps and nearby charging points, using different systems for geo-localization or the vehicle monitoring, and the ambiguity of range representation). Additionally, the Wizard-of-Oz method was used to simulate different HMI functions.

3.3. Outcome measures

Most of the studies reported the use of interviews and ad-hoc surveys to assess the RA (Philipsen et al., 2019; Rauh et al., 2015; Rauh et al., 2020; Jung et al., 2015; Khan et al., 2012). These studies adopted a broad approach, using items to assess drivers' comfort zone and items to assess the cognitive level (e.g., concerns regarding remaining range or insecurity of reaching the destination), the emotional level (e.g., feeling stressed, nervous or even fearful. fear of a vehicle breakdown), and the behavioural level (e.g., intentions to change or recharge the vehicle, changing of driving style).

Other studies reported the use of the PASA questionnaire (Eisel et al., 2016; Franke et al., 2016a; Nastjuk et al., 2016; Rauh et al., 2015; Rauh et al., 2020), developed by Gaab (2009). The PASA consists of 16 items grouped in two subscales: primary (threat and challenge) and secondary appraisal (control expectancies and self-confidence in one's abilities). The tool conceptualizes stress as the product of primary and secondary appraisal according to the transactional stress model of Lazarus and Folkman (1984). The questionnaire was administrated before and after accomplishing the driving task, typically to measure the effect of the experimental manipulation, or to check the role of the BEV drive experience. In addition, the PASA was used to assess the range appraisal (Rauh, et al., 2015; Rauh et al., 2020), which consists in evaluating the available resources, in this case, the individual comfortable range. The higher the individual comfortable range, the lower the tendency to experience range anxiety in a given range situation.

In other studies, the authors used facial expressions and gaze analysis while the subjects were driving, as a behavioural indicator for stress (Rauh et al., 2015; Musabini et al., 2020). On the one hand, facial expression analysis provides an estimation of the emotional and anxiety level of the driver. On the other hand, the number of glances per minute to the battery indicator confirmed the source of the detected anxiety as the remaining range of the vehicle from a behavioural level.

Finally, arbitrarily generated scenarios were used (Pevce et al., 2019). In this case, the authors asked participants two questions about their willingness to charge and about the range preferences in case they want to charge. The authors assumed that if the participants were faced with a low-charge situation, then they would experience RA and, to remedy this, they would be willing to charge the vehicle.

3.4. Outcomes and main studies results

Considering the framework in which the RA phenomenon was accounted, the studies' outcomes are reported in three paragraphs, according to the categories: the psychological framework (individual characteristics), human-factors framework (e.g., interface and in-vehicle features), and Socio-Technical System (social science, BEV's technical features, etc.).

3.4.1. Psychological framework

Some studies shed light on factors that can protect against RA in the everyday usage of BEVs. Franke et al. (2016b) introduced the Adaptive Control Of range Resources (ACOR) model, developed from researches that studied stress control-demand models (Fuller, 2005; Lazarus & Folkman, 1984), that describes user interaction with a low-resource system encompasses coping strategies. There are two paths to coping behaviour, one being through convenient coping opportunities and the other through situational demands. In the context of BEV drivers, they continuously manage the fit of available range resources to their actual range resource needs with the goal

of keeping the available range resource buffer within their comfort zone. The higher the discrepancy becomes between available buffer and drivers' preferred safety buffer, the more likely drivers will experience discomfort and, finally, stress. [Rauh et al. \(2015\)](#) proposed that starting from the acquisition of the available range buffer, the drivers confront the situation with their safety buffer (primary appraisal), evaluating it as threatening or challenging. An additional evaluation occurred when the drivers consider their coping skills (secondary appraisal) to face the situation. When these coping resources are judged to be insufficient, the situation will be interpreted as a threat, and increased stress will result.

