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# Evaluating the Adoption of Pure Electric Vehicles: An Examination of Sociotechnical Barriers Amongst UK Consumers

**Keith Chamberlain**

**Doctor of Philosophy**

**2023**

# Evaluating the Adoption of Pure Electric Vehicles: An Examination of Sociotechnical Barriers Amongst UK Consumers

**Keith Chamberlain**

A thesis submitted in partial fulfilment of the requirements of the University of Lincoln for the degree of Doctor of Philosophy

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February 2023

# STATEMENT OF AUTHORSHIP

I, Keith Chamberlain, confirm that the contents in this dissertation titled "Evaluating the Adoption of Pure Electric Vehicles: An Examination of Sociotechnical and Policy Barriers Amongst UK Consumers" has not previously been submitted for another degree at any other university or educational institution.

Chapters three, four and five are based on three separate peer reviewed published papers, of which I am the first author in all three. I confirm that I was responsible for: conceptualisation, methodology, formal analysis, investigation, resources, data curation, writing – original draft preparation, writing – review, editing, and visualisation. My Doctoral supervisor, Professor Salah Al- Majeed is the second author of each paper and was responsible for overall supervision, joint validation, and joint project administration.

To the best of my knowledge and belief, I confirm that this thesis contains no contents previously published or written by other authors except where due reference is cited.

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# Abstract

This study shows that the three major factors inhibiting EV market growth in the UK are: a lack of standardisation of rapid-charging facilities; sociotechnical issues linked to charge-point trauma (CPT); and a lack of sufficient and contiguous rapid-charging infrastructure. A buyer's decision to choose an appropriate EV that suits their needs and lifestyle, depends upon three exogenous factors: product-related reviews, road tests, and private and government EV and general zero-emission data. This research uses primary and secondary research methodologies to evaluate the impact of the three main inhibiting factors (Chapters 3, 4 and 5) on the choices made by EV buyers/users/owners. The study presents barriers to EV adoption resulting from charge-point non-standardisation protocols. Additionally, the concept of charge-point trauma is introduced to the field for the first time, and finally the study creates a globally adaptable and portable model of calculating the volume of charge-points necessary to a given number of EVs.

This investigation also uses primary research to collect evidence from current EV users and potential adopters concerning the significance of the three main inhibiting factors, showing how they influence consumer behaviour and growth in the sector. By exploring how current EV user's experience influences public reviews and ratings, this research demonstrates the impact this public data has on EV consumer's purchasing behaviour. The study gathered data within the UK through structured surveys of existing EV drivers, and used science-based field testing with data collection to analyse charge-point

infrastructure protocol standardisation. Field tests and driver observation quantified the contiguous charge point network, its availability, and its capacity to satisfy current and future demand.

This investigation utilises a non-generic model in each chapter to study the effects and outcomes of the three study phases, offering a graphical synopsis for all primary impact factors including the principal exogenous ones. The study integrates the principal impact factors to create for the first time, a precise model of behavioural apprehension and growth impedance among EV users and prospective buyers. This model is based on three main elements, including two major multi-locational field tests and trials, and a significant survey of more than 280 participants from the UK-based EV user community. The study develops an innovative, portable model to calculate the number of rapid chargers required to satisfy current and future EV demand anywhere in the world.

This research makes a major contribution to the study of the barriers to adoption in the EV sector by considering all the influencers and stakeholders, that might indicate and potentially predict global trends within EV consumer behaviour. It therefore contributes to bridging the gap between industry and academic knowledge, thus helping reduce barriers to EV sector growth.

# Dedication

I dedicate this thesis to my dearly beloved deceased Mother and Father who did their very best to provide love and support during my formative years. They encouraged me to pursue my love of discovering and developing solutions to enable technology to assist, not hinder our lives. I could not have done this without their constructive support, instilling in me the ethic of hard work and determination to achieve one's goals.

I also dedicate this work to my daughters, in the hope that they may be proud of their father.

# Acknowledgements

I would like to offer my thanks to the numerous people who so generously contributed to the process presented in this thesis.

Special mention goes to my supervisors Professor Salah Al-Majeed and Professor Ahmed Elseragy. My PhD has been a tough yet fulfilling experience and I thank Salah and Ahmed unreservedly, not just for their unwavering academic and structural support but also for their complete faith and trust in me during my PhD.

I am also greatly indebted to my wonderful partner Keiko for being so helpful, supportive, understanding and patient in helping me survive the triple pressures of family life, work, and research, by providing ongoing support and encouragement.

I dedicate my thesis to them and future generations, in the hope that this small but unique contribution to academia will make a difference in the commercial world too, by helping shape and influence policy and regulation to steer our planet toward a green, clean world, in which future generations may reap the benefits of their peers before them.

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# GLOSSARY OF TERMS

| | |
|---|---|
| A | Amp |
| AC | Alternating Current |
| BESS | Battery Energy Storage System |
| BEUC | Bureau Européen des Unions de Consommateurs |
| BMS | Battery Management System |
| BPM | Beats Per Minute |
| CAN | Controller Area Network |
| CAN-bus | Controller Area Network - bus |
| CCS | Combined Charging System |
| CPO | Charge Point Operator |
| CPR | Charge Point Roaming |
| CPT | Charge Point Trauma |
| DC | Direct Current |
| DfT | Department for Transport (UK) |
| ECF | European Climate Foundation |
| EV | Electric Vehicle |
| EVR | Electric Vehicle Roaming |
| EVSE | Electric Vehicle Supply Equipment |
| FDA | Food and Drug Administration (USA) |
| GHG | Green House Gas |
| GPS | Global Positioning System |
| HoC | House of Commons (UK) |
| ICE | Internal Combustion Engine |
| IEA | International Energy Agency |
| IEC | International Electrotechnical Commission |
| ISO | International Organisation for Standardization |
| IVIS | In Vehicle Information System |
| kW | Kilowatt |
| kWh | Kilowatt hour |
| MEB | **M**odularer **E**-Antriebs-**B**aukasten |
| MMS | Multi Model Standardisation |
| NNPC | National Network Planning Committee |
| NGO | Non-Governmental Organisation |
| OOE | Overall Operational Effectiveness |
| OEM | Original Equipment Manufacturer |
| OLEV | Office for Low Emission Vehicles |
| OP | Operational Performance |
| PAYG | Pay As You Go |
| PIG | Plug In Grant |
| PLC | Power Line Communication |
| PPG | Photoplethysmography |
| PWC | Price Waterhouse Cooper |
| RAG | Red-Amber-Green (survey methodology) |
| RFID | Radio Frequency Identification |
| ROI | Return on Investment |
| SAE | House of Commons |
| SAE | Society of Automotive Engineers |

| | |
|---|---|
| SMMT | Society of Motor Manufacturers and Traders |
| SOC | State of Charge |
| SUV | Sports Utility Vehicle |
| UK | United Kingdom |
| USA | United States of America |
| USD | United States Dollar |
| V2G | Vehicle to Grid |
| V2L | Vehicle to Load |
| VHS | Video Home System |
| WLTP | Worldwide Harmonised Light Vehicles Test Procedure |

# Chapter ONE

## 1.0 Thesis Introduction and Objectives

### 1.1 Introduction

Electric vehicles (EVs) offer substantially reduced greenhouse gas emissions (GHG) over traditional fossil-fuel vehicles, minimising air pollution, combatting climate change and offering health benefits to the general population. Despite these advantages, EV growth has remained lacklustre within the United Kingdom market. This is partially attributable to battery range anxiety [1.1] in prospective buyers, including whether an EV can store adequate energy levels or myths that longer commutes are at risk (potentially driven by slow charging speeds) [1.2]. Another factor possibly affecting this slow EV adoption rate, the contribution of the physical charge-point barrier, has received limited attention from the scientific community. This study probes beyond range anxiety to explore additional sociotechnical EV growth barriers in the UK market by creating a theoretical framework to identify contributing elements to charge-point standardisation issues (Ch.3), charge-point anxiety (CPT) (Ch.4), and infrastructure issues such as network planning, location forecasting, deployment and policy on siting charge-points appropriately (Ch.5). To the best of the author's knowledge, this is the first study to demonstrate the impact of distress or trauma on EV drivers at the charge point, which was present across the three areas of investigation in this critical and novel examination.

This thesis employs an extensive set of driver case studies covering a collective distance of more than 2250 miles together with structured surveys across a mix of novel and experienced EV users to examine how non-standardisation of charge-points affects sector growth. The research also evaluated the effects of CPT on this barrier by employing a national survey of motorway service stations to produce data on existing rapid-chargers, in order to lay the foundation for modelling of current and future deployment. The output from this unique and far-reaching study can be employed to stimulate policy shifts and stronger regulation of EV charging infrastructure to meet targeted UK demands. These measures will assist in reducing greenhouse gases and promote a cleaner, energy-efficient transport system for future generations.

High energy demand and oil prices are significant challenges facing all transport sectors, reliant as they are on fossil fuels as their prime energy source. In terms of environmental impact, the transport sector produces one-third of all emitted carbon dioxide [1.3], 41% of which are produced by passenger cars [figure 1.1; 1.4].

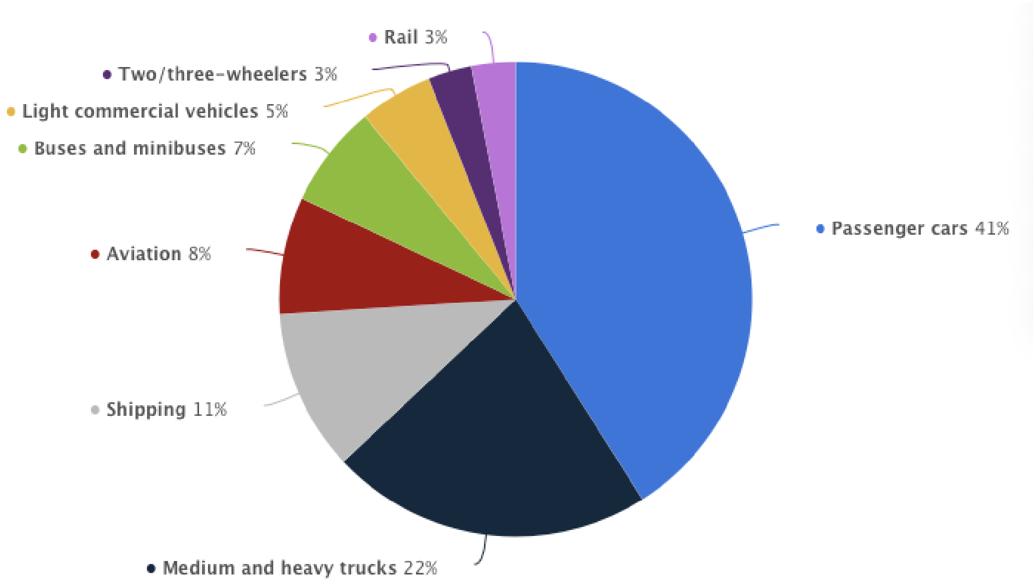



**Figure 1.1**. Breakdown of $CO_2$ emissions in the transport sector worldwide 2020, by subsector. Source Statista 2022. [1.4].

The UK GHG emissions data by fuel-type depicted in figure 1.2 [1.5] show that 30% of harmful gas emissions in the UK originate from the transport sector. Although this sector has seen a steady decline in emissions since 2005, both government policy makers and manufacturers have come to prioritise the need to meet future transport energy demands through alternative green energy sources. The chart shows that one of the UK's significant gaseous contaminants is petroleum, the high level of which has been the main driver of efforts to increase zero-emission transport growth over the past decade. While technological development has reduced harmful emissions from internal combustion engine (ICE) vehicles, Fig. 1.2 highlights the gradual nature of this decline. Significant reductions only began in 2015 as EVs secured a foothold within the UK car market, and most of the subsequent decline in noxious petroleum-based pollutants has been due to the emergence of zero-carbon emission vehicles (Fig. 1.2).

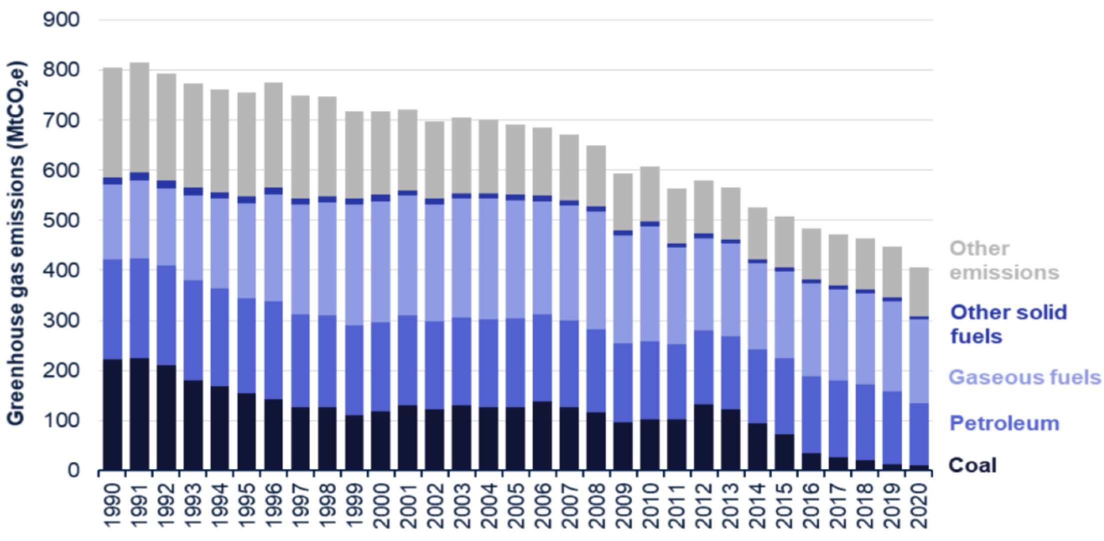



**Figure 1.2** The Territorial UK GHG emissions data, by fuel-type [1.5]

Perceptions of the dependability and reliability of the latest generation of EVs and the infrastructure that supports them are fundamental, predominantly driving public apprehension of this novel technology due to its perceived limited driving range. Acceptance of this novel technology depends mainly on the economic benefits for most potential new adopters and the development and deployment of adequate EV-supporting technology. Although it has generally been assumed that most EVs will be re-charged nightly at home [1.1], the limited driving range of EVs and a growing population of owners without driveway access mean that reliable public charging is of paramount importance for long-distance EV journeys [1.1].

Providing alternatives to home charging will support local distribution utility infrastructure in managing the additional load demand from EVs. Equally, accessibility of public charging infrastructure is critical in promoting EV adoption, since long-haul journeys cannot be achieved with current EVs' limited battery ranges. Consequently, providing a trunk-route-based public rapid-charging service for long-haul commuters will be fundamental in providing an acceptable alternative to ICE vehicles. Rapid-charge points will ultimately develop into a contiguous national network, although the unplanned nature of the current deployment of charging infrastructure could impede EV adoption. Hence, rapid-charger locations and charging rates should be strategically modelled and planned to create a publicly accessible network, from both a commercial and a practical perspective.

Pure EVs have been available to the public for over a decade, and they remain the only viable mainstream substitute for ICE vehicles; therefore, this thesis centres on the EV market sector and questions the causal factors underlying the complex reality of low EV market penetration. This issue has gained even more significance since the

UK government pledged to end production and sales of ICE cars and light commercial vehicles by 2030.

An emerging body of literature has identified numerous barriers to EV adoption [1.6, 1.7, 1.8, 1.9, 1.10], although its conclusions are of somewhat limited use. The majority of empirical studies in Europe describe the outcomes of small city-based demonstrator tests that focussed on drivers already adopting clean technologies [1.9, 1.10, 1,11, 1.12]. Numerous earlier studies reflect the North American environment [1.13, 1.14, 1.15, 1.16, 1.17], concentrating on the effectiveness of alternatively-powered vehicles within a setting where more significant mileage requirements are the norm. This is distinctively different from the European environment [1.12]. These flaws in the existing literature, create a considerable knowledge gap and a demand for evaluation that examines acknowledged barriers to EV adoption within the context of new and prospective vehicle customers within the UK. Furthermore, it is important to investigate the degree to which the myriad of distinct barriers to EV adoption is linked and interconnected. The resulting knowledge can help to significantly diminish the complexity of the barrier issue, thus enhancing policy and academic discussion.

Additionally, access to a novel consumer dataset delivers the prospect of discovering the degree to which driver behaviours and characteristics manipulate barriers. This is significant, as current academic discussion claims that a short-term resolution that would lay the ground in the reduction of barriers on a long-term basis, would be to focus tactically on immediate EV strategy intervention in sectors of the market where growth might be easier to achieve. This could include dense high population cities, affluent consumers who are not deterred by cost but are enticed by the lure of new technology, and novel or younger drivers who are less accustomed to traditional ICE ecosystems and therefore more liable to be interested in the accessibility of this emerging technology [1.18, 1.19, 1.20, 1.21].

### 1.2 Research Aims

This investigation aims to determine if harmonisation of rapid-charge-point technical standards and regulation can lessen EV driver anxiety at the charge-point; if there is a correlation between charge-point operation and EV driver trauma; and if the current UK rapid-charge network strategy and charger deployment planning will meet the projected rise in EV growth demand leading up to the UK government deadline of 2030 for discontinuing all sales of new fossil-fuel-powered cars [1.22].

### 1.3 Research objectives

This research explores the gaps in the literature identified in Section 1.1 through data developed from an evaluation of more than 280 new and experienced UK EV drivers. The UK is Europe's second-largest vehicle market, with a national fleet of 32.7 million licenced cars [1.24]. Moreover, the UK offers an exciting setting to investigate EV adoption and sector growth issues. The evident failure of several UK government policy mechanisms and investment stimuli focused on EV growth compared to more successful adoption trajectories over the past decade in Europe [1.24] strengthens the case for an examination of barriers to EV growth in the UK. Overall, this investigation is based on a three-element strategic model for probing issues around EV sector growth in chapters 3 to 5. It has significant potential to inform a more effective manufacturer and government-led approach and influence a more informed planning and policy strategy on such a crucial matter.

This investigation will deliver several practical and significant contributions. Firstly, it draws upon the UK, European and North American literature in the field to examine and link together the myriad of discrete barriers to EV adoption that they outline. Secondly, two separate mid-scale surveys of drivers in the EV sector deliver a unique dataset which both allows the significance of the barriers to be substantiated and, through investigative analysis, provides a comparative basis for an EV-driver-centric study that I believe to be the first field and survey investigation of its kind. Thirdly, a novel analysis of rapid-charger deployment modelling, tests the degree to which current and future networks are able to alleviate the friction caused by barriers to EV adoption. This research enhances the discussion on barriers to EV adoption, in addition to delivering applied, empirically informed solutions for stakeholders involved in understanding and providing solutions to overcome obstacles to EV adoption within the UK context.

This research has found that three significant parameters create barriers that limit the growth of EVs within the UK: differing standards for charging protocols, payment and charge-point connection guidelines; barrier effects of CPT on UK vehicle growth; and a robust forecast model to optimise EV rapid-charging deployment on the UK trunk-road network. Successful implementation of strategies to deal with these three areas of friction should drive the extent of future EV sales.

Consequently, the work presented in this thesis focuses primarily on these three key parameters. The results consist of three phases, described within Chapters 3-5 below. The first phase addresses EV and charging infrastructure standardisation from both an operational and user perspective, together with its correlation with public rapid-charging capability and availability. The second phase addresses the barrier effects of CPT experienced by recent EV adopters on approach and arrival to a charge-point. The third and final stage addresses the requirement to employ a reliable forecasting tool to optimise the volume of rapid-chargers on UK trunk routes, considering both the quality of service provision [1.25] and the economic benefit associated with rapid-charge-point networks.

## 1.4 Thesis Framework

The balance of this thesis is structured as shown in Fig. 1.3, with details of each chapter as follows:

Chapter two is a concise background literature review covering all the core topics related to this research. Chapter three presents a peer-reviewed and published research article [1.26] entitled 'Standardisation of UK electric vehicle charging protocol, payment and charge-point connection', investigating whether each of these three elements stimulates barriers to growth in the EV sector by employing novel user surveys and secondary data. Chapter four presents a peer-reviewed and published research article [1.27] entitled 'evaluating the barrier effects of charge point trauma (CPT) on UK EV market growth'. This investigation employed a bespoke field analysis of both new and experienced EV drivers in order to evaluate CPT, a psychological, physiological and behavioural condition in which individual EV users' experiences reveal the development of trauma or anxiety at the charge-point location due to various operational factors. Chapter five introduces a peer-reviewed and published article [1.28] entitled 'A novel model to predict EV rapid-charging deployment on the UK motorway network'. The investigation is founded upon the premise that increasing rapid-charger availability and enabling reduced charging times will diminish barriers to EV market growth, increasing adoption of EVs by traditional ICE drivers and expanding the sector exponentially. Chapter six summarises the thesis and highlights its novel contributions, (exhibited by the theoretical framework in Fig. 1.3). It enumerates research outcomes and suggests avenues for future investigative research.

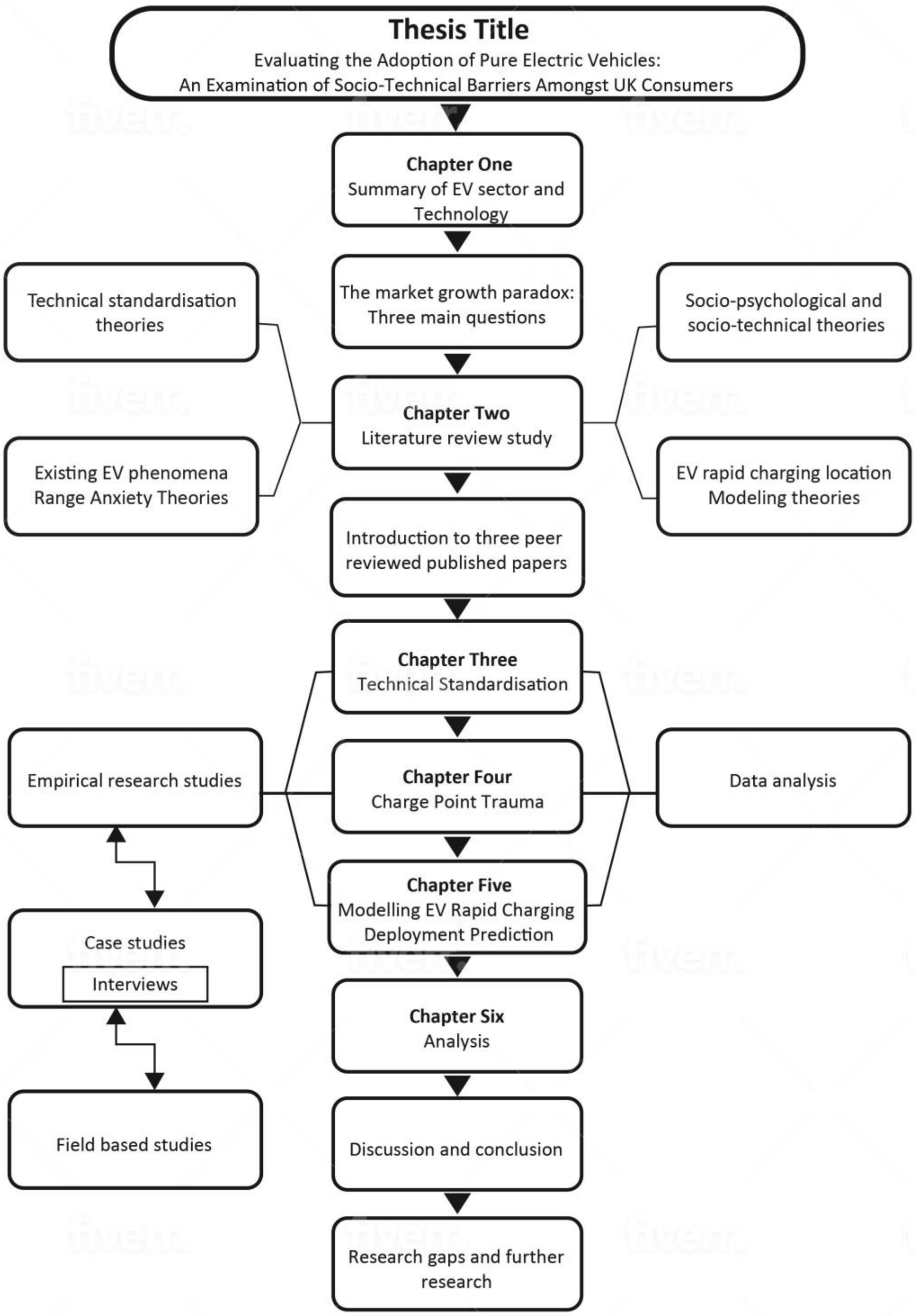



**Figure 1.3.** Theoretical framework

# Chapter TWO

## 2.0 Background to the Study

### 2.1 Cause-and-effect of barriers to EV market growth

A progressively wide-ranging body of literature from various disciplinary viewpoints reveals current market barriers motivating buyer's attitudes toward EV technologies. These comprise previous literature derived from fields such as innovation [2.1, 2.2, 2.3, 2.4, 2.5, 2.6] and transport [2.7]. In examining this literature, a core of 48 articles based on investigations and surveys of ICE drivers or potential EV adopters were identified, all analysing and validating barriers to the adoption and consequent growth of EVs.

It is remarkable to consider that despite developments in EV technology over the past decade, apprehensive perceptions concerning restricted driving range and protracted charging times persist [2.8, 2.9, 2.10]. This implies that buyer's apprehension concerning the untested or undeveloped nature of EV technology still prevails [2.11, 2.12, 2.13, 2.14].

Several studies strengthen this view, citing buyer fears such as battery safety, durability, and range [2.15, 2.16, 2.17, 2.18]. Additionally, evidence is proposed that driving range is the most critical factor in constraining EV adoption [2.19]. Whilst policy and academic discussion tend to dismiss these seemingly obvious barriers as the creation of incompatibility concerning actual versus perceived range required by motorists, previous investigations have revealed that range anxiety can damage the real-life experience of EV owners. In addition, several EV drivers were found to compromise safety by choosing not to activate in-car features, such as air conditioning or heaters, in order to extend battery life [2.20].

Furthermore, range anxiety suggests that many EV users do not contemplate longer journeys, considering EVs as an occasional urban or second car [2.21]; a consequence which, albeit debatable, is at odds with the theoretical environmental advantage of mass market EV transformation.

Range anxiety, in addition to battery performance, is broadly linked to the accessibility of rapid-charging stations. The recharging process of an EV exemplifies a vital shift from homogeneous refuelling behaviour in the ICE environment; one that novel EV adopters do not comprehend, despite substantiation from EV drivers implying that the recharging process is uncomplicated and convenient [2.22, 2.23]. Whilst residents within apartment complexes stated that destination or work charging is preferable, evidence in previous literature indicated doubt on current public charging infrastructure, as several EV users avoided such charge points [2.23, 2.24]. Despite these charge points not being patronised, other investigations point to a shortfall of infrastructure as a barrier to executing EV purchases [2.25, 2.26, 2.27]. Additionally, for those in multi-unit residences or with no access to off-street parking (where home charging is not feasible), concerns over public charge points are profound [2.28].

A consequence of the range of concerns reflected thus far is that countless traditional ICE drivers are reluctant to pay premium prices for the latest EV technology [2.29]. Moreover, the current elevated purchase price of the technology is unaffordable for those who can see themselves as prospective adopters [2.30, 2.31, 2.32]. Additional anxiety over the accessibility of downstream service, repair, and maintenance of the charging infrastructure, only strengthens confusion. It increases reservations in customer’s minds regarding whether the premium price of EVs can be compensated by lower EV total running, and life-costs [2.33]. This theoretically reveals a significant barrier to extensive EV adoption. Contributors to a study from over a decade ago [2.34] suggested that several buyers can be agreeable to spread payment over a maximum period of four years to accommodate the inflated EV purchase price (compared to equivalent classes of ICE vehicles), to be countered by lower running costs. Though this did not account for other expenses concerning servicing, battery service and replacement, and general EV upkeep.

Notwithstanding even when discounting these fundamentals, researchers [2.34] assumed that over four years, the price premium could quadruple the yearly running-cost benefits experienced by ICE drivers. Though this, together with comparable findings, are all causes for concern regarding the economic advantages of EV adoption, the excessive premium paid, combined with protracted payback time, can perpetuate a market growth barrier that negatively influences consumer demand [2.35]. However, recent research published by the Bureau Européen des Unions de Consommateurs (BEUC) 2021 [2.36]) claimed that the total life-ownership of a C-medium segment vehicle (such as the electric Volkswagen iD3®, compared to the petrol Volkswagen Golf®) is already the least costly powertrain over the lifetime of the vehicle. Furthermore, BEUC [2.36] cited that an EV is already the cheaper option for first-owner company cars, due to government tax incentives. While this is encouraging news, it is evident that more needs to be done to persuade consumers. The evidence suggests that short-term uncertainty will perpetuate barriers to EV market growth, whether factual or perceived [2.33].

The perceived residual values realised by current EVs are low compared to ICE alternatives, in the absence of an established second-hand or recycling sector.

Consequently, this epitomises additional influence and intensifies high initial purchase cost [2.36]. The difficulties faced by EV buyers were highlighted in research from the USA (United States of America), emphasising the need to calculate increasing electricity prices, pointing out that another facet of lifetime-cost is the requirement to manage when and where to charge EVs, to maximise savings and efficiencies [2.37]. As argued in this study, this single element swells doubt and uncertainty and is an additional prospective impediment [2.36].

Although financial inducements are employed as a policy driver to leverage price reductions for EVs, studies indicate a limited understanding of this amongst the EV consumer public, particularly in major markets such as the USA. In the UK alone, just 8% of the population within the 21 largest cities were aware of EV incentives [2.38]. Furthermore, the inconsistency, variability, and time-constrained nature of incentives exacerbated confusion for consumers. This confirms that for many conventional ICE motorists, the potential advantages and unique experiences of driving an EV are essentially unfamiliar. This misperception, coupled with uncertainty, misinformation, spin, and developed myths, suggests that comparatively few potential EV adopters are willing to enter into the financial uncertainty of EV adoption [2.38].

Further research illustrates that EV market growth barriers are linked to sociocultural observations and market acceptance. For instance, this embraces the perceived design limitations of EVs due to a universal desire to reduce drag, rendering the vehicle more efficient and effectively extending range. A decade ago, while commenting on a trial-based study, [2.39] researchers presented evidence indicating several traditional ICE drivers viewing EVs as being characterless and absent of visual appeal. These perceptions are important to consider, given that a vehicle is debatably more than just ‘a piece of technology’ and a ‘method of transport’. Instead, one study [2.40] described an EV as an avatar, characterising a driver’s individuality. Often, such poor or featureless design can adversely affect the pleasure that a motorist can gain from owning and driving an EV [2.40]. Such issues are no longer of genuine concern, and there are presently many innovative EV designs, both interior and exterior. There is no longer an issue of limited choice and availability concerning EVs.

Moreover, the current choice of EVs is now on a par with the well-established ICE sector, with its vast selection of model niches and ground-breaking designs. Gone are the days when the only EV choice was the Nissan Leaf®, Renault Zoe®, or BMW i3®. Remarkably, just five years ago, those three models still accounted for just over 62% of EV sales in Europe, during quarter one of 2017 [2.41].

This literature-based analysis has exposed a multi-faceted set of barriers to EV adoption and subsequent market growth, ostensibly working against the mass adoption of EVs. While mapping literature sources, 19 significant barriers were identified (Table 2.1). When presented in this format, the list of growth barriers in the EV sector provides a complex, multi-faceted picture, which is relatively unhelpful to policymakers in planning to promote the uptake of EVs presently and in the future. Although, to date, a significant majority of the literature demonstrates bias, as it still focuses predominantly on prospective EV buyers contemplating the transition from an ICE vehicle to an EV, rather than analysing a novel or experienced EV owner’s concern. Thus, the information in Table 2.1 below will provide a better understanding and reduce complexity. Furthermore, grouping barriers to growth in tabular form below still has considerable value as a foundation for the holistic research presented in this thesis.

**Table 2.1** Barriers to growth in the EV sector (from an ICE user perspective)

| Growth Barrier | Authors |
|---|---|
| High EV purchase price | Hardman et al., (2017), Coffman et al., (2017) Jang et al., (2021), Mitropoulos et al., (2022) |
| EV re-sale value concerns | Song et al., (2022), Kim et al, (2022) Bunce et al. National Research Council – UK (2015) |
| Belief that EVs are inferior to ICE vehicles | Chinen et al., (2022), Wan et al., (2015) |
| No off-street charging for apartment dwellers | Budnitz and Meelen., (2022), Patt et al., (2019) |
| Lack of public charging availability | Pan et al., (2020), Kaufman et al., (2021) Zhang et al., (2018), Afshar et al., (2020) |
| Time taken to charge an EV | Noel et al., (2020), Biresselioglu et al., (2018) |
| Expectation that ICE technology will improve in the future, thus delaying purchase | Islam et al., (2020), Senecal et al., (2019) Choi et al (2020) |
| Expectation that EV technology will improve in the future, thus delaying purchase | Baars et al., (2021), Ambrose et al (2020) Sanguesa et al., (2021), Gnaan et al., (2018) |
| Driver's home not suitable for home charging | Hu et al., (2019), Hardman et al., (2018) |
| Economics of higher EV purchase price vs ICE cars | Moeletsi ME., (2021), Lin and Sovacool., (2020) |
| Battery durability concerns | Asef et al., (2021), Olsson et al., (2018) |
| Limited driving range for day-to-day requirements | Wolbertus et al., (2018), Pevec et al., (2020) |
| Concern that driving style will reduce driving range | Varga et al., (2019), Donkers et al., (2020) |
| Doubt over repair and service infrastructure | De Rubens et al., (2020), Adhikari et al., (2021) |
| Lack of availability and choice in the EV market | Biresselioglu et al., (2018), Lee et al., (2020) |
| Unfamiliar terminology in calculating range and charging costs | Abo-Khalil et al., (2022), Bunce et al. National Research Council – UK (2015) |
| Vehicle design aesthetics appear inferior to ICE cars | Yuan et al., (2018), Rowe et al., (2012) |
| Perceived range anxiety | Akhtar et al., (2022), Noel et al., (2019) Pevec et al., (2019), Guo et al., (2018) |
| Doubt over real environmental effect of EVs | Kostopoulos et al., (2020), Qiao et al., (2019) |

Several significant examples of previous research that aimed to conceptualise the barriers to EV market growth and adoption, delivering fewer multi-faceted sets of growth barrier elements, include the following studies described below.

Haddadian et al. [2.42] ascertained a widespread set of EV growth barriers, encompassing technical, financial, institutional, administrative, commercial, public acceptability, legal or regulatory physical constraints and policy failures. An additional methodology was noted in the same case that isolated barriers into consumer perception, economics, and technical issues. Additionally, recent studies [2.43, 2.44] established that EVs are integrated into a sociotechnical system, comprising cultural, economic, political, social, and technological growth barriers. These have debated the significance of situational and psychological factors, including attitudes, beliefs, economics, past behaviours, policy, regulation, values, and vehicle features, in determining EV purchasing behaviour [2.45]. Furthermore, selected studies contended that there are economic and technical barriers to growth that are intensely influenced by buyer's concerns encompassing the realities of vehicle ownership and operation [2.46, 2.47, 2.48].

The presiding method of scrutinising barriers to growth and adoption of EVs in the literature has been to assess limited EV demonstrator trials. Whilst valued, these analyses are biased toward partakers already contemplating purchasing an EV. Conversely, it is argued that the alternative, focusing on mass-market buyers, suggests that these participants can be less knowledgeable regarding EV technology, possibly constraining the legitimacy of survey responses [2.49]. Although, in this case, it is recommended that to understand mass-market viewpoints concerning EV technology, there is a solid argument to sample ICE drivers who might not be inherently inclined to EVs. In the long term, ICE drivers, misinformed or not, must be convinced to embrace EVs, if large-scale sector penetration (as envisioned by strategy makers) is to be realised.

Research that has examined EV driver's post-adoption is limited and has taken place in significantly differing settings for drivers, such as China, India, or North America, with limited instances of the UK and European markets being covered in this manner. The general applicability of insights offered is open to debate. Hidrue et al. [2.50], for instance, offered a characteristic sample of 17+ year-old US residents. Furthermore, this research is over a decade old and currently unrepresentative, whilst more recent research [2.52] scrutinised a partial number of US urban cities. Within European literature, Lieven et al. drew responses from online buyers only [2.53], whereas O'Neil et al. [2.54] focused on respondents from a population in Ireland of just five million people.

In several cases, it was not stated if the sample consisted solely of drivers or vehicle users, since terms such as 'residents' presents a scenario of both non-drivers and drivers that were appraised. This uncertainty generates challenges for interpreting results, as non-drivers will almost certainly have limited ICE vehicle knowledge. Conversely, parties within this cohort could be attracted to novel forms of transportation. Subsequently, to complement the dominant methods and environments used within previous research in this field, this thesis aimed to scrutinise the authenticity and significance of barriers to EV adoption and subsequent sector growth, from the viewpoint of a significant sample of novel and experienced EV consumers from within the UK.

# Chapter THREE

## 3.0 Standardisation of UK Electric Vehicle Charging Protocol, Payment, and Charge Point Connection [1.26]

### 3.1 Introduction

Standardisation is fundamental to ensuring that new technologies develop and grow unhindered by manufacturer-led standards. Dismissing this vital issue can have a detrimental effect on society concerning the adoption of new technologies, particularly when government targets and regulations are crucial for their success. History reveals competing global industries struggle for dominance, where each had a similar user outcome, but the confusion of differing formats slowed growth. This chapter analyses emerging standards for electric vehicle rapid charging and examines how standardisation challenges affect stakeholders by reviewing the existing literature on single-mode and polymodal harmonisation. By assimilating existing evidence, a new understanding of the science behind multi-model standardisation (MMS) approaches is developed. This study then analyses each mode type's benefit, observing how each example contributes to the overall outcome, and suggests that their impact depends on car to charger handshake operation and timing, and intuitive user interaction.

### 3.2 Sector Standardisation Overview

All EV sector actors recognise that electric vehicles (EVs) are becoming an integral part of sustainable and smart cities [3.1]. However, the lack of standardisation for EVs (i.e., differences between EVs in car and charge connectors, car to charger communication protocols, and charge payment complexity and transparency) has prevented full-scale adoption in the UK [3.2].

During the last century, EVs were proclaimed to be the cars of the future [3.3]. Yet, aside from the early pioneering days of emerging powered transport in the late 19th and early 20th century, they have never achieved commercial viability [3.3]. EVs are once again in focus. Since the mid-2000s, there have been indications that longevity is occurring because of government intervention, the global push for lower carbon emissions, increased deployment of charging infrastructure, and the gradual lowering of battery costs. No longer seen as a niche sector, EVs are emerging as mainstream choices manufactured by traditional incumbents and new entry E-centric companies [3.4]. Currently, all pure mainstream EVs rely on regular cable-based charging to recharge the integrated battery packs, known as conductive charging, which requires supporting charging infrastructure to link them to the electricity network.

Research carried out by PWC (Price Waterhouse Cooper) in 2018 [3.5] found that more than 35% of EV users charged their vehicles at home through the night, leaving 65% of respondents relying on public or work-based charging points during the day. Those who rely on daytime charging are often faced with either two types of slow AC charging connectors or the preferable rapid charging stations offering up to three different charging connector types. None are interchangeable, and all use one of two communication protocols that are not backwards compatible. Many attempts have been made to standardise EV connectors since the first EVs emerged in the late 19th century [3.6]. To further complicate matters, charge point payment systems have also developed independently, creating a complex web of technology that currently prevents complete harmonisation of connectors, communication, and remote operability. The charge point payment system is almost as complex as connector and communication standardisation in the EV rapid charge network, discussed further in Section 3.13.

