A Fundamentals

Within Part A, the foundation for the upcoming studies is provided. This fundamental part is divided into two chapters that introduce the research endeavor and provide a theoretical background for the reader. Section 1.1 explains the motivation behind addressing the range barrier to electric vehicle adoption, while the research objectives and resulting research questions are presented in Section 1.2. Afterwards, Sections 1.3 and 1.4 provide a detailed structure of this dissertation and describe the research design. Finally, Section 1.5 discusses the anticipated contributions for the audience addressed. Chapter 2 covers the theoretical background of the research endeavor. Within the first section of the background, general information about electric mobility is provided. Subsequently, the main barriers to EVs' widespread diffusion are discussed with a particular focus on the range barrier.

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1 Introduction

The first chapter introduces this cumulative dissertation and is divided into five sections. Section 1.1 explains the motivation for this research endeavor and aims to determine the relevancy of analyzing the range barrier to electric vehicle adoption. The research objective and the related research questions are then presented within Section 1.2. Section 1.3 provides the detailed structure of this dissertation while in Section 1.4 its research context and research design is discussed. Finally, Section 1.5 presents the audiences addressed by this dissertation and describes anticipated contributions of the research endeavor for theory and practice.

1.1 Motivation

Environmental pollution has become an issue of serious international concern, as the irreparable harm it causes constitutes one of the biggest problems that the world faces today. As the transportation sector accounts for nearly one-fifth of overall greenhouse gas (GHG) emissions, it holds great potential for reducing these effects. In 2012, 24.7% of total emissions in the European Union (EU) were transportation related, with a staggering 71.9% of this share stemming from road transport (European Comission, 2015b). Such vehicle-induced air pollution has led to health issues and increased mortality in both developing and highly developed countries (United Nations Environment Programme, 2015; Anenberg et al., 2011; Brauer et al., 2002). Yim and Barret (2012), for example, report nearly 7,500 premature deaths per year in the United Kingdom (UK) due to emissions generated by their transportation sector. This tragic figure even exceeds the annual road fatalities of 1,775 deaths in the UK (Department of Transport, 2015).

As a reaction to environmental pollution, many nations have enacted legislation to regulate and alleviate its adverse effects (e.g., pollution control). Consequently, there has been a global paradigm shift from centralized to decentralized electricity generation, with a particular focus on renewable energies. Adopting these thoughts and against the backdrop of increasing global crude oil scarcity, electric mobility is considered a promising solution to counter environmental pollution, as it constitutes an ecologically sustainable means of transportation. Electric vehicles (EVs) are theoretically capable of emissions-free driving when powered entirely by renewable energies and are therefore particularly valuable in achieving governmental climate goals. In China, for example, new energy vehicles such as EVs could reduce GHG emissions of the transport sector by up to 5.1% compared to conventionally driven vehicles, assuming a market share of 10% (Tang et al., 2013).

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Besides their capacity for reducing GHG emissions, electric vehicles also exhibit relatively low operating costs, offering users a huge potential for cost savings over time, as the cost of fully recharging an EV's battery would only constitute a fraction of that of refueling a conventionally powered vehicle (Plötz et al., 2014). When driving a sufficient distance, the lower operating costs can even compensate the higher acquisition costs of these vehicles (Plötz et al., 2012).

Despite these benefits, the market penetration of electric vehicles is still pending, which is reflected in their low sales numbers. In Germany, for example, the current sales numbers of nearly 20,000 EVs in total (Statista, 2015d) fall short of the governmental goal of introducing 1 million EVs by 2020 (NPE, 2012). This is mainly due to three major barriers to the widespread adoption of EVs: (1) their high purchasing price with a premium of up to €15,000 per vehicle (Krause et al., 2013), (2) insufficient infrastructure to enable long-distance trips (Egbue and Long, 2012), and (3) their limited average driving distance due to the battery's low energy density (Bühler et al., 2014). Although the limited range of these cars would theoretically be sufficient to match the usage patterns of most drivers (Neumann et al., 2010), they are generally unwilling to accept it (Duke et al., 2009). According to Egbue and Long (2012), only 15% of the respondents in their study would be satisfied with a vehicle range of 50 miles or less, even though the actual driving distance of 92% of the respondents was below this threshold. This range paradox clearly represents a large gap between actual driving distance and range-related expectations.