Safety buffer refers to the margins, in terms of available energy, within the user feels to be safe; the ability of appraising the required range affects the safety buffer. Driving experience and resistibility to emotions were found positively correlated with safety buffer, while the driver's satisfaction level towards the recharge infrastructure accessibility was negatively connected with safety buffer ([Yuan et al., 2018](#)). Driving experience seems to have an effect on range anxiety at the cognitive, emotional, and behavioural levels ([Rauh et al., 2015](#)). It was previously found that after 12 weeks of BEV use, the average consumer reduced their range safety buffer from 13.8 km to 6.9 km ([Franke & Krems, 2013](#)). In this regard, most range adaptation seems to occur within the first 3 months of BEV use.

Moreover, practical experience (which can increase the users' situation awareness) and coping skills (defined as the ability to estimate and manage the BEV's range under various conditions) had a positive correlation on range appraisal, while tolerance of low range (comfortable range, low-range aversiveness) and the system coping support (trustworthiness of range estimation) were the most critical ([Franke et al., 2016b](#)). These factors were confirmed by [Rauh et al. \(2020\)](#). The authors concluded that teaching users relevant knowledge and skills (e.g., knowledge about factors influencing range, strategies for saving energy while driving) could be one fruitful approach to reduce the experience of range anxiety. Experience and knowledge have the potential to increase drivers' self-efficacy and confidence regarding their abilities. Accordingly, drivers of cars with internal combustion engines (ICE) and BEV users hardly differ regarding the perceived range stress; BEV users even perceive less stress, showing more trust in the vehicle and in the tank/battery indicators ([Philipsen et al., 2019](#)).

Furthermore, low uncertainty (route familiarity), trustful automation and range estimation systems, system knowledge, beliefs in one's skills to control range-influencing factors, coping skills, and beliefs of control (which reflects the degree of control over the events) all decrease range anxiety ([Franke et al., 2016a](#)). However, the role of personality factors such as emotional stability in relation to range anxiety remains unclear.

A negative correlation was found between users' technology commitment (defined as a mean of acceptance, self-efficacy and locus of control in dealing with technology ([Neyer, Felber, & Gebhardt, 2012](#))), risk-taking behaviour and RA. With regard to range stress, it was revealed that it correlated negatively with two dimensions of technology commitment: the greater the technology acceptance and the technology self-efficacy of the users, the lower was the perceived range stress. In contrast, a significant positive correlation was found for risk-taking behaviour (defined as the wiliness or attitude to take risks) ([Philipsen et al., 2019](#)).

In summary, it becomes evident that employing a survey would be advantageous for evaluating the psychological aspects associated with Range Anxiety. This survey could ideally incorporate the PASA questionnaire and incorporate additional inquiries inspired by previous studies. For instance, including questions about route familiarity, similar to the approach taken by [Franke et al. \(2016a\)](#), could enhance the survey's comprehensiveness. Likewise, integrating questions about tolerance for low range, coping mechanisms (as seen in [Rauh et al., 2020](#)), technology acceptance, self-efficacy, risk perception, and willingness to take risks (similar to [Philipsen et al., 2019](#)) would contribute to a well-rounded exploration of the topic.

3.4.2. Human-Factors framework

[Khan et al. \(2012\)](#) found that the estimated range of the vehicle is one of the most critical pieces of information for drivers. They observed that the majority of drivers wanted an estimated range figure and felt this would be useful. Drivers whose vehicles did not provide a range representation inferred this from the SoC. The authors suggest that a single figure reporting the number of miles, or kilometres, that can be covered before recharging is an insufficient indicator of range. The results also identified a clear requirement for information that will enable drivers to drive more economically, such as driving speed, outside temperature and other factors that affect the energy consumption. According to [Pevet et al., \(2019\)](#) the key parameters were SoC and Remaining Range. Non-BEV owners are more inclined to charge when SoC drops below 15%, a level at which most of the BEVs prompt a warning about the low battery capacity. Furthermore, the Remaining Range has a stronger influence on RA than the SoC for non-BEV owners.