This research investigates how the disparate connector standards have evolved and to what extent, if any, standardisation has materialised. Therefore, this analysis will focus on the hardware, the connectors that link the EV to the rapid charging system, and the ‘handshake’ communication protocol between the EV and the charging system. The study focuses wholly on the DC high-voltage rapid charge infrastructure rather than the slower, lower-voltage AC charging infrastructure. This chapter will evaluate the economic, technological, behavioural, and regulatory obstacles of myriad rapid charge standards and communication protocols that may disrupt the full-scale rollout of EVs. Solutions are proposed to aid EV accessibility and wide-market adoption. To bolster the existing literature in these study areas, primary research is conducted utilising a survey of 282 EV motorway rapid charge EV users by employing a structured questionnaire based on the Likert scale [3.7].

The investigation compares hypotheses with the survey and existing literature. Additionally, this investigation appraises key stakeholders, including car manufacturers, government, national electric grid planners, distributors, and end-users, by investigating their role in influencing a route to standardisation in hardware and software. Note that all nomenclature used for connectors and sockets is the terminology used in accordance with IEC (International Electrotechnical Commission) standard 62196 [3.8].

### 3.3. DC Charging and Interconnect Communication

Fig. 3.1 highlights the four main DC socket and connector configurations, highlighting each type's maximum operating current and voltage rating. DC rapid charge connectors and cables are always tethered to the DC rapid charge unit for safety and safe operability. They often require frequent cooling while active, due to high current delivery [3.9]. A typical DC rapid charger schematic diagram is represented in Fig. 3.2, highlighting the relationship between its principal elements that collectively enable a rapid charge to initiate, accept, lock, charge, and unlock safely and effectively. The AC source can be either a low carbon solution using a renewable AC grid supply or a hybrid mixed energy main grid with renewable supply [3.10].

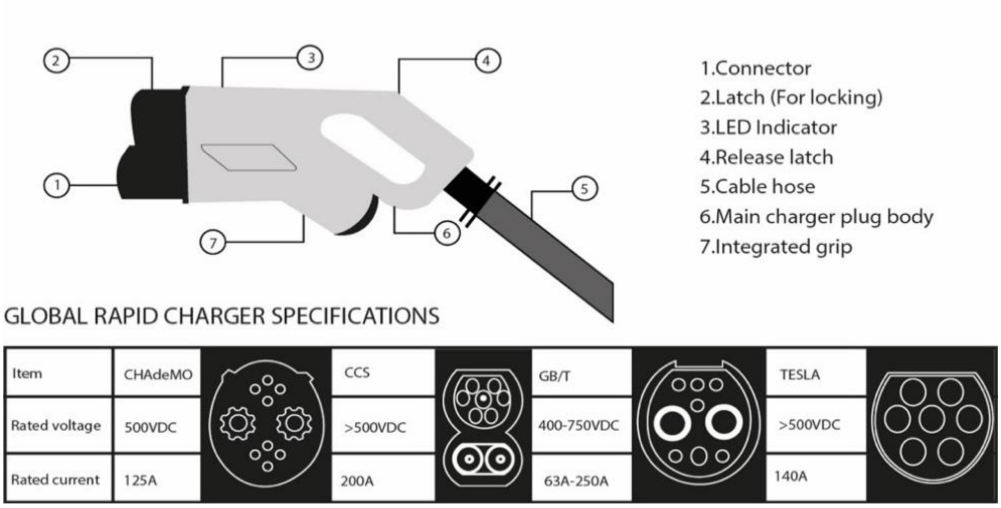



**Figure 3.1.** Global DC rapid charger connector configurations.

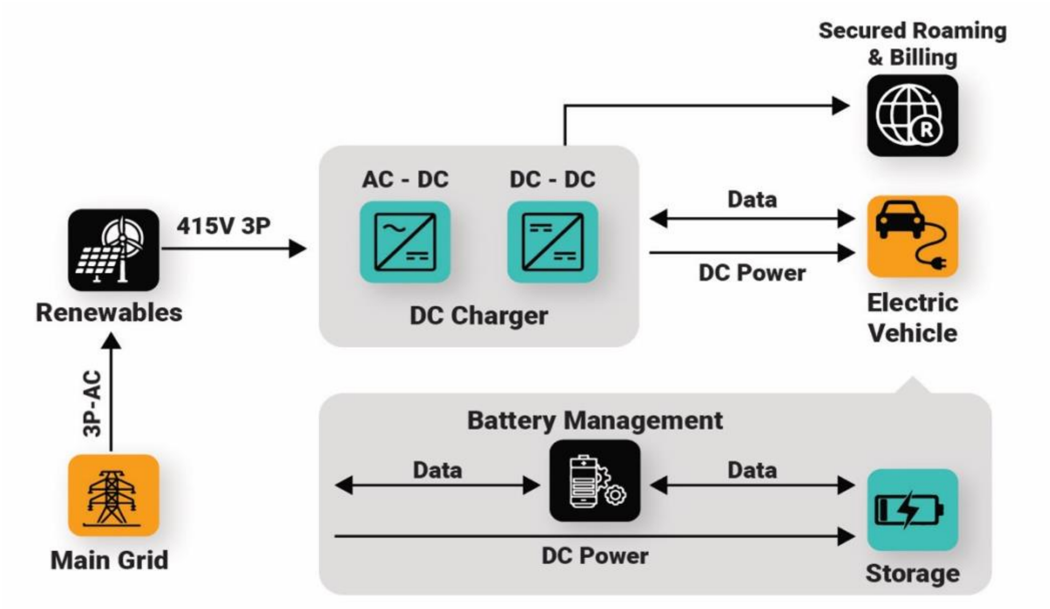



**Figure 3.2.** EV DC rapid charger elements illustrating communication charger supplied by renewable micro-grid. Adapted - Infineon. [3.11].

One of the major user issues for EV drivers is that the location of rapid chargers is generally determined by the grid supply and availability, not the most appropriate location for EV users. The lower block in Fig. 3.2 represents a potential solution to this major hurdle using a micro-grid that stores DC current in an integrated battery energy storage system (BESS), fed generally from solar, converted AC wind power, or off-peak grid power. This component can be smart-managed by the grid operators for peak lopping, enabling off-grid battery-only charging to the EV at grid peak demand and introducing off-peak period charging and pricing capability, reducing grid demand and operational costs [3.10]. Fig. 2 also illustrates the data control management communication path between the DC rapid charge unit and the EV, supplied in this instance with a zero-carbon supply from a renewable micro-grid to EV [3.11]. EV connection can be established using one of two protocols chosen by the manufacturer to communicate between the charger and vehicle [3.12]. For example, the Nissan Leaf EV uses a Controller Area Network (CAN) as its communication protocol. This is a robust vehicle bus protocol designed to permit microcontrollers and devices to connect with each other in applications without the use of a host computer or processor. This method of handshake communication is used primarily by a Japanese consortium of manufacturers through their CHAdeMO connector standard [3.13].

Conversely, the BMW i3, Jaguar iPace and Tesla 3 use the Power Line Communication (PLC) protocol, becoming the de-facto handshake communication process between an EV and its host charger. PLC is the same system used for power grid communication, making it easy for the EV to connect with the grid as a smart device by sending signals through the power line. Neither of the two protocols are inter-communicable without an intermediary interface.

### 3.3.1 Contextual Standardisation Trends

The UK EV sector is home to many charging modes, all of which are manufacturer charge connection protocol and global connector type dependent. However, this research concentrates on rapid charging only and focuses exclusively on UK major trunk routes and motorways where the highest concentration of rapid chargers are situated and where a rapid charger is essential for EV users due to time constraints and long journey routes. Fig. 3.3 illustrates all four modes for comparison [3.14]. This research focuses on Mode 4, where the EV is indirectly connected to the main supply using an off-board charger (rapid or ultra-charger) and typically a tethered charger cable that conforms to the technical specifications stated by the EV manufacturer and has local safety protocols in place.

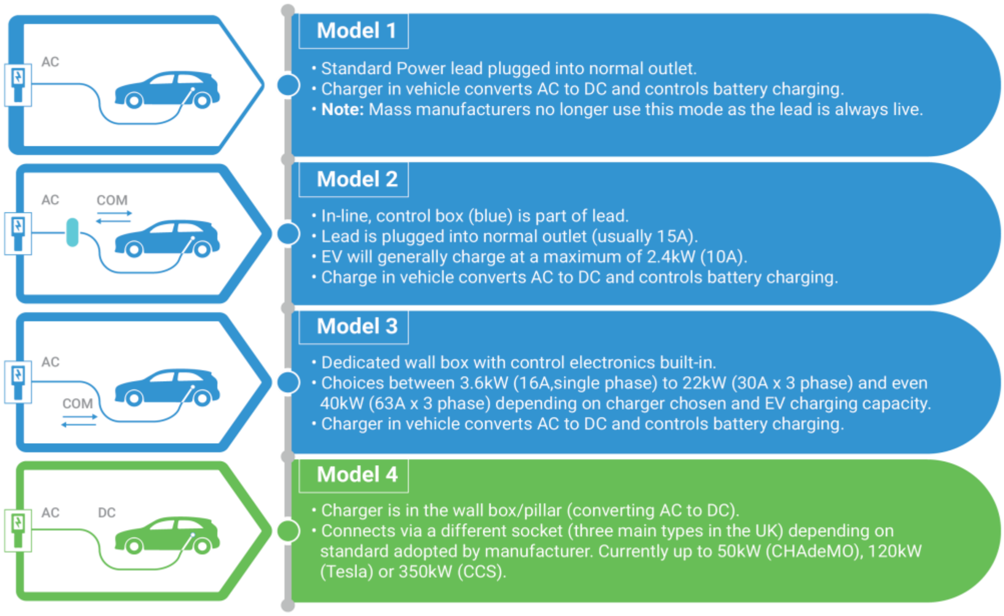



**Figure 3.3.** International EV charging modes. [3.14]

The standardisation of EVs is a complex matter since the technology marries both automotive and electrical technologies, the international standardisation of which is treated by international bodies such as the International Organization for Standardization (ISO) [3.15], and the International Electrotechnical Commission (IEC) [3.16], respectively. Automotive manufacturers are traditionally vertically integrated and less reliant on external component suppliers and standards, while the electro-technology world has a stronger and longer tradition of harmonisation with the establishment of the IEC in the UK during 1906 [3.17]. Due to disparate cultural approaches to standardisation in these two technological fields, a consensus was established to set boundaries of the technology, with vehicle-centric aspects being dealt with by the ISO and infrastructure-centric aspects and electrical components dealt with by the IEC. The main committees responsible for the IEC and ISO are TC69 and TC22, respectively [3.18].

In 2006, the Society of Automotive Engineers (SAE) set up a task force to design a new set of standards to supersede existing protocols from 1990 that were designed for lower power levels [3.19]. In 2009, a new connector design was created and certified as being capable of greater power delivery and faster-charging speeds. The SAE approved this latest design in January of 2010, known as the SAE J1772 standard connector [3.19]. The connector enabled charging at 120V to 250V, including two additional features due to the presence of two additional pins, one being utilised for a safety feature and the other for communication between the charger and the on-board charge controller. Both features resulted in the development of smart fast chargers. The connector is classified as a type 1 connector, also known as the Yazaki plug derived from the manufacturer [3.20]. The connector was collaboratively developed with leading Japanese and USA automotive giants and, as a result, caters to the localised grid architecture and 110–250 V supply voltage design used in the Japanese and US markets, although this was only suitable for single-phase use.

In parallel, it was determined that the European grid system is more powerful and capable than the US and Japanese grid system, and, subsequently, type 1 connector specifications were deemed inappropriate for the European market. Instead, a different connector was designed to meet the higher power level requirements. Previously, type 1 connectors used fixed connector and cable design only, as untethered cables increased fear of theft and vandalism. Type 2 connectors could be used both tethered and untethered. Thus, a newer connector design evolved, jointly developed with major car manufacturers and electrical component companies. This new connector had comparable security and communication features, the major difference being increased power delivery capability and safety standards. This was classified as an IEC 62196 (Type 2) connector named Mennekes after the company that developed it [3.8]. Unlike type 1 connectors, Type 2 were capable of both single and three-phase operation and were widely accepted and implemented by major automotive companies across Europe.

The European standard for charging connectors appeared set until a group of French and Italian electrical equipment manufacturers organised themselves in the EV plug alliance and rejected the Type 2 connector design, choosing to propose their own instead. The alliance rejected the Type 2 connector based on an electrotechnical safety requirement that required shutters to be present in the plug's design to prevent children from being able to insert their fingers inside the Connector [3.8]. Therefore, an alternative connector was developed with the technical safety feature, named the Scame™ connector.

Following development of the Scame™ connector standard, it was accepted that this development alone would not meet new and future requirements. Thus, a new combined charging system was required to increase flexibility and ease of use. Mating Type 2 connectors with two added DC input pins, a combined charging system (CCS) could be used for both AC and DC charging without changing two different charging ports with varying types of connectors [3.20]. Tesla, on the other hand, developed an independent standard for all its EVs, incorporating safety and power delivery protocols effectively, creating their very own Tesla ecosystem. Consequently, at this point, each country and manufacturer had its own set of standards, employing differing connector types, dependent on local regulatory bodies and grid architecture.

### 3.3.2. Complexity in Harmonisation of Standards

The development of EV charging standards is a vital requirement recognised by all major stakeholders [3.1]. This would allow universal accessibility and allow for EVs to be widely accepted and shown to be a practical alternative to standard internal combustion engine (ICE) vehicles. It is understood from many sources that the practicality of EVs on longer trips is affected by the presence of compatible rapid chargers on longer routes.

EV charging standardisation seems slow to be realised due to a myriad of factors, that can be described by four primary categories: (1) grid network architecture, (2) standardisation bodies, (3) unionisation, and (4) CCS. Grid architecture differs in all countries. In the USA and Japan, type 1 is still widely in use. Type 2 is generally used in European countries for single and three-phase AC charging up to 22 kW. In contrast, type 3 AC fast charging has generally been replaced by type 4 DC rapid charging; countries tend to follow their own set of standardisation rules and have regulatory bodies that oversee the technical specifications and approval of new technology [3.8]. This makes it difficult for a consensus to be achieved. An exemplary scenario can be seen in the Type 2 connector and Scame connector case, where a widely accepted Type 2 connector was challenged on a technical basis to no avail. Next, each country has its own set of local regulations that are determined by its governing bodies. They are also influenced by the ease of use and production determined by the manufacturers. Such manipulation of standards to enable ease of use is a further obstacle in the development of universal standards. For example, a union of Japanese car manufacturers proceeded to develop their own connector and charge delivery mechanism despite the presence and usage of Type 1 connectors. This power delivery mechanism was named CHAdeMO [3.18]. This standard was primarily designed for the Japanese market, although, due to the export of Japanese cars, the use of a global CHAdeMO connector for all export countries was thought vital as their vehicles would be unusable without it. Thus, providing a clear argument as to why a unified standard is essential since it would reduce significant capital investment and permit ease of access for all end users. Finally, the European-derived combined charging system (CCS) appears to be the panacea that could break the global deadlock. It is the first system that can use Type 2 single-phase or three-phase chargers and, additionally, through the same connector, be used for DC rapid charging. In principle, CHAdeMO could also do this, but not through Type 2 for normal universal fast charging. In the USA, a similar CCS is in use combined with a type one connector. Accordingly, the study arrives at a comparable parallel point in history; the Betamax vs. VHS (Video Home System) standardisation wars [3.21]. Once one standard dominated and was accepted by the market, growth in personal video recorders and players grew exponentially [3.21].

### 3.3.3. Standardisation—The Principal View

For EVs to replace current fossil fuel vehicles, a standard must be developed for all aspects of EV use. Service infrastructure, at least equivalent to that of fossil fuel, must develop for charging, operability, availability, and ongoing maintenance. For such infrastructure to be developed, certain standards and operating protocols must be employed. If a global standard is not created, it will be challenging for EVs to replace fossil fuel-powered vehicles completely. Differing standards and charging methods will prevent travel on long-haul routes due to the required rapid charger type's unavailability. For these reasons, an agreement must be prepared and decided between all sector actors on EV charge procedure, operability, availability, and free-roaming payment for electricity [3.15].

Standards play a vital role in the development and deployment of technology in society, providing a solid base for innovation and technological advancements and widespread acceptance of such technology. The presence of harmonised standards permits multilateral cooperation and innovation. Customers will be the key factors in the widespread commercial success of EVs. Standardisation will provide customers with a convenient and consistent experience with the freedom of choice, allowing them to choose from multiple electric suppliers without being limited by charge Connector types, communication protocol and cable limitations.

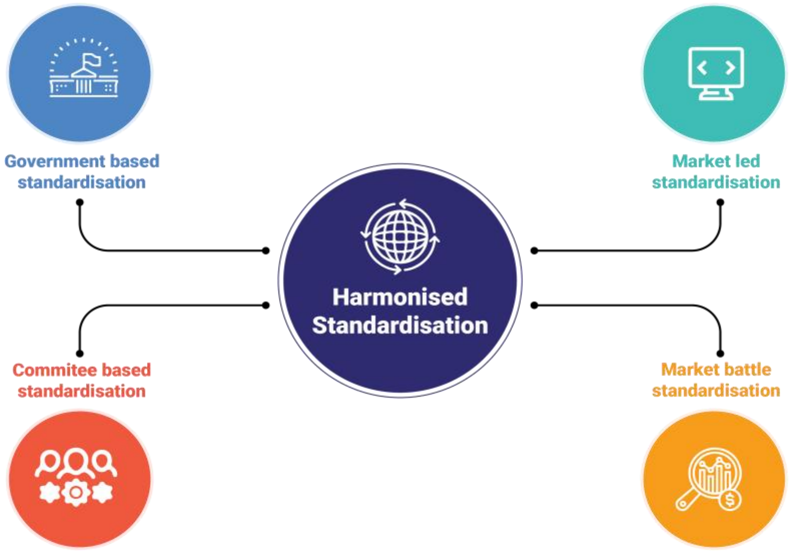
#### 3.3.4. Implications and Options to Accelerate Polymodal Harmonisation

Harmonised standards for charging connectors and handshake protocol are not inter-communicable. For example, Japan, China, the USA, and Europe use separate charging connector standards and disparate communication and handshake protocols [3.20]. Harmonised standards would lead to charge point interoperability, economies of scale and power EV growth in sales, and popularity. Not all EV models support both slow and rapid charging due to design and pricing limitations. Similarly, not all charging equipment can output all power levels or offer all connector types, resulting in complications for EV users in locating suitable charging stations. Exclusive contract chargers prevent EV users from freely using their vehicles due to the inability to charge using 'pay-as-you-go' or inter contract roaming. Standardisation of payment would allow for increased customer satisfaction. Layouts of charging stations are variable depending upon the provider and maintainer of the location. Such variability increases user anxiety due to the constant need to adapt to unfamiliar standards, protocols, and needs.

Planning of charging stations in cities and highways is also limited due to planning restrictions imposed by both local authorities, governments, and grid network operators, propagating an artificially disjointed network of rapid chargers across the UK. This subsequently forces EV drivers to deviate from direct routes, resulting in greater mileage and journey times than conventionally powered vehicles. [3.22]. There is a consensus that the development of a globally harmonised charger standard and trunk route charger locations in line with conventional filling stations would provide peace of mind and familiarity in conjunction with encouraging healthy competition in the EV market to benefit the end-user [3.10].

Harmonisation of standards can reduce unnecessary or conflicting standards that may have developed individually. The objective is to discover commonalities and categorise critical requirements that must be preserved, reducing excessive or opposing standards that may have evolved independently.

The goal is to find commonalities and to identify essential needs that must be maintained and deliver a collective standard. Consequently, four differing approaches toward the harmonisation of standards are appraised in Fig. 3.4.




## 3.4. Models of Standardisation Driving EV Protocol Harmonisation

### 3.4.1. Government-Based Standardisation

Government-based standardisation [3.22] uses the government's hierarchical powers to decree and impose a pre-developed standard established elsewhere or to self-develop standards. This form of standardisation is not generally employed in the EV infrastructure sector.

### 3.4.2. Market-Led Standardisation

Standards are established with collaboration between competitors to develop a collectively acceptable standard to the benefit of each party [3.23]. Such standardisation requires greater cooperation and effort but results in a harmonised standard that allows for further mutually beneficial research and development.

### 3.4.3. Committee-Based Standardisation

Standards developed by independent private entities responsible for testing and developing technical specifications in line with government regulations comprise committee-based standardisation [3.24]. Examples in the EV sector include SAE [3.19], ISO [3.25], IEC [3.8], CHAdeMO [3.26], all of which are private entities who are responsible for unified EV Infrastructure standardisation.

### 3.4.4. Market Battle Standardisation

Market competition exploitation to develop a common standard is known as market battle standardisation [3.24]. Multiple solutions are developed in this model, and eventually, a de-facto standard is established. Companies in the EV sector are slowly moving from this form of standardisation to a hybrid of committee-based and market-led standardisation.

## 3.5. Polymodal Harmonisation and Heterogeneity in a Technical Context

EV owners do not enjoy the freedom of standard refuelling systems accessible to conventionally powered vehicles. The development of harmonised EV charging standards has been slow and subject to frequent disruption. Hence, EV owners need incentives and support in addition to increased combined effort towards the development of standardisation. In the EV context, polymodal harmonisation is the effective fusion of four dominant charging connector types and two communication protocols to merge as one harmonised charge point standard to all stakeholders' benefit. This, in turn, will increase attainability and growth toward a zero-carbon transport future.

Significant innovation has developed in the EV industry with improvements in battery technology, decreased charge times, and increased energy density, delivering an increase in vehicle range, providing a per-charge range on par with conventional vehicle users. However, the most promising research is underway into wireless charging capabilities of EVs [3.20], with great attention focused on the technicalities and efficiency of systems associated with untethered charging, with a focus on safety related to the transfer of large amounts of power wirelessly. Efforts are also underway to standardise off-peak power rates from grid distribution operators and between various EV charge point companies.

### 3.5.1. Static Inductive (Wireless) Charging

Wireless or inductive charging appears to be the panacea for a universal EV conundrum. However, inductive charging is currently very inefficient, requires high infrastructure and hardware costs for both the charge point operator (CPO) and user, and the communication protocols are far from inter-operable. Fig. 3.5 illustrates the difference between conductive and inductive charging. Although significant progress is being made by IEC [3.27], the lack of universal agreement on standards in static inductive chargers allows manufacturers to independently decide the charging features and protocols for each vehicle and each charger manufacturer. End-users are thus presented with myriad factors when choosing an inductive charge

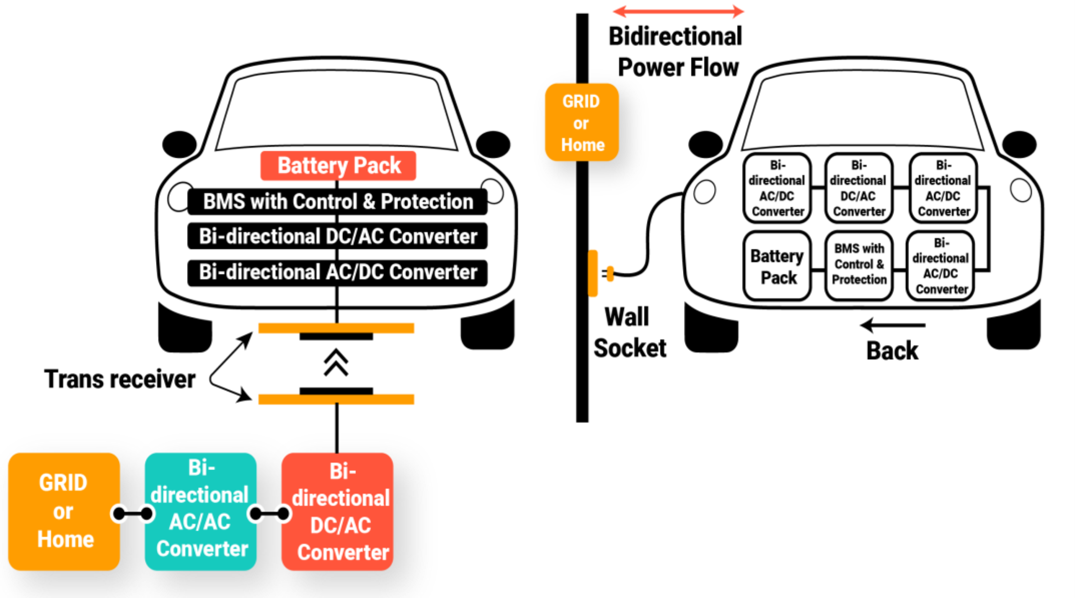



**Figure 3.5.** (a) Inductive (b) conductive charging. Source [3.20].

Key considerations include the vehicle's handshake protocol, the availability of static EV charging stations employing a compatible plate inductor in their location or route, per-charge range of the EV, and on-board charger compatibility provided by the manufacturer. Additionally, home charger options do not include inductive charging for most users due to the high cost of installation. However, Type 2 home chargers provide lower-powered charging in single-phase form, resulting in increased charge cycling at a much lower purchase cost of installation, making conductive charging the preferred choice for most users. Both single and three-phase supplies can feed Type 2 chargers; the latter can charge at 22 kW. The plethora of technical considerations and initial installation costs due and lack of standardisation could point to a significant reason for EV buyer reluctance.

### 3.5.2. Charger to Car Handshake Protocol

The complexity of charging an EV, generates a continuous flow of information and communication between the charger and the vehicle, including:

- Authentication state
- Battery capacity
- Charge time
- Correct voltage output
- Maximum charging current available
- Instructions to bypass the vehicles on-board AC-DC charger if utilising a DC fast charger
- State of charge.

Communication between EVs and chargers is vital for the user's safety and the longevity of the battery, charger, and charge connectors. The vehicle must be able to determine that the connector is locked in place before drawing the current. The vehicle must detect when a latch or button is pressed for it to cease charging before allowing the connector's removal, preventing an arc discharge. The EV must also determine which voltages are compatible with the EV electronic control system and battery management. The vehicle and charger must also be able to check for earthing faults in both the vehicle and charging system to prevent charge leakage. IEC 61851-25 is the international standard covering both protocols in a conductive charging system [3.16].

The two protocols that establish communication between EVs and their chargers are PLC and CAN-bus. Power Line Communication (PLC) is a standard used for communication between EVs and chargers. CCS uses the PLC protocol. All connector types have dedicated pins for uninterrupted communication through charge connectors from the charger to EV. Controller Area Network (CAN) bus is the CHAdeMO connector communication standard, a robust vehicle bus protocol that allows devices to converse without using a host computer. Additionally, the IEC is currently undertaking the role in standardising wireless charging within the framework of IEC61980 [3.27].

### 3.6 Heterogeneous End User Payment Systems

Only two approaches of accessing a public EV charge point (Fig. 3.6) were discovered in the literature [3.2], subscription and pay as you go, although only one method is likely to satisfy the long-term demands of EV users. Specifically, subscription payment methods are contract-based using a mobile phone application or a smart card. In contrast, pay as you go (PAYG) methods allow EV users to access a charge point anonymously with no connected services, typically using a credit card. The Department for Transport (DfT) consultation papers [3.2, 3.28, 3.29] cite payment discrepancies using differing methods of end-user payment for energy at charging stations is a significant issue faced by EV users. Diverse peak hours, payment rates, and technical limitations result in interoperability issues and resultant charge point anxiety amongst users. Through charging stations, disparate payment and identification systems range from the employment of radio frequency identification (RFID) to user IDs provided by the charging station management. Some stations offering vehicle-specific charging features such as stations maintained by EV companies that only allow EVs manufactured by them to access the charging stations, such as Tesla. The most common method used is RFID, limiting users to charging stations owned by the companies to which they are registered [3.30]. The PAYG option is still rare, but the UK government is pressing charge point operators (CPOs) to move towards a dual payment system offering both options. The positive outcome of PAYG is that it offers unrestricted access to all EV users, pending correct connector availability. In contrast, this option results in a reduction in the customer relationship and loyalty to the CPO network [3.31].

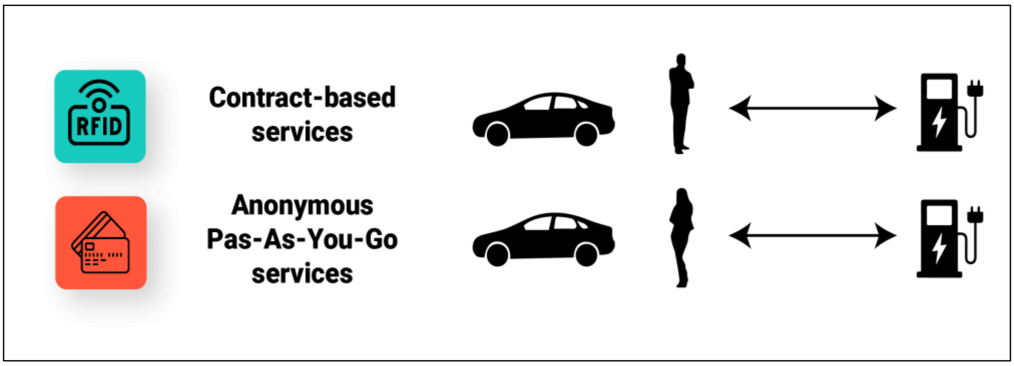



**Figure 3.6.** Public charge point payment access options

Momentum is gathering in the UK for a harmonised roaming charge point system, known as Electric Vehicle Roaming (EVR) or charge point roaming (CPR) [3.32]. EV roaming is a market model in consumer-based EV transport, denoting the contractual obligation, relationship, and subsequent collaboration of the market actors.

### 3.6.1. Connection of Isolated Solutions

Charging stations are generally equipped with an exclusive billing system. Thus, the use of these charge points focused on a limited customer network, whereby only EV drivers who have established an agreement with the charge point operator can access it. EV roaming offers all EV users the option to charge their vehicles at any charge point—irrespective of any contractual agreement entered into with other CPOs [3.33]. Subsequently, billing occurs through the

EV user's own contracted CPO [3.33], similar to mobile phone roaming billing, illustrated in Fig.3.7.

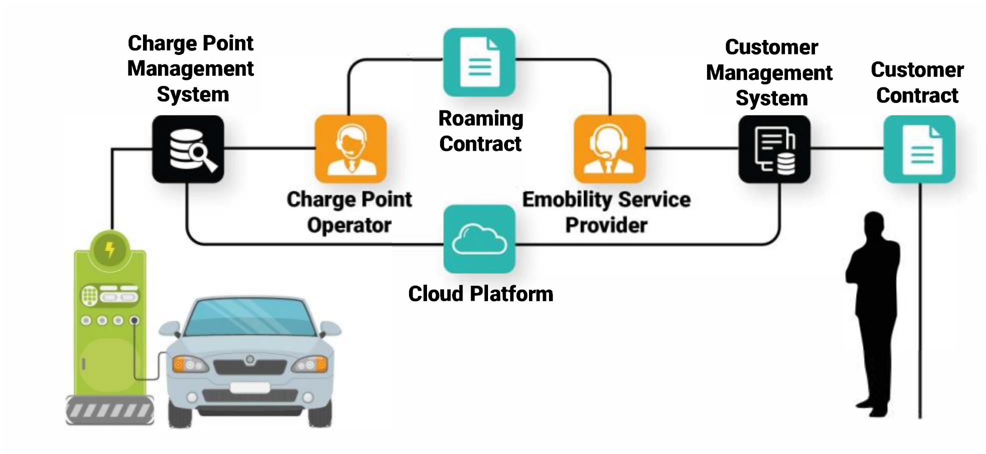



**Figure 3.7.** EV charge payment roaming - key elements

Accordingly, the EV market is networked through individual business hubs and IT cloud-based platforms. This network, if harmonised, can provide a cross-CPO charging framework and is the long-term goal for the UK government [3.2], EV manufacturers, CPOs, and consumers [3.31]. Despite new entrants developing platforms to support this harmonised architecture, the UK appears to be several years away from a fully harmonised system [3.18].

### 3.6.2. Current Evolution of Polymodal EV Connector Standardisation

Despite its early lead, the CHAdeMO protocol is now trailing in the race to become the connector of choice through its market battle standardisation model. Current EVs are designed for DC rapid charging rates of 100 kW or more, and carmakers are now overwhelmingly backing CCS as the standard charging protocol due to its ability to supply up to 350 kW charging and Type 2 7kW single phase AC and 11kW 3Phase AC [3.28]. Next-generation rapid charging deployment networks in the UK are also favouring CCS, reversing the growing deployment of CHAdeMO (Fig. 3.8). Even Tesla, with its proprietary connector and comms protocol, has now switched its EVs to CCS on its Model 3 and Y. This phenomenon across most major manufacturers is a synthesis of market-led and market battle standardisation, coordinated amongst EV manufacturers to expand consumer acceptance and confidence in their markets of sale. The next phase to harmonise existing multiple protocols with manufacturer recognition and approval will be through standard implementation based on multiple factors. For example, the CCS and Type 2 charging protocol has been dominating the competition over the past four years, though most rapid charging stations continue to provide support for the main two connectors (CCS and CHAdeMO), whilst Tesla continues to deploy their own charging network. The data in Fig. 3.8. points to almost equal deployment of CHAdeMO and CCS charge points.

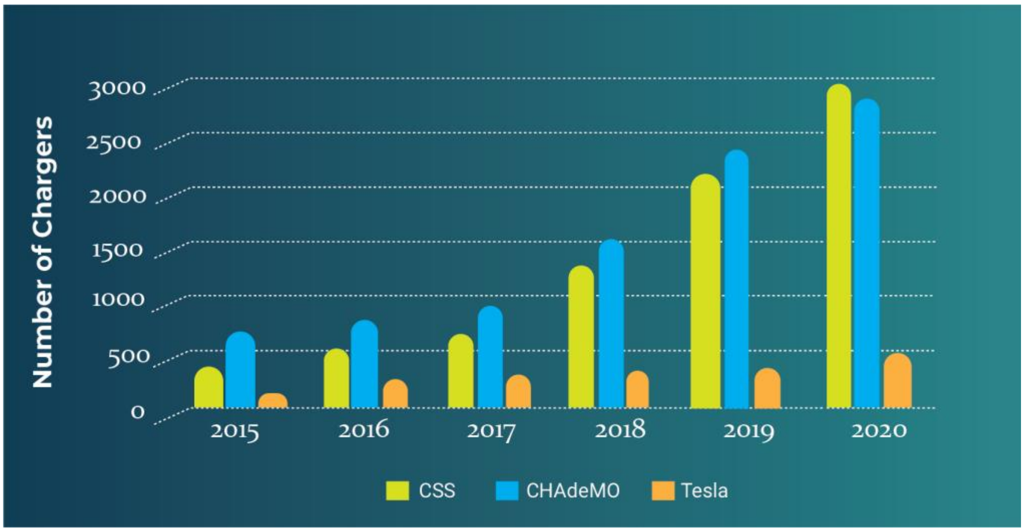



**Figure 3.8**. CCS vs. CHAdeMO vs Tesla UK charge point connector deployment. [3.5, 3.28]

### 3.6.3 Government and Research-Based Findings

The literature points to governments worldwide becoming increasingly attentive to the development and growth of the EV market [3.28]. In the UK, the government is actively granting incentives to develop infrastructure to benefit EV users, including the provision of grants to customers purchasing an EV, albeit reduced from the original £5,000GBP to £2,500GBP per EV under a capped threshold of £35,000 GBP. The UK government has also increased investment into the EV sector with special packages crafted to stimulate and develop nationwide charging stations.

### 3.6.4 Infrastructure Investments Trends and Growth in CCS Adoption

The initial development of multiple standards with manufacturers and countries opting for different protocols and manufacturers developing cars with other charging systems, led us to observe that the initial market chaos of charge point scarcity, coupled with multiple connector standards, left customers considering moving into EVs to view this as a high-risk market to enter [3.34]. With organic development and investment in fast-charging infrastructure, market growth and acceptability are gaining traction. The rate of investment into the UK EV rapid charging network based on actual and forecast data from SMMT (Society of Motor Manufacturers and Traders, 2020) [3.35] in Fig. 3.9.

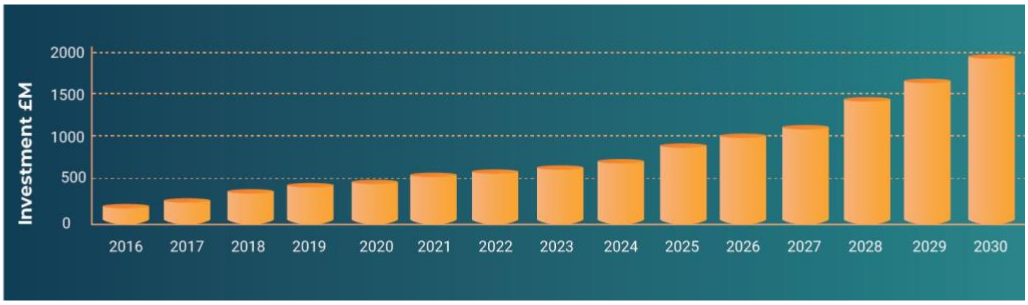



**Figure 3.9.** Annual UK investment in charging infrastructure (£millions)

This study points to an underlying issue faced by consumers and EV makers concerning inadequate rapid charge points in the right place and with correct and available connectors for their cars. To develop a viable solution and for the EV market to continue to grow, the disjointed and uncontrolled deployment of EV-supporting infrastructure may flatten the curve of the sharp rise in UK EV adoption [3.36]. Furthermore, it is argued that this is a prime example of where government regulation is needed now to prevent significant user issues in the future.

Evidence in Fig. 3.10 illustrates that CCS EVs amount to 78% of all new car production, with only two pure EV manufacturers using CHAdeMO, namely Nissan and Lexus. However, Nissan has announced that its next model will move to CCS as its charging standard [3.37]. The remaining models use either Type 2 connectors only or Tesla proprietary connectors. Even then, prior research reveals that all new and future Tesla models will use the CCS protocol. Therefore, there is a huge disconnect in rapid charger connector type roll out, particularly as even Nissan, the only current user of CHAdeMO, is announcing that their current model, the Leaf, will be the last car they produce using the CHAdeMO protocol. The CCS protocol's growth curve versus CHAdeMO and Tesla's proprietary connector protocol is shown in Fig. 3.10.

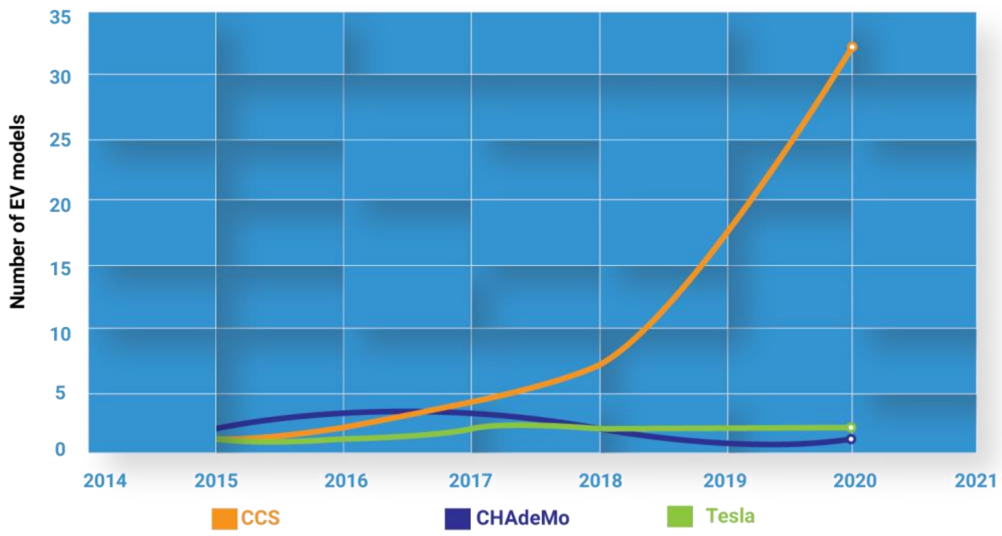



**Fig. 3.10.** CCS adoption in UK, versus CHAdeMO and Tesla [3.38]

There is an increase in both government and commercial investment into the charging infrastructure. This will not meet the current and forecast demand of UK EV growth, as highlighted in Fig. 3.9. It is made clear in Fig. 3.11 that the number of new cars supporting the CHAdeMO charging protocol amounts to just one manufacturer. This investigation reveals that every charge point being deployed in 2020 still includes an equal number of dual CCS and CHAdeMO charge outlets. Although this does not support or correlate with the higher growth and demand in the CCS EV market in Fig. 3.10, and model specific data in Fig. 3.11, that could lead to substantial availability issues for the dominant CCS type EV owners soon. This may lead to even greater consumer resistance, frustration, and slower growth.