Moreover, users often report serious concerns about not reaching their planned destinations due to battery depletion, which is commonly referred to as the phenomenon of range anxiety (Nilsson, 2011b). To ease these worries, users tend to underutilize given range resources (Botsford and Szczepanek, 2009); however, such actions are unsustainable (Franke and Krems, 2013b). The main reasons for this anxiety are the underdeveloped charging infrastructure (including the long charging times necessary to fully charge the battery) and the limited driving range of EVs (Tate et al., 2008). The phenomenon of range anxiety can be considered a domain-specific type of stress that is experienced in present or anticipated situations with insufficient range resources (Franke et al., 2015d). Thus, range anxiety is likely to trigger an increased stress perception, which in turn appears to put the driver at a greater risk for accidents and thereby affects road safety (Matthews et al., 1998). Furthermore, the resulting lack of confidence in using an electric vehicle for longer distances negatively affects the buying decision and thus poses a barrier to their widespread adoption (Franke and Krems, 2013c; Egbue and Long, 2012; Carroll and Walsh, 2010). It is therefore clear that research must strive to better understand the phenomenon of range anxiety and how it affects both present and future EV drivers.

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Simply increasing the battery size does not meet expectations due to physical and chemical boundaries that complicate economically feasible improvements. It would also affect the EVs' sustainable character, as compensating for their large initial environmental impact is difficult during lower polluting operations (McManus, 2012; Held and Baumann, 2011). Researchers and practitioners should, therefore, focus on strategies that enable drivers to exploit the maximum usable range of a given battery capacity, thereby mitigating range anxiety (Franke et al., 2015d). In this regard, the deployment of charging stations and provision of suitable information systems (IS) are widely discussed approaches to alleviate range anxiety. However, an in-depth understanding about how these strategies exactly affect range anxiety is still pending. In this regard, most studies have focused on how range utilization behavior (Franke et al., 2015c; Franke and Krems, 2013a; Franke et al., 2012b), practical experience with EVs (Rauh et al., 2015a; Chaudhary, 2014), and improving range estimation accuracy (Fechtner et al., 2015; Kondo et al., 2013) influence the perception of range anxiety. The aim of this cumulative dissertation is, therefore, to analyze the range anxiety phenomenon in detail while identifying measures to mitigate range-related concerns in the context of electric vehicle use. Applying suitable measures to alleviate or even overcome range-related concerns might positively affect the attitude against using EVs, thereby ensuring that these vehicles become more competitive. Furthermore, a valuable contribution to road safety could be achieved by reducing range-related driver stress.

1.2 Research Objective

As explained above, the adoption of electric vehicles remains rather limited, despite their potential to reduce GHG emissions. A key reason for this lack of success is based on psychological processes, reflected in a generally negative attitude toward EVs. It seems contradictory that many users consider the limited driving range of EVs to be an issue, as on average it would be sufficient to match most of their mobility needs. In alignment with these thoughts, this dissertation has two overarching goals. First, it aims to determine measures that can be taken to effectively reduce range-related concerns when driving an electric vehicle. Second, this thesis attempts to evaluate the possible impacts of these measures on the attitude toward using an electric vehicle. To achieve these two goals, it is necessary to better understand the phenomenon of range anxiety and how it affects EV users. In this regard, Nilsson (2011b) hints at the need to address several issues that could have larger implications for mitigating range anxiety, such as developing measurement approaches and conceptual frameworks, examining physiological responses to critical range situations, and evaluating the relation between range anxiety and other variables. Inspired by these issues, this dissertation is structured according to four research questions.