In-vehicle information systems (IVISs) represent potential solution in reducing the RA. A navigation system (maps + more, 12.7 cm diagonal), which provided detailed information about nearby charging points, hurts the PASA sub-scales threat and challenge, thus the users perceive the provided IVISs as a supportive resource, enabling them to better evaluate the likelihood of experiencing range problems. IVIS has no significant effect on the locus of control and self-concept (secondary appraisal). Therefore, the provision of IVISs did not have a strong enough impact to shape the participant's experience, and thus affects the individuals' ability to manage the critical range situation ([Eisel et al., 2016](#)).

One main problem of IVIS is their accuracy. The range gauge is considered to be highly volatile (due to, e.g. variety in acceleration or elevations on the route) in electric vehicles and thus constitutes an additional source of uncertainty ([Nastjuk et al., 2016](#)). Displaying error-prone information ambiguously might be advantageous rather than hiding them from users ([Salah & Kama, 2016](#)). Thus, the knowledge of error-prone information can lead to improvements in driving experience and trust towards the BEV, and it might consequently decrease RA. The authors concluded that increasing the actual range of a BEV might be less important than providing the drivers with reliable information and how to use that information to control and manage the remaining range. The beneficial effects of presenting information ambiguously were even stronger in critical and highly stressful situations ([Jung et al., 2015](#)). Additionally, 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. The driving style was affected by the ambiguity as well: people with the imprecise

display drove more agile when having enough resources but drove more carefully when driving with limited resources (Jung et al., 2015).

Nastjuk and colleagues (2016) found that people perceived less RA when provided with a geo Information-System (IS) (which informs the driver about the road conditions, like traffic and charging spots) compared to those equipped with a monitoring system (which aims to provide the driver with all relevant information about the status of the vehicle, such as remaining range). Considering the Psychological Framework, the geo IS leads to a lower threat and challenge (primary appraisal) and to a higher perception of being in control over the critical range situation, as well as an increased perception of one's own competencies to manage the situation (secondary appraisal). Accordingly, it was found that the navigation system was a key element for a better the driving experience (Musabini et al., 2020). Moreover, the mitigation effect of an adaptive IVISs, or HMI (Human-Machine Interface), could be reach if it provides coping strategies (e.g., transmitting how to save energy when the vehicle approaches a traffic light) and global information (e.g., proximal charging stations, SoC level, remaining mileage). The proposed coping strategies were important contributions to the driver's understanding of BEV power management. Therefore, by mitigating RA, a contextual and adaptive HMI could contribute to the acceptance of BEV technology.

The estimated range is a critical piece of information for drivers. In-vehicle information systems can potentially reduce range anxiety by providing drivers with reliable information, while its accuracy is crucial. Error-prone information should be displayed ambiguously rather than hidden. Moreover, contextual and adaptive information could contribute to the acceptance of BEV technology by mitigating RA.

In conclusion, the Human-Factors framework encompasses a range of investigative techniques, including the manipulation of the HMI, as demonstrated in studies by Jung et al. (2015) and Musabini et al. (2020). Additionally, this framework involves conducting field experiments within actual traffic scenarios, as evidenced by research carried out by Esidel et al. (2016) and Nastjuk et al. (2016).

3.4.3. Socio-technical system framework

The socio-technical framework can provide a holistic perspective on RA issue by taking into account the interdependence between technology, urban-planning and society.

Musabini and colleagues (2020), reported that the four important physical parameters that could make a difference in RA level are the following: battery capacity (kWh), energy consumption (mostly affected by car weight; kWh/km), charging rate (kW), and minimal state of charge (%). Salah and Kama (2016) reviewed the possible solutions to mitigate RA, reporting the charging solutions (e.g., charging while driving system), efficient route selection (e.g., availability of charging infrastructure, the topography of the route, wind speed, weight of BEV, real-time road traffic, historical consumption of energy by BEV) BEV owner's driving behaviour (speed, operation of the air conditioner/heater, driving time), and in-vehicle energy management.