**Fig. 3.11.** Charger connector types on UK EVs (November 2020)

### 3.6.5 Theoretical implications and Agenda for Deeper Research

Theoretical standardisation models need refinement in this area, and therefore it is recommended that further research should address multi-model harmonisation of standards using three viewpoints: (1) governmental role and other enabling actors, (2) policy formulation for individual actors, and (3) the impact of multi-model standardisation and how coordination affects the overall process.

### 3.6.6 Implications in Practice

The research demonstrates a lack of cooperation between key actors, particularly horizontal compatibility [3.39], confirming how the development of charging standards and harmonisation of communication protocol will allow for increased practicality and acceptance to this new technology, allowing ease of transition towards a sustainable, emission-free mode of transport.

### 3.6.7 Polymodal Standardisation in a Technical Context

The probe incorporates historical development of disparate standards from 2010 to 2020, including polymodal charge connector types, communication handshake protocols, and user payment systems and, although numerous papers and articles were discovered covering single standardisation issues [3.5, 3.21, 3.31, 3.34, 3.40], no significant collaborative single harmonisation of rapid charge point standards exists to date. Side issues exist concerning EVs effect on grid load capacity at peak times to service the forecasted growth in EV numbers, although most papers are now outdated [3.39]. Moreover, it is argued that this can be countered using battery energy storage systems (BESS), charged at off-peak times to complement, buffer and de-stress the grid at peak times, known as peak lopping or shaving [3.10].

However, in April 2020, at the International Green Car Congress, the CHAdeMO group announced a new Asian consortium that recently developed a new-generation connector standard, named CHAOJI. It can significantly advance CHAdeMO with a charge rate ability up to 1000 kW to a maximum of 1500 V DC [3.41]. Another advantage is that this new standard is backwards compatible with the two dominant incumbents, CCS and CHAdeMO. CHAOJI is bi-directional, capable of enabling the EV to act as a stand-alone generator [6]. The EV world has not yet reached the point of total harmonisation in the rapid charging protocol and connection, and as technology progresses, this barrier to growth will mutate and proliferate for many years to come. Fig. 3.12 illustrates key topics in this field, pointing to further areas of enquiry [3.42].

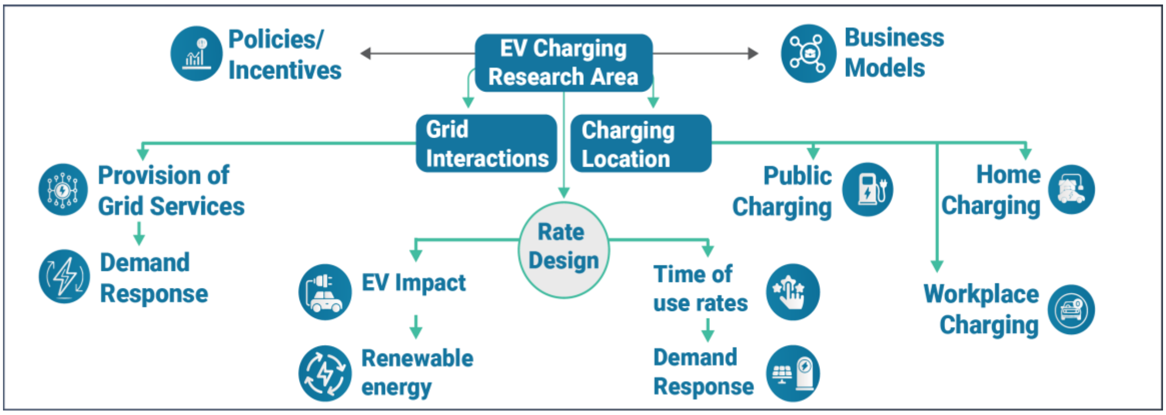



**Figure 3.12**. UK EV charging protocol and charger to car connection analysis

### 3.6.8 Standardisation and Its Impact on Innovation

The research reviews the role of EV charge point standards and standardisation through the many phases of innovative progression ranging from the grid supply side to the demand side, such as commercial procurement. Furthermore, intellectual property rights, particularly patents, should be considered. Previously, principles have been studied periodically in standards development to encourage innovation [3.43]. Hence, the volume of experiential studies evaluating the influence of the harmonisation of standards on innovation is somewhat inadequate. Conversely, compared to the conventional perception of a conflicting relationship, this analysis finds that the problem encourages innovation, particularly if numerous structural circumstances such as the openness of the harmonisation process are available for scrutiny and mutual improvement. Thus, future innovative protocols and success can be measured by the opportunities that harmonisation of EV charge point standards offer.

Notwithstanding the mounting significance of polymodal standardisation, it has received surprisingly little consideration in research. The principal view in the literature [3.44] assumes that every standardisation development relies solely on one of the four modes that were investigated. Though there are many historical instances, such as the market battle between Betamax and VHS [3.21] and ISO 9001's committee-based harmonisation, that conform with this view, it remains that a mounting quantity of cases remain unresolved. In this investigation, the enquiry contributes to engendering a greater acceptance of these developments and the related standardisation models.

Based on the secondary data review in the first part of this investigation, the next phase of this process encompasses live investigations to gauge the real-life experiences and opinions of novel and proficient EV drivers through a conducted structured survey.

## 3.7. Methodology, Results and Discussion of field study

### 3.7.1. Methodology

Data sets describing user preferences and habits were collected using a series of structured interviews based on the four-point Likert scale system [3.7] using a sample of 282 EV end-users, spread across eight public rapid charge point centres on the main UK motorway network over three months. The choice of location was based on the premise that most long UK journeys requiring charge-ups along the way, occur on the UK motorway network. Therefore, eight strategic sites all grouped on known commuting routes and amongst the country's busiest service areas [3.45], including the major conurbations of Manchester, Birmingham, Bristol, and London, were selected, including the world's longest city ring road, the M25, encircling the city of London.

Survey data was gathered from 282 rapid charge point user respondents from a total of 363 potential EV users invited to participate. Interviews were conducted over 12 weeks to capture both commuters and leisure-based EV users to minimise user profile bias. Since time was often a constraint for interviewees, a standard structured questionnaire was used for the interview process. The only personal details asked were age group, gender, average mileage using pure EV and length of time that the vehicle was owned, rented, or leased. No questions were user identifiable, whilst most questions were simplified using a four-number ranking user satisfaction system for data analysis ease.

The core survey questions included usability, operability (charger out of action), cost of charge, charge time, charge time satisfaction, car model, vehicle range satisfaction, and ease of making payment. The full survey results are highlighted in the final section. The average survey completion time for respondents was 25 minutes.

All predesigned questionnaire interviews were recorded in real-time using a computer tablet. The interview responses were instantly backed up using a dedicated 4G cloud server to ensure secure data capture. Collected data was then transcribed in preparation for analysis. Fig. 3.13 shows the number of survey respondents at each location.

Following the interview process, data was gathered and analysed. Secondary research was performed to cross-check and examine the collected data for overlaps or inconsistencies between the participants' experiences. This analysis was validated and verified using the Red Amber Green (RAG) system to ensure that the most relevant data were used for each subject matter. The coding and verification process is based on an original framework designed by a research group at Columbia University, New York [3.46].

### 3.7.2. Results

The survey of 282 adult EV drivers across a sample of the busiest trunk routes and service stations of the UK from 4th September 2019 to 21st November 2019 questioned UK EV users about their satisfaction ratings concerning their own user experience on a range of questions focused on the UK motorway service EV rapid charge point stations. This section provides a summary and overview of key analytical points of the survey. Fig. 3.13 indicates the number of respondents surveyed at each location.

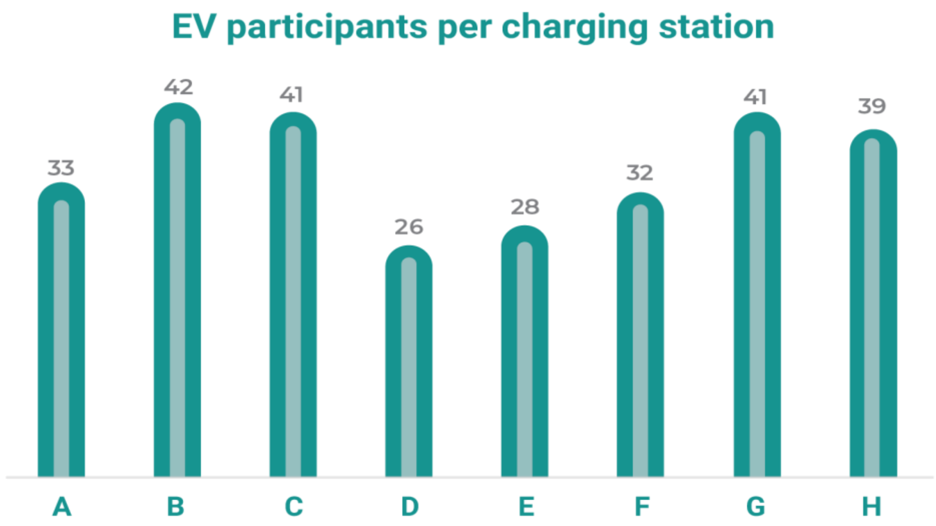



**Figure 3.13**. Survey investigation at 8 locations. September–October 2019

This investigation found that just 16% of female EV drivers used rapid charging stations compared to 84% of male EV drivers, with the 61–75 age range making up the highest percentage (shown in Fig. 3.14). The ratio of female EV drivers using rapid charge points does not correlate with the ratio of female drivers using conventional fuel stations on the motorway, which equates to 35% of all drivers [3.47]. By comparison, the female to male ratio of drivers overall in the UK is even greater, at 46% [3.29], suggesting that most long-distance travel in the UK is made by male drivers overall. Just one person declined to confirm gender, the consequence of which is not significant to the outcome of this survey.

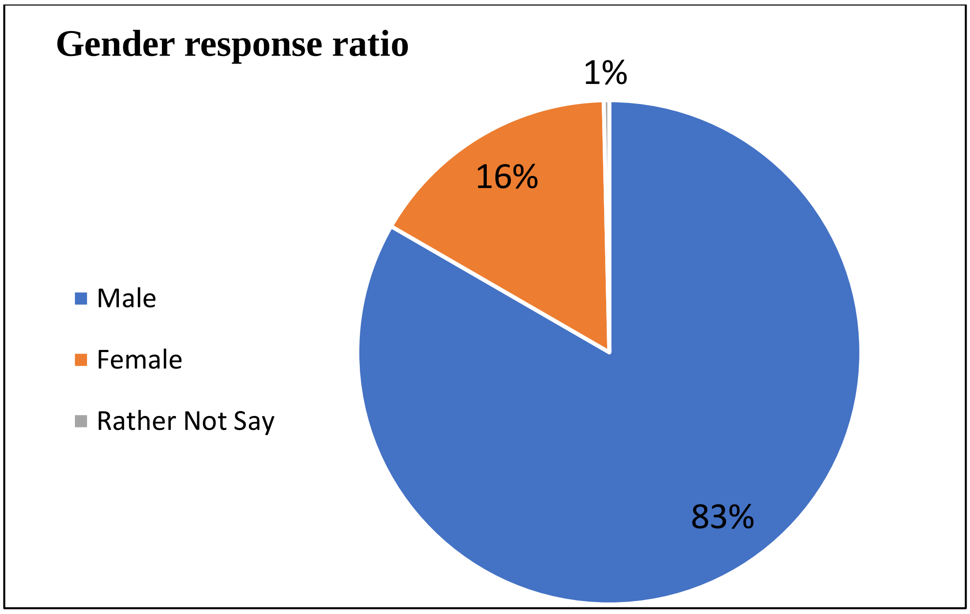



**Figure 3.14.** Survey gender response percentage.

The age range of EV user responders (Fig. 3.15.) varied from 17 to over 75, with the largest age range of EV users being 31–45, correlating closely with conventional ICE drivers using traditional fossil fuel service stations on the UK motorways [3.29].

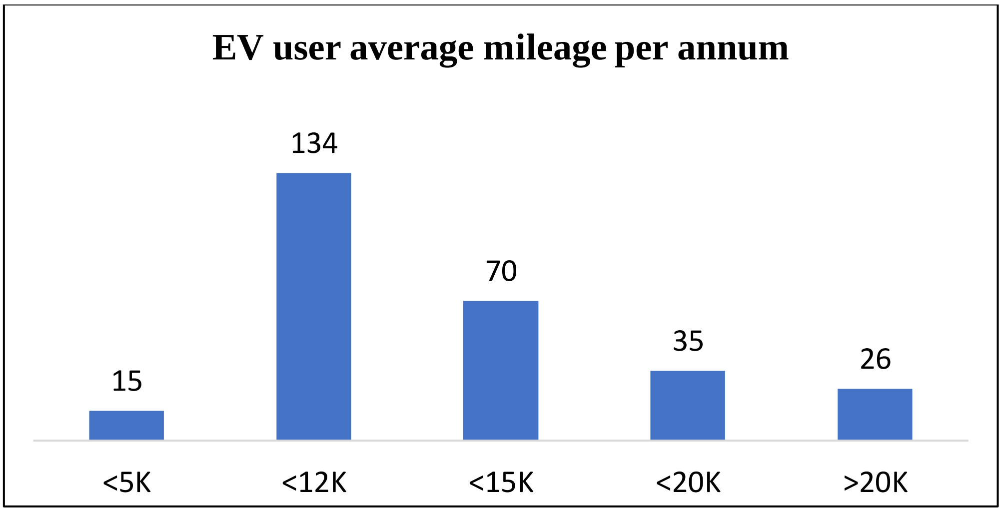



**Figure 3.15.** Number of survey responses by mileage group.

The EV ownership period per EV driver for this relatively new mass form of transport is, not surprisingly low, with the most significant number of drivers only having owned an EV for less than six months and only 18% of respondents having owned an EV for longer than 18 months (Fig. 3.16).

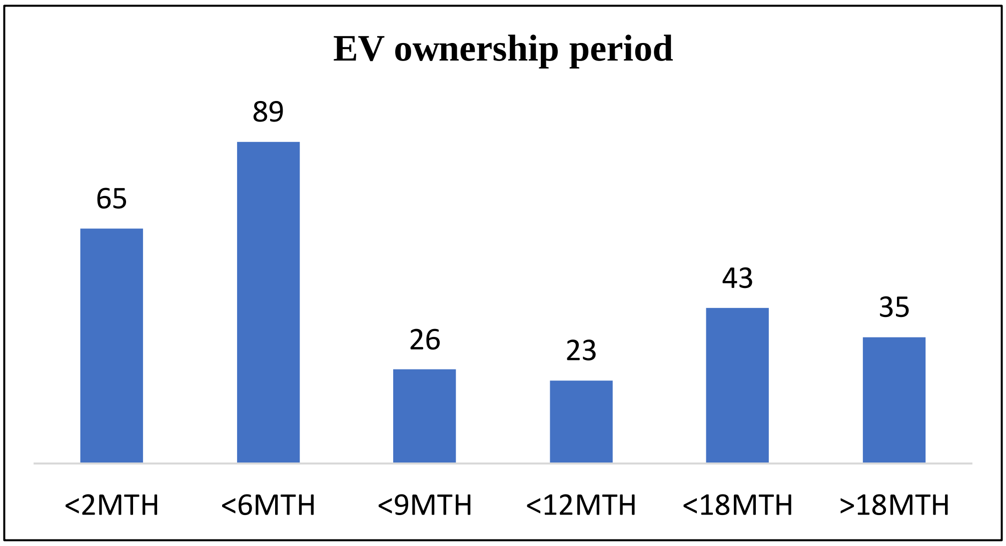
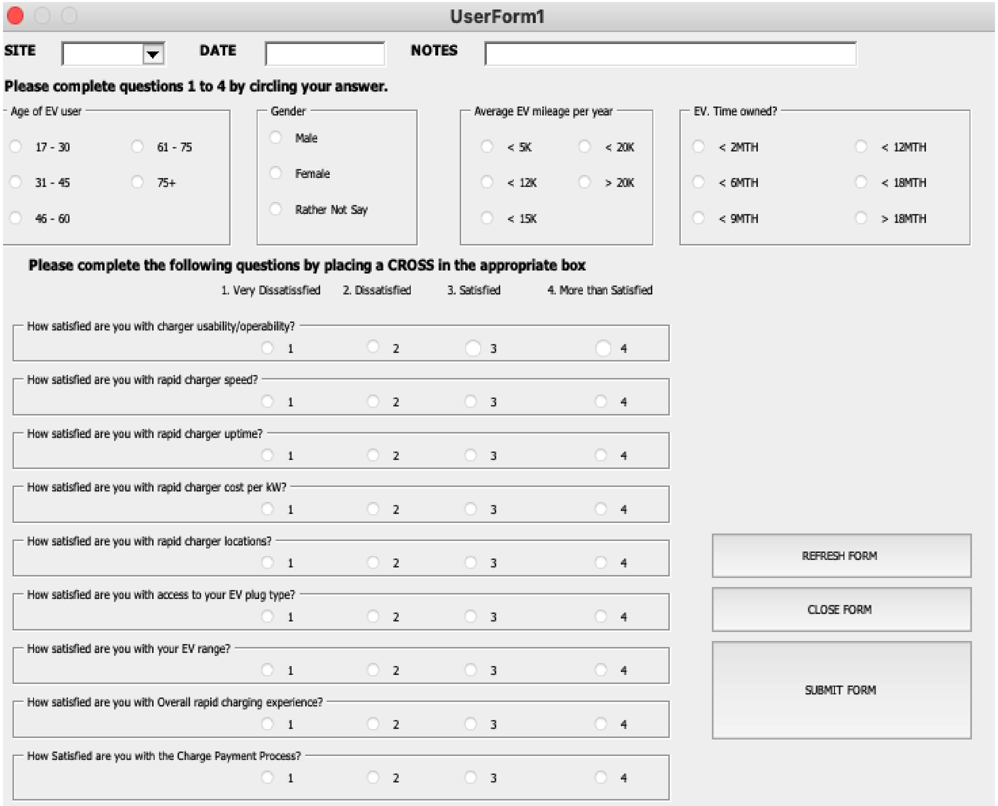



**Figure 3.16.** Length of EV ownership per response group.

Using an adaption of the Likert scale for this nine-question section of this survey [3.7], a four-answer structured methodology was selected to avoid any neutral answers. This questionnaire design method is frequently cited as having bipolar dimensions since responses can be presumed to underlie the semantic differential, according to a publication by Green and Godfried (1965). However, this prevalent rating scale was deemed ideal for this investigation. It was simple for the responders to understand, it averted a neutral response and was quick to complete and simple to conduct data analysis. The questionnaire template (Fig. 3.17) was used on both a tablet auto-linked to a cloud-enabled 4G connected database and in paper form. The template was concise and intuitive to use, and simple to populate for both interviewer and respondent.



UserForm1

SITE DATE NOTES

**Please complete questions 1 to 4 by circling your answer.**

Age of EV user: 17 - 30; 61 - 75; 31 - 45; 75+; 46 - 60

Gender: Male; Female; Rather Not Say

Average EV mileage per year: < 5K; < 20K; < 12K; > 20K; < 15K

EV. Time owned?: < 2MTH; < 12MTH; < 6MTH; < 18MTH; < 9MTH; > 18MTH

**Please complete the following questions by placing a CROSS in the appropriate box**

1. Very Dissatissfied 2. Dissatisfied 3. Satisfied 4. More than Satisfied

How satisfied are you with charger usability/operability? 1 2 3 4

How satisfied are you with rapid charger speed? 1 2 3 4

How satisfied are you with rapid charger uptime? 1 2 3 4

How satisfied are you with rapid charger cost per kW? 1 2 3 4

How satisfied are you with rapid charger locations? 1 2 3 4

How satisfied are you with access to your EV plug type? 1 2 3 4

How satisfied are you with your EV range? 1 2 3 4

How satisfied are you with Overall rapid charging experience? 1 2 3 4

How Satisfied are you with the Charge Payment Process? 1 2 3 4

REFRESH FORM

CLOSE FORM

SUBMIT FORM

**Figure 3.17**. Survey data input template used in both tablet and paper form.

In conducting this section of the survey, nine relevant questions were asked, in which the answers may indicate whether the study hypotheses could be proved or disproved from the survey outcome. Question eight asked respondents to rate their overall satisfaction for their rapid charging experience

In the first question, the EV users were asked for their satisfaction rating of rapid charger useability and operability (Fig. 3.18). This covered whether the charger was operating on arrival and, if so, how easy it was to use. The results show that a significant number of users were satisfied (76%) or very satisfied (17%), with only 7% dissatisfied or very dissatisfied. This contrasts markedly with the hypothesis and is the reverse result of a recent survey by UK DfT [3.2].

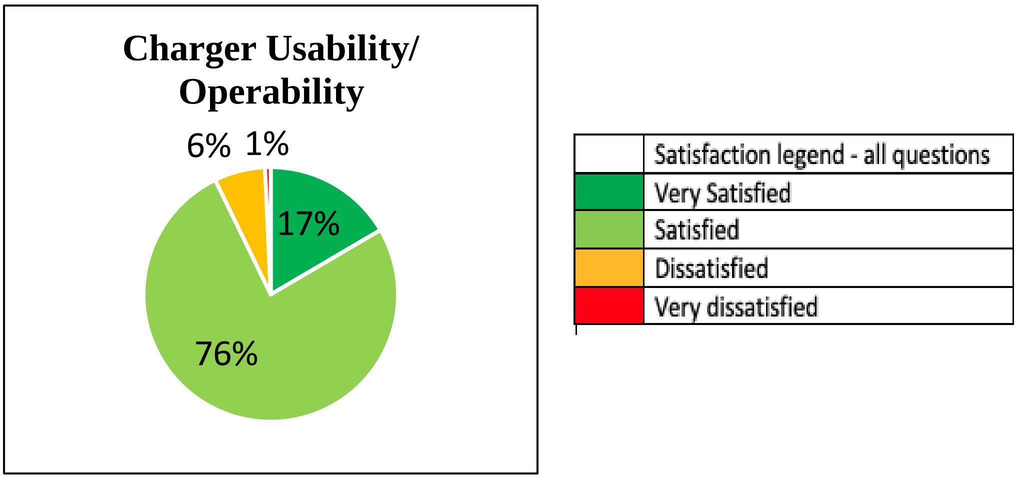



**Figure 3.18.** Rapid charge usability, availability, and operability satisfaction

The second survey question asked for the EV users satisfaction ranking regarding the charge point charging speed (Fig. 3.19). Again, this produced a positive result, with just 17% of respondents citing dissatisfaction, and may suggest that the user is achieving full or adequate charging speed when charging.

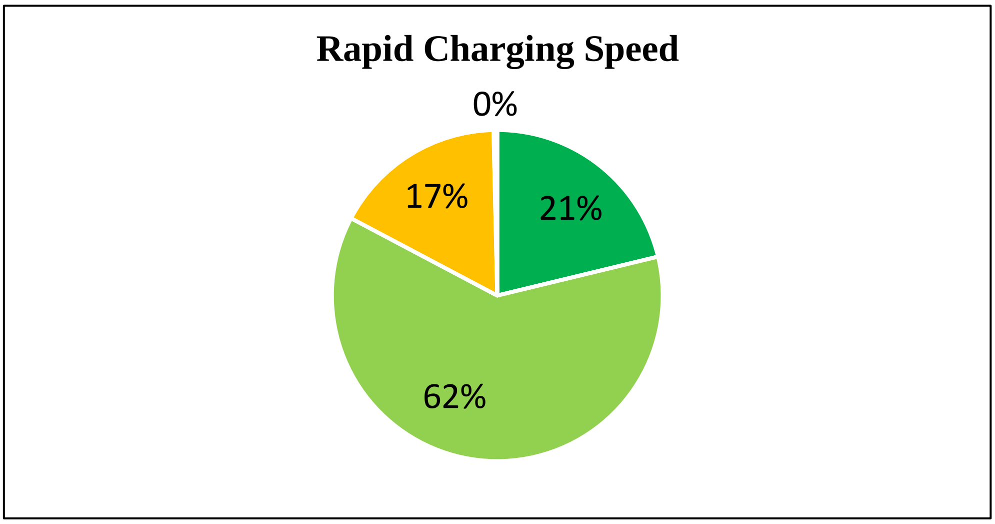



**Figure 3.19**. User satisfaction toward rapid charge point speed.

In the third question, the EV users were asked for their satisfaction ranking for charger uptime availability (Fig. 3.20). The results conflict with question one because they are both related to the rapid charger network reliability. Fifty-four per cent of respondents cited being very dissatisfied or dissatisfied, versus 46% being either satisfied or very satisfied. This is backed up by a recent survey for the Times UK by Zap Map [3.38].

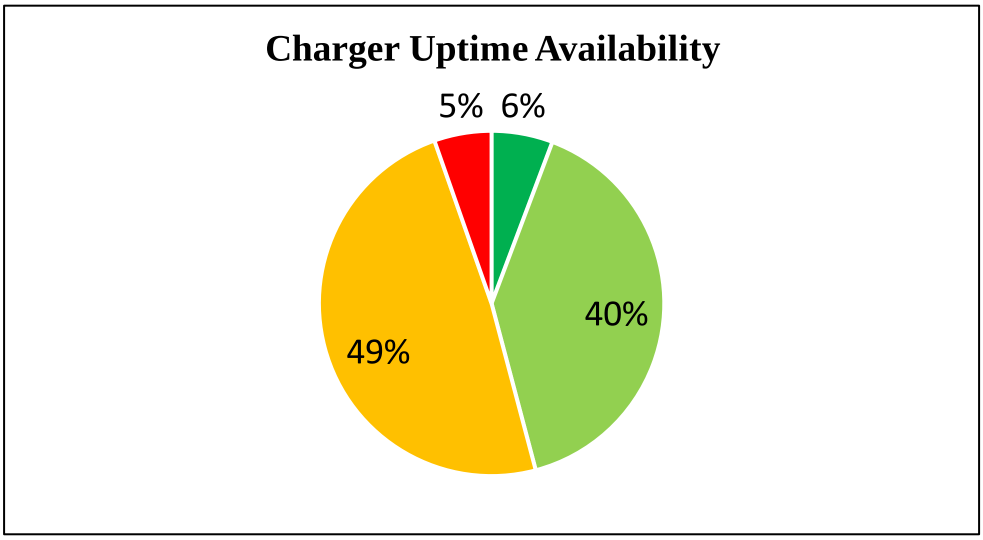



**Figure 3.20.** Rapid charge point uptime availability satisfaction.

Question four relates to the user's experience with charge payment, particularly cost per kW of charge (Fig. 3.21). The result of this question was overwhelmingly negative, with the percentage of respondents either dissatisfied or very dissatisfied amounting to 95%. This sentiment is backed up by several publications including Serradilla, J. et al [3.48] pointing to the dissatisfaction of long-haul EV users that rely on rapid charging systems, backed by a statement made by BP Pulse on their website that they charge GBP 0.42 per kWh, costing an average long haul EV user GBP £37.80 per 230 miles, which is more expensive to refuel than, a medium-size petrol or diesel-powered SUV (Sports Utility Vehicle) [3.5].

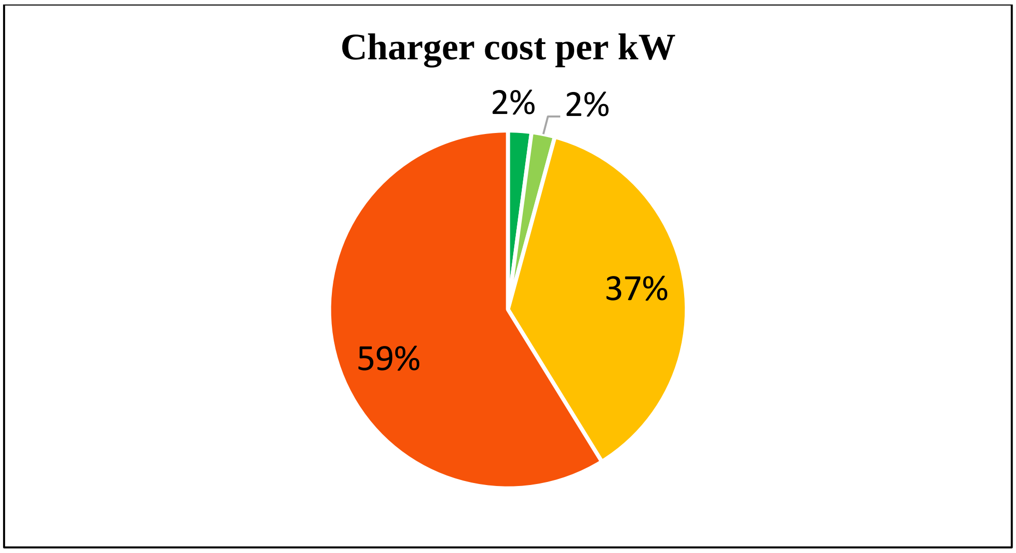



**Figure 3.21**. Satisfaction of charger cost per kW.

The fifth question in the survey relates to where the rapid chargers are located (Fig. 3.22). Each respondent was asked how satisfied they were with the location of rapid chargers within the service station. Ninety-seven per cent of respondents were either dissatisfied or very dissatisfied with the rapid charging network location in general. The research failed to find any reputable journal or report to back up or counter this evidence.

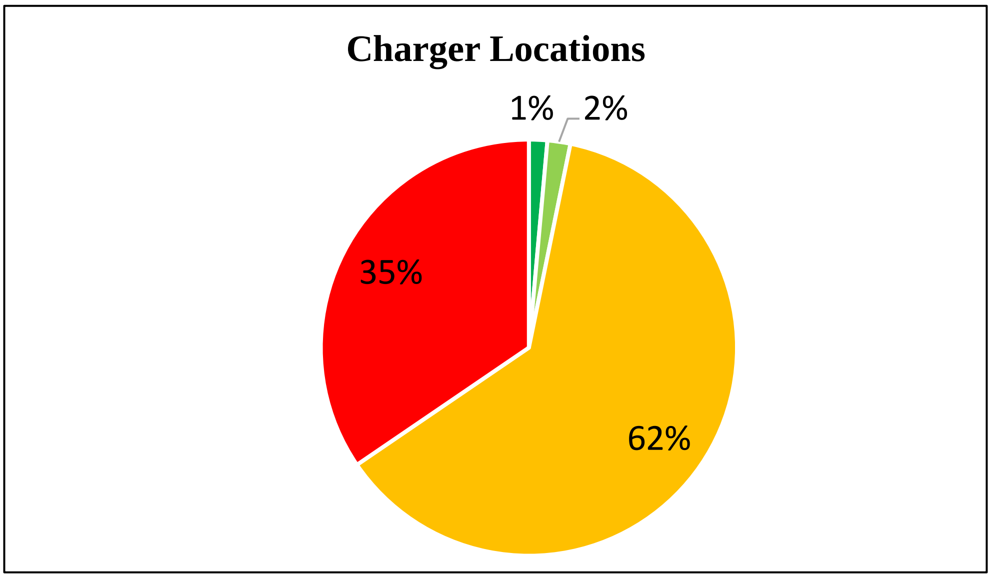



**Figure 3.22**. Respondent's satisfaction of rapid charger locations.

Question six asks the EV users how satisfied they were with access to the EV charger plug type for their vehicle (Fig. 3.23). Ninety-eight per cent of respondents cited that they were either satisfied or very satisfied, suggesting that dual-mode chargers' roll-out is the solution for almost all EV drivers.

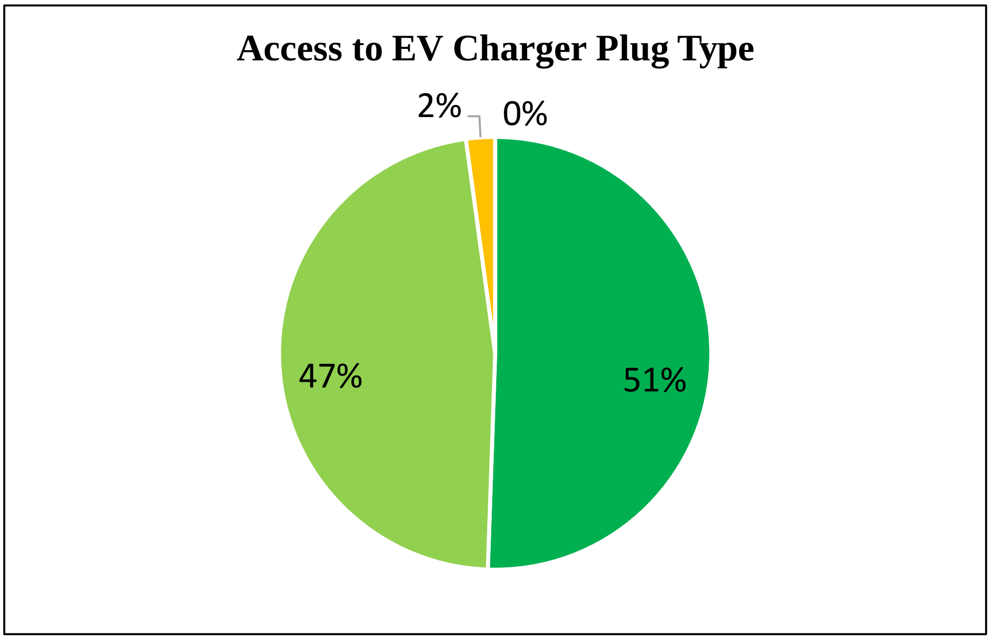



**Figure 3.23.** User satisfaction toward availability of charger connector.

In question seven, the EV users were asked how satisfied they were with their EV range (Fig. 3.24). The purpose of this question was to check that their EV range was not influencing a subconscious bias on the EV user's response to the questions overall. In the event, a significant 74% of EV users were either satisfied or very satisfied with their vehicle's range.

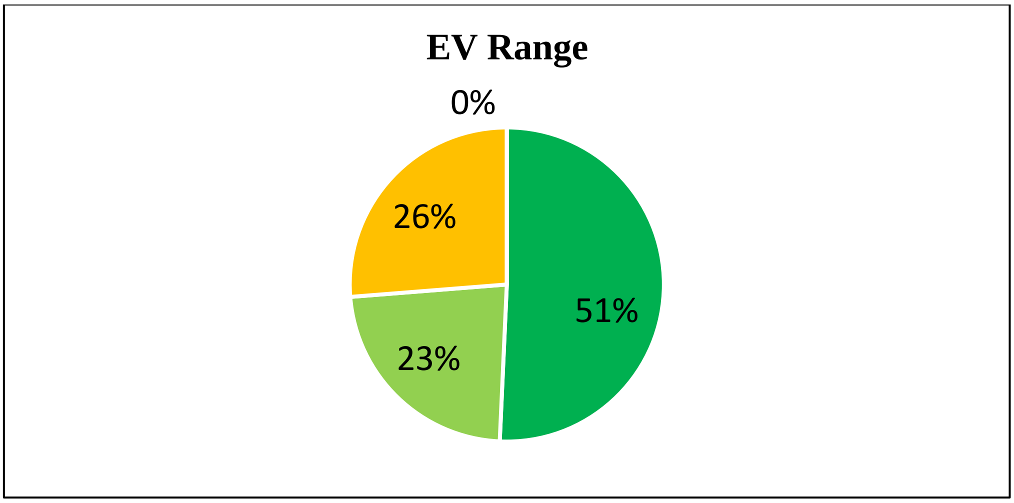



**Figure 3.24**. User satisfaction of their EV range.

Question 8 in this survey asked respondents for their overall rapid charging experience (Fig. 3.25). Eighty-four per cent indicated that they were either satisfied or very satisfied with their overall rapid charging experience.

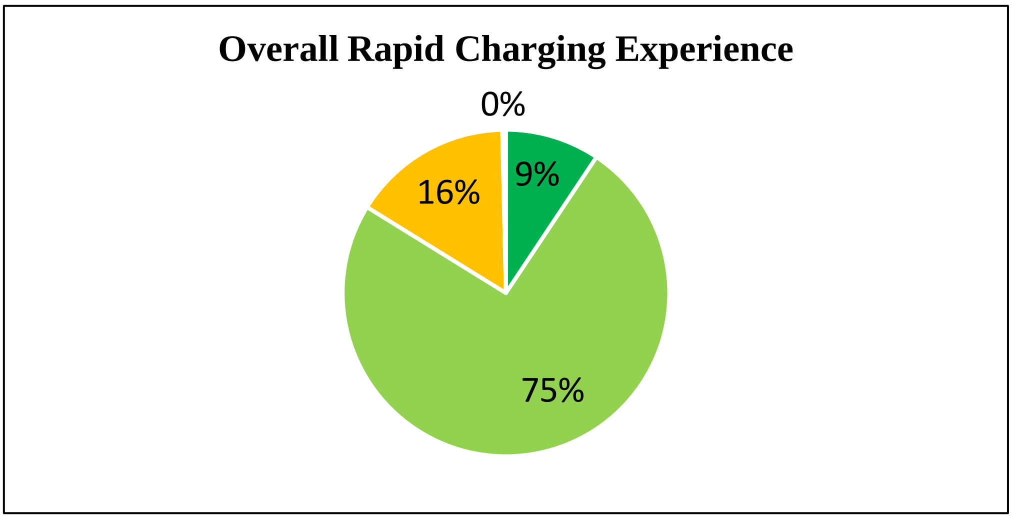



**Figure 3.25**. User's overall rapid charging experience.

The final survey question asked EV users how satisfied they were with the charge payment system of rapid chargers (Fig. 3.26). A significant number of respondents indicated that they were either dissatisfied or very dissatisfied with the charge payment system. This amounted to 73% of respondents and was similar in outcome to question 4, which was also related to the charge payment system, concurring with recent findings regarding charge payment harmonisation and standardisation [3.5, 3.28, 3.37].

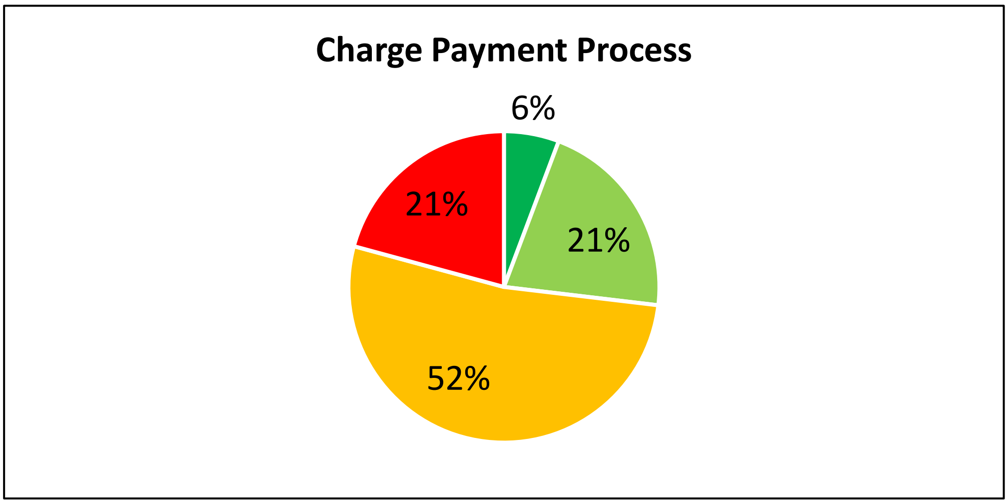



**Figure 3.26.** User charge payment process satisfaction.

The data was then cross-checked with a system-generated user satisfaction outcome across all questions combined that found a conflict between user sentiment in question 8, versus a combined satisfaction outcome across all questions using the system generated result (Fig. 3.27).