The foundation for this research endeavor is an exhaustive literature review based on the approach of Webster and Watson (2002). Studies related to concerns regarding the limited

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range of EVs – conducted by both the IS community as well as other fields – were analyzed to help researchers understand the existing body of knowledge. It is thus possible to provide a theoretical foundation for the proposed study that helps to identify where new research is needed. Hence, the first research question is derived as follows:

1) *What have the IS community and other research streams done to analyze range-related barriers to EV adoption with a particular focus on the phenomenon of range anxiety?*

As the phenomenon of range anxiety constitutes a severe problem for most EV users, solutions to overcome this psychological barrier must be developed. Simply increasing the battery capacity would of course help to alleviate range-related concerns but would also inevitably raise the purchasing price of EVs, which itself already represents a significant barrier to the adoption of these vehicles. Therefore, different approaches must be examined to facilitate their diffusion. Widely suggested approaches are the provision of additional charging infrastructure (Chen et al., 2015) and the application of suitable information systems (Franke et al., 2012) that provide relevant information to the driver, for example, in terms of remaining range, navigation, or charging opportunities. However, methods that account for an appropriate measurement of range anxiety have yet to be developed. Therefore, the second research question is formulated as follows:

2) *How can range anxiety be measured? Which factors account for changes in the perception of range anxiety?*

This work centers on the impact of in-vehicle information systems (IVIS) on the range-related concerns that users perceive prior to and during driving an electric vehicle. These IVIS have gained increasing attention regarding driver assistance, affecting the relationship between automobile and driver. The automobile of today is regarded as a mobile computer equipped with interactive safety systems (Krum et al., 2008), representing a key factor in the reduction of road traffic accidents (Gerónimo et al., 2010). For electric vehicles in particular, information systems play an even more important role, as their low driving range poses additional challenges for the driver (i.e., range anxiety). Recent research has suggested that domain-specific information systems might be useful for mitigating range-related concerns (Franke et al., 2012), especially in reducing uncertainties about remaining range resources (Rauh et al., 2015b). Devices supporting the driver with relevant information could thus be crucial for reaching a planned destination, particularly against the backdrop of frequently reported mistrust against the range-related information provided (Osswald et al., 2012; Wellings et al., 2011).

To date, however, IS research has primarily focused on information systems as a cause of stress reactions (e.g., technostress), largely ignoring its potential for alleviating stress perceptions (Ayyagari et al., 2011; Tarafdar et al., 2010; Ragu-Nathan et al., 2008). The ambiguity between triggering and mitigating stress reactions thus calls for further research.

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This dissertation aims to adopt these thoughts and transfer them to the context of applying IVIS within EVs to reduce range-related stress perception (i.e., range anxiety). The underlying appraisal processes are crucial for a comprehensive understanding of range anxiety. However, these appraisal processes have not yet been sufficiently explored. Likewise, psychophysiological reactions, as a consequence of experiencing range anxiety, have mainly been ignored in prior research. Therefore, the third research question is derived as follows:

3) *Are in-vehicle information systems suitable to mitigate range anxiety? How do in-vehicle information systems affect an individual's range-related stress perception when driving an electric vehicle?*

Besides providing appropriate IVIS, some studies have shown that EV users demand an appropriate charging infrastructure, as they feel more comfortable when there are charging opportunities along their routes (e.g., Kearney, 2011; Aoki, 2010). However, as investments in charging infrastructure are hardly profitable at the current low penetration rates – only 0.6% of new vehicle registrations in Germany in 2015 were for EVs – suppliers demand a higher market share of electric vehicles before undertaking infrastructural measures (Statista, 2016; Schroeder and Traber, 2012). This chicken-and-egg problem of EVs and charging stations has resulted in a scarcity of (semi-)public charging opportunities. Most approaches for allocating charging stations are based on economic- and distance-related characteristics (e.g., He et al., 2013; Schroeder and Traber, 2012; Ge at al., 2011). However, against the backdrop of range anxiety and the fear of getting stranded that comes along with this phenomenon, charging opportunities with high visibility for the drivers could counteract this effect (Aoki, 2010). It is assumed that a greater awareness of charging stations is correlated with a lower level of range anxiety (Chaudhary, 2014), encouraging EV drivers to venture farther with their vehicles (Bakker, 2011). In this regard, A small number of quick chargers might be sufficient to have a large impact on reducing range anxiety (Aoki, 2010) and is seen as key factor for the acceptance of electric vehicles (Bakker, 2011). Although this issue is serious, the integration of range anxiety remains underexplored in the context of allocating charging stations. It is therefore suggested that customer preferences be considered when allocating charging points, as they reflect the desire for mitigating range concerns. Accordingly, the fourth research question is formulated as follows:

4) *How can customer preferences be implemented in a location-planning model for allocating EV charging stations that aims to mitigate range concerns?*

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1.3 Structure of the Thesis

This work is a cumulative dissertation consisting of four parts (A, B, C, and D). While the first and last part frame this thesis with respect to the research objective of evaluating the phenomenon of range anxiety and its effects, Parts B and C cover the studies conducted to achieve this objective by answering the research questions.

Part A begins with the motivation behind addressing the range barrier to electric vehicle adoption, followed by the research objectives and resulting research questions. Afterwards, the structure of the dissertation as well as the research design and the audience addressed are outlined. The next chapter provides the theoretical background for understanding the main barriers to the widespread diffusion of EVs, with a particular focus on the phenomenon of range anxiety.

Parts B and C represent the core of this cumulative dissertation and cover the six studies conducted to answer the research questions. An overview of the studies is provided in Table A–1 below. Part B comprises two studies that provide insights for a better understanding of the range anxiety phenomenon. To assemble a thorough overview of previous research related to this topic, a structured literature review is conducted in Study 1. Based on the approaches of Webster and Watson (2002), Levy and Ellis (2006), and Rowe (2014), it aimed to synthesize past knowledge from within and outside the information systems community while simultaneously identifying existing knowledge gaps. The literature review is thus intended to extend the existing body of knowledge and provide a firm understanding of the range anxiety phenomenon. Moreover, in a first attempt to grapple with users' perceptions of range-related concerns, a concept to quantitatively assess the phenomenon of range anxiety is developed in Study 2. In this regard, a survey is conducted to evaluate users' concerns about not reaching their planned destinations with respect to different charging levels in various scenarios. Moreover, a group comparison is conducted to gain insights into the relation between information systems and range concerns when driving an electric vehicle.

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Table A–1
Overview of the studies included in this thesis.

No.	Chapter	Core research question	Contribution	Outlet	Ranking
1	B.1	*What is the state of the art in range anxiety research?*	Overview of related literature and identification of knowledge gaps	Unpublished	-
2	B.2	*What are the relevant factors influencing range anxiety and how can changes in it's perception be measured?*	Conceptualization and operationalization of range anxiety	Multikonferenz Wirtschaftsinformatik 2014	D (n.a.)
3	C.1	*Do mobile applications address attributes related to the disadvantages of EVs?*	Investigating the contribution of apps in addressing EVs' perceived disadvantages	Wirtschaftsinformatik 2015	C (68)
4	C.2	*Which appraisal processes are influenced as a consequence of using in-vehicle information systems?*	Insights into the perception of range-related concerns when driving an EV are presented	International Conference on Information Systems 2014	A (96)
5	C.3	*How do in-vehicle information systems affect range-related stress perception in real traffic situations?*	Evaluating the impact of in-vehicle information systems on range-related concerns	Transportation Research Part F: Traffic Psychology and Behavior (2nd round of revisions)	n.a. / Impact. Factor: 1.5 (n.a.)
6	C.4	*How can customer preferences be implemented in a location-planning model for EV charging stations?*	Suggestions for how to allocate charging stations with respect to customer preferences	International Electric Vehicle Conference 2014	n.a. (96)

The ranking was conducted according to VHB Jourqual 3; The downloads are as of May 2016.
A complete list of the author's publications can be found in Appendix 1.