Pevce et al. (2019) focused on the aspect of charging infrastructure by assessing the preferred distance between two neighbouring charging stations, which they used as a metric to define range anxiety. This individual preference was highly dependent on the settlement hierarchy. The results indicated that two neighbouring charging stations should be located approximately 0.12 km closer together compared to the distance between gas stations. Traditional refuelling infrastructure is well-developed in larger or urban areas, whereas it is often lacking in smaller rural areas and villages. As a result, consumers from major cities may be less flexible in their desired distances between charging stations compared to those residing in smaller areas.

Moreover, Sankaran et al. (2020) claimed that reducing range anxiety can be achieved through various means such as providing fast charging facilities, increasing the number of charging stations, optimizing vehicle performance attributes (e.g., torque, acceleration demand), utilizing connected car technologies (e.g., State of Charge, lithium-battery State of Health), and implementing battery swapping techniques.

Regarding battery swapping techniques, an interesting case study was analysed by Noel and Sovacool (2016). "Better Place" was introduced in the electric mobility market as an innovative company aiming to reduce battery costs ("Better Place" owned the battery in the electric vehicle, and consumers paid for an annual "mileage plan") and alleviate range anxiety ("Better Place" constructed a network of chargers and battery swapping terminals for consumers to recharge or switch their batteries). In discussing why "Better Place" did not overcome range anxiety, the authors reported that it may be an overstated concern, pointing out that the range of most electric vehicles is already more than sufficient for the vast majority of trips taken by personal vehicles. However, among the factors contributing to range anxiety (battery size, charging infrastructure, and charging time), reducing charging time is the least significant barrier. People are willing to pay 44% more to extend the range of an electric vehicle than to decrease the charging time. The authors concluded that range anxiety is not solely dependent on the technical aspects of the BEV or the charging system but is instead entirely dependent on individual characteristics and identity. They recognized that behaviors, expectations, and attitudes are often stable, thus minimizing alterations to lifestyle and behavior compared to traditional vehicles becomes the remaining solution.

Noel et al. (2019) argue that RA is often used as a rhetorical excuse to avoid behavioral change. They found that BEVs can fit the driving needs of 95% of consumers, even with a 20% loss of battery capacity. The study also identified three categories of consumer reactions to BEVs based on Hirschman's Rhetoric of Reaction (method originally developed to analysis how conservatives respond to broader or revolutionary social reforms) (Hirschman, 1991): the jeopardy thesis (where the technology is seen as novel and can threaten older innovations), the perversity thesis (once there are any negative experiences to use as examples), and the futility thesis (once the diffusion nears its end, as the thesis argues that the diffusion would not have changed anything). Participants expressed concerns about the possibility of starting fires while charging (jeopardy thesis), the belief that RA may never be solved (perversity thesis), and the argument that BEVs are no less polluting than internal combustion engine vehicles (futility thesis). In conclusion, the authors noted that RA concerns continue to be the foremost reason why consumers are disinterested in BEVs. They added that RA exists in a spectrum, with individuals often having a mixture of technical, psychological and rhetorical aspects to their range anxiety.

In conclusion, a socio-technical framework, solutions to mitigate RA must consider both technical and social factors. For example, improving public awareness and educating consumers on the benefits of BEVs can help reduce psychological barriers related to RA. Social solutions such as incentives for early adopters, public-private partnerships for developing charging infrastructure, and government policies to inform the population can encourage the adoption of BEV, facing the rhetoric concerning RA. The contribution of this framework to the investigation of Range Anxiety could involve observing potential behaviours and beliefs through the examination of alternate simulated scenarios. These scenarios would entail variations in resources and conditions, providing insights into how individuals respond to different situations related to range limitations in electric vehicles.

3.5. Overview of the variables that affect RA

The variables that had an effect on the RA are reported in this section. For a comprehensive scheme see Fig. 2. The plus and minus signs specify the relation effects, where “-” means that the original variable decreases the following one, and the “+” means that the original variable increases the following one. Because some findings result from reviews, correlations and case studies analysis, not all the arrows depicted in Fig. 2 represent cause-and-effect.