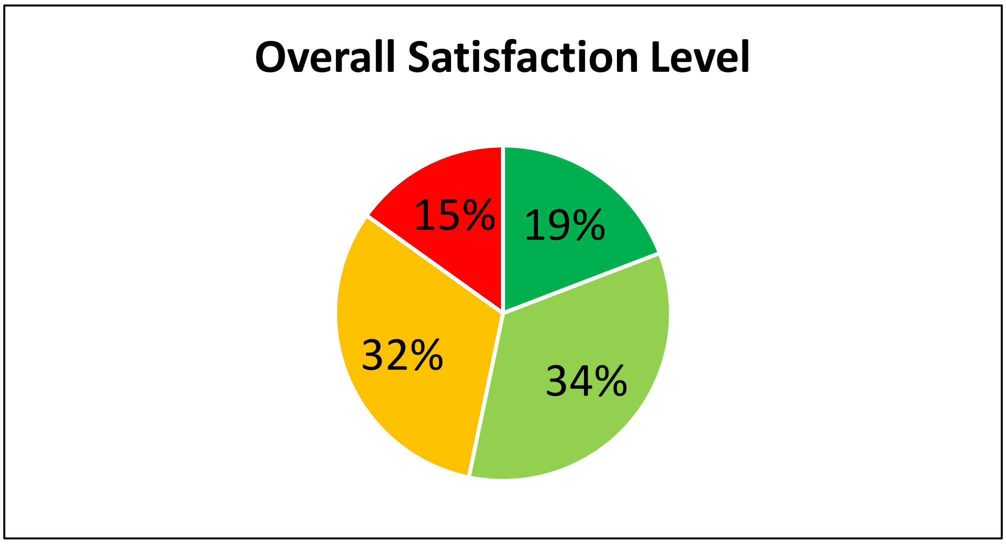



**Figure 3.27.** System generated overall satisfaction level.

### 3.8. Discussion

The interview results suggest that the effect of a ‘Winner-takes-all’ strategy, is paralleled in a recent case [3.49], maybe influencing the fragmented standards that are indirectly causing user dissatisfaction in some areas, such as charger location and payment experiences. Though the sector of their research is not directly related to rapid charging, the commercial outcomes reflect a similar cause and effect, resulting in a race to establish a championed standard for charge point connection. This phenomenon may be a factor that leads to EV user anxiety that might create barriers to EV growth by propagating negative user experience through mainstream media, word of mouth and social media. This was evident, particularly in the areas of charger usability, charger operability, location of charge points and charger payment experiences, graphically illustrated in the full results of the survey in the final section.

Additionally, it is vital to not merely recognise historical secondary data within this dynamic and fast-moving technological field, but rather to refine under what circumstances current and future EV user issues will create barriers to growth. Furthermore, it was found that this data may be dominated by certain results exhibiting biases, leading researchers to the resources they seek, thus pointing to a variety of outcomes. The primary investigation’s particular characteristics will increasingly determine whether government intervention can evolve as the panacea in this market battle, leading to the mutual benefit of all actors as either facilitator or as an influential gatekeeper in EV process harmonisation. In practice, the two are hugely influential and intertwined.

In the survey's design and methodology, care was taken not to mention (both verbally or implicitly) standardisation or harmonisation. Furthermore, there was no mention any of the three key areas that formed the basis of this investigation. To do so would have influenced the user's answers and introduced an element of bias. Thus, the questions concerning this investigation were purposely agnostic by design, aimed at achieving minimal response bias.

Each question is either directly or indirectly linked to one of the three main question areas, known henceforth as H1, H2 or H3, with H covering two or more main question areas, and general user questions known as G. Dominant responses to each survey question are shown in Table 3.1.

| | Questions | | | | Subjects | H |
|---|---|---|---|---|---|---|
| | Very Satisfied | Satisfied | Dissatisfied | Very Dissatisfied | | |
| Q1 | | 76% | | | Charger usability and availability | H1 |
| Q2 | | 62% | | | Charger speed | H1 |
| Q3 | | | 49% | | Charger uptime and operability | H1 |
| Q4 | | | | 58% | Charge cost | H |
| Q5 | | | 62% | | Charger locations | H1 |
| Q6 | 51% | | | | Connector availability | H3 |
| Q7 | 51% | | | | EV range | G |
| Q8 | | 75% | | | Overall experience | H |
| Q9 | | | 52% | | Payment process | H3 |
| CGA | | 34% | | | Satisfaction level average | H |

**Table 3.1.** Dominant results from each survey question.

- **H1** Does non-standardisation of charge connection and the three dominant connector types (CCS, CHAdeMO and Tesla) affect charge point availability and user satisfaction, or are they the product of other contributing factors?

- **H2** Will standardisation of the two dominant car to charger communication protocols improve user satisfaction and benefit all stakeholders?
- **H3** Will charge point payment standardisation benefit all stakeholders in the long term, and most importantly, improve user satisfaction?
- **H** Subject covering more than one standardisation area
- **G** General user satisfaction questions.

**Key**

- Q1, etc. Question number.
- CGA Computer-generated average.
- H Hypothesis match—1–3.
- G General question relating to user EV

### 3.8.1 Analysis of Survey Data

While it was never certain that all questions in this survey would yield tangible pathways to reduce barriers to growth in the EV sector, it was anticipated that some areas would help shape and drive standardisation for UK rapid charging infrastructure in the future, to the benefit of the end-user.

Question 1. was an area that was felt would not produce positive responses from EV users, particularly as a recent article [3.38] ranked UK motorway rapid charging bottom of an EV user survey. Yet, 93% of respondents in this study were either very satisfied or satisfied with charger usability and availability. This area needs further investigation using either workshops or semi-structured interviewing techniques and may result in a slightly different outcome. The survey result suggests that despite known downtime issues on the UK motorway rapid charge network, EV users appear to have high tolerance levels towards low levels of service availability. Existing users' experience in this area does not introduce a barrier to growth where harmonisation of standards is well catered for, with all three connectors available at every motorway rapid charging station.

Question 2 is an area that demonstrates higher levels of tolerance towards rapid charge speed than anticipated. One area that does distort the overall outcome of both question one and two is that 15% of all respondents had access to the Tesla motorway supercharger network. This network scored highly in the recent survey of UK motorway network ranking [3.38], although 83% of users ranked this area overall as very satisfied and satisfied combined. Thus, by removing the Tesla network influence, the overall satisfaction level is still good. Despite the main charger stations providing a maximum of 50kW, the high user tolerance to relatively low speed levels appear to have little effect on user satisfaction. Therefore, it cannot be claimed that harmonisation of standards would improve user satisfaction significantly.

Question 3 relates to charger uptime availability and is the first result in this survey that shows a high user dissatisfaction level. The research found that 54% of EV users were either dissatisfied or very dissatisfied with the charger uptime or reliability. The UK motorway network was installed more than ten years ago when CHAdeMO was the dominant charge point connector [3.38]. The network later upgraded its chargers to accept CCS, and it is known that this CCS upgrade has always proved an issue, especially in the handshake protocol between car and charger. Therefore, this is a crucial area where harmonisation of standards would help raise user satisfaction to the benefit of all stakeholders, as CCS now accounts for 88% [3.38] of all-new EVs.

Question 4 focuses on charge payment for power used by the EV. This is the second outcome revealing high levels of dissatisfaction at 96%. Costs of up to GBP £0.40/kW for non-Ecotricity (the company that owns the motorway charging network) members are noted, meaning the cost to charge an average EV can be close to the cost of fuelling a petrol car, compared to charging from home, that is typically GBP £0.10/kW. This and one other area in question nine leads to the conclusion that the fragmented UK payment process for rapid charging is an area where harmonisation of standards is needed now. More than 20 major charge point companies operate in the UK [3.30], with few roaming agreements, some PAYG, but mostly members-only clubs with charger access typically by RFID card or a mobile phone application. Compare this experience with refuelling a conventional car, and it is clear why some EV drivers become anxious to travel long distance in an EV.

Question 5 is an area that centres on the location of rapid chargers. The UK rapid charger network is often tucked away at the far side of a service area car park, rarely close to the conventional petrol filling station. At times of renovation, it can be shut down without notice [3.38], often leaving EV drivers stranded. The location directly correlates with the growing sentiment of EV users [3.50] to a huge dissatisfaction level, amounting to 97% of respondents. This issue can only be resolved if UK EV drivers are treated with similar harmonised standards that traditionally fuelled ICE drivers enjoy. This probe suggests that whilst the outcome alone may not deter new entrants to the EV market, it may encourage EV drivers to return to conventional vehicles, and accordingly act as a barrier to growth.

Question 6 relates directly to the EV user's direct access to the correct EV charger connector on arrival at a charging bay. An overwhelming 98% of users were either satisfied or very satisfied that they had good access to the correct charger plug on arrival. However, further research will need to be implemented soon to see if this is still the case, as a growing number of exclusively CCS EVs enter the market. Therefore, these results do not currently suggest that the lack of harmonisation of standards affects EV user satisfaction in this area. Still, as the market grows, the investigation indicates that a lack of CCS charge points may be a growing concern as connector standards head towards a market predominantly equipped with CCS connection.

Question 7 does not directly relate to the harmonisation of standards, but it indirectly has a shared link, where EV owners with lower range models rely more on rapid chargers, especially on longer commutes. Thus, each respondent was asked how satisfied they were with their EV range. The result was predictable due to a small percentage of drivers that were still using first generation EVs. Each respondent in this first-generation EV category cited dissatisfaction with their EV range. The lower the battery range, the more stops to recharge are made on average for similar distances compared with a new EV. Thus, these drivers must have easy and open access to the rapid charge network. Almost all drivers in this category drove cars equipped with CHAdeMO charge point connection. Whilst this issue will not directly slow EV growth, it does highlight the need for harmonisation of connecting and payment standards.

Question 8 is centred on how each EV driver rates their overall rapid charging experience. Overall, it was discovered that 84% of EV drivers, especially those with vehicles less than eighteen months old, were either satisfied or very satisfied with the rapid charging process. No respondents were very dissatisfied, suggesting that overall, the rapid charging experience had a positive outcome, considering this is a relatively new technology.

Question 9 is specifically related to the overall charge payment process on rapid chargers. The survey outcome reveals that 73% of respondents were either dissatisfied or very dissatisfied with the charge payment system and concurs with recent findings regarding charge payment harmonisation of standards [3.5, 3.28, 3.37]. The response to this question is similar to question 4 (Charge cost satisfaction). It again highlights that harmonisation of standards is vital for the confusing UK payment process for rapid charging. With more than 30 major charge point operators in the UK [3.30], and few roaming agreements, many member-only clubs using RFID or dedicated apps outnumber charge points that operate on an open PAYG system by a ratio of 10:1 [3.50]. Compare this experience with refuelling a conventional car, and it is clear why some EV drivers develop anxiety when embarking on long-distance trips in an EV.

Fig. 3.27 reveals a simple computer-generated cross-check combination of data from all questions to simply compare, particularly with question eight, in which EV users were asked to state their overall rapid charging experience. One would expect that this outcome would mirror the result in question eight. However, the effect was a marked contrast that showed that 53% were either satisfied or very satisfied with EV charging in the computer-generated calculation based on actual question results, compared to EV users own general preference. This phenomenon is known as hypothetical bias and is common in stated preference questionnaires, confirming that further analysis in this area should be semi-structured in construction and delivery, to improve data quality [3.51].

### 3.9 Conclusion and Implications for Practice and Further Research

This investigation emphasised implications for theory building that is also relevant in practice. The primary research suggests that all stakeholders in the ongoing technological and greater social transformation are likely to be impacted by the consequence of EV rapid charger standardisation practice for charge connections and communication, which was anticipated to become monomodal over the next decade. Business actors, NGOs (Non-Governmental Organisation), and research and trade associations should therefore be cognisant of standards development. Should they choose to contribute to the process, they must consider the range of choices that polymodal harmonisation can contribute to their policies by offering single point, `available to all' rapid charge points, like traditional fuel service stations' forecourts. A single standardisation model can be achieved by encouraging government intervention, which demands appropriate resources, timing, and consideration.

From the survey results, although end-users are generally satisfied with their EV, significant areas of dissatisfaction persist, including charger uptime and availability, charge cost, charger location and payment processes, all of which would be positively impacted by systemic standardisation. Furthermore, a lack of charge point connector standardisation has resulted in the introduction and adoption of new node-specific charge point communication protocols over the past decade, resulting in handshake issues between the car and charge point, initiating reduced charger uptime and availability.

Additionally, charge cost, charger locations and payment methods, the high price of charging away from home, and the lack of convenient locations directly result from the lack of standardisation among charge point operators (CPO's) and EV manufacturers. Many CPOs require paid monthly membership, depriving EV drivers of the freedom to simply charge their EV at the station offering the lowest price, with limited payment options. Additionally, not all EV connectors are supported at every charging station, and the need for charge support for multiple charge point options limits the number of chargers available to users. Multi-level systemic standardisation can be used to solve these issues, supported by the detailed literature review in Section 1. In addition to improving general user satisfaction, addressing these issues would also lower barriers that currently act as a deterrent to new end users entering the EV market. This approach will benefit all stakeholders, leading to a ubiquitous EV charge delivery system on par with the universal standardisation experienced by non-EV drivers at traditional fossil fuel stations.

Furthermore, it is demonstrated that stakeholders who do so gain a wide variety of options to encourage standardisation, many of which only materialise at key stages of the process. To employ these choices as part of a reasoned approach, actors should be mindful of the subtleties that are liable to result from this. Participants must be prepared for competitor's actions if they decide not to harmonise specific modes. Additionally, they must reflect on whether to introduce new processes and methods and avoid being rushed by outcomes resulting from dormant modes, such as the continued roll-out of CHAdeMO relating to just one model by Nissan®.

The research argues that regulators need to mould their processes in such a way that they are reactive to stimuli from other approaches and appealing for participating actors who have the choice between engaging in panel-based standardisation and other modes. They should also be prepared for increased competition within the panel-based model, since actors from other sectors such as IT, are establishing potentially appropriate opportunities for standard development or because of the rise of new entrants such as open-source groups. Policies to maintain suitability in this setting may comprise managing harmonisation schemes, so that standards are not just established and sanctioned, but additionally, their deployment is stimulated and sustained. Moreover, sector actors could highlight their strengths, then agreement among varied groups of stakeholders might focus their input where these strengths are most significant. For instance, sector actors could promote committee-based collaboration to outline all-embracing frameworks and designs for new large-scale harmonised rapid charger systems that provide activities in the sector to create standards for the individual elements within them, such as connectors, communication protocols and payment systems. When solutions that meet sector demands for a standard develop in the market, it may be appropriate to merge them into a fully scaled harmonised standard, thus avoiding replication of effort. Similar outcomes are possible to apply to other industries, or government groups pursuing committee-based harmonisation events.

Legislative policymakers can follow this study's conclusions by adopting harmonisation of EV rapid charger standards to reinforce public policy or when they contemplate intervention in the regulation of standards, particularly where there is strong opposition and significant societal consequences. Where standards are used to reinforce policies, it is observed that these came mainly from actors in a committee-based standardisation model, whereas the prominence of market-based standardisation in certain sub-sectors implies that government might further benefit by combining standards into their greater policy portfolio, rather than adopting the development of new committee-based standards with established practices. This is particularly relevant in the context of EV rapid charging and its associated complex enablement systems, where standards cannot stand alone long-term but instead must be aligned, thus preventing the emergence and permanent fragmentation of rapid charging standards in a UK context. Hierarchical mediation may thus be needed as a last-ditch attempt where committees and sector actors such as Tesla, CCS and ChaoJi with their opposing agendas, are likely to lead to poor long-term results.

Aside from the well-defined polymodal connector standards, this survey established that improved EV connectivity and crucial data sharing point to the need for a homogeneous smart charging solution founded on actual consumer behaviour and real-time status of both vehicles and chargers. This is in stark contrast to the current situation that requires drivers to manually advise some charge point operators of their proximity and current state of charge via their in-car systems or mobile applications to obtain GPS (Global Positioning System) coordinates and availability of the nearest working charge point [3.52].

In the course of this research, the evidence confirms that the single most urgent element of rapid charger harmonised standards is the ability to plug any EV into any rapid charge point at the most appropriate location. Study analysis revealed that the market-led CCS connector is rapidly becoming the de-facto standard in all cars with a rapid charge DC facility, except for the CHAdeMO equipped Nissan Leaf and Lexus LX300e. Nevertheless, it is observed that CHAdeMO has now developed a new Far East standard named ChaoJi **[3.**13] that is gaining rapid acceptance in China and Japan. In direct competition with this new Asian standard, the CCS consortium is developing a similar advanced standard. This suggests that the market battle for standardisation is not yet won. Fig. 3.28 illustrates a rapid charge protocol harmonisation model, illustrating the transition from a polymodal to a monomodal outcome, based on this investigation using primary and secondary data and historical trends, noting past sociotechnical market battles such as Betamax versus VHS [3.21].

Additionally, there is significant evidence [3.20, 3.22] to suggest that improved EV sharing of data and the implementation of direct EV connectivity can encourage innovative smart charging solutions that are founded upon genuine EV status monitoring and customer behaviour, thus eliminating manual user and operator intervention. Little research has been carried out in this important field of EV infrastructure automation. Moreover, the by-product of not resolving the current process flaw of multi-communication protocol and polymodal connector standards (Fig. 3.28) will remain a constant user issue and barrier to growth amongst the UK ICE and EV user community. Furthermore, there has been a great deal of research on range anxiety, and there remain many unanswered questions in this field of research. However, as new EVs enter the market with greater range and faster charge capabilities, range anxiety may become a distant memory as rapid chargers pass through this developmental stage of the EVs resurgent lineage. This can be bolstered by government intervention through more attractive plug-in grants (PIG) and UK government incentives to promote a broader range of EV usage.

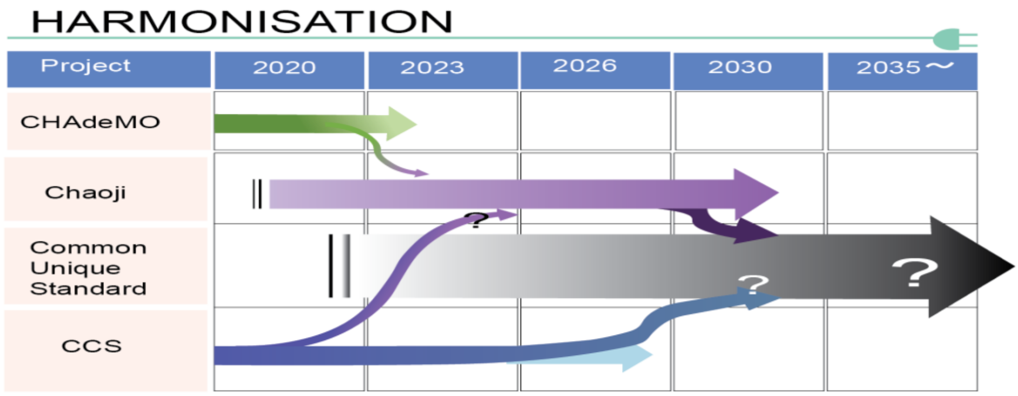



**Figure 3.28.** Polymodal to monomodal EV rapid charge connector model. Adapted from source [3.41]

If the investigation conclusions are recognised and acted upon by both government and industry actors, then any user anxiety may dissipate as a key barrier to EV adoption in the UK market. Nevertheless, a more inclusive electric transport strategy is required to encourage the growth of EVs in the UK to achieve the UK government's ambitious `road to zero' targets [1.22]. The research is but a fraction of the more significant challenges that lie ahead. EVs will undoubtedly become a key element leading to sustainable cities through large scale acceptance. Such transformation may alter the UK's political and economic dynamics. This investigation and conclusions are effectively the start of this process but can be used to guide regulation that may shape transport and energy policy into the future. Furthermore, the findings can direct EV developers and manufacturers to integrate user preferences into future EV infrastructure and electric vehicle design.

### 3.9.1. Research Limitations and Implications

This study focuses on the discussion of the interactions between EV users and UK rapid charge points by evaluating their experience and outcomes without fully considering the impact of social environment and educational background that could influence user behaviour and perception. Moreover, this investigation focuses on only eight of the UKs rapid charger locations, that are sited exclusively alongside the main arterial motorway routes of the UK, purposely dismissing slower charge points in low-traffic volume areas. A quantitative research method was created to construct the relationships between UK EV CP users on trunk roads because the critical focus was how users would respond psychologically and emotionally to the complete EV rapid charging experience on long-distance motorway routes.

### 3.9.2 Practical Considerations

The study extended the application of EV user experience and satisfaction levels to expand standardisation theory and how it can eliminate barriers to growth in this relatively new, fast-growing transport market. Additionally, the research method and model used in this paper may serve as a guide to other interested scholars who intend to explore relevant variables and perform further research on the influencing factors of the harmonisation of standards in the EV sector.

Since commencing this research, a private consortium [3.53] has announced that following government criticism [3.2], the UK motorway rapid charger network will be completely replaced and upgraded to 150–350kW superchargers. Therefore, it is suggested that a further survey be implemented on completion of this deployment, to contrast and compare satisfaction levels and determine how this then affects EV growth in the UK market. The survey suggests that EV users tolerate slower speeds than are available off the main motorway network. Therefore, charge speed does not appear to be a negative issue for existing users and harmonisation of charger standards is not currently adversely affecting sales growth.

### 3.9.3. Social Implications

Numerical data are collected in a structured manner in this research, ensuring reliability, thus maintaining respondent consistency, though restricted by the multiple-choice questions in the survey. This chosen method reduced survey time with busy commuters and identified new variables on this critical subject. As a result, the investigation extracted the fundamental causes of user satisfaction or dissatisfaction in EV users charging experience and potential connections with the three main hypotheses. Appropriate scholars, EV users, and commerce may analyse, manage, and forecast EV users' rapid charging anxieties and behaviour, providing guidance for the proposal of corresponding future deployment strategies.

### 3.9.4. Study Value and Originality

Relevant investigations in this area generally focus on the EV purchase price and EV range, with a scarcity of EV rapid charging studies from the EV user’s perspective, particularly in the UK. Furthermore, in contrast to this investigation, there is limited research that investigates standardisation of connection, charging protocols, car to charger communication and charge payment process analysis through the examination of EV user experience and satisfaction outcomes. Fig 3.29. shows the complete dashboard of survey data.

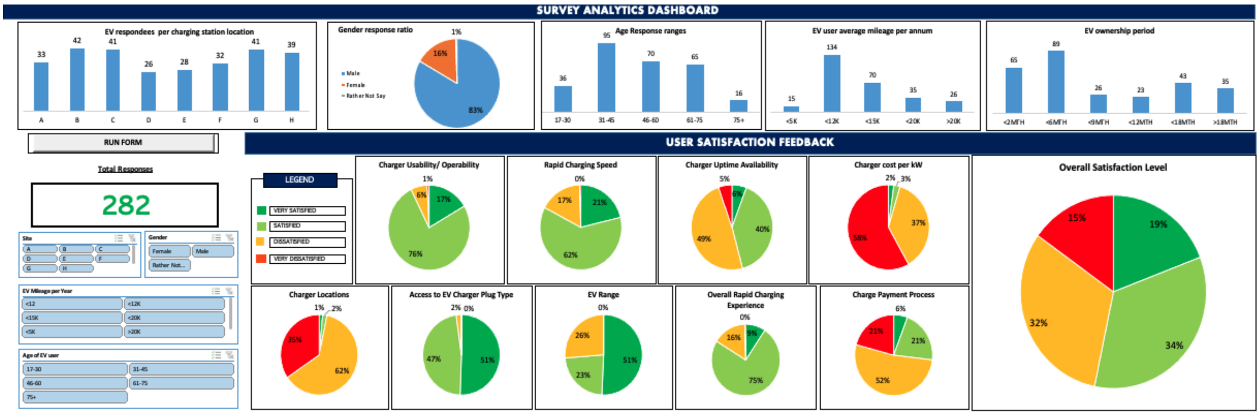



**Figure 3.29.** Survey database front end dashboard highlighting all responses

# Chapter FOUR

## 4.0 Evaluating the Barrier Effects of Charge Point Trauma (CPT) on UK Electric vehicle Growth [1.27]

### 4.1 Introduction

For electric vehicles (EVs) to realise the UK government's goal of mass-market dominance, there are surmountable hurdles to resolve before car users accept this radical shift in motoring technology. This chapter focuses on recent EV adopters who may experience a new psychological phenomenon, defined as the psychological, physiological, and behavioural condition where EV user's experiences develop trauma or anxiety in response to the availability of sufficient charge points, locations, payment processes, and operability [1.27].

EVs are often depicted as the panacea to decrease air pollution and facilitate a zero-carbon future. To prove its intent and commitment to carbon reduction, the UK government has accelerated its plan to ban all diesel and EVs from 2040 to 2030 [1.22]. Many EV growth barriers require resolution before the government's ambitious goal can be realised. As increased EV battery range lowers range anxiety amongst new and existing EV users, consumer's current fears point to the absence of sufficient charging infrastructure for EVs, particularly rapid chargers located on main motorway and trunk roads. Rapid charge point availability and geographic location concerns are cited as the leading barrier to the growth of EV purchases and user satisfaction in the UK [4.1]. EV development in the UK is significant due to growing consumer demand. However, the UK market lacks extensive investigation [4.2] since most

EV research focuses on the USA and China-based [4.3] markets. This UK centric investigation will concentrate on motorway rapid chargers, the lifeblood for EV drivers partaking in long-range commuting.

This study considers whether electric vehicle (EV) drivers suffer from a broader traumatic phenomenon than the established psychological experience of range anxiety. We hypothesise that a new source of distress or trauma is emerging that does not simply focus on an EVs range but extends to user apprehension and resulting behaviour. Primary causes include rapid charger location, availability, disparate payment processing, variable charge costs and general operability. In contrast, we contend that these impediments are seldom experienced by ICE drivers.

### 4.2.1. Defining elements and theoretical framework

This investigation focuses on new and existing EV adopters who may experience this emerging phenomenon that we describe as CPT. In addition to the highly cited phenomenon of range anxiety [4.4, 4.5, 4.6], this study defines CPT as the psychological, physiological, and behavioural condition where EV user's experiences and anxiety vary in response to the availability, location, payment process and operability of an EV public rapid charge point. This research contends that resolving these five significant obstacles to EV use reduces long-term barriers to sector growth, thus stimulating a decline in CPT, illustrated in Fig. 4.1. Although not grouped as a collective phenomenon named CPT, these five EV driver anxieties are investigated in recent research [4.7].

Whilst range anxiety is well-defined over the past decade, to date, no examination has explicitly looked at CPT, a new phenomenon that is closely tied to all five elements in Fig. 4.1 and is validated by research in a recent peer-reviewed survey [4.7] that is the first study to investigate four of the five elements, forming this new phenomenon denoted as CPT.

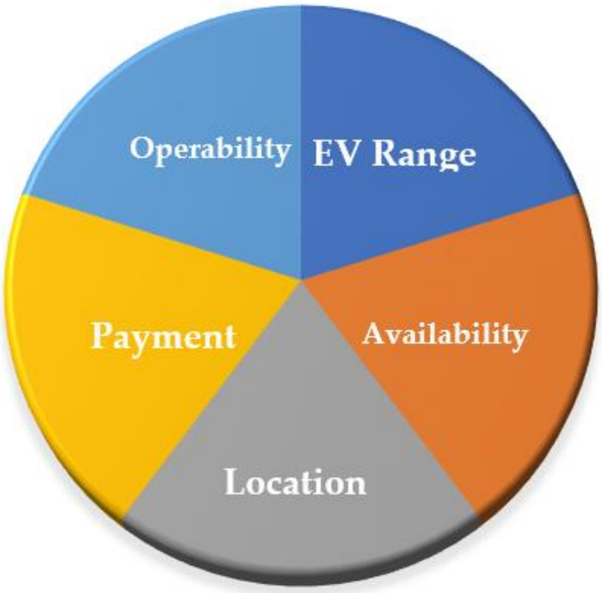



**Figure 4.1**. Significant EV driver concerns

Creating a theoretical framework to define a broad relationship between the established range anxiety phenomenon and CPT is fundamental. To illustrate these two distinct phenomena, this study establishes that range anxiety occurs en-route, and CPT develops at the charging location. Fig. 4.2. Illustrates the interrelationship between range anxiety and CPT and defines the boundaries between both phenomena. One of the four elements that contribute to CPT, the location of the charge point, is additionally a critical variable that contributes to range anxiety, illustrated in Fig. 4.2. In Section 4.3, this enquiry analyses the results of the seven case studies, revealing range anxiety as a common thread running throughout the data that played a significant part in raising trauma levels before arriving at the charge point, despite the extended range of the EV employed in this investigation.

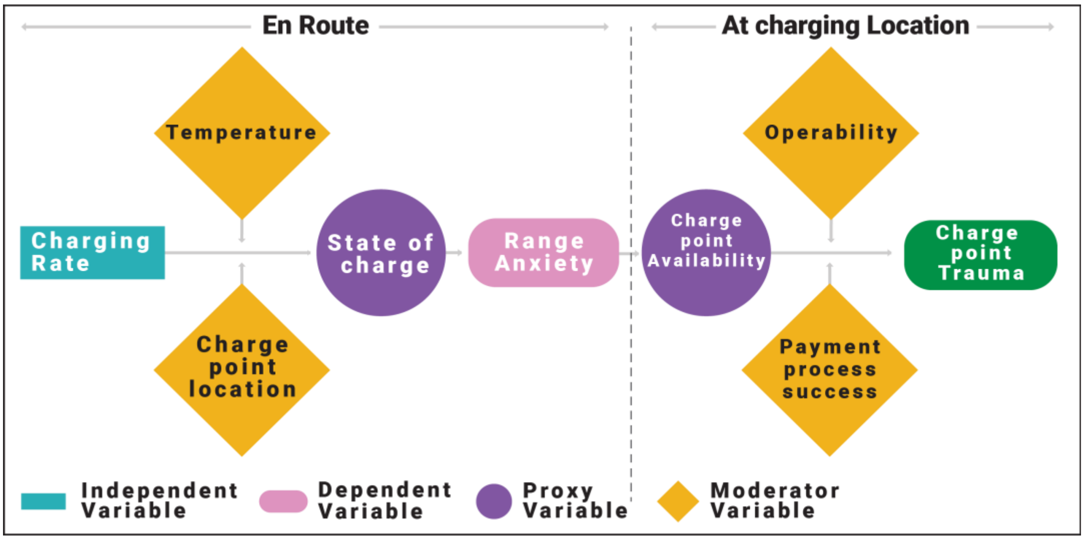



**Figure 4.2.** Theoretical framework showing the interrelationship between range anxiety and CPT

### 4.2.2. Research concept and design

To date, no investigation has explicitly looked at CPT. Therefore, to validate the hypotheses, the first part of this study considers the phenomenon of range anxiety to underpin the theoretical basis of this investigation, pointing to more significant trauma and its effect on new and existing EV drivers. The investigation then examines the current EV sector by comparing sales volume, forecasts, and the lack of contemporary literature surrounding CPT extending beyond range anxiety. Rapid chargers were chosen as the research focus since they are the only charging option for long-range EV commuters on the UK motorway network, enabling a relatively quick full charge in under one hour. This timescale is accelerated if (a) the car can accept higher charge rates and (b) if the rapid charger can deliver higher charge rates above the de-facto rapid charging standard of 50 kW per hour.

### 4.2.3 Range anxiety

EV drivers typically experience greater anxiety levels than traditional ICE drivers due to a developing, relatively immature rapid charging network [4.8]. Advanced levels of range anxiety can potentially lead to adverse effects on an EV driver's reactions and may even cause unsafe driving behaviours. Because of this potential safety issue, several studies [4.8 and 4.9] have developed to comprehend range anxiety, including evaluation models and influential factors. Moreover, various solutions are proposed in the literature to mitigate range anxiety.

Rauh et al. [4.8] examined the assumption that range anxiety affects only inexperienced EV drivers and disappears as the driver gains more driving experience. However, the research suggests that even experienced EV drivers experience higher anxiety levels than experienced ICE drivers in similar situations. In a recent article [4.8], participants with diverse driving experiences are given a critical range situation, where the remaining EV range was lower than the journey length. By gauging range evaluation and range stress with different scales, investigators learnt that driving experience significantly affected all measured variables. With more experience, EV drivers tend to have less harmful range evaluation and hence range anxiety. Therefore, it is essential to increase the efficiency and effectiveness of the learning process for EV drivers. This analysis concurs with the field-based investigation in Section 3.

To enhance the factors that can relieve range anxiety, a similar article [4.9] designed a field study environment to examine several factors contributing to lower *Everyday Range Stress* (ERS). The case revealed that variables such as consciously reducing instances of critical range situations, higher practical experience, emotional range competence, tolerance of low range, and experienced dependability of the EVs range calculation display were related to lower ERS. Furthermore, Franke et al. [4.9] confirmed that range anxiety is directly related to range and EV satisfaction.

Few studies were found to validate the influence of in-vehicle information systems (IVISs) on range anxiety. However, Eisel et al. [4.10] performed a battery EV field experiment under a live traffic state. The investigators noted the participant's psychometric range appraisal and psychophysiological feedback. They concluded that individuals perceived the critical range situation as less challenging and threatening with the provided charge rate calculating display. However, although the IVIS accuracy reduced the mean value of stress throughout the driving task, the investigators discovered that participants using IVIS's had higher levels of stress perception. These results indicate that often, range displays, however accurate, can increase depletion cognisance of range resources over time.

Many solutions are proposed in current literature to reduce EV drivers' range anxiety. Tannahill et al. [4.11] studied the future of range anxiety solutions by investigating a driver alerting algorithm proposed to minimise range anxiety. The critical advance of the algorithm is the progressive accuracy of EV range estimation. No complex computations are involved in the algorithm. Hence the algorithm can be applied on affordable microcontrollers and still achieve accurate results.

An article in 2016 [4.12] suggested a path arrangement model based on battery capability and energy cost analysis, equating the battery capacity of the EV with the least energy cost of a round trip to the rapid charging station. If the battery capacity is lower than the distance to the charging station, the study advises the driver to recharge, avoiding being stranded. This model can also provide an accurate calculation of the available range to the EV driver. This model can moderate range anxiety, ultimately stimulating the growth of EVs.

A similar investigation [4.13] proposed an algorithm that creates real-time recommendations in EV charging route planning. The algorithm is based on the collective calculation of a state of charge (SoC) estimation method and GPS, which can calculate and predict the EVs remaining range to the journey destination with the driver's data input. The function is realised through a real-time indicator system run by the algorithm. The EV user experience could effectively be improved by reduced range anxiety during the trip.

Further novel methods suggest range calculation based on a SoC calculation method [4.14]. This new approach accounts for a wide range of environmental, driver style, and behavioural factors. Thus, range estimation can be more precise than results drawn by established techniques, which simply consider vehicle efficiency and the SoC. This new range estimation method can notify the driver of the EVs range capability and propose recommendations on whether the EV needs to recharge before reaching the destination. However, this thesis evidence suggests that five years since this probe, range estimation methods in EVs have significantly improved, now providing very accurate real-time range estimation.

This literature investigation is essential in verifying and advancing previous range anxiety studies that this analysis argues forms a significant part of CPT's extended EV driver trauma phenomenon. Previously evaluated methodology [4.14] was employed in route two, Section 3 of this investigation, and produced almost identical results when analysed in Section 4. This experiment provided insight into individual differences in range stress when EV drivers are faced with a critical range situation for the first time, where participants were given a route of which the range was tailored close to the EVs range capacity. The results were helpful to formulate strategies aimed at reducing early EV experience range stress that may lead to lower CPT, as discussed in Section 4.

### 4.3. Study concept and design

For three months, seven controlled case studies were conducted that were split across two distinct routes, both using either motorways or A class trunk routes, described in Section 3. In each case, an EV driven by a novice driver set the benchmark for the successive ICE and EV drivers. In the benchmark trip, a novice EV driver was employed for both routes. Anxiety pinch points were recorded and used for key measurements in each successive journey regardless of skill. Further detail on each anxiety milestone is contained in the final section.

During the seven benchmark studies, the driver's heart rate was recorded at critical points in the journey and transposed into anxiety levels using a simple matrix design detailed in Section 3. The same anxiety pinch points were retrospectively plotted for each trip made in an ICE vehicle, using the heart rate data assigned in real-time data paired with correlated anxiety calculations to provide a valid comparison with all case study EV journeys. The critical anxiety pinch points are mapped in the two routes used in Fig. 4.3 and Fig. 4.4.


**Figure 4.3.** Route 1. Southwest

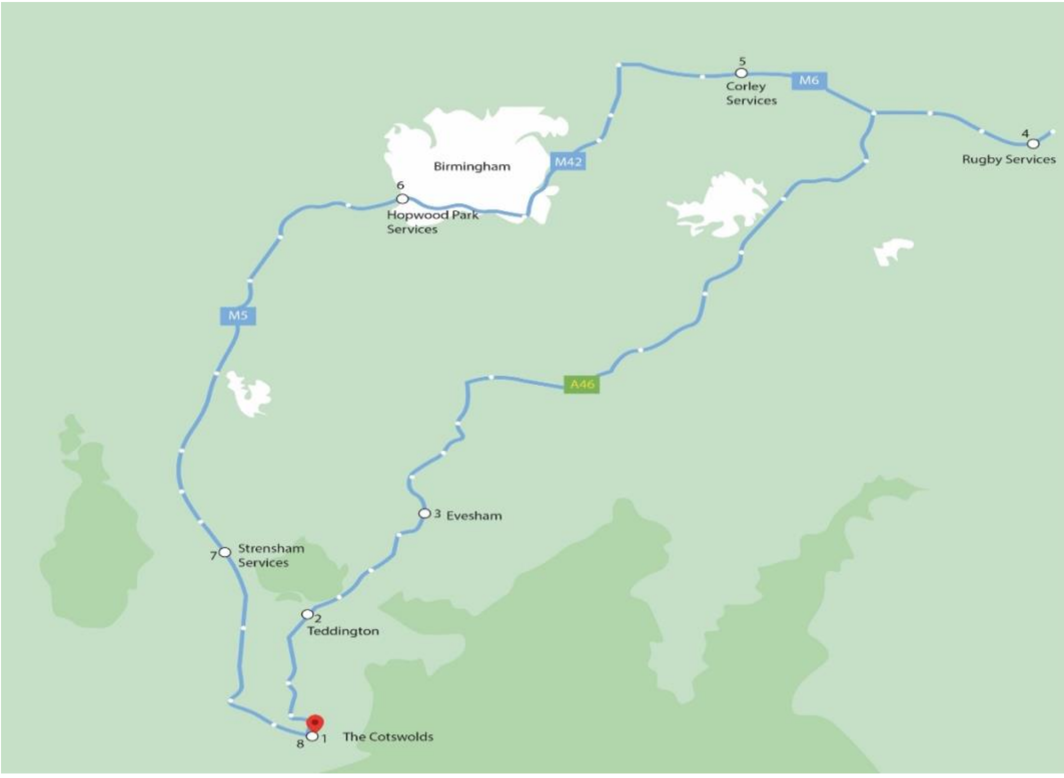



**Figure 4.4.** Route 2. North

Section 4 discusses the case output and potential methods to mitigate CPT, one of the current barriers to EV adoption, leading into Section 5: where results and investigation limitations are presented. Finally, Section 6 summarises the conclusion, suggesting future research opportunities.

### 4.3.1 Current EV Market

According to the Society of Motor Manufacturers and Traders (SMMT), the number of EVs on UK roads has increased from 2012 to 2020, as shown in Fig. 4.5 [4.15]. Additionally, the investigation shows that from 1 January 2012 to 31 December 2020, 199,660 pure EVs were sold cumulatively in the UK market (excluding plug-in hybrids).