The third part C of this cumulative dissertation presents four studies that were conducted to evaluate measures for alleviating the range barrier of electric vehicles. Against the backdrop of high investments that would be necessary to increase the battery capacity of EVs and expand their charging infrastructure, it can be assumed that these strategies would substantially reduce their usefulness in mitigating range anxiety if EV users have to bear these costs, as the purchasing price itself constitutes a major barrier to EV adoption. Therefore, other measures to tackle the problem of EVs' limited driving range might be more suitable. As mentioned above, the focus lies on the impact of (in-vehicle) information systems on range-related stress perception and the diffusion of electric vehicles. In this regard, information systems and mobile applications enable physical mobility to be

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integrated into the digital landscape, thereby affecting the way in which cars are used. It is therefore interesting how exactly the information affects the driver, especially against the backdrop of possible negative impacts, such as distracting or overwhelming the driver. In this regard, Study 3 reveals attributes that reflect individuals' personal perceptions of electric and conventional vehicles and compares them with functionalities that are provided by mobile applications. Thus, the contribution of apps in addressing EVs' perceived advantages and disadvantages is investigated. Through this observation, the usefulness of information for the diffusion of electric vehicles as well as the disruptive potential of alternative forms of sustainable mobility are examined in the course of this study.

Based on the prior findings, Study 4 evaluates the influence of in-vehicle information systems on range-related stress perception in greater detail. To do so, the psychological stress theory of Lazarus (Lazarus and Folkman, 1984) was used as starting point. By means of a mental simulation experiment, Study 4 then underwent an explicit analysis of which appraisal processes of the Lazarus model are affected by the use of in-vehicle information systems when driving an electric vehicle with limited range buffers. In particular, it is determined whether these information systems show alleviating effects with respect to range-related stress perception. Finally, Study 4 analyzes possible impacts of range stress on the attitude toward using an electric vehicle. Based on the findings of the mental simulation experiment, a field experiment with real traffic situations was designed in Study 5. Again, the influence of in-vehicle information systems on range-related stress perception while driving an EV is evaluated with a focus on how and to what extent the appraisal processes are affected. In addition to the psychometric measurements, psychophysiological biofeedback is analyzed within the frame of this study. One of the key aspects of the study is the alignment and comparison of both measurement approaches.

Another approach to addressing the problem of range anxiety is discussed in Study 6. The study aims to alleviating range concerns by allocating charging stations for electric vehicles according to user preferences. Recent research revealed that the mere presence of charging stations along traveled routes has mitigating effects on users' concerns of not reaching their planned destinations (Aoki, 2010). Therefore, a study is conducted with respect to allocating charging stations according to users' preferences with the purpose of implementing charging stations at sites where they are perceived to provide the largest use.

Finally, the findings of the studies conducted to achieve the research objectives are presented within part D of this dissertation. Implications for both theory and practice are then derived from these findings. Moreover, an integrated framework is provided with respect to the phenomenon of range anxiety. The thesis closes by providing concluding remarks and discussing its limitations as well as the potential for further research. An illustration of this dissertation's structure is depicted schematically in Figure A–1.