Considering the Psychological Framework, the experience was found to have a direct negative relation with RA: as experience increases, RA decreases (Rauh, 2015). An indirect effect was found considering its influence on increasing the confidence in one's ability and expectancies on control (primary appraisal), and decreasing the perceptions towards the threatens and challenging nature of the situation (secondary appraisal) (Franke et al., 2016a). In particular, the primary appraisal was affected by the knowledge of the vehicle's system, and the secondary appraisal was influenced by internal control beliefs in dealing with technology and subjective range competence. Furthermore, the trustworthiness of the system and the trust felt towards the automation decrease the RA through the reliability of the range estimation system.

The experience with BEVs can increase the perception of the safety buffer (Franke et al., 2016a), which in turn can reduce the RA (Yuan et al., 2018). Moreover, the provision of coping information for inexperienced BEV drivers (Rauh et al., 2020), and coping skills in general (Franke et al., 2016b) can reduce the RA.

Some individual characteristics can enforce the subject's resistance to the RA. This is the case of the personal aversiveness of low-range, which increase the tolerance of low-range (Franke et al., 2016b). Additionally, the technology acceptance and perception of self-efficacy towards technology was observed to decrease the RA, while the propensity to take risks was found to increase the RA (Philipsen et al., 2019).

Recalling the Socio-Technical System Framework, engineering (Musabini et al., 2020; Salah & Kama, 2016) and urban-planning features, such as the distance between two neighbouring charging stations, could affect the perception of the RA (Pevce et al., 2019) as well as the public communication addressing BEVs (Noel et al., 2019).

Examining the Human-Factors Framework, certain functions of HMIs and in-vehicle system features are essential for mitigating RA (Eisel et al., 2016). Concerning road conditions, it has been found that providing a system that informs the driver about traffic and helps select the appropriate route can reduce RA (Nastjuk et al., 2016).

The combination of range estimation and SoC would be beneficial. Khan and colleagues (2012) observed fluctuations in the calculated range value, suggesting that road conditions, driving speed, outside temperature, and driving behavior have an immediate effect on it. Therefore, a single figure indicating the number of miles or kilometers that can be covered before recharging becomes necessary is an insufficient indicator of range. In this regard, an ambiguous range display would be beneficial (Jung et al., 2015; Salah & Kama, 2016). Error-prone information led to improvements in driving experience, behavior, and trust towards the car.

The provision of adaptive coping strategies was found to be a useful tool for reducing RA (Musabini et al., 2020). The term “adaptive” refers to the dual capability of the HMI to suggest actions that may be static (available at all times to inform the driver) or

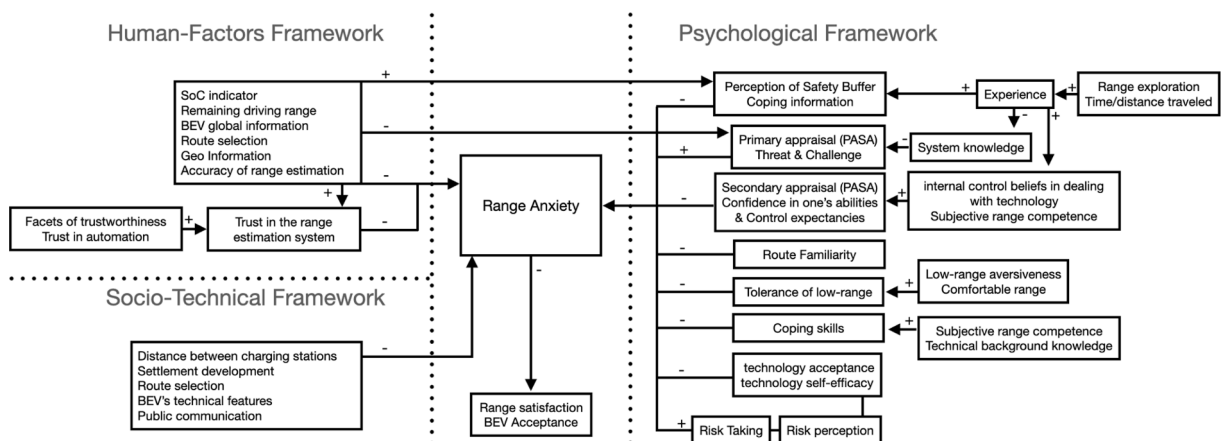


Fig. 2. Variables antecedent to Range Anxiety. “-” means that the original variable decreases the following one, and the “+” means that the original variable increases the following one. Not all the signs represent cause-and-effect.