The increase in new EVs on UK roads directly affects availability and increased use of the UK rapid charging network, increasing additional driver anxiety compared with refuelling and commuting in traditional ICE vehicles. The logic behind this statement is that the average number of EV rapid charge points on UK Motorways ranges from 2 to 4 units, compared with 16 to 20 traditional fuel pumps in fossil fuel service stations.

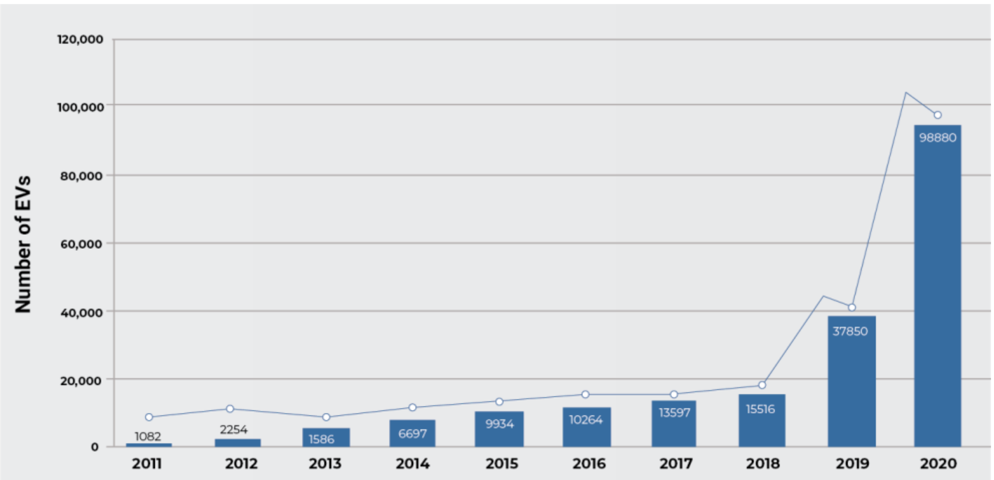



**Figure 4.5** Growth in the number of EVs in the UK market 2011–2020 [4.15].

The UK market share of pure EVs amounted to 5.8% of total new car sales [4.5], which is a significant milestone considering EVs current limited mass production. Traditional car companies have a limited portfolio of EVs compared to pure EV companies such as Tesla, who offers five EV models (2020). For example, Mercedes-Benz, BMW, and Audi have only two fully electric sport utility vehicles (SUVs), each in their current model ranges, while Jaguar has only one model. Further research reveals the SMMT and the International Energy Agency (IEA) [4.16] forecast that the demand for EVs will grow exponentially in line with the global transition to electric mobility [4.3,4.4]. The IEA also predicted that growth would be bolstered by increasing concerns regarding anthropogenic contamination of the environment, charging infrastructure deployment, policy changes, and EV affordability.

## 4.4. Aims of this investigation

The principal aim of this analysis is to determine whether CPT exists as a phenomenon among new and existing EV drivers and establish what factors stimulate this anxiety. Secondly, using the study's primary research, the study aims to develop a possible link between weaknesses in the deployment and operation of the UK's current motorway rapid charging network strategy leading to CPT by embracing four main topics areas of research. The following four questions originate from the previous published survey's top four EV driver concerns [4.7] upon arrival at a charging station. Answers to these four questions will elucidate whether CPT is an emerging phenomenon.

1. Are there sufficient rapid chargers to meet current UK growth?
2. Are the operability service levels acceptable?

3. Are established rapid chargers live and available to use?

4. Is there an operational issue with payment processing?

Finally, the research will determine if the cumulative effect of any weaknesses in these areas reveal a cause-and-effect relationship that may negatively impact the future growth of the UK EV market through analysis of the data from the seven case studies by employing a correlated *T*-Test analysis.

Following comprehensive analysis of the primary research through case studies and field surveys, a proposal proceeds based on future examination with suggestions for further analysis. The main emphasis is to reduce barriers to EV growth connected to *CPT*, thus setting a path of equivalence with 'always available' traditional fossil fuel service stations by exploiting a proposed technological and regulatory solution.

### 4.4.1. The existing reality of EV rapid charging

Although a body of research has discussed EV user experiences in general terms [4.2, 4.15, 4.17], less attention is paid to charting EV user involvement and CPT for typical long-distance travel that relies entirely on the motorway rapid charger network. Fig. 2 illustrates an archetypal long-distance EV commute using a mid-range 60 kWh battery to travel a maximum 500-mile notional route comparable with case studies one, two, three, and four.

One of the chief differences between traditional fossil fuel and EV commuting is that, generally, ICE vehicles have a greater range per refuel than EVs. Furthermore, there are three additional differentiators for EV users that traditional ICE drivers would not experience. The study argues that these three factors (points 1, 2, and 3 in Fig. 4.6) are the prime source of a psycho-technical and behavioural phenomenon amongst EV drivers that is notionally designated as CPT.

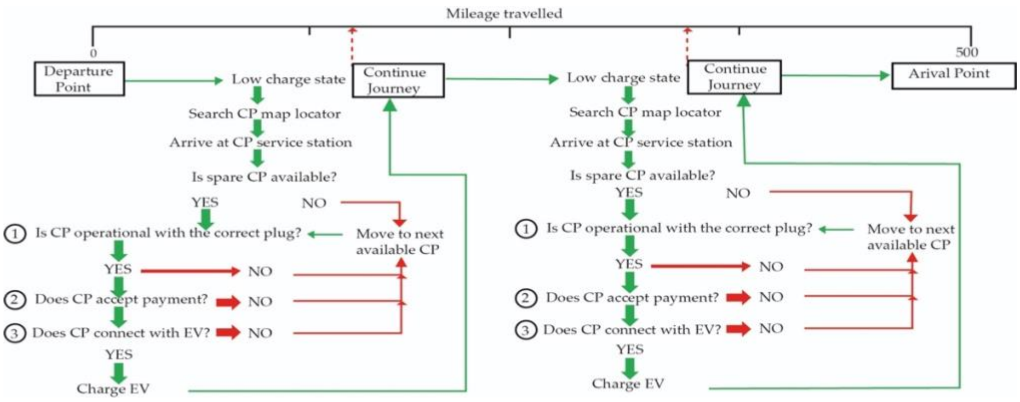



**Figure 4.6**. EV user long distance commute - flow chart highlighting three main user issues

This investigation is the first to focus on the four significant causes of CPT. These causes have been identified through a peer reviewed EV user survey in Q4 of 2019 [4.7] including recent case study investigations. The top four issues concerning most new and existing EV users are:

1. Lack of sufficient rapid chargers in key commuting locations.
2. Charge point operating correctly with correct EV connector available.
3. Charge point payment process (i.e., contactless pay-as-you-go or subscription model only)
4. Charge point connection. Does the charge point communicate with the EV correctly, successfully delivering the required charge?

These issues are unfamiliar to a traditional ICE driver. The research [4.7] emphasises four main concerns that face every EV driver visiting a public rapid charge station that proliferates the phenomenon of CPT backed by data analysis in Section 4. Furthermore, despite a decade of research on the technological aspects of EVs and their user effects, existing research has primarily focused on the declining phenomenon of range anxiety in a similar context. Furthermore, Pevec et al. [4.18] agree that increasing EV battery capacity has made range anxiety much less of an issue for day-to-day driving. Current EVs are increasingly built with larger capacity batteries offering far greater mile range per charge.

### 4.5. Supporting statistics

The distribution of the rapid charging station is another potential cause for CPT since long-range EV drivers must align their journey with the rapid charger network. Deviation from the route could result in inconveniences and increased mileage for customers. Additional concern surrounds some rapid charging stations with exclusivity to individual EV brands, leaving owners of other EV brands unable to access these rapid charger networks. Furthermore, although the number of public charge stations has increased tenfold from a low of 3672 in 2015 to 21,989 in December 2020 (Fig. 4.7), *CPT* is expected to continue since the growth of rapid charge points has not aligned with the demand for EVs [4.19].

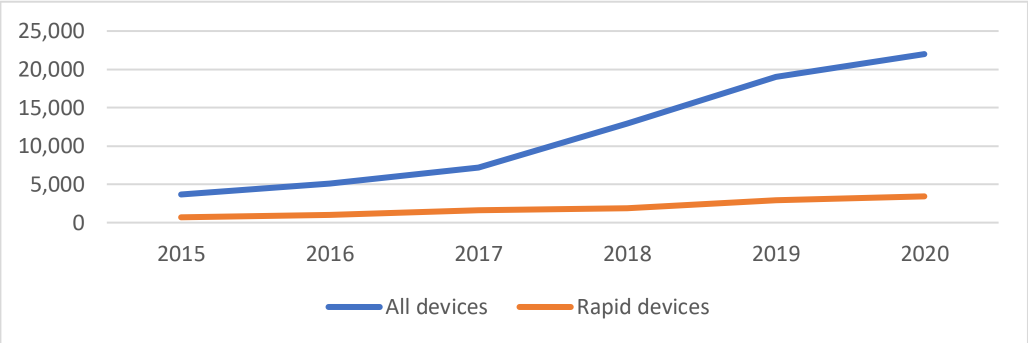



**Figure 4.7**. Growth in public charging station network across the UK [4.19]

#### 4.5.1 EV rapid charging review

The service availability of rapid charging stations is critical considering the limited mile range of available EVs [4.20, 4.21]. Although Tesla has a significant network of supercharger points for EVs across UK trunk routes [4.22], they have not been included in the investigation because they are exclusive to Tesla drivers. Further, observations drawn from Tesla's website regarding the Charge point distribution is consistent with an investigation of EV and infrastructure in the UK by Hirst [4.1]. This study concurs, arguing that public charge points are still unevenly distributed across the UK, implicating that access to charge points is still something of a postcode lottery.

Bunce et al. [4.2] report survey results of EV drivers in the UK, establishing that EV driver anxiety was most pronounced in new owners. The survey of commuting rapid charge EV users on main motorway routes confirms this finding. After a three-month follow-up, the drivers had a more positive perception of recharging. However, no driver equated their experience to traditional petrol/diesel vehicle refuelling [4.2], which is a critical area linked to the CPT research in Section 3. This study contends that this has been overlooked in past studies that investigate EV driver anxiety.

The positive attitudes towards EVs among the surveyed drivers in the group were paradoxical, considering they did not rely solely on public charging infrastructure, instead opting to charge their EVs overnight at home when feasible. According to Bunce et al. [4.2], UK EV drivers maintained that public charging infrastructure for EVs was unnecessary, with 83.7% of the surveyed drivers opting to charge their EVs in private residences. However, only 20% of these respondents were long-distance commuters. This study argues that the preference for overnight charging at home can be partly explained by the inadequacy of the EV public charging infrastructure in the UK, as shown in Fig 4.8 [4.19]. Furthermore, it is contended that as EVs become mainstream, there will be a growing number of potential EV users living in terraced houses and apartments with no access to, or ability to install an overnight home charger, making the availability of rapid or superchargers essential for this UK demographic.

Moreover, this investigation agrees with Delbosc et al. [4.23], noting that early adopters were likely to be more affluent and own stand-alone homes with drives or garages for practical installation of individual charging points, rather than urban dwellers who may rely on public street charging facilities. The UK pattern contrasts significantly with the charging behaviours of US and Chinese EV consumers who, according to M. Nicholas et al. [4.24], rely more heavily on public charging infrastructure due to the greater distances between towns. This reveals that fundamental technological constraints apply to both urban and long-haul inter-city commuters alike [4.25].

#### 4.5.2 EV energy storage technologies driving CPT: R&D challenges

From an engineering perspective, the progress made in battery energy storage systems predicts EV efficiency in terms of mileage and charging requirements. This claim is supported by a comparative analysis of EV batteries, mileage range, charge times, energy costs, and Wh/km [4.26]. Based on the information from this research, there is a direct relationship among the standard charging time, range, Wh/km, and battery chemistry. Higher capacity batteries generally require longer charge times that superchargers may be able to address. The downside of larger battery packs is the weight of the batteries, which contradicts previous claims by Tarascon and Armand [4.26], who argued that lithium-ion batteries offered a lightweight design, whereas most EVs comparable to equivalent ICE vehicles weigh between 30% to 50% more [4.27].

Energy storage faces multiple technological barriers, including EV energy requirements, since higher energy translates to higher battery costs and extra weight. However, even if these cost and weight factors are addressed, lithium-ion capacity depletion remains a problem for EVs [4.27] linked to the degradation of electrode materials, accumulation of substrates, higher depth of discharge and thermal-induced damage [4.28].

The challenges linked to power and energy fading and the degradation in lithium-ion batteries have attracted considerable research attention towards developing novel supercapacitor electrode materials from diverse resources. Examples include carbon nanomaterials [4.29], graphene [4.30, 4.31], boron, and titanium [4.32, 4.33], among others. However, achieving both high power and high energy density has remained a challenge. The inherent limitations of supercapacitors have left lithium-ion batteries the preferred energy storage systems for EVs [4.34]. The main question is whether combining these two energy storage technologies could facilitate exploiting the synergistic benefits afforded by both [4.35]. Based on the current state of research regarding development of charging infrastructure, it can be argued that technological limitations for energy storage devices have had a domino effect on the uptake of EVs in the UK market. This view is consistent with market research by

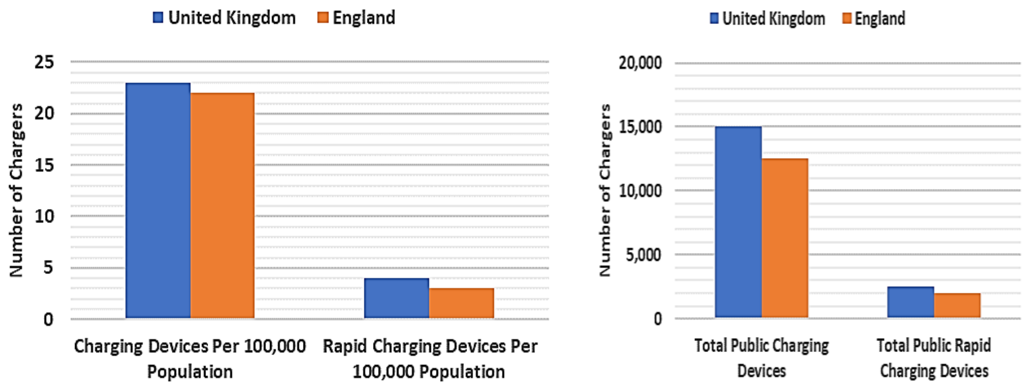
McKinsey Consultants [4.36] who explain how EV battery energy storage was one of the major problems facing EV owners and potential consumers, contributing to range anxiety.

However, the theoretical arguments made in the investigation concerning the adverse impact of energy storage technologies on the sale of EVs can be discounted, considering that cost was also a critical impediment to the availability of EVs. The list prices for most new EVs are incomparable to standard fossil fuel-powered vehicles if you compare them with similar ICE rivals that generally still boast a more significant range per refill.

### 4.5.3. Cost and purchase of EV charging infrastructure

The cost of EV technologies and CPT has indirectly contributed to the limited purchase of EVs in the UK [4.37]. The capital expense of EV technologies encompasses the cost of installing a nationwide public charging infrastructure for EVs in addition to the purchase cost of EVs. According to the US Department of Energy [4.38], like the UK, charge point systems are grouped into three areas: level 1, level 2, and DC rapid charge based on the power requirements and cost. The power requirements and cost estimates for charging infrastructure are balanced through grid planning and user needs [4.37]. The data presented in Fig. 8a and Fig. 8b shows the secondary requirements and power demands for different levels of charging infrastructure contributing to CPT. Rapid charging equipment is expensive and requires additional modifications to the local electricity grid. In many cases, rapid charge stations are located far from main trunk routes to satisfy grid availability rather than EV user’s preference and convenience [4.39]. Conversely, the more affordable

Level 1 and 2 charging infrastructure provides a far slower rate of charge leading to limited range versus charge time but is generally far less expensive to install and with no location constraints due to the low power requirements.




**a**) **b**)

**Figure 4.8. a)** EV Charge Points 2019 [4.19] **b)** EV Charge Points per capita 2019 [4.19]

Considering the link between range and charging infrastructure, DC rapid and supercharging infrastructure installation is necessary. This observation is consistent with a report from the UK House of Commons [4.1] recommending an increase in charge stations. However, it is paradoxical to note that most current deployed charge infrastructure is categorised as a Level 2 standard charge, as shown in Fig. 4.9 [4.40]. The installation of typical charging infrastructure provides limited reprieve for EV owners considering that EVs with longer mile ranges have higher energy requirements. Beyond this, other concerns include the pace of deploying charging infrastructure. Based on data collated by Statista [4.40], the number of regular charge stations had increased from 1500 to 20,451, which translates to about 19,000 new charge stations over eight years. If these growth trends are sustained, there will be a critical shortage of charging infrastructure in the UK by 2030 [4.1].

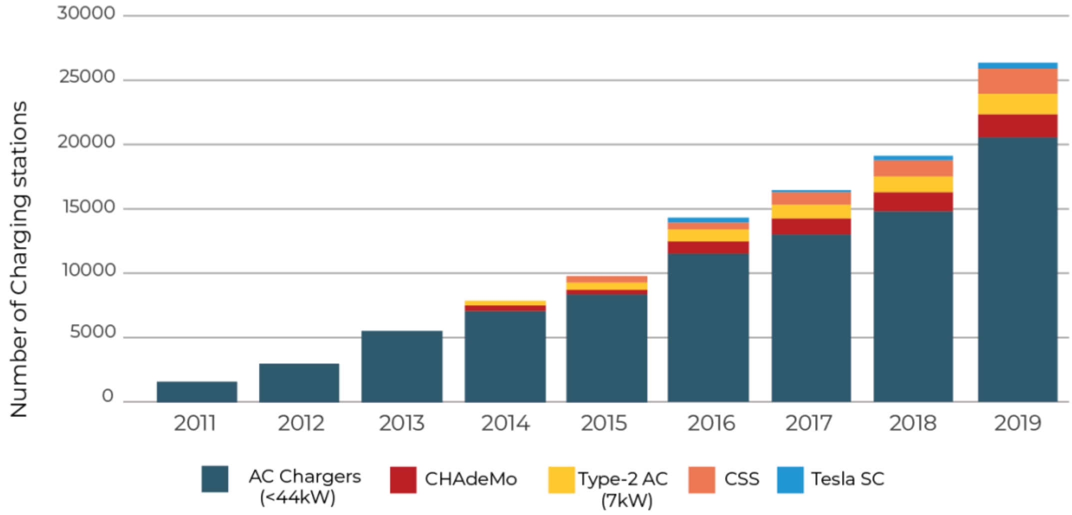


**Fig. 4.9**. Growth in UK charge points by connection type. [4.40]

According to a 2019 government report [4.19], the number of charging stations should increase in line with the ratios presented in Fig. 9. However, it is essential to note that these estimates are grounded on the assumption of constant projected growth in EV sales. There is no certainty that this projected growth is sustainable from an abstract perspective, considering that the EV market's development depends on multiple confounding variables. Moreover, it is difficult to accurately predict the number of private charge stations required for residential homes or offices.

Beyond the concerns illustrated in Fig. 4.9, CPT is exacerbated because current EV models do not have standard power requirements [4.7]. Additionally, EVs require different connectors to charge in the public charging infrastructure, as highlighted in Fig. 4.10. The lack of universally compatible infrastructure limits the utility of available charging infrastructure. As noted in the preceding sections, the existing charging infrastructure is often dedicated to a specific brand. For example, non-Tesla vehicles cannot participate in the Tesla supercharging network. The incompatibility of charge devices and infrastructure is the third leading contributor to CPT [4.7]. For instance, GB/T is a Chinese-based consortium standard, not yet released or used in the UK, but employed extensively across the Far East and may be introduced globally. To further investigate the extent that CPT may have impeded EV growth in the UK thus far, it is essential to test the hypothesis using the case studies and peer-reviewed surveys in Chapter 3.

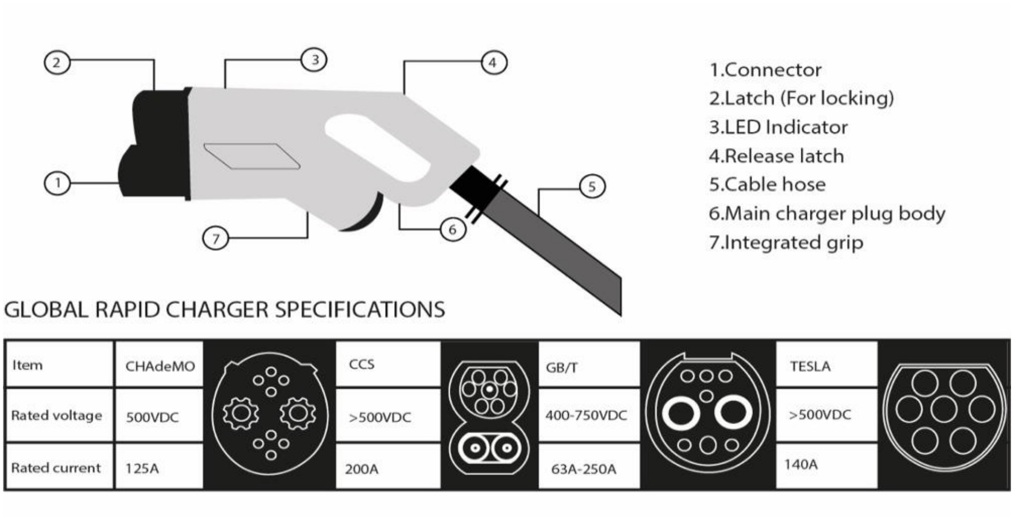



**Figure 4.10.** Disparate rapid charge connector standards in UK (excepting GB/T)

## 4.6. Research Methodology and Analysis

### 4.6.1. Setting

The research setting is the UK EV sector (i.e., England, Scotland, Wales, and Northern Ireland). However, some comparisons are made with Norway [4.41], USA [4.42], and China [4.43] in the secondary data set to establish benchmarks and compare countries because they have made significant technological progress in EVs and supporting infrastructure that could address CPT in the UK. All three countries benefited from generous stimuli and incentives, more so than the typical low-level incentives and grants offered in the UK. The Norwegian EV market is the most developed in the world per capita [4.41]. It has conversely attracted the highest-level government subsidies in the form of EV grants of up to fifty per cent of the purchase price. Additionally, Norway's state-sponsored charging network incentives are typically 100% of installation and material costs [4.41].

Research has reported that government subsidies toward car purchases vary from state to state in the USA, with up to $7,500 USD offered on all new EV sales and up to 100% government or federal grants toward charging infrastructure installation and material costs [4.42]. Similar car subsidies currently exist in China, averaging $2,500 USD per EV whilst charging infrastructure is typically fully subsidised for material and installation costs [4.43]. By contrast, UK EV grants are only available for cars sold under £30,000 GBP, and that subsidy currently equates to only £2,500 GBP. Furthermore, UK subsidies for charging infrastructure and material costs are generally awarded via a bidding process. As a result, they typically amount to 70% of total costs, although this does not apply to all charge point deployment [4.44].

#### 4.6.2. Data Analysis

The data obtained from this examination were analysed using the investigator's primary quantitative data, coded from a study, to provide a balanced result. This is an ideal method for exploring qualitative and quantitative information [4.45, 4.46], even though there are some minor concerns regarding the trustworthiness of this approach. Additionally, data obtained from the House of Commons report [4.1], SMMT [4.40], Deloitte [4.47], and other stakeholders were evaluated. However, it was found that older datasets (i.e., before 2015) were unusable due to obsolete data presented in each report, making them unrepresentative of the current dynamic growth in the EV environment.

### 4.7. Case Study Introduction, Survey Outcome and Methodology

To validate the hypothesis in Section 1, it was necessary to underpin the investigation by generating valid data using a robust method of measuring the anxiety levels experienced by two archetypal EV drivers [4.48] - one experienced in EV driving for more than a year and one completely inexperienced in EV driving. Table 4.1 illustrates the complete trip and driver profile of this study. Each investigation was benchmarked using two separate routes shown in Fig. 4.3 and Fig. 4.4 by employing a novice EV driver. This methodology created a map of novice EV driver situational anxiety markers, and these pinch points were subsequently used for anxiety measurements in each successive case. Full details of why these points resulted in high anxiety levels are detailed in Appendix A. There were more marker points on the outward journeys due to several forced stops to recharge, due to either faulty chargers, inability to pay by card or charge point closed, detailed in Appendix A. On the return journeys, each driver learned which charging stations were operative with a card payment facility, thus negating the same number of stops and subsequently raised anxiety levels.

**Table 4.1.** Driver profiles across both routes in Section 3 case studies

| | | Route 1 - Southwest | | | | Route 2 - North | | |
|---|---|---|---|---|---|---|---|---|
| | Driver profile | CS1 | CS2 | CS3 | CS4 | CS5 | CS6 | CS7 |
| Driver 1 | Experienced ICE driver was employed in study one and five. This driver had more than ten-year's experience with a variety of ICE vehicles and long-distance driving knowledge. | | | | | | | |
| Driver 2 | Novice EV driver used in study two and six. This driver was an experienced ICE driver with long distance driving knowledge, but this was the driver's first experience in an EV. | | B | | | | B | |
| Driver 3 | A different novice EV driver was used in study 3. This driver was an experienced ICE driver with long distance driving knowledge, but this was the drivers first experience in an EV. | | | | | | | |
| Driver 4 | One experienced EV driver was used for studies four and seven. This driver was an experienced ICE driver in long distance driving, with more than two years driving experience in an EV. | | | | | | | |

| Key | CS | Case study | | B | Benchmark study |
|---|---|---|---|---|---|

At the start point, finish point, and each intermediate stop, the driver's heart rate was monitored by an Apple smartwatch worn by each driver throughout every trip. The watch measured real-time heart rate beats per minute (BPM) and stored on a cloud-based server, updated each minute. We chose the FDA (Food and Drug Administration) approved heart rate monitor Apple Series 4 smartwatch with an integrated heart monitor app. The Apple Watch Series 4 employs two light sensors to track the user's heart rate using photoplethysmography (PPG) in blood in peripheral circulation [4.49]. PPG is deemed medical grade and accurately measures heart rate in normal sinus rhythm with a 96% efficacy rate by employing a simple optical process that detects changes in volumetric variations or pulses in blood [4.50]. Although not a clinical precision instrument, it was deemed appropriate for each of the five case studies. Furthermore, the literature has recently confirmed Apple Watch accuracy [4.51], supporting its efficacy for consumer use.

The effectiveness of using heart rate measurements as an indicator to monitor anxiety has been recognised in a recent paper by Khanade and Sasangohar [4.52]. This is considered a vital method to observe the state of anxiety, PTSD, and other related disorders. Thus, key journey points in each case (one to four) were ranked by anxiety levels using the measured driver's heart rate for each significant journey point using data from the driver's smartwatch heart rate monitor. Cases five to seven further reinforced the investigation by conducting an alternative route for ICE and EV journeys compared with stage one case studies. As a benchmark, each driver's resting heart rate was measured the previous day. Both were within the same age range stating that the maximum healthy BPM should be 160 BPM [4.53]. In the first three case studies, driver one's resting BPM rate measured 65, and driver two's resting heart rate measured 61 BPM. In case studies four and five, the driver's resting heart rate measured 63 BPM.

The heart rate data was then converted into anxiety levels ranked from 1 to 10, with resting heart rate ranked as 1 in the range of 60–65 BPM up to and including rank 10, which represented 160 BPM or above (Table 4.2). All rest stops consisted of either water or decaffeinated tea or coffee to prevent caffeine from artificially increasing the heart rate of both drivers. In addition to caffeine [4.54], in new research by Chapman et al. [4.45], it was found that sugar or fructose-sweetened drinks can similarly affect heart rate and blood pressure. Hence, the drivers consumed only sugar-free beverages, caffeine-free drinks, or sugar-free snacks during the investigation.

**Table 4.2.** Heart rate levels correlated to anxiety level ranking for data analysis

Level 1 is considered negligible, while level 10 is extremely high.

| Heart rate | 60–65 | 66–74 | 75–84 | 85–94 | 95–104 | 105–114 | 115–124 | 125–134 | 135–144 | 145–160 |
|---|---|---|---|---|---|---|---|---|---|---|
| Anxiety level | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |

### 4.7.1 Case study 1. Route 1.

Round trip from the Cotswolds to Cornwall and back—UK

Vehicle: 2L diesel compact SUV ICE

Experienced ICE driver

Round trip 430 miles.

Payment method: Apple Pay via iPhone 12 Pro Max

Time to destination: 3 h 42 mins. Average speed 58 mph.

Return trip back to the start point: 3 h 55 min. Average speed 55.2 mph.

Date: 17 April 2021.

The first case analysis plotted a direct round trip. It is replicated in case two to four to compare the 430-mile journey using a modern diesel-powered ICE SUV with an EV. The ICE vehicle used in case one and five has an official maximum range of 480 miles per full tank. Despite the ability to complete this round trip without refuelling, the convenience of driving the ICE test vehicle is that it is possible to use almost any service station to refuel. Additionally, drivers can make a simple payment transaction with a contactless smartphone at the pump or payment kiosk.

The drivers used two iPhone® 12 Pro Max smartphones with fully functioning Apple Pay contactless apps set up for these studies. The motive for adopting this payment method is that it is widely accepted at most retail outlets, with more than a quarter of a million UK stores and service stations receiving this form of payment. All drivers were bound by UK, Covid 19 pandemic cashless payment rules and guidelines during this investigation. Additionally, most retail premises took only contactless payments at the time of this investigation, accepting either contactless credit and debit cards, Apple Pay, Samsung Pay, or Google Pay. Neither driver nor passenger took cash or card with them for case one, two or three. The driver's heart rate was monitored and uploaded live to an Apple cloud-based server throughout the journey. Correlating anxiety levels were retrospectively accessed to match all key points driven by the EV trips' events.

The drivers acquired a 2-Litre diesel medium-sized SUV for case studies one and five. This is a typical long-distance family class vehicle, with a World Harmonised Light Vehicle Test Procedure (WLTP) of 45 mpg consumption, equating to 480 miles on a full fuel tank.

The plotted route was predominantly based on motorways and dual carriageways using ZapMap® EV rapid charging data [4.55]. The route was entered into the in-car satellite navigation from point A in the Cotswolds to point B in Cornwall UK—215 miles. The investigators were confident that the ICE 2 Litre SUV would make the round trip on a single tank of fuel. However, to mitigate any refuelling or payment problems along the route, the drivers erred on the side of caution, deciding that it would be prudent to fill up mid-way on the return leg of the journey to cover any unforeseen en route complications.

The researchers departed the Cotswolds at 07:00 on Saturday, 17 April 2021. The ambient temperature was 12 °C. Two adults were travelling without luggage. The critical points of the journey were recorded using the driver's heart rate data, and corresponding anxiety levels were entered in the table below in Table 4.3.

**Table 4.3.** Case study 1. Journey anxiety levels based on heart rate for ICE SUV

| Key Points on the Journey | Driver 1 Outbound | | Driver 2 Inbound | |
|---|---|---|---|---|
| | Heart Rate | Anxiety Level | Heart Rate | Anxiety Level |
| 1. Departure—Cotswolds | 61 | 1 | | |
| 2. M5 J.11 | 72 | 2 | | |
| 3. Taunton Deane Services | 66 | 2 | | |
| 4. Arrival and return—Cornwall | 66 | 2 | 71 | 2 |
| 5. Taunton Deane Services | | | 73 | 2 |
| 6. Arrival—Cotswolds | | | 63 | 1 |

### 4.7.2 Case study 2. Route 1.

Round trip from the Cotswolds to Cornwall and back

Vehicle: VW iD3 pure electric hatchback

Novice EV Driver

Round trip 430 miles.

Payment method: Apple Pay via iPhone 12 Pro Max

Time to destination: 4 hrs 49 mins. Average speed: 45 mph (including stops).

Return trip back to the start point: 3 hrs 57 mins. Average speed of 54 mph.

Date: 24 April 2021.

The second case analysis determined whether it was possible to travel a round trip of 430 miles in a modern EV in the same manner and with the same ease as driving conventional petrol or diesel cars (case one). Again, two iPhone 12 Pro Max smartphones were used for payment on this trip, with fully functioning Apple Pay contactless apps already set up and established for regular use in the UK. Rapid charging locations were selected based on each location's claim that contactless payment is available in *guest mode*. Neither driver nor passenger took cash or card with them for this investigation. A VW iD3 was acquired for this case examination since it is a new EV model in the small hatchback family class, and the WLTP range is stated at 264 miles on a full charge.

The drivers plotted an identical route to case study one. The route was predominantly motorway and dual carriageway based on ZapMap® EV rapid charging data [4.55] and entered with a start and finish coordinate using the in-car satellite navigation system from point A in the Cotswolds to point B in Cornwall, a total distance of 215 miles. The investigators were reasonably confident that the VW iD3 would narrowly reach the destination point on a single charge if charging or payment problems were encountered along the route. However, it was still deemed prudent to top-up at the halfway point to cover any unforeseen eventualities that may lie ahead.

The researchers departed the Cotswolds at 16:00 on Saturday, 24 April 2021. The ambient temperature was 15 °C. Two adults were travelling, plus two overnight suitcases. The departure point was just 9 miles from the M5. Critical points of the whole journey were recorded with the driver's heart rates and corresponding anxiety levels entered in the table, highlighted in Table 4.4.

**Table 4.4.** Case study 2. Journey anxiety levels based on heart rate—EV full electric.

| Key Points on the Journey | | Driver 1 Outbound | | Driver 2 Inbound | |
|---|---|---|---|---|---|
| | | **Heart Rate** | **Anxiety Level** | **Heart Rate** | **Anxiety Level** |
| 1. | Departure—Cotswolds | 76 | 3 | | |
| 2. | M5 J.11 | 87 | 4 | | |
| 3. | Cullompton Services | 89 | 4 | | |
| 4. | A30 garden centre | 107 | 6 | | |
| 5. | Supermarket charger | 110 | 6 | | |
| 6. | Cornwall Services | 107 | 6 | | |
| 7. | Destination—Cornwall | 88 | 4 | | |
| 8. | Departure back | | | 85 | 4 |
| 9. | Cullompton services | | | 88 | 4 |
| 10. | Arrival—Cotswolds | | | 71 | 2 |

### 4.7.3 Case study 3. Route 1.

**Round trip from the Cotswolds to Cornwall and back—UK**

Vehicle: VW iD3 pure electric hatchback

Novice EV Driver

Round trip 430 miles.

Payment method: Apple Pay via iPhone 12 Pro Max and two contactless credit cards

Time to destination: 4 h 32 min. Average speed: 48 mph (including stops).

Return trip back to the start point: 3 h 57 min. Average speed: 54 mph.

Date: 1 May 2021.

The third case examination replicates case two with the addition of access to Apple Pay or contactless credit cards. The researchers anticipated that this trip would produce far lower anxiety levels than case two and produce results comparable to case one. Again, two iPhone 12 Pro Max smartphones were used for payment on this trip, with fully functioning Apple Pay contactless apps already set up, and two contactless credit cards were made available for locations where Apple Pay was not acceptable. Rapid charging locations were selected based on each location's claim that contactless payment is available in guest mode.

Again, a VW iD3 was used for this case. The drivers plotted an identical route to case one and two. The participants were reasonably confident that the VW iD3 would reach the destination point on a single charge if charging or payment problems were encountered along the route. Although, the drivers planned to top-up at the halfway point to cover any unforeseen eventualities that may lie ahead.

The two-person team departed the Cotswolds at 15:30 on Saturday, 1 May 2021. The ambient temperature was 17 °C. Two adults were travelling, plus two overnight cases. The departure point was just 9 miles from the M5. The critical points of the whole journey were recorded with the driver's heart rates and corresponding anxiety levels entered in the table, highlighted in Table 4.5.

**Table 4.5.** Case study 3. Anxiety levels based on heart rate—EV (cards and Apple Pay)

| Key Points on the Journey | | Driver 1 Outbound | | Driver 2 Inbound | |
|---|---|---|---|---|---|
| | | Heart Rate | Anxiety Level | Heart Rate | Anxiety Level |
| 1. | Departure—Cotswold's | 65 | 1 | | |
| 2. | M5 J.11 | 77 | 3 | | |
| 3. | Cullompton Services | 89 | 4 | | |
| 4. | A30 garden centre | 78 | 3 | | |
| 5. | Supermarket charger | 81 | 3 | | |
| 6. | Cornwall Services | 84 | 3 | | |
| 7. | Destination—Cornwall | 76 | 3 | | |
| 8. | Departure back | | | 78 | 3 |
| 9. | Cullompton services | | | 83 | 3 |
| 10. | Arrival—Cotswolds | | | 71 | 2 |

### 4.7.4 Case study 4. Route 1

**Round trip from the Cotswolds to Cornwall and back—UK**

Vehicle: VW iD3 pure electric hatchback

Experienced EV Driver

Round trip 430 miles.

Payment method: Apple Pay via iPhone 12 Pro Max and two contactless credit cards

Time to destination: 4 h 32 min. Average speed: 48 mph (including stops).

Return trip back to the start point: 3 h 57 min. Average speed: 54 mph.

Date: 1 May 2021.

The fourth study replicates case two, with access to Apple Pay® contactless payment app. The researchers anticipated that this trip would produce far lower anxiety levels than case two and three, producing results comparable to case one due to the relatively long EV experience of the driver. Again, two iPhone 12 Pro Max smartphones were used for payment on this trip, with fully functioning Apple Pay contactless apps already set up. Rapid charging locations were selected based on each location’s claim that contactless payment is available in *guest mode*.

Again, a VW iD3 was used for this case analysis. The drivers plotted an identical route to case one, two, and three. The investigators were reasonably confident that the VW iD3 would reach the destination point on a single charge if charging or payment problems were encountered along the route. Although, the driver planned to top-up at the halfway point to cover any unforeseen eventualities that may lie ahead.

The driver and observer departed the Cotswolds at 15:30 on Saturday, 1 May 2021. The ambient temperature was 17 °C. Two adults were travelling, plus two overnight cases. The departure point was just 9 miles from the M5. The critical points of the whole journey were recorded with the driver’s heart rates and corresponding anxiety levels entered in the table, highlighted in Table 4.6.

**Table 4.6**. Case study 4. Anxiety levels based on heart rate—EV (cards and Apple Pay)

| Key Points on the Journey | Driver 1 Outbound | | Driver 1 Inbound | |
|---|---|---|---|---|
| | Heart Rate | Anxiety Level | Heart Rate | Anxiety Level |
| 11. Departure—Cotswold's | 68 | 2 | | |
| 12. M5 J.11 | 77 | 3 | | |
| 13. Cullompton Services | 73 | 3 | | |
| 14. A30 garden centre | 85 | 4 | | |
| 15. Supermarket charger | 78 | 3 | | |
| 16. Cornwall Services | 84 | 3 | | |
| 17. Destination—Cornwall | 76 | 3 | | |
| 18. Departure back | | | 78 | 3 |
| 19. Cullompton services | | | 83 | 2 |
| 20. Arrival—Cotswolds | | | 71 | 1 |

By overlaying all four case studies in a linear representation Figure 4.11 (1, 2, 3, and 4), the driver anxiety levels reveal the true extent to which EV charging experiences affect driver anxiety levels compared to the same journey in a traditional ICE vehicle. The extreme EV driver anxiety levels were recorded in case two. Equipped with only a contactless payment app on a mobile phone, drivers anxiety levels proved to rise to higher levels than analysis of case one and three due to rapid charger access and payment issues. The reasons for differing anxiety levels are examined in Section 4.8.