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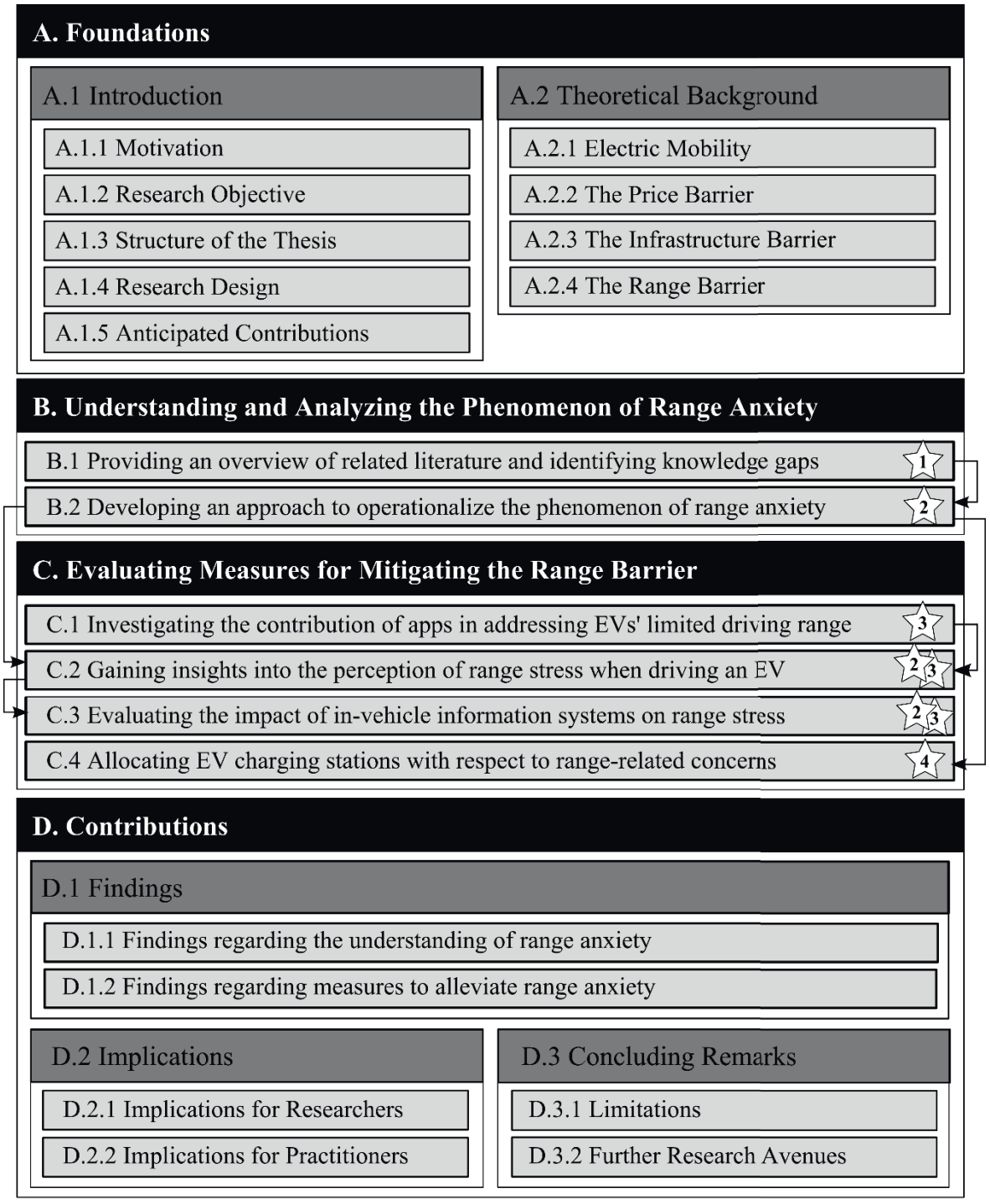

Figure A–1. Structure of the cumulative dissertation.

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1.4 Research Context and Design

Information systems research is an interdisciplinary research stream with a diversity of methods and research designs that is considered to be one of its major strengths (Venkatesh et al., 2013; Sidorova et al., 2008). Robey (1996) claims that the advantages of this diversity are much greater than its disadvantages, particularly reflected by its potential to attract top researchers from different disciplines. Literature discusses the methodology of information systems research at two levels (Wilde and Hess, 2007): On a highly aggregated paradigm-oriented level, the relevance of epistemological aspects such as rigor and relevance or behavioral and design science are discussed. On a micro level, however, information systems research addresses the application of the various methods and evaluates their strengths and weaknesses.