dynamic (triggered by specific events, such as a drop in battery level). Some of the suggested coping strategies by the HMI were changing behavior when approaching a hill (informing the driver that the battery would discharge uphill and recharge downhill) and slowing down gradually at a red traffic light to recover energy. The remaining battery percentage was found to instill confidence in the drivers. Finally, options such as “charging station proposal” and “calling assistance and taxi” were considered useful.

4. Discussion

This review has identified the factors that allow drawing a picture of the RA phenomenon concerning the psychological, Human-Factors and Socio-Technical system frameworks. Despite the rapid growth in BEV industries, the articles that report studies on RA cover only the last decade. This suggests that the RA phenomenon is a current and open problem.

In order to answer our research question, in the following paragraph it is reported how the psychological characteristics, Human-Factors and socio-technical context affect the Range Anxiety sensation.

Analysing the role of experience, RA seems to rise during the early period of BEV usage, suggesting that an adaptation process occurred. According to the self-regulatory model, grown experience with BEV can reduce the threatening perceptions towards the environment (Rauh et al., 2015) and enforce the self-efficacy feeling of drivers' abilities (Rauh et al., 2020). Moreover, it was shown that the opportunity to have experience of BEV decrease the perceived RA. The technology commitment and self-efficacy towards BEV was reported to be negatively correlated with the RA (Philipson et al., 2019), which foster the idea of a positive attitude about BEV contributes to reducing the RA and increasing the BEV acceptance. This finding follows the Technology Acceptance Model (TAM), which emphasizes the unidirectional causal relationships between cognitive beliefs and behaviour intentions (Davis, 1989).

Furthermore, the range safety buffer was considered the bound after which the drivers will experience more likely discomfort and stress (Yuan et al., 2018). Besides the individual variance in tolerating low ranges, the perceptions towards the trustworthiness of range estimation were found as a potential factors that contribute to lowering the RA. The safety buffer span increases by experiencing BEV (Pevce et al., 2019).

Considering the acceptance of electric vehicles, a study comparing BEV drivers and non-BEV drivers (Kawgan-Kagan & Daubitz, 2014) suggests that providing more information and education regarding the capabilities of BEVs as an everyday mode of transportation is necessary. System features, such as advanced information systems or advanced range displays, have been proposed as viable options to further reduce range anxiety (RA) (Musabini et al., 2020; Philipson et al., 2019; Rauh et al., 2015). Typically, the in-vehicle system could include the estimated range of the vehicle, SoC, and the location of charging stations (navigation devices). People are more influenced by the remaining driving range than the SoC when making decisions about how far they are willing to drive to reach another charging station, considering the possibility of it being occupied or available (Pevce et al., 2019). The authors reported that SoC is an important factor in the decision to charge, as the results indicate that people feel uncomfortable when their SoC is below 30%.