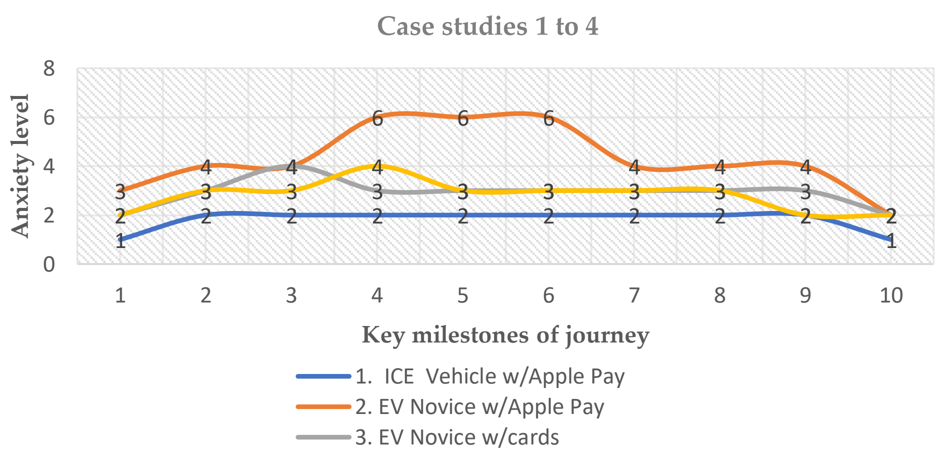



**Figure 4.11.** Case studies 1, 2, 3, and 4. Anxiety level data across all journey points.

The investigators then planned a route north of the Cotswolds spanning a main A-Class trunk route and three different motorways. The mid-way recharging and refreshment point was a new service station on the M6, hosting traditional refuelling facilities and the UK's latest cluster of eight `available to all' 350 kW ultra-rapid chargers, plus eight dedicated Tesla superchargers.

**4.7.5** Case study 5. Route 2

**Round trip from the Cotswolds to Rugby and back, via Birmingham, UK.**

Vehicle: 2-L diesel compact SUV ICE

Experienced ICE Driver

Total distance: 156 miles.

Payment method: Payment method: Apple Pay via iPhone 12 Pro Max

Vehicle range on departure 92 miles

Round trip back to the start point: 2 h 56 min. Average speed of 53.8 mph.

Date: Friday, 14 May 2021.

The fifth examination employs an independent driver and one passenger with the role of researcher-observer. The car in this study is identical to case one, a 2-litre diesel compact SUV ICE. The driver was trained in the diesel SUV operation and basic working theory, including familiarity with all controls. Additionally, the driver was fully insured for the research journey before the commencement of the investigation. This investigation aims to benchmark the route for an ICE vehicle, including the driver's anxiety level, before carrying out an identical journey in an EV (case 6). One researcher travelled as a rear seat passenger and monitored the driver's behaviours associated with using conventional petrol or diesel cars. The driver's only form of payment was a contactless Apple smartphone using Apple Pay®. The driver was provided with Zap Map [4.55] to plot a break in the journey mid-point for refreshments and fuel top-up and wore an Apple Watch 4 to monitor and measure heartbeat at critical points along the route. These data were then used to measure and correlate anxiety levels throughout the journey.

The driver plotted a new route for a round trip, starting and finishing at the Cotswold start point. The route was predominantly motorway, dual carriageway and A-class trunk roads based on Zap Map® EV rapid charging data [4.55]. The driver entered the start, interim, and finish coordinates using the in-car satellite navigation system from the Cotswolds to Rugby, then past Birmingham and finally returning to the start point in the Cotswolds. The total journey distance was 156 miles. However, the investigators deliberately provided the car to the driver with just a 92-mile range, compelling the driver to refill with diesel at the mid-way point.

The driver and observer departed the Cotswolds at 13:00 h on Friday, 14 May 2021. The ambient temperature was 17 °C. The critical journey points were recorded with corresponding driver heart rates and resultant anxiety levels entered in the table, highlighted in Table 4.7.

**Table 4.7.** Case study 5. Anxiety levels based on heart rate—ICE SUV (Apple Pay only)

| Case Study 5 | Driver Round Trip | |
|---|---|---|
| Key Points on the Journey | Heart Rate | Anxiety Level |
| 1. Departure—Cotswolds | 68 | 2 |
| 2. Teddington Hands Roundabout—A46—no stop | 74 | 2 |
| 3. Morrisons supermarket—Evesham A46—optional charge point | 72 | 2 |
| 4. Rugby Services—M6 mid-way—charge and refreshment break | 70 | 3 |
| 5. Corley Services—M6—no stop | 67 | 2 |
| 6. Hopwood Park Services—M42—no stop | 69 | 2 |
| 7. Strensham Services—M5—no stop | 73 | 2 |
| 8. Arrival—Cotswolds | 72 | 2 |

### 4.7.6 Case study 6. Route 2.

**Round trip from the Cotswolds to Rugby and back via Birmingham—UK.**

Vehicle: VW iD3 pure electric hatchback

Novice EV Driver

Total distance: 156 miles.

Charged range on departure: 88 miles (31% charge)

Payment method: Apple Pay via iPhone 12 Pro Max

Return round trip back to the start point: 3 h 05 min. Average speed: 50 mph.

Date. Tuesday, 18 May 2021

The sixth case analysis employs one driver entirely new to EVs. The driver was trained in the EV operation and basic working theory, including familiarity with all controls. The driver was fully insured for the research journey before the commencement of the investigation. This study aimed to observe how an experienced driver who has never driven an EV manages a round trip of 156 miles in a modern all-electric vehicle. One researcher travelled as a rear seat passenger and scrutinised any changes in the driver's habits. As in case five, the driver's only form of payment was a contactless Apple smartphone using Apple Pay®. The driver was provided with Zap Map [4.55] to plot a break in the journey mid-point for refreshments and suggested recharge. The driver planned charging options based on each location's claim that contactless payments were available in PAYG Guest mode.

Again, a VW iD3 was acquired for this examination. The driver used an Apple Watch 4 to monitor and measure heartbeat at critical points along the route. These data were then used to measure and correlate anxiety levels throughout the journey.

The 156-mile route used in case five was duplicated for this investigation. The driver entered the start, interim and finish coordinates using the in-car satellite navigation system from the Cotswolds to Rugby, then on to Birmingham and finally returning to the start point in the Cotswolds. The total journey distance was 156 miles. The driver and observer departed the Cotswolds at 13:00 h on Tuesday, 18 May 2021. The ambient temperature was 17 °C. Two adults were travelling, comprising one researcher as an observer and one driver. The critical points for the whole journey were recorded using the drivers heart rates and corresponding anxiety levels entered into the table, detailed in in Table 4.8 below.

**Table 4.8**. Case study 6. Anxiety levels based on heart rate—VW iD3 EV (Apple Pay only)

| Case Study 6 | | Driver Round Trip | |
|---|---|---|---|
| | Key Points on the Journey | Heart Rate | Anxiety Level |
| 1. | Departure—Cotswolds | 77 | 3 |
| 2. | Teddington Hands Roundabout—A46—no stop | 96 | 6 |
| 3. | Morrisons supermarket—Evesham A46—optional charge point | 118 | 7 |
| 4. | Rugby Services—M6 mid-way—charge and refreshment break | 107 | 6 |
| 5. | Corley Services—M6—no stop | 98 | 5 |
| 6. | Hopwood Park Services—M42—no stop | 107 | 5 |
| 7. | Strensham Services—M5—no stop | 88 | 4 |
| 8. | Arrival—Cotswolds | 69 | 2 |

### 4.7.7 Case study 7. Route 2.

**Round trip from the Cotswolds to Rugby and back via Birmingham, UK.**

Vehicle: VW iD3 pure electric hatchback

Experienced EV Driver

Total distance: 156 miles.

Charged range on departure: 86 miles (31% charge)

Payment method: Apple Pay via iPhone 12 Pro Max

Return round trip back to the start point: 3 h 01 min. Average speed: 50 mph.

Date. Wednesday, 19 May 2021

The seventh case analysis employed one experienced EV driver (D). The driver was trained in the iD3 EV operation and basic working theory, including familiarity with all controls. The driver was fully insured for the research journey before the commencement of the investigation. This probe observed how an experienced EV driver manages a round trip of 156 miles in a modern all-electric vehicle. One researcher travelled as a rear seat passenger and scrutinised any changes in the driver's habits. As in case six, the driver's only form of payment was a contactless Apple smartphone using Apple Pay®.

The driver was provided with Zap Map [4.55] to plot a break in the journey mid-point for refreshments and suggested recharge. The driver planned rapid charging options based on each location's claim that contactless payments were available in PAYG guest mode.

Again, a VW iD3 was acquired for this case examination. The driver used an Apple Watch 4 to monitor and measure heartbeat at critical points along the route. These data were then used to measure and correlate anxiety levels throughout the journey.

The 156-mile route used in case studies five and six was duplicated for this case analysis. The driver entered the start, interim and finish coordinates using the in-car satellite navigation system from the Cotswolds to Rugby, then on to Birmingham and finally returning to the start point in the Cotswolds. The total journey distance was 156 miles. The driver and observer departed the Cotswolds at 13:00 h on Wednesday, 19 May 2021. The ambient temperature was 16°C. Two adults were travelling, comprising one researcher as an observer and one driver. The critical points for the whole journey were recorded using the drivers heart rates and corresponding anxiety levels entered into the table, detailed in Table 4.9, and highlighted in graphical form in Fig. 4.12.

**Table 4.9.** Case study 7. Anxiety levels based on heart rate—VW iD3 EV (Apple Pay only)

| Case Study 7 | Driver Round Trip | |
|---|---|---|
| Key Points on the Journey | Heart Rate | Anxiety Level |
| 1. Departure—Cotswolds | 71 | 2 |
| 2. Teddington Hands Roundabout—A46—no stop | 76 | 3 |
| 3. Morrisons supermarket—Evesham A46—optional charge point | 88 | 4 |
| 4. Rugby Services—M6 mid-way—charge and refreshment break | 85 | 4 |
| 5. Corley Services—M6—no stop | 76 | 3 |
| 6. Hopwood Park Services—M42—no stop | 77 | 3 |
| 7. Strensham Services—M5—no stop | 79 | 3 |
| 8. Arrival—Cotswolds | 68 | 2 |

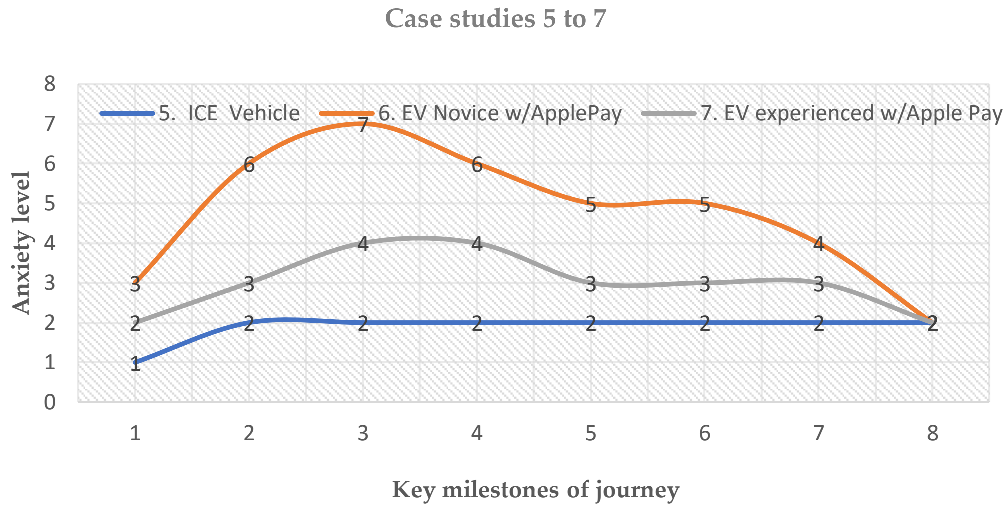



**Figure 4.12**. Anxiety levels for case study 4, 5, and 7. EV drivers using Rapid Chargers in Critical Service Station Locations in the UK

The higher anxiety levels among EV drivers resulting from the seven case studies, highlighted in Fig. 4.11 and Fig. 4.12, link with observations and existing data from the previous peer-reviewed analysis [4.7]. A structured survey of 282 EV motorway rapid charging EV users found four main areas contributing negatively towards growth in the EV sector 1) rapid charger geographic locations. 2) charger uptime and operability at point of use, 3) restrictive payment process, and 4) rapid charge cost per kWh. Table 4.10 compares the results from the previous survey revealing anxiety levels of EV users ranging from very satisfied to very dissatisfied, all critical issues that correlate directly with the researcher's findings within the EV long-distance case studies two, three, four, five, and six. The survey results are shown in Table 4.10. The study [4.7] concentrated wholly on the UK motorway and A-Class UK trunk road network. In contrast, the seven new case studies in this research included a mix of over 570 miles of motorways, dual carriageways, and A-class single lane trunk roads.

**Table 4.10.** Dominant outcomes from each survey question [4.7]

| UK Motorway EV Rapid Charging User Survey | | | | | |
|---|---|---|---|---|---|
| | Questions | | | | Subject |
| | Very Satisfied | Satisfied | Dissatisfied | Very Dissatisfied | |
| Q1 | | 76% | | | Charger availability |
| Q2 | | 62% | | | Charger speed |
| Q3 | | | 49% | | Charger operability |
| Q4 | | | | 58% | Charge cost |
| Q5 | | | 62% | | Charger locations |
| Q6 | 51% | | | | Connector availability |
| Q7 | 51% | | | | EV range |
| Q8 | | 75% | | | Overall experience |
| Q9 | | | 52% | | Payment process |
| CGA | | 34% | | | Satisfaction average |

### 4.7.8 Case study and recent user survey summary data

It is impossible to precisely reproduce each route due to variables that cannot be replicated on the day. Among the most important of these is ambient temperature, which can adversely affect EV battery range. Other factors may include weather conditions such as wind, rain or snow, and general traffic conditions or disruption, all of which may affect the range of an EV.

### 4.8. Discussion

In Tables 4.11 and 4.12, the case studies reveal that an EV driver's experience is more traumatic than a conventional ICE vehicle driver, with far higher anxiety levels being measured throughout their journey. This result is supported by recent survey [4.7] of drivers across major service stations on the UK network, revealing that most EV drivers considered charge cost, charge point operability, charge point location, payment process, and access were significant areas of dissatisfaction. The results suggest that CPT exists because of a significant correlation between increased heart rate at key journey points. Moreover, the literature confirms a significant link between heart rate and anxiety levels [4.52]. This study contends that unless urgent interventions are implemented to alleviate this growing EV user issue, then the introduction of enforced sector regulation to improve overall parity with ICE fuel service stations should be investigated.

**Table 4.11.** Case studies 1, 2, 3 and 4 anxiety level comparison table.

| Key Data Points on the Journey | Case Study 1 (ICE) | Case Study 2 (EV) | Case Study 3 (EV) | Case study 4 (EV) |
|---|---|---|---|---|
| 1. Departure—Cotswold's | 1 | 3 | 2 | 2 |
| 2. M5 J.11 | 2 | 4 | 3 | 3 |
| 3. Cullompton Services | 2 | 4 | 4 | 3 |
| 4. A30 garden centre | 2 | 6 | 3 | 4 |
| 5. Supermarket charger | 2 | 6 | 3 | 3 |
| 6. Cornwall Services | 2 | 6 | 3 | 3 |
| 7. Destination arrival—Cornwall | 2 | 4 | 3 | 3 |
| 8. Departure back | 2 | 4 | 3 | 3 |
| 9. Cullompton services | 2 | 4 | 3 | 2 |
| 10. Arrival—Cotswold's | 1 | 2 | 2 | 2 |
| Average heart rate | 67.9 BPM | 90.8 BPM | 78.2 BPM | 76.6 BPM |
| Combined mean average anxiety levels | 1.80 Experienced | 4.3 Novice | 2.9 Novice | 2.8 Experienced |

**Table 4.12.** Case studies 4 and 5 anxiety level comparison table.

| Key Data Points on the Journey | | Case Study 5 (ICE) | Case study 6 (EV) | Case study 7 EV |
|---|---|---|---|---|
| 1. | Departure—Cotswold's | 1 | 3 | 1 |
| 2. | Toddington Services—A46 | 2 | 6 | 2 |
| 3. | Morrisons Evesham | 2 | 7 | 2 |
| 4. | Rugby Services—M6 mid-way | 2 | 6 | 2 |
| 5. | Corley Services—M6 | 2 | 5 | 2 |
| 6. | Hopwood Park Services—M42 | 2 | 5 | 2 |
| 7. | Strensham Services—M5 | 2 | 4 | 2 |
| 8. | Arrival—Cotswold's | 1 | 2 | 2 |
| Average heart rate | | 67.2 BPM | 93.6 BPM | 70.4 BPM |
| Combined mean anxiety levels | | 1.75 Experienced | 4.75 Novice | 1.87 Experienced |

### 4.9. Results and Analysis

The sample for this investigation included experienced ICE drivers, novice EV drivers, and an experienced EV driver. The rationale for the mix of driving experience was to monitor and validate any differences between the three driver cohorts, travelling the same route under the same conditions, with only driver experience and vehicle type being variables (Table 4.1). Heart rate was captured and logged via a cloud-based database, using a 4G mobile link, by the minute throughout each journey.

Before analysing the data, it was noted the benchmark novice EV drivers BPM as EV range dropped before arriving at each charging station. From the data and noting the drivers concerns regarding range en route, BPM and anxiety heightened as the EV range lowered before arrival at the charging station on both routes. These data, coupled with the driver's changing behaviour and growing anxiety, confirmed that, even though modern EVs such as the test car had a range above 260 miles, the novice EV drivers were still experiencing reasonably high levels of range anxiety. This was also confirmed through *t*-test correlation analysis that can be observed in detail in the last chapter section.

This initial case study prompted the design of a field-based theoretical framework (Fig. 4.2) to map not just the elements of CPT, but to illustrate how range anxiety still forms a significant component of the EV driving experience and behaviour, despite the ever-increasing mileage ranges of newer EVs. It is clearly seen from the data that although range anxiety is the catalyst for increased EV driver anxiety levels amongst novice drivers, there was a significant increase in anxiety once the driver had entered the charging zone.
Moreover, anxiety levels lowered once a successful charging cycle commenced. Conversely, when the novice EV drivers entered a charging zone and encountered one of the three barriers to charging that contribute to CPT (Fig. 4.2), then significant increases in anxiety were noted (Fig. 4.13 and Fig. 4.14). The data confirm a significant correlation between heightened EV driver anxiety and barriers to charging encountered at key milestone five in route one (Fig. 4.13). The novice EV driver continued to the next charging station in a state of higher anxiety. The data reveals that there is a combination of CPT experienced at the charge point and then heightened range anxiety displayed onward. Again, this phenomenon is observed with a clear correlation between higher anxiety and barriers to charging experienced at key milestone three in route one using a novice driver (Fig. 4.14).

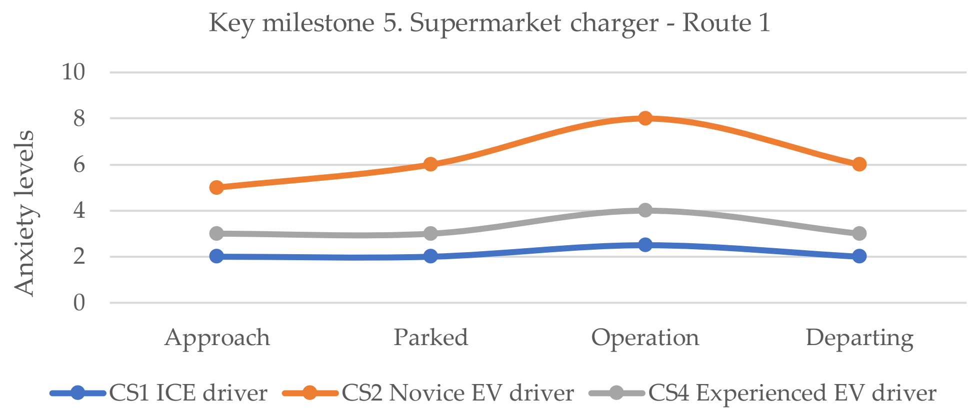



**Figure 4.13.** Comparative analysis of EV driver anxiety state at an inoperable charge point.

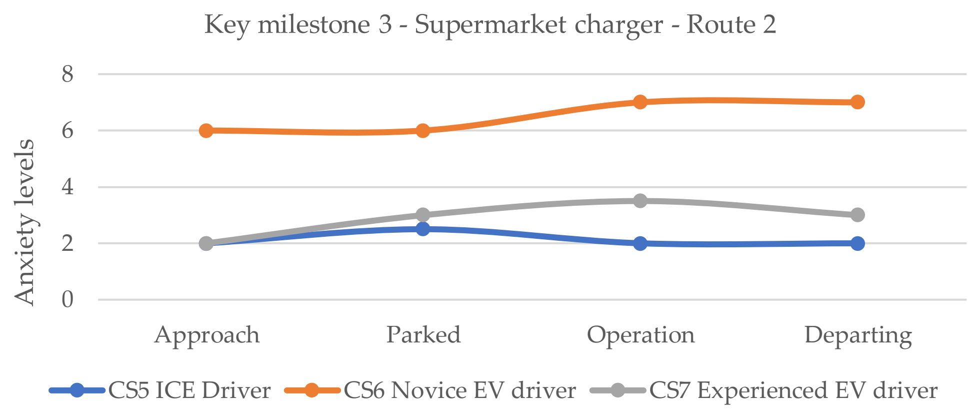



**Figure 4.14.** Comparative analysis of driver anxiety state at an inoperable charge point

For the experienced EV driver, the levels of range anxiety were still heightened en-route, but at a markedly lower level overall when entering the charging zone compared to the novice drivers. This suggests that as experience and familiarity with an EV develops, then range anxiety and CPT levels are correspondently lower as confidence in the vehicle increases.

To confirm this theory, the data was further investigated. The drivers state of anxiety was observed when approaching a charge point, parking up, plugging in, experiencing a trouble-free charge, then continuing the journey on departure. The key milestone three was investigated at the M5 Cullompton services on route one, inbound journey (Fig. 4.15). This time, a fractional, insignificant rise in the ICE drivers state was noted immediately before refuelling. In contrast, there was no further rise on the journey approach in the driver's state of anxiety. Once refuelling and charging for all drivers were in progress, there was a significant drop in anxiety for both novice and experienced EV driver's at and after recharging. This confirms the hypothesis that where no barriers to charging exist, then EV drivers state of anxiety is consistently lower in this research analysis.

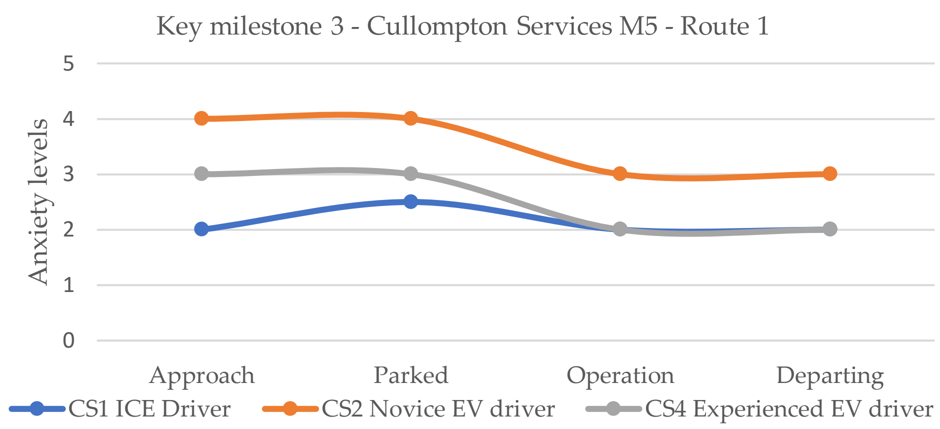



**Figure 4.15.** Comparative analysis of anxiety state of drivers at an operable charge point.

Finally, the data from key milestone four was analysed to Rugby services M6 on route 2 (Fig. 4.16). This time no rise in the ICE driver's state immediately before refuelling was observed. Once refuelling and charging for all drivers was in progress, there was a significant drop in the state of anxiety for both novice and experienced EV drivers. Furthermore, after recharging, particularly for novice EV drivers, their anxiety level dropped markedly, demonstrating increasing confidence in their vehicle. Again, this confirms the hypothesis that where no barriers to charging exist, the EV drivers state of anxiety is always lower in the case studies. Even after recharging, the novice EV drivers' state of anxiety was higher than the experienced EV and ICE driver, confirming that prolonged EV driving experience reduces anxiety relating to both vehicle range and CPT.

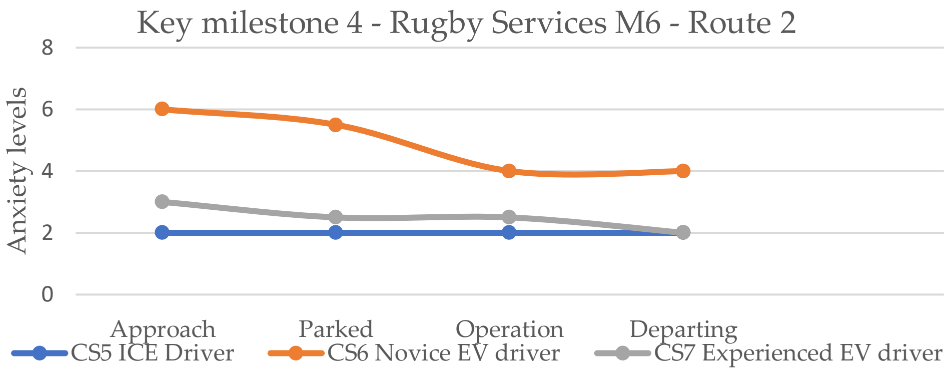



**Figure 4.16**. Comparative analysis of anxiety state of drivers at an operable charge point.

The descriptive results in Appendix B indicate that drivers in route two had a higher average heart rate than drivers who undertook route one. The main reason for this is that route one drivers started the journey with a full charge, whereas, on route two, both ICE and EV vehicles were limited with just enough fuel or charge to make it to the mid-point stop at Rugby Services, forcing a refuel or recharge.

Finally, the ICE driver with more than ten years of experience with long-distance driving rarely encountered the same levels of anxiety experienced by either type of EV driver. One of the main reasons behind this phenomenon is because the ICE vehicle's range enabled it to travel the total round-trip distance of the south-westerly route with fuel to spare. Moreover, on the shorter northern route two, even faced with just enough fuel to complete half of the trip, the ICE driver's confidence maintained a constant low state of anxiety. This lack of range anxiety in an ICE vehicle is almost certainly because the ICE fuelling network is greater than 99% reliable [4.15] and thus builds confidence in a driver's ability to refill on-demand. Moreover, due to tight regulation on opening hours, crewed fuelling stations operate to highly regulated service level agreements on uptime and operability. There was practically no heightened anxiety with this cohort of drivers. To date, there is little regulation across the UK network for EV rapid charging stations.

Although this research points to increased anxiety at the charge point, and the analysis points to CPT, further in-depth research should be conducted to establish that CPT is more than extended range anxiety. Since this investigation confirms from the data, that in all cases anxiety rises at the charge point zone when some form of operational problem creates a barrier to charge point use. This enquiry is the catalyst for further investigation.

By providing insight into CPT, this research illuminates potential EV owner's preferences regarding charging station infrastructure. The results indicate that the location of charging stations heightened a state of anxiety, and for this reason, the charging stations should be closer to each other to reduce range anxiety. This can lead to higher EV growth by encouraging more vehicle users to purchase an EV versus a traditional ICE vehicle. Taking this into account, it is argued that this investigation covers the CPT phenomenon from four different perspectives—location, accessibility, payment access, and operability.

Using the data collected via the case studies and user surveys described in Section 4.4, research questions introduced in Section 4.1 are answered as follows:

- Future EV owners will require a charging station infrastructure denser than the current ICE refuelling infrastructure due to an average EV taking up to ten times longer to refuel [4.7].
- As EVs replace ICE vehicles, there will be a surplus of traditional ICE fuelling stations due to lowering demand for their services. These may be converted to high power EV rapid charging stations to reduce the EV charge point deficit, subsequently alleviating current anxiety levels amongst EV drivers, thus lowering CPT (subject to grid availability).
- For future studies, it is planned to increase the survey participant sample with a more focussed and targeted audience by including drivers who are either undecided about, or on the point of making an EV purchase. This phase is critical in understanding and quantifying that the CPT phenomenon is not only a significant issue and potential barrier to EV growth, but should be a requirement to credibly remodel charge point infrastructure planning as an essential element to driver EV acceptance.

### 4.9.1. Distribution of charge points and CPT

The distribution of charge stations across the UK reveals that the charging infrastructure is not well-developed. The uneven distribution of charging infrastructure reported by the DfT [4.19] is consistent with public EV charging infrastructure observations. Specifically, the DfT argued that there are no predefined criteria for infrastructure installation, and manufacturers have relied on a `postcode lottery' approach leading to *user anxiety*. Beyond the uneven distribution of rapid charge infrastructure, the manufacturer's low transition to electric mobility and low EV mileage range indirectly contribute to *CPT*, discussed in Section 4.2.

### 4.9.2. Manufacturer's Low Transition to Electric-Powered Mobility

Current industry data shows that established manufacturers fulfilled the limited EV development of EVs. This phenomenon is reinforced by a comparative analysis of the market share and the state of growth of carbon fuel-po1red vehicles. According to SMMT data [4.37], the principal UK manufacturers largely maintained their market share in the 2018/2019 financial year. In addition, the number of non-EVs sold was incomparable to the ratio of EVs traded, noted by SMMT [4.37]. The Business, Energy, and Industrial Strategy Committee of the House of Commons (HoC) similarly established that manufacturers showed varying commitment levels to electric mobility [4.1]. Both Volkswagen and Mercedes committed to achieving a 25% transition to EVs by 2030, seen as unsatisfactory within the UK government report [4.1]. Volvo and Toyota have announced their intentions to transition to 50% within this period by 2030. Porsche and Jaguar were the only exceptions, with both companies proposing a 100% transition by 2030 [4.1]. This inconsistent commitment to the electrification of the powertrain could contribute to a slowdown in the adoption of EVs in the UK market, considering that Volkswagen and Mercedes have a combined market share of 17% as of 2019 [4.37]. The above observation is supported by the fact that limited EV development would make the installation of brand-specific charging infrastructure economically unsustainable. Further research is required to ascertain the extent to which commitment to electrification slowed EV growth in the UK.

The level of rapid-charging network growth in the UK is comparable to similarly established European markets, as shown in Fig. 4.17 below. Conversely, the UK lags China, Norway, and the USA in the number of vehicles adopted but are similar as a per capita ratio to China and the USA. Furthermore, the UK, USA, Norway, and China are market leaders in EV technologies and vehicle development. This problem could be addressed if stakeholders collaborate to develop the charging infrastructure jointly. Nevertheless, private sector efforts are inadequate without government-supported policy support changes by the government. According to Hirst [4.1], examples of such policies include EV registration tax exemptions, VAT exemption at the point of purchase, ongoing zero road tax, access to free municipal parking and elimination of tolls, parking, and bridge fees for EVs. This study concurs with Hirst that such policy changes would incentivise charge point operators to increase charge station's deployment [4.1].

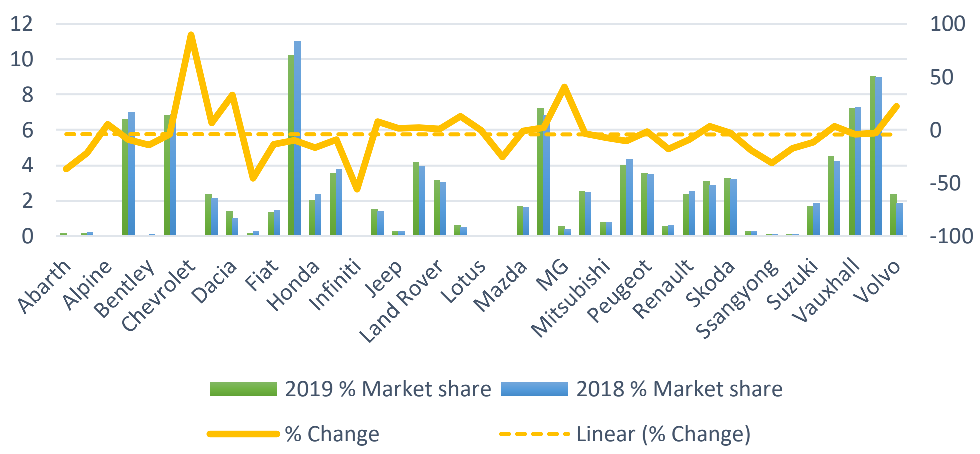



**Figure 4.17.** Market share % in the ICE segment (2019 versus 2018).

### 4.9.3. Recommendations

The following recommendations are informed by best practices applied in the UK, US, China, and Norway. All four countries act as a reference point and benchmark since they are global leaders by EV volume per capita.

First, policymakers should calculate the total number of EVs on the road, including forecasts up to 2030. Second, EV power requirements and regional variations in the power demands should be determined. Analysing the power requirements will help determine the charge duration and the number of chargers needed per square mile, and how the chargers are categorised. Thirdly, more government intervention should regulate the UK's rapid charging network's operation, availability, and location. Fourthly, there needs to be more investment from government and manufacturers to incentivise consumers toward the transition to an electric future. The Norwegian model is a testament to how inducements can stimulate the transition towards a 100% electric target. Norway currently has the world's highest number of EVs per capita, totalling 55.9% of the total car market in 2020 [4.15]. By adopting the four-point analysis above, the investigation argues that it may reduce the incidence of CPT by removing anxiety pinch points that many EV drivers experience now [4.7].

### 4.9.4. Limitations

The primary drawback of this investigation is the overall lack of published literature concerning CPT. Although new, relevant, and current research was conducted through case studies and user surveys, the results are limited by sample size. Bodies such as SMMT, International Council on Clean Energy, Deloitte, and other stakeholders have published various EV reports. Still, some of these reports and data sets are not updated and may be biased toward the intended reader. For example, information published between 2010 and 2017 does not reflect the current state of the EV sector because the industry is dynamic and continuously evolving. Additionally, there was an inherent risk of bias in published data by EV manufacturers, partners, and regulators with a vested interest in the industry. These limitations demonstrate the need for further primary research, and it is suggested that this will be an ongoing necessity in this fast-moving, dynamic market.

These proposals should also be employed to test against the UK government's latest target of banning all new petrol and diesel-engined cars by 2030. Moreover, in a report by Deloitte [4.47], almost one in four EV drivers would not have access to a driveway or a private charging station. This position may exacerbate CPT unless it is effectively addressed by installing new roadside public rapid charge stations. Even though there is a consensus on the need to develop a contiguous nationwide network of rapid-charging stations [4.3, 4.31, 4.46] and to transition from the current postcode lottery system [4.1], there is no long-term framework for funding or regulation. Concerns about funding transition should be addressed since the installation of charging infrastructure is hugely capital intensive.

### 4.9.5. Statement of Significance

The findings drawn from this research may provide important implications for policymakers, EV manufacturers, charge point operators (CPO's), and EV owners by taking stock of the progress made in EV manufacturing and assimilation into the automotive sector, the prospects for growth, and the barriers linked to the absence of sufficient operable and available charging stations with equivalence to fossil fuel station access. Furthermore, the investigation of the link between CPT and the growth of EVs in the UK may help inform future decision-makers in the development of nationwide contiguous charging infrastructure, satisfying the requirements of EV consumers, accelerating user acceptance to make the change to an EV, and subsequently driving growth by reducing current barriers to adoption and use of EVs.

### 4.9.6. Chapter conclusion

The following observations were made from this investigation. First, there is a level of evidence in the research and analysis regarding the link between CPT that, if ignored, may act as a barrier to EV growth in the UK due to significant EV user dissatisfaction in fundamental areas [4.7]. Both primary case studies and surveys revealed user ambiguity in the following five areas. 1) range anxiety, an element that was discounted initially, but still intensely exists, 2) rapid charger locations, or lack of, 3) point of use availability, 4) disparate payment processing and variable charge costs, and 5) general operability (Fig. 1). The evidence is informed by industry statistics, research and the seven case studies correlated with previously obtained survey results [4.7]. Secondly, the study found that the level of anxiety lowers with experience and vehicle familiarisation. Finally, the consumer concerns are further validated by the often-random network planning of rapid charger deployment, due chiefly to grid availability rather than user-accessible trunk route location [2]. It is therefore recommended that a government-funded National Network Planning

Committee (NNPC) be formed to eliminate the current barriers facing EV drivers using the UK rapid charging network. This will ensure that before random EV charging locations are granted local planning permission, every project must add tangible value to the overall national network. This will prevent charge point blackspots or, conversely, excess charge points in one area, ensuring contiguous coverage, equal to the current ICE fuelling station network.

Founded on the findings proving a direct correlation between heart rate and anxiety levels, the case studies revealed a worrying upward trend in EV driver anxiety levels caused by infrastructure pinch points, such as lack of available chargers and payment processing complications. Therefore, this research to date through detailed data analysis confirms the hypothesis that there is a critical CPT link to the EV user anxiety levels experienced in the case studies and the dissatisfaction of EV users in four key areas, revealing significant increases in anxiety levels, compared to corresponding journey range anxiety. However, a more stringent investigation covering a much larger sample size may confirm or refute these findings.

From an engineering and technological perspective, it can be argued that there is a casual connection between technical limitations in EV energy storage systems (energy density versus power density) and CPT, because the power limitations in level 1 and 2 Rapid charging systems are linked to the constraint of available technologies. In brief, the central research hypothesis is validated by the current data. Further, the case studies, supported by the recent user survey of 282 motorway EV drivers, revealed a correlation between the four main user survey areas of dissatisfaction [4.7] and the high anxiety events witnessed in the seven case studies, confirming a clear link between anxiety or trauma levels experienced by EV drivers compared to ICE drivers. This is the first examination of its kind and one which will hopefully lead to substantial future investigations. The study argues that CPT will increase amongst EV users and propagate adverse publicity through traditional and digital media channels. A growth slow-down could also be reversed by intervention through governmental regulation and harmonisation in standards for all charge point operators [4.7]. This would bring parity of EV user experience to that of regular ICE drivers.

In general, this research has advanced the current body of knowledge on EV user's post-acquisition by exploring a critical theme beyond the availability and service of the UK EV rapid charge network and mileage range of EVs.

As this study is the first example of an investigation to link four constituent barriers to EV growth that together results in a new phenomenon identified as CPT, it is suggested that further research should focus on the most critical negative EV user issue—to reverse the practice of continuous deployment of rapid chargers in grid friendly outlying areas, rather than locating rapid charge points in areas where they are most needed to fulfil EV users' needs on main trunk routes. From the evidence in this study, it can only be remedied through government intervention, design, and enforcement of new regulations. The deployment of emerging AI-driven technology to integrate with grid availability and control is recommended, rather than discounting this vital issue.

More complete and accurate documentation, including additional case studies during peak summer months, with higher traffic volumes, higher ambient temperature, and a more detailed driver profile (i.e., age, gender, and physical fitness), may produce a more comprehensive assessment of individual circumstances, leading to complete knowledge of the processes affecting long-term trauma levels in EV drivers. Once a clearer understanding emerges of the relationship between CPT and factors such as age, length of ownership, and familiarity with the EV, measures can be designed and implemented to improve the UK's EV long-distance commuting user experience. This would include a ubiquitous pay-as-you-go system for all contactless payment types, regardless of whether the EV user is a brand member of the charge point operator (CPO).

Furthermore, a legally binding service level agreement between the CPO and the Department for Transport (DfT) regulator mandating a minimum uptime for operability and accessibility of all users is recommended. Additionally, it is estimated that hundreds more rapid charge points are required across all UK main trunk routes. The study found that the average time spent at a charge point was approximately 50 minutes to one hour during the case analysis observations. It is also seen that most UK motorway service stations had just two rapid chargers (two exceptions had four). Given that the UK government is banning the sale of diesel and petrol cars by 2030, the number of rapid charge points on main trunk routes will need to increase at least ten-fold to avoid major queuing at service stations and subsequent delays in an EV user's journey, leading the investigators to pursue ongoing research in this area.