The domain of information systems research can be segmented into two intertwined research paradigms: behavioral science and design science. The goal of behavioral science is to develop and justify theories for explaining and predicting human (or organizational) behavior (Hevner et al., 2004). This research paradigm therefore observes and analyzes existing IT solutions and human–machine interactions. Based on these findings, one can draw conclusions with respect to cause and effect. The second important paradigm of IS research, design science research, has been gaining increasing acceptance as a legitimate approach (Hevner and Chatterjee, 2010). Its goal is to create innovative artifacts that enhance human capabilities and aim to achieve desired outcomes (Hevner et al., 2004). Design science research comprises a variety of socio-technical artifacts, such as decision support systems, modeling tools, and IS-related methods and strategies, which are evaluated afterwards in a real environment (Gregor and Hevner, 2013; Kuechler and Vaishnavi, 2012; Orlikowski and Iacono, 2001). This thesis primarily follows the behavioral science–oriented approach and focuses on gaining a deep understanding of how people perceive EVs' limited driving range and the resulting phenomenon of range anxiety in order to explain and predict their behavior.

Rather than allocating this dissertation to the broad domain of information systems research, the focus of this work lies on its interdisciplinary subdomain of human–computer interaction (HCI) - one of the five research streams of IS research (Banker and Kauffman, 2004). This subdomain has become increasingly important with the rapidly expanding integration of computers and mobile devices into everyday life (Kim, 2015). In general, HCI deals with the design, implementation, and evaluation of how humans interact with computing devices (Kim, 2015; Zhang and Galletta, 2006), focusing on both understanding how people make use of systems that incorporate computational support as well as designing new systems that improve human performance (Carroll, 2006). Like information systems research, the HCI domain is built upon a plethora of research streams (e.g., ergonomics, computer science,

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linguistics, psychology, and social science) that reflect its importance and its complexity (Gerlach and Kuo, 1991). In this regard, Zhang and Li (2004) identify a broad range of research methods employed within the HCI subdomain with dominant methods lying in empirical studies such as surveys or lab experiments. In line with this finding, this dissertation also focuses on empirical studies.

Aside from HCI, the work at hand is also related to the field of transportation research, particularly its subdomain of traffic psychology, which studies the relation between driving behavior and psychological processes. Accident research constitutes a broad field of application, studying the influence of behavior to assess the causes and effects of accidents (Rothengatter, 1997). With this information, suitable measures for accident prevention can be developed, thus improving traffic mobility. Besides external factors that influence the risk for accidents, internal factors such as distraction or stress play an important role in traffic psychology. Because these factors are affected by the use of in-vehicle information systems, which are analyzed herein for their potential to alleviate range anxiety, this cumulative dissertation includes studies at the intersection of these two research streams.

Table A–2 summarizes the points raised above in tabular form and provides an overview of this dissertation's research design. A detailed description of the approaches and methods used to answer the research questions can be found within the studies conducted.

Table A–2
Overview of the research design of the studies included in this thesis.

No.	Core research question	Paradigm	Data collection	Data analysis
1	*What is the state of the art in range anxiety research?*	Behaviorally oriented	Structured literature analysis	Data analysis with concept matrices
2	*What are the relevant factors influencing range anxiety and how can changes in it's perception be measured?*	Behaviorally oriented	Cross-sectional analysis/survey	Conceptual model and mean comparison
3	*Do mobile applications address attributes related to the disadvantages of EVs?*	Behaviorally oriented	Survey/secondary data	Systematic data analysis
4	*Which appraisal processes are influenced as a consequence of using in-vehicle information systems?*	Behaviorally oriented	Laboratory experiment	Structural equation modeling
5	*How do in-vehicle information systems affect range-related stress perception in real traffic situations?*	Behaviorally oriented	Field experiment	Regression analysis and mean comparison
6	*How can customer preferences be implemented in a location-planning model for EV charging stations?*	Behaviorally oriented	Cross-sectional analysis/survey	Mathematical analysis

Note: The methods used are categorized according to Palvia et al. (2006) and Wilde and Hess (2007).

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