In terms of the driver's awareness of the vehicle's status, one of the main concerns is related to range estimation (Nastjuk et al., 2016). The vehicle's autonomy level and energy consumption depend on various factors, such as the ability to recharge the battery while braking, vehicle characteristics, road elevation, and more (Modi, Bhattacharya, & Basak, 2020). Some vehicles recalculate the estimated range frequently enough to accurately represent the vehicle's performance (Khan et al., 2012). When inquiring about confidence in range estimation, 58% of participants expressed trust in the vehicle's range information, while 35% reported having no trust. Nastjuk et al. (2016) found that participants perceived the range display as unreliable due to its high volatility. In this regard, displaying error-prone information ambiguously may be advantageous, leading to improvements in driving experience, behavior, and trust towards the BEV, ultimately reducing range anxiety (RA) (Salah & Kama, 2016). This assumption was demonstrated by Jung and colleagues (2015) who found that an ambiguous range display promoted a more “mindful” and adaptive driving style, making participants feel calmer. Additionally, the authors suggest that the range prediction is non-linear, which can elicit user frustrations. Displaying progress information ambiguously may be a strategy to enhance the user experience (Jung et al., 2015; Nastjuk et al., 2016). Furthermore, it was found that drivers without a range estimation system experienced less range anxiety compared to those with such a system. The authors justified these results by stating that the range gauge system increases the driver's perceived inability to predict the actual remaining range. Additionally, it imposes an additional cognitive load on the driver who needs to constantly check the range gauge since they are not familiar with highly volatile range feedback (Nastjuk et al., 2016).

A contextual and adaptive HMI could contribute to the acceptance of BEV technology by proposing coping strategies that enhance the driver's understanding of BEV power management (Musabini et al., 2020). Following the principles of human-technology interaction, coping strategies that were easily understandable were more appreciated. Instead of leaving the driver to explore the strategies on their own, presenting them at the appropriate moment was found to be beneficial.

As mentioned earlier, the authors emphasized that the GPS navigation system was a crucial aspect of the driving experience, although it was underestimated by the participants. In conclusion, some users felt overwhelmed by the abundance of information presented by the HMI. This could potentially result in driver distraction from the primary driving tasks and further increase anxiety (Musabini et al., 2020). The authors suggested that incorporating features such as prioritizing displayed information, using a combination of meter-navigation display, and providing two-way communication capability with real-time information would be advantageous for inexperienced BEV drivers.

It has been argued that road conditions, the use of the heater and air conditioning, and driving behaviour have an immediate impact on the vehicle's range estimation (Khan et al., 2012). In this regard, individual traits influence perceptions of range anxiety (RA). For instance, it has been found that people differ in their preferences regarding the distance between charging stations, which can be attributed to varying levels of risk-seeking behaviour among participants (Pevce et al., 2019). The HMI can help reduce the threatening

and challenging aspects of driving by influencing individuals' expectations of managing demanding events. The availability of information through the HMI plays a crucial role in increasing the sense of security. However, no results were found regarding the effect of the HMI on locus of control and self-concept. It was expected that providing relevant information, such as the location of nearby charging stations, could enhance an individual's ability to identify alternative actions to address uncertainties in critical range situations. Self-concept and locus of control are related to personality traits and are considered relatively stable. Moreover, these factors are primarily shaped by a person's experiences with the environment, thereby influencing their ability to take action. The authors concluded that the provision of in-vehicle information systems did not have a strong enough impact to shape the participants' experiences and subsequently affect their ability to manage critical range situations. Lastly, it was found that participants who held negative attitudes towards BEVs exhibited a higher level of perceived range anxiety (Eisel et al., 2016; Nastjuk et al., 2016).

On the other hand, it was found that the navigation system, which provides information about road conditions and current traffic, can lead to a lower appraisal of threat and challenge and a higher perception of being in control over critical range situations. It also enhances the perception of one's competencies to manage such situations (Nastjuk et al., 2016). The availability of information regarding local charging possibilities enables individuals to identify alternative actions in critical range situations. The authors commented that primary and secondary appraisal processes are highly influenced by the available information about a situation and the perceived level of uncertainty associated with it.

A model was proposed to represent the relationships between range anxiety and variables related to psychology, human factors, and socio-technical aspects. Regarding the psychological framework, coping information, perception of being in the safety buffer, confidence in one's ability, expectancies of control over the situation, familiarity with the road, tolerance of low range, coping skills, technology acceptance, and technology self-efficacy directly reduce RA. On the other hand, risk-taking behaviours, perceiving the situation as threatening and challenging, directly increase the sensation of RA.