In the short to medium term, whilst it is fully understood that there will be a penalty of additional upfront capital costs in developing dedicated EV service areas; it is expected that this can be offset by greater use of the charging station and increased footfall in on-site amenities due to locality, convenience, and access to main trunk routes. If implemented, the findings and recommendations point to a significant correlation between lower CPT and greater EV user satisfaction, indicating an acceleration in the adoption of EVs by mitigating current barriers to growth and promoting incentives in line with the government “Road to Zero” target [1.22]. In conclusion, the study recommends that all stakeholders, including manufacturers and government, should be fully invested in reducing CPT since it may slow EV adoption and could be a significant barrier to growth in the EV sector. Furthermore, an acceleration of current rapid charger deployment will also diminish current levels of range anxiety due to increased rapid charging capacity across the UK

### 4.9.7 Supporting data

#### **4.9.7.1** A.1. Route 1 - 4 Case Studies Using Different Drivers for Each Trip

Table 4.13. Case study 1. Journey anxiety levels ICE SUV. Experienced ICE driver and observer.

| Key Points on the Journey | Driver 1 Outbound | | Driver 2 Inbound | | |
|---|---|---|---|---|---|
| | Heart Rate (HR) | Anxiety Level | Heart Rate (HR) | Anxiety Level | Driver Observations |
| 1. Departure—Cotswold’s | 61 | 1 | | | Driver is calm and focused. Low BPM. |
| 2. M5 J.11 | 72 | 2 | | | Driver has slightly higher BPM but remains calm |
| 3. Taunton Deane Services | 66 | 2 | | | Driver exhibits constant BPM and remains calm |
| 4. Arrival and return - Cornwall | 66 | 2 | 71 | 2 | Driver exhibits constant BPM and remains calm |
| 5. Taunton Deane Services | | | 73 | 2 | Driver exhibits constant BPM and remains calm |
| 6. Arrival—Cotswold’s | | | 63 | 1 | Driver arrives calm and focused. Low BPM. |

**Table 4.14** Case study 2. Novice EV driver – including one Experienced EV driver and observer

| Key Points on the Journey | Driver Outbound | | Driver Inbound | | Driver Observations |
|---|---|---|---|---|---|
| | Heart Rate (HR) | Anxiety Level | Heart Rate (HR) | Anxiety Level | |
| 1. Departure—Cotswold's | 76 | 3 | | | Driver has above average BPM and appears slightly anxious. |
| 2. M5 J.11 | 87 | 4 | | | Driver appears more anxious as the car approaches busy motorway. Higher BPM. |
| 3. Cullompton Services | 89 | 4 | | | Still significantly high BPM. Driver concerned with range and very concerned that identified services were not found. |
| 4. A30 garden centre | 107 | 6 | | | Very anxious that premises were closed for the day with no available charger. Significant rise in BPM and demonstrating anxiousness on the EVs range ability. |
| 5. Supermarket charger | 110 | 6 | | | Again, very concerned that charge point was not available. Constant high BPM pointing to significant range anxiety and CPT due to inoperable CP's |
| 6. Cornwall Services | 107 | 6 | | | Maintaining range ability of EV en route to charge point. On arrival, chargers required subscription. Driver is now very concerned about reaching destination even though cars range has 30 miles excess charge to destination. Comments that he is apprehensive about range. Still in eco mode. High BPM. |
| 7. Destination—Cornwall | 88 | 4 | | | Although higher than average BPM, the driver is now much calmer after arriving at the destination without further charge. |
| 8. Departure back | | | 85 | 4 | Day 2, and EV now fully charged, higher BPM suggests driver is still anxious, even though there is a charge stop mid-way. |
| 9. Cullompton services | | | 88 | 4 | Refreshment stops only as chargers require a subscription. Driver is still anxious that he may not get to the destination without further charge, despite excess range displayed. Driver switches to eco-mode. |
| 10. Arrival—Cotswolds | | | 71 | 2 | Driver relieved to arrive at home base. BPM lower |

**Table 4.15** Case Study 3. Novice EV driver—including one researcher/observer (with cards and cash).

| Key Points on the Journey | Driver 1 Outbound | | Driver 2 Inbound | | Driver Observations |
|---|---|---|---|---|---|
| | Heart Rate (HR) | Anxiety Level | Heart Rate (HR) | Anxiety Level | |
| 1. Departure—Cotswold's | 67 | 2 | | | Driver BPM is steady and reading just above previously measured standing BPM. Commented that he felt much more confident taking both cash and cards for payment. |
| 2. M5 J.11 | 77 | 3 | | | Slight rise in BPM as we approach major motorway. |
| 3. Cullompton Services | 86 | 4 | | | Arrived at the service station. Drivers BPM was high en-route. The rapid charger works successfully, and BPM is lowering. |
| 4. A30 garden centre | 78 | 3 | | | Now the car is fully charged again, we monitored the driver's BPM at this key point. Calm and focused |
| 5. Supermarket charger | 81 | 3 | | | Calm at this point when reading was taken. No need to stop as excess charge remaining to destination. Still anxious. |
| 6. Cornwall Services | 84 | 3 | | | The driver opted not to stop at this service station, but the observer took BPM. Calm and focused |
| 7. Destination—Cornwall | 76 | 3 | | | Driver calm and commented 'relief at arriving', despite having 111 miles of range remaining. BPM above average |
| 8. Departure back | | | 78 | 3 | Leaving with 111 miles range, the driver knew that we had to stop mid-way and appeared slightly anxious re: range. |
| 9. Cullompton services | | | 83 | 3 | On arrival at the service station, the car had 15 miles range left. The driver commented that he was concerned but knew he would make the station with excess charge to spare. Mid BPM |
| 10. Arrival—Cotswold's | | | 71 | 2 | The driver's last BPM check confirmed that with half a charge remaining, there was no anxiety at this point. |

**Table 4.16** Case study 4. Experienced EV driver – including one researcher/observer with cash and cards.

| Key Points on the Journey | Driver 1 Outbound | | Driver 2 Inbound | | Driver Observations |
|---|---|---|---|---|---|
| | **Heart Rate (HR)** | **Anxiety Level** | **Heart Rate (HR)** | **Anxiety Level** | |
| 1. Departure—Cotswold's | 65 | 2 | | | Driver BPM is steady and only just above previously measured standing HR. Driver was calm and looking forward to the trip. |
| 2. M5 J.11 | 77 | 3 | | | Slight rise in BPM as we approach major motorway. Driver appears calm. |
| 3. Cullompton Services | 73 | 3 | | | Constant BPM as we enter the service station for break and refill. Attempted to charge car, but all four chargers are not accepting cards. Driver appeared calm with more range than destination requires. The driver said, 'he was not concerned'. He switched the car to eco mode for maximum economy and proceeded to the next charge point. Although displaying signs of anxiousness. |
| 4. A30 garden centre | 78 | 4 | | | Arriving slightly earlier than the previous trip, the centre was closed and locked to the public. The driver was calm and proceeded to the next charge point. |
| 5. Supermarket charger | 81 | 3 | | | A previous encounter with this charger required membership. The driver was calm at this point when reading taken and proceeded to next service station. |
| 6. Cornwall Services | 84 | 3 | | | The driver opted not to stop, but the observer took BPM. Driver still calm and focused. |
| 7. Destination—Cornwall | 76 | 3 | | | On arrival at the destination point, the driver commented that the car still had 39 miles of range remaining. He said he was calm and happy to have finished the long journey. BPM was measured, standing HR suggesting signs of anxiety. |
| 8. Departure back | | | 78 | 3 | Leaving with a full charge, the driver knew that he could make the journey in one go. However, there was a planned refreshment and charge stop at Cullompton services. BPM was just above average, suggesting slight anxiety. |
| 9. Cullompton services | | | 83 | 2 | On arrival at the service station, the car had 144 miles range left. The driver commented that he was confident he would make the station with excess charge to spare. He found that the chargers would still not accept a card for payment. Calm as he started his last 102 miles in eco mode. |
| 10. Arrival—Cotswold's | | | 71 | 2 | The driver's last BPM check confirmed that with 41 miles remaining, there was almost no anxiety, and he was very calm and happy to be back at home base. BPM was slightly above the average resting rate. |

### *A.2. Route 2—Using Different Drivers for Each Trip*

**Table 4.17**. Case study 5. Journey anxiety levels—one experienced ICE driver and researcher/observer.

| Key Points on the Journey | Heart Rate (HR) | Anxiety Level | Driver Observations |
|---|---|---|---|
| 1. Departure—Cotswold's | 68 | 1 | Driver is calm and focused. Low BPM. |
| 2. Teddington Hands Roundabout—A46—no stop—this is a key HR observation point. | 74 | 2 | Slight rise in drivers BPM but remains calm |
| 3. Rugby Services—M6 mid-way—charge and refreshment break | 70 | 2 | Driver remaining calm and focused. On approach to the midway point, driver has a Steady BPM |
| 4. Corley Services—M6—no stop—this is a key HR observation point. | 67 | 2 | Driver is calm and focused. Steady BPM |
| 5. Hopwood Park Services—M42—no stop—this is a key HR observation point. | 69 | 2 | Driver remains calm. Steady BPM |
| 6. Strensham Services—M5—no stop—this is a key HR observation point. | 73 | 2 | Driver remains calm. Steady BPM |
| 7. Arrival—Cotswold's | 72 | 2 | Calm and focused. Steady BPM |

**Table 4.18**. Case study 6. EV—Journey anxiety levels—one novice EV driver and researcher/observer.

| Key Points on the Journey | Heart Rate (HR) | Anxiety Level | Observations |
|---|---|---|---|
| 1. Departure—Cotswold's | 77 | 3 | Slightly high BPM on departure but driver appeared calm. |
| 2. Teddington Hands Roundabout—A46—No stop—this is a key HR observation point. | 96 | 6 | High HR and very concerned about remaining range but always remained focused. Driver did not switch the car to eco mode as suggested. |
| 3. Morrisons supermarket—Evesham A46—optional charge point | 118 | 7 | On approach, the driver's BPM reached 118. Driver was very anxious on arrival because charger was not available for use. BPM remains high at this stage. The driver commented that he was very concerned about making it to the mid-way charging point due to low range but remained focused. |
| 4. Rugby Services—M6 mid-way—charge and refreshment break | 107 | 6 | Still anxious. BPM level on approach is 107 but relieved that charger is operable, and the car is now fully charged. BPM was very high, showing significant anxiety at this stage. |
| 5. Corley Services—M6—no stop—this is a key HR observation point. | 98 | 5 | BPM dropped, but the driver commented that he was still not completely confident with cars range despite full charge. |
| 6. Hopwood Park Services—M42—no stop—this is a key HR observation point. | 107 | 5 | BPM still moderately high. Driver comments that he still lacked confidence in the cars range ability. |
| 7. Strensham Services—M5—no stop—this is a key HR observation point. | 88 | 4 | Close to the home base, drivers BPM dropping, and anxiety noticeably lessens |
| 8. Arrival—Cotswold's | 69 | 2 | Much lower BPM as home base is reached. Driver commented that he was relieved and relaxed after the round trip. |

**Table 4.19** Case study 7. EV—Journey anxiety levels—one experienced EV driver and researcher/observer.

| Key Points on the Journey | Heart Rate (HR) | Anxiety Level | Observations |
|---|---|---|---|
| 1. Departure—Cotswold's | 77 | 2 | BPM is just above average. Driver appears calm. |
| 2. Teddington Hands Roundabout—A46—no stop—this is a key HR observation point. | 96 | 3 | Calm, but BPM is rising on approach to the first charging stop. |
| 3. Morrisons supermarket—Evesham A46—optional charge point | 118 | 4 | BPM rises when driver discovers that charger cannot be used without a subscription. Although, the driver still appeared calm and focused. |
| 4. Rugby Services—M6 mid-way—charge and refreshment break | 107 | 4 | BPM maintains a similar mid-rate on arrival at mid-point charging stop |
| 5. Corley Services—M6—no stop—this is a key HR observation point. | 98 | 3 | Driver's BPM lowers once the EV has been fully charged |
| 6. Hopwood Park Services—M42—no stop—this is a key HR observation point. | 107 | 3 | Driver appears calm. Although, drivers BPM is above the resting rate. |
| 7. Strensham Services—M5—no stop. This is a key HR observation point. | 88 | 3 | Again, no significant change in BPM, appearing calm and focused. |
| 8. Arrival—Cotswold's | 69 | 2 | Drivers HR drops on arrival to home base at just above resting rate. Driver commented, that he enjoyed the trip. |

#### **4.9.7.2** Data Analysis and Results

Descriptive Analysis

A descriptive analysis was conducted to examine the average heart rate and anxiety levels for each case investigation, and overall (all case studies and routes 4 combined), utilising the mean, standard deviation, minimum, and maximum statistics to conduct the analysis. The results established from the analysis undertaken is presented in Table 4.20 below. The highest rank represents the lowest BPM and anxiety level, and the lowest rank represents the highest BPM and anxiety levels

**Table 4.20.** Descriptive Analysis of Study Variables Per Case.

| Case Study | | N | Mean | SD | Min | Max | Rank |
|---|---|---|---|---|---|---|---|
| 1 | Heart Rate | 7 | 67.43 | 4.65 | 61 | 73 | 7 |
| | Anxiety Level | 7 | 1.71 | 0.48 | 1 | 2 | 7 |
| 2 | | | | | | | |
| | Heart Rate | 10 | 90.80 | 13.21 | 71 | 110 | 2 |
| | Anxiety Level | 10 | 4.30 | 1.34 | 2 | 6 | 2 |
| 3 | | | | | | | |
| | Heart Rate | 10 | 78.10 | 5.86 | 67 | 86 | 3 |
| | Anxiety Level | 10 | 2.90 | 0.56 | 2 | 4 | 4 |
| 4 | | | | | | | |
| | Heart Rate | 10 | 76.60 | 5.78 | 65 | 84 | 5 |
| | Anxiety Level | 10 | 2.80 | 0.63 | 2 | 4 | 5 |
| 5 | | | | | | | |
| | Heart Rate | 7 | 70.43 | 2.64 | 67 | 74 | 6 |
| | Anxiety Level | 7 | 1.86 | 0.38 | 1 | 2 | 6 |
| 6 | | | | | | | |
| | Heart Rate | 8 | 95.00 | 16.37 | 69 | 118 | 1 |
| | Anxiety Level | 8 | 4.75 | 1.67 | 2 | 7 | 1 |
| 7 | | | | | | | |
| | Heart Rate | 8 | 77.50 | 6.61 | 68 | 88 | 4 |
| | Anxiety Level | 8 | 3.00 | 0.76 | 2 | 4 | 3 |
| Overall | | | | | | | |
| | Heart Rate | 60 | 80.00 | 12.65 | 61 | 118 | |
| | Anxiety Level | 60 | 3.12 | 1.36 | 1 | 7 | |

Heart Rate Descriptive Analysis

Considering the results presented in Table 4.20 above, the minimum heart rate level for case one driver was 61, while the maximum was 73. The driver in case one had an average heart rate of 67.43 with a standard deviation of 4.65 measured across seven measuring points along the departure and return route.

Route 1. Southwest Round Trip

The minimum heart rate level for case two drivers was 71, while the maximum was 110. The driver in case two had an average heart rate of 90.80 with a standard deviation of 13.21 measured across ten measuring points along the departure and return route.

The minimum heart rate level for the case three driver was 67, while the maximum was 86. The driver in case three had an average heart rate of 78.10 with a standard deviation of 5.86 measured across ten measuring points along the departure and return route.

The minimum heart rate level for case four driver was recorded as 65, and the maximum was 84. The driver in case study four had an average heart rate of 76.60 with a standard deviation of 5.78 measured across ten measuring points along the departure and return route.

Route 2. Northern Route Round Trip

The minimum heart rate level for the case five driver was recorded as 67, while the maximum was 74. The driver in case study five had an average heart rate of 70.43 with a standard deviation of 2.64 measured across seven measuring points along the departure and return route.

The minimum heart rate level for the case six driver was recorded as 69, while the maximum was 118. The driver in case six had an average heart rate of 95.00 with a standard deviation of 16.37 measured across eight measuring points along the departure and return route.

Lastly, case seven driver's minimum heart rate level was recorded as 68 while the maximum was 88. The driver in case seven had an average heart rate of 77.50 with a standard deviation of 6.61 measured across eight measuring points along the departure and return route.

Overall, all drivers' minimum heart rate level was recorded as 61, while the maximum was 118. The overall average heart rate level of all the drivers was 80.00, with a standard deviation of 12.65. This study now analyses the full trip: the novice EV driver in case six is described as having the highest average heart rate level (*M* = 95.00, *SD* = 16.37) while the lowest heart rate level was for the experienced ICE driver in case study one (*M* = 67.43, *SD* = 4.64). The second-ranked driver in terms of highest average heart rate was the case two novice EV driver (*M* = 90.80, *SD* = 13.21), then followed by case study three driver (*M* = 78.10, *SD* = 5.86), followed by case study seven driver (*M* = 77.50, *SD* = 6.61), followed by case four driver (*M* = 76.60, *SD* = 5.78), and lastly case five driver (*M* = 70.43, *SD* = 2.64). These results are graphically represented in Fig. 4.18 below.

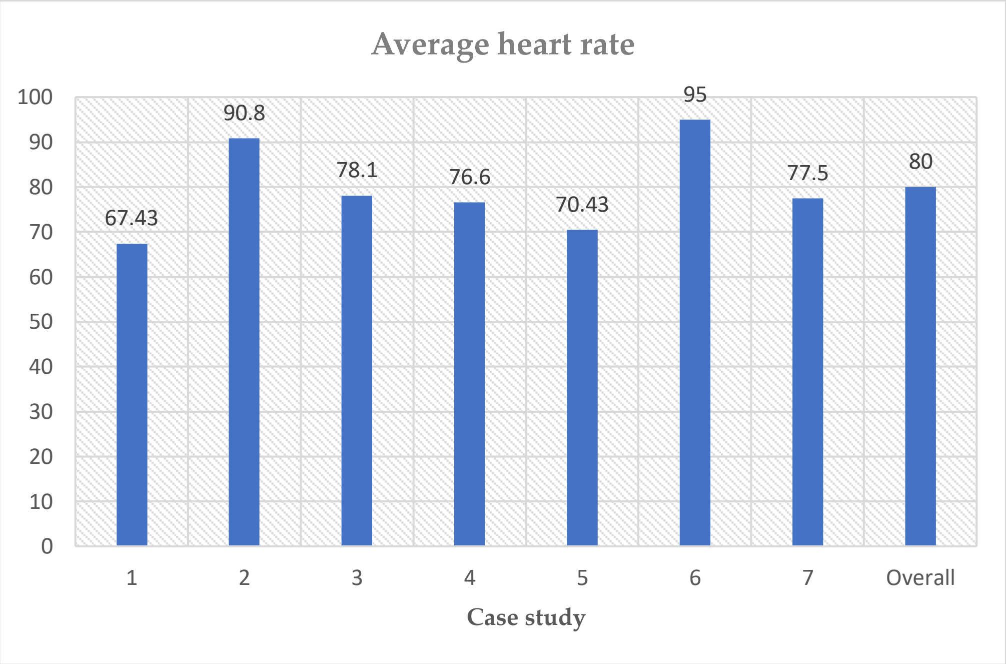



**Figure 4.18.** Average heart rate (BPM).

**4.9.7.3** Anxiety Level Per Case Study

Additionally, by inspecting the results presented in Table 4.19, the minimum anxiety level for case study one driver was recorded as 1 while the maximum anxiety level was 2. The driver in case one had an average anxiety level of 1.71 with a standard deviation of 0.48 calculated across seven measuring points along the departure and return route.

The minimum anxiety level for case two driver was recorded as 2, while the maximum level was 6. The driver in case two had an average anxiety level of 4.30 with a standard deviation of 1.34 calculated across ten measuring points along the departure and return route.

The minimum anxiety level for case three driver was recorded as 2, while the maximum level was 4. The driver in case three had an average anxiety level of 2.90 with a standard deviation of 0.56 calculated across ten measuring points along the departure and return route.

The minimum anxiety level for case four driver was recorded as 2, while the maximum level was 4. The driver in case four had an average anxiety level of 2.80 with a standard deviation of 0.63 calculated across ten measuring points along the departure and return route.

The minimum anxiety level for case five driver was recorded as 1, while the maximum level was 2. The driver in case five had an average anxiety level of 1.86 with a standard deviation of 0.38 calculated across seven measuring points along the departure and return route.

The minimum anxiety level for case 6 driver was recorded as 2, while the maximum anxiety level was 7. The driver in case 6 had an average anxiety level of 4.75 with a standard deviation of 1.67 calculated across eight measuring points along the departure and return route.

Lastly, the minimum anxiety level for case seven driver was recorded as 2, while the maximum level was 4. The driver in case seven had an average anxiety level of 3.00 with a standard deviation of 0.76 calculated across eight measuring points along the departure and return route.

Overall, the minimum anxiety level for all drivers was recorded as 1, while the maximum level was 7. The overall average anxiety level of all the drivers was 3.12, with a standard deviation of 1.36. In case six, the novice EV driver had the highest average anxiety level (*M* = 4.75, *SD* = 1.67), while the lowest average level was for the experienced ICE driver in case one (*M* = 1.71, SD = *SD* = 0.48). Additionally, the second-ranked driver in terms of highest average anxiety level was the case two novice EV driver (*M* = 4.30, *SD* = 1.34), followed by case seven experienced EV driver (*M* = 3.00, *SD* = 0.76), followed by case three Novice EV driver (*M* = 2.90, *SD* = 0.56), then followed by case four experienced EV driver (*M* = 2.80, *SD* = 0.63), and lastly, case five experienced ICE driver (*M* = 1.86, *SD* = 0.38). The average anxiety level results are graphically represented in Fig. 4.19 below.

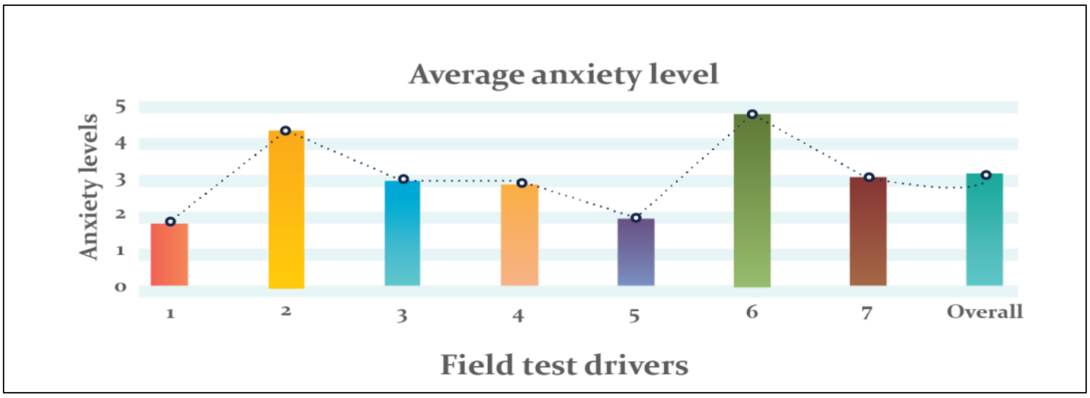



**Figure 4.19.** Average anxiety levels.

#### 4.9.7.4 Descriptive analysis per journey

The investigation prompted a descriptive analysis to examine the average heart rate and anxiety levels for each journey. The first route was covered by drivers in case studies 1, 2, 3, and 4, while the second route was covered by drivers in case studies 5, 6, and 7. This study utilised the mean, standard deviation, minimum, and maximum statistics to conduct the analysis. The results obtained from the descriptive analysis are presented in Table 4.21 below.

**Table 4.21.** Descriptive Analysis of Study Variables Per Journey

| Journey | | N | Mean | SD | Min | Max |
|---|---|---|---|---|---|---|
| 1 | Heart Rate | 37 | 79.11 | 11.43 | 61 | 110 |
| | Anxiety Level | 37 | 3.03 | 1.21 | 1 | 6 |
| 2 | | | | | | |
| | Heart Rate | 23 | 81.43 | 14.57 | 67 | 118 |
| | Anxiety Level | 23 | 3.26 | 1.60 | 1 | 7 |

Heart rate analysis

Considering the results presented in Table 4.21 above, the minimum heart rate level for the first journey was 61, while the maximum was 110 among all drivers who completed route one. The average heart rate of all route one drivers was 79.11, with a standard deviation of 11.43 based on 37 measures. The minimum heart rate level for route two was 67, while the maximum was 118 among all drivers who completed route two. The average heart rate of all route two drivers was 81.43, with a standard deviation of 14.57 based on 23 measures. The descriptive results indicate that drivers in route two had a higher average heart rate than drivers who undertook route one. The main reason for this is that route one drivers started the journey with a full charge, whereas on route two, both ICE and EV drivers were purposely given vehicles with just enough fuel or charge to make it to the mid-point stop at Rugby Services. One lesson learnt from these results, is that lower charge levels significantly increased anxiety amongst the cohort of drivers in route two compared to the drivers in the route one study. The latter departed with a full tank of fuel or a fully charged battery.

#### 4.9.7.5 Anxiety levels per journey

Additionally, using the results presented in Table 4.21 above, the minimum anxiety level for the first journey was 1, while the maximum was 6 among all drivers who drove on route one. The average anxiety level of all route one drivers was 3.03, with a standard deviation of 1.21 based on 37 measures. Conversely, the minimum anxiety level for route two was 1, while the maximum level was 7 among all route two drivers. Additionally, the average anxiety level of all route two drivers was 3.26, with a standard deviation of 1.60 based on 23 measures. The descriptive results indicate that drivers in route two cohort had a higher average anxiety level than drivers of route one due to route two drivers starting with minimal fuel or charge to enable vehicles to reach the mid-way point.

#### Differences in heart rate and anxiety levels

The researcher investigated a significant difference in the heart rate and anxiety levels between route one and two drivers by employing a two-independent sample *t*-test analysis technique for the investigation and using a

0.05 level of significance for the test. The results of the analysis conducted are presented in Table 4.22.

**Table 4.22** Results of Independent Samples Test (*n* = 1419).

| Journey | T | Df | Sig. | Mean Difference | 95% Confidence Interval of the Difference | |
|---|---|---|---|---|---|---|
| | | | | | Lower | Upper |
| 1 | 0.689 | 58 | 0.493 | 2.33 | −4.43 | 9.08 |
| 2 | 0.641 | 58 | 0.524 | 0.23 | −0.50 | .96 |

Considering the *t*-test results presented in Table 4.22, both results for heart rate [$t$ (58) = 0.689, $p$ = 0.*463*, $p > 0.05$] and anxiety level [$t$ (58) = 0.641, $p$ = 0.*524*, $p > 0.05$] were established to be insignificant. The results established indicate that there is no statistically significant difference between the journey one drivers heart rate levels ($n$ = 37, $M$ = 79.11, $SD$ = 11.43) and journey two drivers heart rate levels ($n$ = 23, $M$ = 81.43, $SD$ = 14.57). Nevertheless, the results established indicate that there is no statistically significant difference between the route one drivers' anxiety levels ($n$ = 37, $M$ = 3.03, $SD$ = 1.21) and route two drivers' anxiety levels ($n$ = 23, $M$ = 3.26, $SD$ = 1.60). Therefore, based on these results, the data provides enough evidence to conclude that there is no significant difference in the heart rates and anxiety levels between route one and two drivers. This confirms that the matrix in Table 4.19 in the main body of text and Table 4.23 below, converting BPM to anxiety levels, is statistically correct.

Based on the data collected, there is significant correlation between the drivers' heart rates and anxiety levels in the seven case studies. A 0.05 level of significance was utilised for the test. The results established and presented in Table 4.23 below shows a significant correlation between the driver's heart rate and anxiety levels, $\alpha = 0.05$, $r = 0.953$, $p < 0.05$. These results suggest a statistically significant strong positive relationship between the heart rate and anxiety levels of the driver's, confirming that as the heart rates of the driver's increase, so does their anxiety levels.

**Table 4.23** Correlation Analysis Summary Results.

| | | | 1 | 2 |
|---|---|---|---|---|
| 1. | Heart rate | Pearson Correlation | 1 | 0.953 * |
| | | Sig. (2-tailed) | | 0.000 |
| 2. level | Anxiety | Pearson Correlation | 0.953 * | 1 |
| | | Sig. (2-tailed) | 0.000 | |

*Correlation is significant at the 0.05 level (2-tailed).

# Chapter FIVE

## 5.0 Predicting Electric Vehicle (EV) Rapid Charging Deployment on the UK Motorway Network [1.28]

### 5.1 Introduction

Recent transformations from ICE vehicles to EVs are challenged by limited driving range per charge, thus requiring improvement or substantial deployment of rapid charging infrastructure to stimulate sufficient confidence in EV drivers. This Chapters investigation aims to establish the necessary level of EV motorway service station charge points for the United Kingdom (UK) based market. The hypothesis is: by increasing appropriate rapid charger speed and availability, thus shorter charging time, then greater throughput of EVs can be accommodated per rapid charge point.

### 5.2 Sector development and overview

Throughout the industrialised and developing world, there has been a gradual transition from the ICE to EVs, defined by the Department for Transport (DfT) [5.1], and the Office for Low Emission Vehicles (OLEV) [5.2]. Furthermore, the rapid development and use of lithium-ion batteries, such as storing electricity for grid supply and powering EVs requires more reliable methods to understand and predict battery performance, range, and life. However, the importance of this investigation is focussed on creating a forecasting model that can calculate the quantity of UK motorway rapid chargers for any given number of EVs, speed of rapid chargers, or battery size and chemistry. The benefit of this approach is that the forecasting model is not historic in its outcome but is scalable and future proof, through key variables in the investigative computations.

Research published in 2018 [5.3] calculated the volume of rapid chargers necessary to charge a notional number of EVs. The result suggested that a network of 500 chargers working at 15% capacity, will deliver the same as 75 chargers working at 100% utilisation, and that the current low level of chargers in the UK are sufficient for long distance EV commutes. However, this thesis notes that EV charging, mirrors electricity peak demand curves at the same time of day. Conversely, the study acknowledges that no charger is working 24 hours a day, seven days a week. Therefore, this thesis expands by probing deeper into this concept by introducing 2022 data and peak locational demand.

In another study, [5.4], EVs were found to be inferior to traditional ICE vehicles mainly due to range. Although, more recent data from sources such as the established publication Autocar [5.5] suggest that some 2022 model EVs, such as BMW iX, Mercedes EQS, and Tesla Model X have crossed a Worldwide Harmonised Light Vehicles Test Procedure (WLPT) 350-mile range threshold. Although the RAC suggests that the average daily range of twenty-six miles is acceptable [5.6], there is a natural restraint to travel beyond an EVs range without certainty of charging services en route. In 2014, 61% of Norwegian EV (Electric Vehicle) owners took their cars on holiday journeys, and by 2016 this had reduced to 37%. Figenbaum et al. explained this phenomenon as the normalisation of EV as a vehicle type [5.7]. Whilst Namdeo et al. [5.8] suggest that the limited range of electric vehicles is still seen by many as the critical barrier to the mass uptake of EVs. Two methods could address this. EV range needs to be improved, or a substantial deployment of rapid charging infrastructure must stimulate confidence in EV drivers to complete their journeys and top up their charge as required. This has resulted in the archetypal early adopter who is content to tolerate an apparent lifestyle adjustment and perceived inconvenience. However, this is arguable, with much of the population to be convinced of the evident benefits of EV adoption. In observing people and social phenomena, this consumerism characteristic applies mainly to the physical EV. The deployment of the UK charging infrastructure is still maturing and does not satisfy the demand or locational siting to offer genuine consumer choice.

Previous research [5.9, 5.10] shows that the current UK rapid charging environment splits EV users into two areas. In scenario one, there are EV drivers who, given the option, will make a value judgement in an urban or rural environment. Whilst in the other example, motorway EV users are confronted with a largely unregulated, expensive, and unreliable monopolised network [5.10], facing a phenomenon that is often referred to as the Nash Equilibrium [5.11] or a zero-sum phenomenon [5.12]. Both concepts reflect a situation that involves two perspectives, in this case, an EV driver and charging supplier, where the result is an advantage for one side and an equivalent loss for the other. Thus, the driver can search for a better deal at a net loss to the supplier, but this differs significantly between urban and national motorway networks.

This investigation reveals a similar pricing development in the urban environment as private operators of rapid chargers are imposing margins, frequently more than 100% of a standard kW price [5.10]. In contrast, many local authorities are offering free AC low speed charging at the point of use. Furthermore, Neaimeh et al. [5.13] observed consumer information from manufacturers and the UK government regarding EVs and how to charge. However, there is no tangible evidence of a national strategy to deploy a nationwide network of rapid chargers. Dependence on network progress relies mainly on an independent website, Zap Map [5.14], reporting charger deployment progress and availability rather than strategy. Fig. 5.1. reveals the results of a recent survey in 2021 [Ch.3] highlighting five critical areas of concern for existing EV drivers, mirroring concerns cited on vehicle blog sites globally as reasons for not making the transition from ICE to EVs.

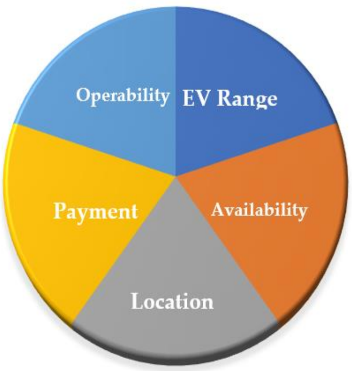



**Figure 5.1.** Key concerns discouraging drivers from purchasing an EV

EVs are often compared with other electrical consumer devices, with similarities drawn with other revolutionary technology such as compact discs and mobile phones. In their early evolution, high technology mobile phones and compact disc players were introduced to the public with a similar lack of supporting infrastructure. Mobile phones initially only supported use in large conurbations as operators deployed their transmission networks, and compact disc players were launched with just a handful of albums available in their early years. This study emphasises a clear risk for car producers to introduce products with an evident operating limitation in the expectation that infrastructure would match demand to encourage new EV buyers to buy a new technology with blind trust. Although EVs and mobile phones need a charging facility, the significance of a mobile phone exhausting its charge is far less than an EV. Hence, it is argued that to enable the adoption of EVs, a contiguous network of charging points must be developed to supplement the option of charging at home [5.9]. As with all commercial strategies, there must be a business case to back investment from either private or government funding and support options.

However, evolving variables are proliferating. For the EV manufacturers to gain a competitive advantage, they often fail to publish their model's real-world range, instead, relying on the very conservative measuring protocol laid down by WLTP rules [5.10]. Additionally, the charging infrastructure sector is developing and providing installations offering greater charge rates than most EVs can utilise. Further analysis reveals traditional fuel companies entering the EV sector by installing charge points (BP and Shell). Furthermore, independent EV charging OEM's (Tesla and Ionity), are expanding their networks. Previous research [5.9, 5.10] shows that DC rapid chargers are demanded by the EV owner and new EV buying population nationally and are critical to providing an extended range for longer journeys.

One conundrum discussed at national and local government levels is: how many EV charging bays does a motorway service station require? Hence, the overall goal of this investigation is to establish what infrastructure is necessary for a given population of EVs by service station, based on a direct replacement of power requirement and filling time from fossil fuel to electric supply with an assumption of rapid charge dependence. The analysis displays theoretical maximum demand specifically for high-power rapid charging and its grid impact. A world-leading countrywide example of EV adoption is Norway. Thus, data from Norwegian research is also applied in this work. The methodology applied is not specific to any one country, but the data is. Currently, the EV owner or user has four basic choices: 1) charge at home, 2) charge at work, or 3) charge at a slow charging public charge point, or 4) charge quickly at a rapid charging point. Recent research reveals that 35% of households have no access to off-street parking outside Greater London, whilst in London, this rises to 63% (5.15). The societal challenge is that the OEMs understand how their product is operating in the market by sales achieved or pre-orders placed. The infrastructure is not optional for the prevalent paradigm (ICE vehicles) since the owner must travel to a filling station. The ICE home or work charging choices are not an option for most of the population. However, for EV users, the customer can choose where they want to charge, and these options may include car parks, at home, public spaces, hotels, service stations and supermarkets. It is forecast [5.6] that the EV filling station equivalent of a petrol station with rapid chargers will develop rapidly, such as the UK's first electric-only service station in Fig. 5.2.

**Figure 5.2**. Gridserve Electric Forecourt®, Essex, UK. Source: Gridserve™ 2022

However, this study argues that EV technology in vehicles and infrastructure is still evolving and is continually developing in parallel with sales. Theoretically, according to the independent EV Database UK, in quarter one of 2022, the mean average useable capacity of UK sold EVs stands at 62.5kWh [5.16]. Additionally, the average real-world range (not the higher measure by WLPT rules) during the same period stands at 201 miles [5.17]. The following methodology has been established to determine the most appropriate approach and investigate the correct infrastructure level in UK-based rapid charging. Driver behaviour is based on the current mean average battery size of 62.5 kWh as the norm for EVs, and this investigation will determine whether EVs charge, in relation to power tolerance versus time. Furthermore, the mean average of the maximum charge rate as of quarter one, 2022 was observed. It is also clear from previous research [5.9, 5.10], that several variables affect the total grid power requirement for a given EV population to travel the distances in a day that traditional ICE vehicles achieve.

Currently, there are only two national high-power EV charging networks. (5.2) The Ionity open high power 350kW hub network [5.18], jointly owned by a consortium of OEMs including BMW Group, Mercedes-Benz, Volkswagen Group, Ford, and Hyundai. The remaining UK nationwide high-power network is Tesla, although this is currently dedicated for use by Tesla owners only. Other open national networks such as the Gridserve Electric Highway at most motorway service stations are open to all vehicles, including CCS compatible Tesla cars. Ionity provides up to 350kW CCS charging, whilst Tesla delivers up to 250kW peak rate. Power delivery from a rapid charger is presently 50kW (DC) to 350kW (DC) and covers the current maximum power accepted by mainstream EVs from 50kW to 275kW. Beside the Tesla network, 441 rapid chargers [5.14] are installed across UK motorway services. The usage and siting of rapid chargers are the focus of significant analysis. For instance, Dong et al. [5.19] studied concerns around the location and siting of rapid charging stations. Moreover, the European Commission part-funded a pilot of the Rapid Charge Network (RCN) in 2015 [5.4], covering an investigation into driver reactions.

An extensive trial studied the behaviour of drivers as well as their usage patterns of rapid chargers [5.4]. This investigation provided the basis for an account surrounding the role of rapid chargers in the adoption of EVs [5.13]. In contrast, Latinopoulos et al. [5.20] explored the reaction of EV users to pricing strategies concerning dynamic charging. Recent investigation has focused on the significance of rapid chargers and EV driver's usage habits. Although this research does not account for the volume of chargers that will be required. An investigation by Harrison and Theil [5.21] presented the conception of an EV charging infrastructure based on a charging methodology that accounts for deployment, equipment costs and running costs versus desired return on investment (ROI). However, whilst this is a tried and tested standard commercial formula, it may not address public requirements.

Furthermore, the International Energy Agency (IEA) recently published its Global EV Outlook 2021: Technology report [5.22], in which they summarise that: notwithstanding the wide variability of the scarce electric car market and stock shares, the EV/EVSE (Electric Vehicle Supply Equipment) ratios have been projected to converge towards 130 EVs per openly available rapid charger. These calculated results were founded on EV deployment projections and assumptions on the EV/EVSE ratios (at charger level). The derived beliefs were based on an overview of the past expansion of the EV/EVSE ratios, where the EV/EVSE ratios are mapped against both the EV car market share and the EV stock share. This investigation looks at the quantity of rapid chargers needed based on power (kW) delivery and EV consumer behaviours. The outcome of this investigation provides a sum of 434 rapid chargers for a given population of EVs which relies on rapid chargers for mobility requirements, which is less than a 5% variation from the data produced by two different approaches. In defining the quantity of chargers required, the investigation includes EVs that cannot be charged at work, in the street, at home, or partake in long-distance commuting. Unlike the current Internal Combustion Engine vehicles, an EV differs since the yield of fuel during the filling or recharge process is determined by the unique battery control system integrated into each vehicle, being non-linear and differing from EV to EV.