A human-machine interface that displays information regarding State of Charge level, remaining range, BEV states, and geo-information can help reduce RA. An in-vehicle information system that assists the driver in selecting the appropriate route and presents the aforementioned indicators with an appropriate level of accuracy can further contribute to the reduction of RA.

Considering the socio-technical system, indiscriminately increasing the number of charging points without careful consideration of their location does not seem like the optimal choice. Therefore, a thoughtful selection of charging point placement, taking into account settlement dimensions and the distance between charging points, along with a public communication campaign, can reduce range anxiety and enhance BEV acceptability.

Lastly, in terms of methods, measures, and tools for assessing range anxiety, the PASA questionnaire appears to be the most suitable choice, along with behavioural indicators such as facial expression and gaze analysis. The review has demonstrated that the most effective study designs for assessing range anxiety are those that involve experiments conducted in real traffic fields.

Concluding, it is worth to mention that several measures have been implemented to address range anxiety and provide drivers with information about the State of Charge level and remaining range of the battery electric vehicles. Most BEVs already feature a human-machine interface (HMI) that provides drivers with real-time information about the SoC level and the estimated remaining range based on their driving behaviour. On this regard, it is necessary to make additional progress in the development of algorithms that take into account environmental factors when estimating the range, while also assessing the user's driving behaviour. Additionally, the HMI should consistently provide the driver with information about how specific conditions can affect energy consumption. This feature would help drivers monitor their battery status and plan their journeys accordingly.

Further researches can be conducted to improve the accuracy of range estimation algorithms. This could involve incorporating real-time data from various sensors, such as weather conditions, traffic patterns, and road topology, to provide more precise predictions of remaining range. On the other hand, it might be interesting to see whether precise or vague information can alleviate or increase the range anxiety in accordance with driving conditions. Applying machine learning and artificial intelligence techniques to analyse historical driving data can help refine range prediction models and drivers' profiling. By learning from individual driving patterns, these models can provide personalized solutions to overcome critical range situations. Finally, educational or informational campaigns can address misconceptions and provide accurate information to reduce anxiety levels.

5. Limitations

This review has several limitations. Firstly, out of the 17 studies included in this review, only 3 utilised random samples. Secondly, many studies had small sample sizes, which reduces the generalizability of our results. Moreover, in the non-randomized studies, the control group was often missing, and the studied sample is not representative of the general population of car drivers but rather represents potential BEV customers over the coming years.

Regarding the considered human-factors framework, none of the studies encompassed the concepts of mental workload and situation awareness, which was expected based on their broad acceptance in this research tradition. Furthermore, in acknowledging the psychological approach, only one of the studies adopted a physiological measurement (electrodermal activity) to assess range anxiety, even though research has shown that both emotions and stress are accompanied by arousals.

Finally, due to our approach, articles specifically reporting advancements in engineering and technological features were deliberately avoided, despite the growing interest in those topics (Jiao, Ran, Chen, Meng, & Li, 2017; Esmaili, Shafiee, & Aghaei, 2018; Xie, Wu, & Boyles, 2019; Sankaran et al., 2020; Xu et al., 2020).

6. Conclusions

Range Anxiety and long charging time may not be the most significant barriers to electric vehicle adoption. The range of most electric vehicles is already more than sufficient for the vast majority of trips taken by personal vehicles. The results of this review demonstrate that RA is not solely dependent on the technical aspects of the electric vehicle or the charging system, but rather on individual characteristics. In this regard, according to the Integrative Model of Fishbein (2000), it is possible to leverage attitude, expectations, and self-efficacy to promote behavioral change towards the adoption of BEVs. However, since expectations and attitudes regarding BEVs can be stable, the best solution to mitigate RA may be to design improvements that minimise lifestyle and behavioural alterations compared to traditional vehicles.

In conclusion, the authors of this work propose additional in-field experiments (in real traffic situations or during the initial trial stage for new BEV purchasers) to monitor the contribution of attitude towards BEVs and driving style to RA.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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