This investigation introduces a methodology that provides an infrastructure figure specifically relating to motorway service stations. These facilities will be the most common form of recharge options used by long-distance EV users. It is based on a consideration of logical components and analysis of existing technology both on and off car, by examining what volume of power delivery can genuinely be delivered from a specified rapid charger. Recent studies such as Buzna, L, et al. [5.23] focused on how EV and charging infrastructure expansion impacts grid supplies regionally. They argue that EV load forecasting is problematic at a hierarchical level. Suggesting that a robust model must be applied to forecast load at high level, since EV charging curves and power delivery differ significantly from model to model. This, they suggest, should be factored into any long-term forecasting to increase the accuracy of problematic prediction compared with non-hierarchical approaches.

Hence, a significant consideration is that delivering power to an EV is not constant during its charging cycle. Whereas the traditional delivery method for an ICE vehicle is that the petrol pump can supply a linear volume of fuel over a given period that, when allowing for customer rotation in the filling bays, permits calculation of the maximum volume of fuel delivered if needed. In a recent case by Arias, M.B. et al. [5.24], the investigation concluded that to realistically predict EV charging power demand, the model must account for charging power differences between EVs. Divergent charging patterns at some charging stations formed non-replicating contrary samples. The study's result cites that peak grid demand times mirrored peak charging times at service stations. Therefore, a form of dynamic power management connected to the generator was recommended to smooth maximum demand peaks. This outcome will form the basis for future research outside the scope of this investigation.

The current UK EV population size of 420,400 is not a large enough sample to build a balance of requirements for constant usage in terms of back-to-back charging versus registered UK ICE vehicles, numbering more than 32 million. The archetypal power delivery constituent in the estimation for charging infrastructure numbers, requires an evaluation of what is probable to be adequate charging behaviour of one-hour segments over a 24-hour timescale with nominal 10-minute vehicle changeover, per charging period.

The following sections explain the source of the base formula to calculate a charging infrastructure quantity. Accurate power delivery is a fundamental element. This study presents a methodology in Section 5.3, explaining the importance of the sample EV types used in this analysis and the significance on the broader EV sector. Subsection 5.3.1 then explains the data inputs. Their justification is then described, demonstrating the statistical consistency, how and why the variables are selected, followed by an analysis of how the study will calculate rapid charger quantities. Then, Section 5.5 emphasises the relationship between the state of battery charge versus time, describing how average power delivery is calculated and explains the development of calculating average power delivery. Subsection 5.6.4 then focuses on establishing a developed model that will estimate power in kW charge per hour using significant variables in the calculations. Subsection 5.6.5 explains how this case aims to predict the necessary rapid chargers for current and future EV user demand. Section 5.6.9. introduces a summary of the previous chapters and outcomes for discussion, explaining why the results are significant and the investigations implication for future use due to its inherent scalability for current and future EVs and charging systems. Finally, the conclusion in Section five, summarises the salient points of the enquiry, explaining the importance of forecasting the power consumption in an archetypal EV. This is interpreted in terms of probable user behaviour, describing the statistical reliability of the suggested number of rapid chargers assessed based on the variability of the elements creating the calculation [5.25]. Therefore, average power consumption and delivery numbers are used to evaluate operational efficiency and thus evaluate the present and future rapid charger infrastructure need.

## 5.3 Methodology

### 5.3.1. Evolving a forecasting method to calculate rapid charger needs

When analysing the confounding factors when planning charger numbers to satisfy user demand, the critical issues include EV numbers, EV average daily activity, daily power demand, and the EV time spent in its charging bay. Typical input data from varied sources are employed to challenge these issues (Table 5.1). Realistic statistics for some of these components are derived from open data sources, whilst elements with no data are based on assumptions. Although the values tabulated are best estimates, they are still beneficial in evolving a methodology and delivering a realistic figure on which to base calculations.

By employing data provided by the RAC [5.6], it is known that there are 32M cars in the UK, of which the current % of EVs is 1.32%. Thus, 422,400 EVs (1.32% of 32M) is calculated. This research assumes all EVs can accept rapid charging. The RAC [5.6] cites 26 miles on an average journey per car, per day (all car types). Employing this mileage, the sum of miles driven in EVs per day is 422,400 x 26 miles = 10.972m miles per day. Through observation and publication [5.16], this study shows that an EV can deliver a mean average across all models (2022) of 3 miles per kWh (this is driving style dependant and best case per EV model). Therefore, the energy required to cover 10.972m miles is 3.58 MW.

In line with ICE driver behaviour, EV drivers do not generally recharge every day, although some long-haul EV commuters will charge and discharge frequently. In contrast, remaining EV rapid charge drivers will use them since there is no local alternative, even though they still maintain the average daily mileage. Hence, the utilisation ratio of rapid chargers will be distinguished by comparing urban EV users versus long-distance users. Power delivery per rapid charger and the number of hours each device is used per day will be a significant factor in calculating the number of rapid chargers required to satisfy demand. Table 5.1 highlights average power delivery from a base 50kW rapid charger against charge time. The following section describes a sensible method to conduct a real-world investigation applying a technique of inverse engineering as described in the following section, since there are no published data for average power delivery. A suggestion for charge time is made based on the experiment results.

### 5.4. Selection of Test EVs and Rationale for Use

All long-distance EVs are capable of being rapid charged and are ideal for long motorway commutes [5.10]. The VW iD3 45Wh and 58kWh have been used as an example because they are currently among the most common family style long-range EVs. The VW iD3 45kW and 58kW models were selected since they use the common Volkswagen Audi Group (VAG) EV platform, known as ***M****odularer* ***E****-Antriebs-***B****aukasten* (MEB). The chassis and a combination of its batteries are used on more than 100 different models globally, across five distinct brands, including VW, Audi, Skoda, Seat, Cupra, and all VAG commercial EVs. Additionally, the MEB platform is licensed to Ford globally for its current and future models [5.26]. Therefore, this makes the VAG MEB module (Fig. 5.3), the most widely used bespoke EV only chassis and battery architecture globally, and an ideal platform on which to base this investigation.

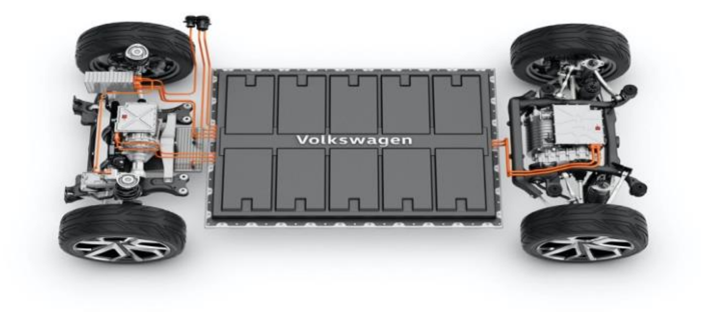



**Figure 5.3.** VAG - MEB EV platform. Source: VAG™ 2021

### 5.4.1. Applied experiment demonstrating average power delivery

The EV regulates the flow of power when a DC rapid charger is connected and delivering a charge. The power delivery is not linear or constant and fluctuates considerably from EV to EV, even between same make models. The investigation uses existing technology, but references will be made, discussing more powerful capacity batteries and higher power charging devices. Power curves were measured on Gridserve™ rapid chargers at one-minute intervals. The test was carried out at varying external temperatures (from 5 to 18 degrees

Celsius) to understand the influence of ambient temperature. The group of data was then repeated on the higher capacity battery.

Data from the following elements were gathered by the minute:

- State of charge
- Time interval
- Volts
- Amps

Data collection was carried out five times with a standard 45kWh battery and twice with a 58kWh battery. This method was employed to reproduce driver behaviour as their confidence in EV range develops. Hence users should be arriving with a State of Charge (SoC) of approximately 10%. Neaimeh et al. [5.13] discovered that drivers often arrive with up to 40% SoC. Consequently, these scenarios were similarly incorporated.

### 5.4.2. Statistical consistency in quantifying rapid charger numbers

The investigation established a need to recognise the uncertainty in the estimate, aside from advocating the magnitude of chargers required. Employing the variance synthesis method described by Morrison [5.25], the difference in the assessment is estimated by a weighted grouping of the variances of the individual elements. The partial differentials are evaluated at the variable's mean value, whilst the weights are the squared partial differentials of the estimate concerning the variable.

Variance (K= number of chargers) ~ sum of {(partial differential of K for each variable)$^2$ x variance of variable}. Although the differences of the elements are not known, these must be previsioned.

### 5.4.3 Functional performance

The resulting equation is based on a recognised industry gauge of Overall Operational Effectiveness (OOE) that comprises availability x speed against design x quality of the product. To measure the performance of a charger in the investigation, the Operational Performance (OP) is determined as Power x Utilisation (design vs delivery) x availability.

## 5.5 Outcome and Analysis

### 5.5.1. Calculation

The calculation for the suggested number of chargers is a compound of the different elements.

The number of chargers is K = $\frac{A \times B \times C \times D}{E \times F \times G}$

Thus:
A = % of UK cars that are EV
B = number of cars
C = average daily mileage
D = % of mileage needing rapid charging
E = miles per kWh
F = average delivered power in kWh (charge time-dependent) assumed at 60 minutes
G = Total hours charger is in use
K = The scale of K is $\frac{\text{miles per day}}{(\text{miles/kW}) \text{ x kW x hours per day}}$ and is thus dimensionless.
Values are acquired from numerous sources and presented in Table 5.1.

**Table 5.1** Statistical input.

| Variable | Variable | Data | Derivation | Source |
|---|---|---|---|---|
| B | Volume of UK cars (all types) | 32M | Resultant | [5.5] |
| C | Distance driven daily - per car | 26 miles | Resultant | [5.5] |
| BxCx365 | Miles driven per year in total (UK) | 303bn | Resultant | [5.5] |
| A | Percentage of cars that are pure EV | 1.32% | Resultant | [5.14] |
| E | Mean average Miles per kWh | 3 miles | Resultant | Actual performance of a 45kWh VW iD3 |
| F | Mean average power delivery - 50kW rapid charger | 27kW | Computed | As described previously - experimental |
| D | Percentage of EV drivers charging at work or home | 85% | Implicit | Considered prediction |
| | Charge time | 60 minutes | Established | Employing 80% rule over 30 minutes |
| AxB | Current number of registered EVs (UK) | 422,000 | Resultant | [5.14] |

## 5.6 Calculating average power delivery

### **5.6.1** SoC vs time

It is established that a 58kWh vehicle has the same charging time to 80% state of charge (SoC) as the 45kWh vehicle. This is achieved by the 58kWh battery accepting more power at circa 350V - 410V volts DC. The results are shown in Fig. 5.4 The chart also highlights that an additional 15% of charge adds a further 25 minutes to the charge time.

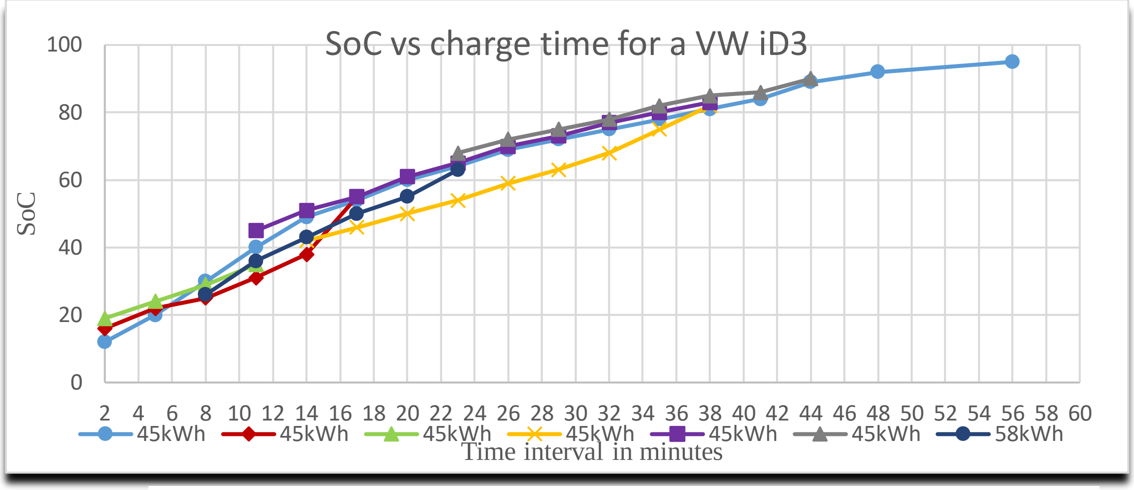



**Figure 5.4**. SoC vs time for a Volkswagen iD3 58kWh and 45kWh

The individual lines represent different ambient temperatures. This study confirms that ambient temperature had little impact on the charging curve. The start temperatures when data was collected varied from 4 to 16 degrees Celsius. By referencing Met Office data (2010 – 2020), the average minimum temperature for the UK is 6.4 degrees, and the maximum average temperature is 14 degrees Celsius, although this variable was dismissed for this case. [5.27]

### 5.6.2 Power delivery consequence

Watts or power is then calculated (volts x amps). The variables are amps (Fig. 5.4) and power (in W) on the vertical axis and percentage of the SoC on the horizontal axis. The distinctive plots denote ambient temperature. The variance between the 45kWh and 58kWh iD3 is evident since the 58kWh iD3 is taking a greater current level for an extended period.

The significant crossover points in Fig. 5.4 are:

- SoC of 65% in 20 minutes
- SoC of 85% in 30 minutes
- Charge of 95% SoC in 55 minutes

Fig. 5.5 demonstrates that the 58kWh VW iD3 sustains high power (received), capturing approximately 380 volts and 106 amps (40kW) up to a 65% SoC, then it systematically reduces as SoC increases. In comparison, the 45kWh iD3 demonstrates a significant drop in power from the start of its charging cycle. Furthermore, it is also evident that power decreases for both the 45kWh and 58kWh batteries following a comparable power curve after 65% SoC. At 65% SOC, it is significant to note in Fig. 5.5 that this power reduction appears after 20 minutes. At 85%, a similar power slope was observed, marking the termination point of the trajectory following 30 minutes. The ensuing period (Fig. 5) established the average power delivery to a 65% SoC and then 66% to an 85% SoC. Contradicting data from a RAC Foundation report [5.5] assumed mistakenly that a 30-minute charge from a 50kW charger will deliver 25kW but acknowledges it will not be a linear charging line. However, this analysis (Fig. 5.5) shows disparity within and among models from the same manufacturer (VW iD3 45kWh and 58kWh) and demonstrates the non-linearity of charge rate in EVs.

### 5.6.3. Average power delivery development

From the analysis of data in Fig. 5.5 collected from trials, it is now possible to determine that the charging traits for a 45kWh iD3 EV connected for 30 minutes are:

- 41kW for 20 minutes which is 22.66kWh
- 20 kW for 10 minutes which is 7.8 kWh

Thus, one 45kWh car charging for 30 minutes will consume 30.46kWh. Moreover, statistics from the Electric Vehicle Database [5.17] suggest delivery over 30 minutes will be greater if a 58kWh battery is charging. Thus, assessing an EV car sample of more than two million cars (UK car fleet), demonstrates a significant energy miscalculation.

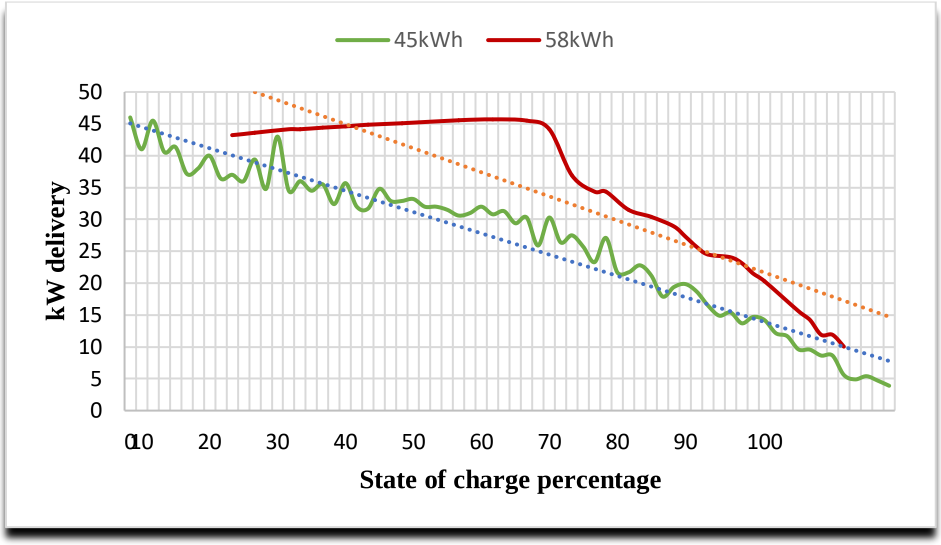



**Figure 5.5.** Power delivery as the state of charge increases, using averages for 45kWh VW iD3 and 58kWh VW iD3

### 5.6.4 Developing a model to estimate power (kW) charge per hour

Fig. 5.5 highlights the source and rationale supporting an average 40 minute 80% SoC published in Volkswagens specification declarations. This curve provides reference data for the necessary calculation of delivered kW per 1 hour period. From previous research [5.9], alternative payment methods are now established as follows:

- Payment by units of time
- Pay per kW plus a connection charge
- Fixed fee per month for unlimited charging per vehicle
- PAYG via contactless card or mobile phone, per kW
- Subscription with a monthly fee plus reduced charge per kW used

The research confirms that the average swap over from one EV completing a charge to an uncharged EV reconnecting in the same charge bay is, on average, 9.5 minutes [5.10]; hence a minimal swap-over of ten minutes has been provisioned. The previous investigation [5.10] showed that drivers at fuel stations drive straight in, refuel, and then drive out, and the average swap-over time was 4.5 minutes. However, EV drivers generally reverse into a bay and use an app to initiate the charge, and this whole process has proved to take twice as long as an ICE driver in a traditional filling station.

Factoring in the swap-over time, there is a fifty-minute recharge session per hour. The study does not predict continual use for 24 hours. The Charger Operation Calculation will employ a diversity factor. Numerous Charge Point Operators (CPOs) are investigating diverse payment techniques [5.9] primarily founded on three standard methods: a kW delivered cost plus a single connection charge, a straightforward kW unit cost multiplied by the time used, or a subscription model based on a combination of the two. UK studies in the past were commonly investigated through an era when UK motorway charging was payment free at delivery to the EV user. The leading free charging CPOs were Tesla and Ecotricity. Though, payment was ultimately introduced by these and subsequent CPOs in 2018 on the UK motorway network. The effect of applying a rapid charging payment has not been widely researched. It may present evaluation challenges over the next decade as competing CPOs test and evaluate suitable payment models across the charging network. This investigation assumes that the EV user will not be significantly influenced by price, despite several global factors that occurred during this analysis that have enforced severe price increases, such as the Covid 19 pandemic affecting supply chains, the 2022 Ukraine conflict, and substantial global increases in energy costs. To appraise the average power provided by a charger, the detected power provision curve (Fig. 5.5) demonstrates a clear power provision trend to 65% SoC up to 20 minutes, followed by a reduced delivery after ten minutes to 85%. Thus, a thirty-minute charge is calculated as twenty minutes plus ten minutes. Furthermore, a mean average ten-minute switch between EV users is considered and included in the calculations with a diversity factor to simulate real-world daily use using data gathered from the previous examination [5.10]. Fig. 5.6 reveals a combined percentage use basis, at the most prevalent charge point utilisation times of the day. Whereas Fig. 5.7 illustrates the aggregated figure for an entire study by the time of day.

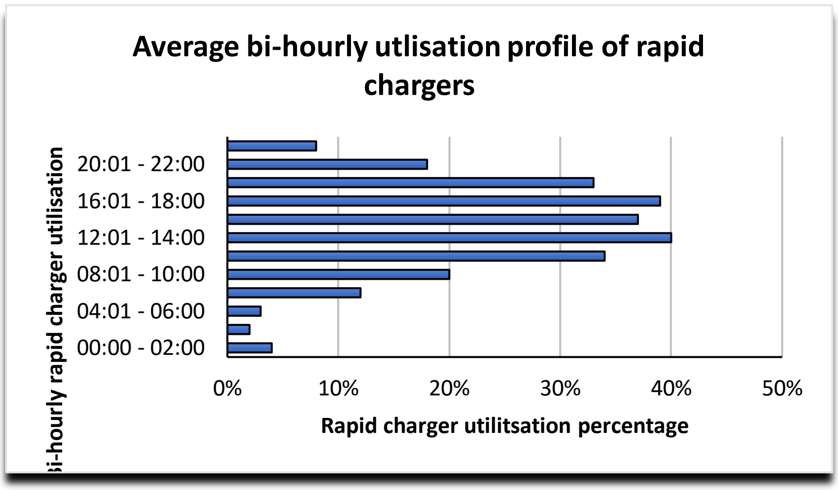



**Figure 5.6**. Daily charging characteristics versus time as a percentage [5.9]

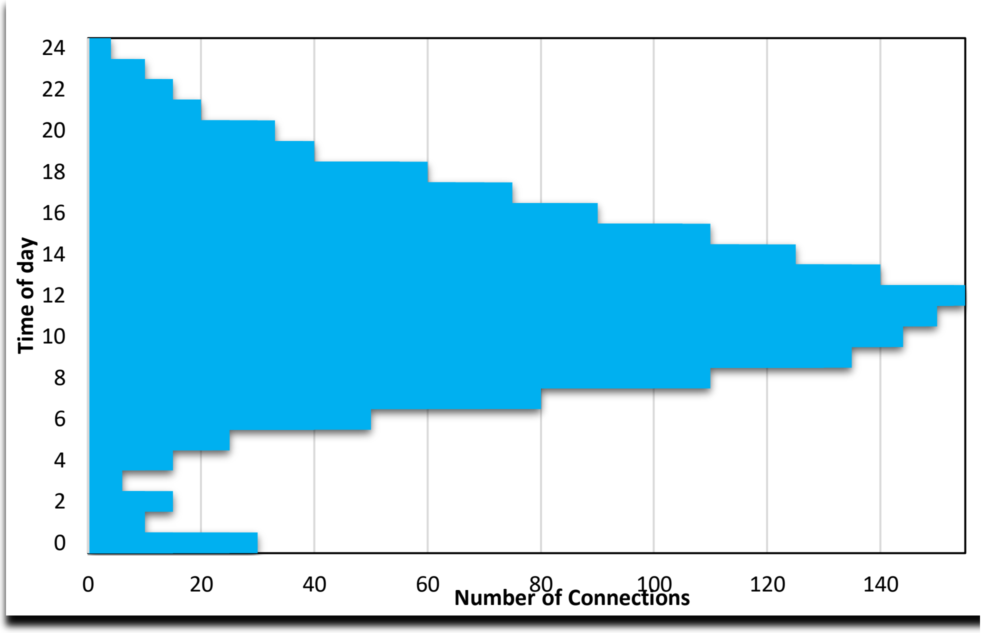



**Figure 5.7.** Volume of connections versus time [5.9]

Fig. 5.7 illustrates a contiguous national charging network employed per hour and day. Additionally, Fig. 5.6 and Fig. 5.7 above challenges widely held theories. The study mirrors articles from the DofT [5.15] and National Grid [5.28] that: demand for rapid charging will occur during busy daytime commuter periods, with peaks for rapid charging occurring in the morning and evening rush hours. The statistics reveal that the core 60% of total consumption occurs between 10 am and 6 pm, supporting recent research [5.4] and DofT research [5.1]. Rapid charge network utilisation illustrated in Fig 5.8. provides greater detail, and reveals well-defined daily behaviours regarding usage, mirroring a recent probe highlighted in Fig 5.9. Observing assumed peak times per 24 hours (6:00 hrs to 20:00 hrs), the data comprises approximately 4% of total utilisation, 8 am until 10 am constitutes 8% of the utilisation, while the evening (18:00 to 20:00) equates to 13% of total utilisation. This investigation confirms that urban morning rush hour ends by approximately 09:00 hrs.

In comparison, motorway traffic volumes increase around 09:00 through to 20:00. Thus, the morning urban peak period experiences lower grid utilisation at under 12%, less assumed before this examination. However, the peak evening period is more condensed on the motorway network and generally reduces by 20:00 hrs. demonstrating a comparable utilisation of the morning peak at 13%. This suggests that rapid chargers are being used specifically for the intended role. That is to extend the range of EV journeys rather than for commuting. Gathering a more significant sample of data on how rapid chargers are used may ratify this notion, although presently this may be too commercially complex.

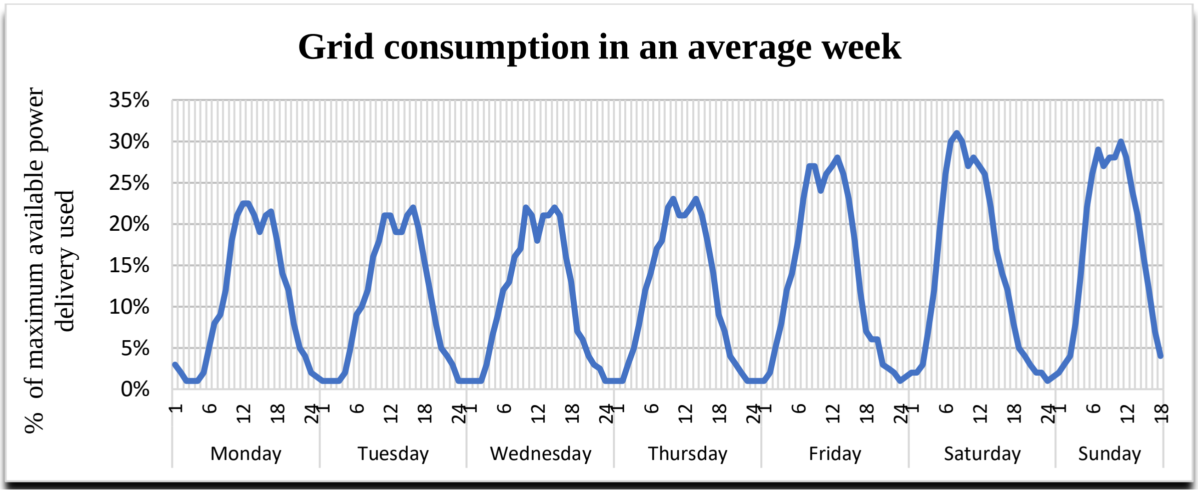



**Figure 5.8.** Daily percentage of grid supply usage versus time [5.8]

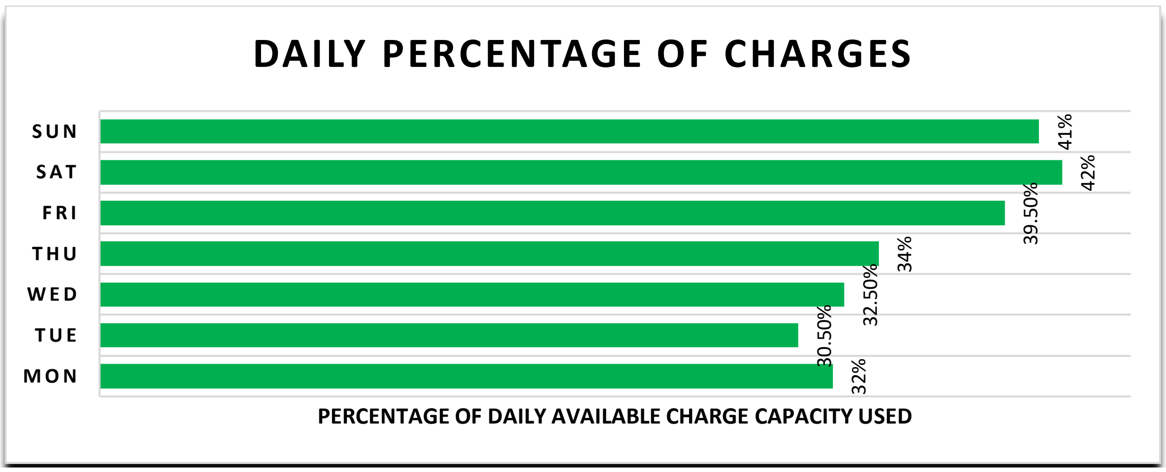



**Figure 5.9**. Charging activity shown as a percentage by day

A minor utilisation variation is witnessed on weekdays by observing the extent of charging per day (Fig. 5.9) from the same CPO. However, there is a more significant usage on Friday and the weekend. This indicates long-distance leisure travel that necessitates rapid charging.

The impact of EV batteries larger than 58kWh and higher-power charging will need further evaluation in future studies. This investigation assumes that most rapid charging by VW iD3 cars, requires rapid charging CPOs to further develop the UK motorway network for long-distance travel. To establish a notional maximum charge delivery, this analysis assumes consecutive charging moderated by a diversity factor. The analysis reveals that the customer, rather than the infrastructure or vehicle, determines the time spent on a rapid charger, with most users overriding a complete charge cycle at an average SoC of 85-90%. Fig. 5.10 illustrates typical EV rapid charger usage across a seventy-minute period.

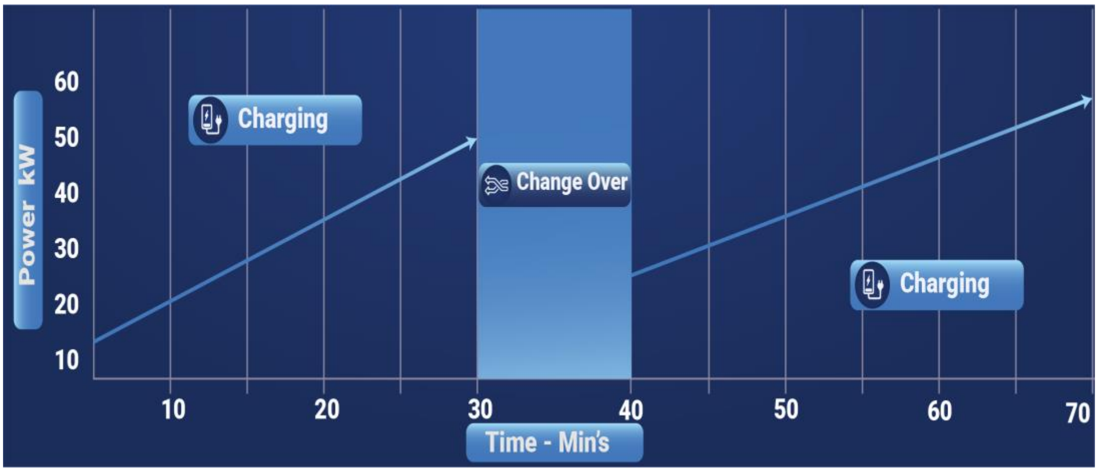



**Figure 5.10.** Characteristic hourly charging period.

### 5.6.5 Power delivery profiling

One 45kWh iD3 charge proceeded by a second 45kWh iD3 charge = 39.92 kWh (50kW for 20 minutes is 16.66 kWh plus 50kWh for 10 minutes equating to 8.33 kWh, plus 50kWh for 20 minutes amounting to 16.66 kWh).

Fig. 5.11 highlights 39.92 kWh delivery for three iD3 EVs charging consecutively, allowing a 10-minute swap over across a period of 110 minutes.

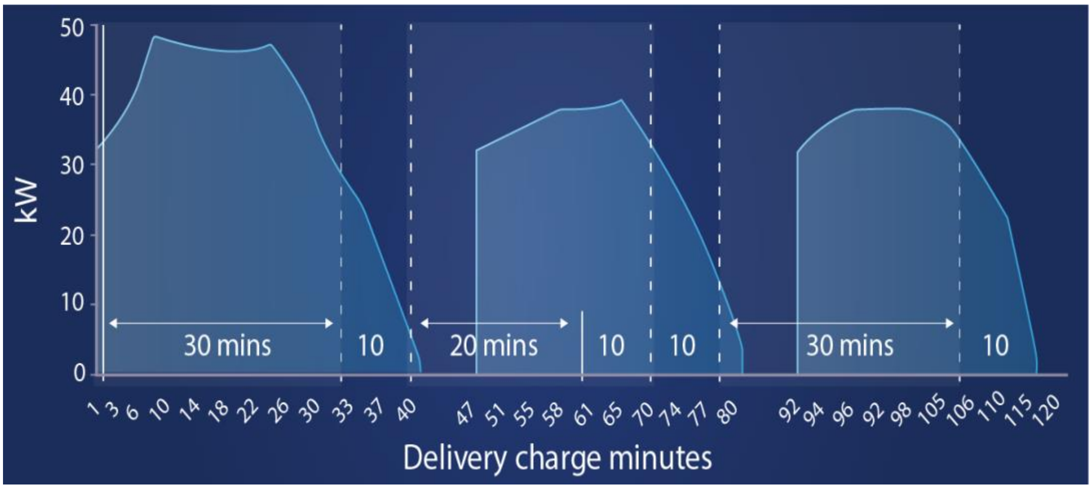



**Figure 5.11**. The charger utilisation is founded by price, requirement, and location.

Assuming consecutive full-use rapid charging, then using a 45kWh + 45kWh + 45 kWh car pattern illustrated in Fig. 5.11, a total power delivery is realised amounting to [23.32 + 0 + 13.66] + [8.33 + 0 + 24.99 + 0] = 70.30kW over 2 hrs. or 35.15kW per hour.

Providing EV users with the choice of a 50-minute delivery on a 50kW charger will require more rapid chargers to meet current demand at charge point sites and service stations. An additional 15-minute charge will provide an average of 9kWh. The significance of this is that rapid charging bays will be fully occupied, though delivering small amounts of power towards the end of the charge cycle, creating a commercial challenge between an EV user who wishes to obtain a full charge before setting off and the commercial and countrywide necessity to supply the most significant amount of power in the shortest period. This problem was illustrated by Neaimeh et al. [5.13], revealing that regarding the charge period, 32% of these events in the UK and 21% of similar events in the USA stood above 30 minutes. In line with the investigation, the charging rate reduces when the battery nears complete SoC controlled by the car's battery management system, extending charging sessions that affect the rapid charger's availability for a new EV user.

Based on the assumption of consecutive charging and larger batteries will become the standard. Furthermore, by accepting that higher capacity batteries will continue the trend of extending EV range, the figure of 35.15 kWh has been selected as a basis for the calculations.

### 5.6.6 Calculation to predict required rapid charger numbers

The quantity of chargers can now be considered as K = $\frac{A \times B \times C \times D}{E \times F \times G}$

Thus
A = 1.32% of cars that are EV in the UK
B = 32M number of total cars
C = 26 average daily mileage
D = 10% of mileage needing rapid charging
E = 3 - Miles per kWh
F = 35.15kWh average power delivery
G = 24 hours profile charger is in use
K = 434 is derived as follows:

A=1.32% current proportion of the total of all types of UK registered cars (B=32M) are EVs, equating to 422,400 EVs. Average daily mileage is calculated at C=26 miles

Miles per kWh is E=3

Thus: 422,400 $\times \frac{26}{3}$ = 3,660,800 kW is needed per day

If 90% of charging is at home or work, then 10% of the national mileage per day requires rapid charging, so D=10% of the national EV mileage per day requiring rapid charging; thus, 366,080 kWh maximum is consumed

A 50kW rapid charger can currently deliver F=35.15kW per hour for G=24 hours, which is 843kW of energy.

Hence, this is calculated as $\frac{366{,}008kW}{843kW}$ = K = 434 chargers.

This assumes that all rapid chargers will be working 24 hours a day, which the research has shown in this investigation will not be the norm.

According to Zap Map data [5.29], there are 5497 rapid chargers in the UK. A requirement of 434 chargers is calculated, working at 100% utilisation. This suggests the network is currently running at 7.89% utilisation, almost mirroring the average sum supplied by a selection of CPOs [5.30]. The assumption is made that all charges are 100% EV, since few hybrid plug-ins can take a one-hour 50kW charge. Furthermore, it is known that specific rapid chargers will be heavily used by EV users on busy commuter routes and motorways, and some that are deployed to allow ad-hoc speculative travel will be somewhat underutilised. Throughout the initial phase of EV adoption, it is noted by many researchers [5.2, 5.10, 5.15, 5.23] that a more significant percentage of EV users will charge at home where feasible and receive 100% charge, predominantly overnight. Thus, this phenomenon misrepresents rapid charger deployment by decreasing dependence.

Presenting the current rapid charger deployment of 5497 at full use and 10% use by the EV population would support a UK population of 1.4m EV. Furthermore, by employing 42,240 vehicles (10% of 422,400) currently using rapid chargers, presenting approximately eight cars to each rapid charger if operating at their conjectural 24-hour utilisation rather than operational utilisation.

### 5.6.7. Statistical consistency of the number of rapid chargers

The statistical consistency of the suggested rapid charger numbers (434) can be assessed, founded on the irregularity of the elements forming the calculation using variance synthesis [5.25].

The statistical consistency of the number of chargers will be:

Consistency (number of chargers) ~ sum of

$\{(\text{partial differential of K regarding each variable})^2 \times$ consistency of variable$\}$

Calculating partial differentiation of the equation for K, the variability of the number of chargers:

$$= \left(\frac{B\times C\times D}{E\times F\times G}\right)^2 \ [\mathrm{Var(A)} + \mathrm{Var(B)} + \mathrm{Var(C)} + \mathrm{Var(D)}] + (-1)(A\times B\times C\times D)(E\times F\times G)^{-2}[(F\times G)\mathrm{Var(E)} + (E\times G)\ \mathrm{Var(F)} + \times (E\times F)\ \mathrm{Var(G)}]$$

The partial differentials are calculated at the mean value point of the variable. Variability is the square of standard deviation.

**Table 5.2** Variance consolidation.

| Variable | A % EV | B - Cars | C - Miles | D %charging | E kWh | F - kW | G - Hours |
|---|---|---|---|---|---|---|---|
| Mean | 1.2 | 32,000,000 | 26 | 0.1 | 3 | 35 | 24 |
| Standard deviation | 0.0001 | 320,000 | 1 | 0.01 | 0.2 | 1 | 0.1 |
| Coefficient | 24.074 | 0.00 | 3 | 722 | -14 | 3 | -3 |
| Influence | 6 | 0 | 8 | 52 | 8 | 7 | 0 |

In this study, standard deviations are best predicted from familiarity in the methodology that obtained values (A to G). By applying the means and standard deviations in the table, the variance of charger numbers is 81, calculated from the sum of the influencers illustrated in Table 5.2, bottom row. Table 5.2 highlights the conflict largely dominated by D since its influence on the variance is significant. Thus, the variance can be assumed as a confident sum for the number of rapid chargers. Reliance on 1% charging, shown in Table 5.2, has a significant influence on the consistency of the sum of the number of rapid chargers. Though, the ambiguity in the number of vehicles has little effect.

The analysis calculates twice the standard deviation on either side of 72, by employing a 95% tolerance period for the number of rapid chargers. Standard deviation is the square root of the variance; therefore, standard deviation = 9. Moreover, a 95% tolerance period is circa 72+/-18, resulting in 54 to 90 chargers. Hence, it is vital to consider any doubt in the estimate of the number of rapid chargers since this helps reinforce the reliability on the current estimate.

**5.6.8.** Operational functionality

The performance of a rapid charger or the operational functionality will be calculated as: Utilisation x power (delivery vs design) x availability or hours utilised/24.

Thus, power vs design is the power transfer figure of 35.15kW divided by the maximum power transfer from a charger which is 50kW rated. Consequently, for a charger operating for a total of 1.5 hrs. per day (6% usage) and availability of 97%, calculates as:

$$100 \times \frac{26.5}{50} \times 0.97 \times .06 = 3.08\%$$

- Power transfer is restricted by the EV battery and its capability
- Availability is established by the frequency of utilisation, design, and maintenance

The calculation to deliver operational functionality indicates a level of 6% for the CPOs network, suggesting that a portfolio of, say 1200 chargers operating at 6% would provide the same as 72 at 100% capacity usage. Consequently, assuming the present range and utilisation is factored in the calculation, it equates to approximately to 5481, almost mirroring the current UK rapid charger network deployment. Note: An average number is used since some chargers see light utilisation, whilst others will experience heavy use.

## 5.7 Summary and Discussion

The results above are based on a continual flow of EVs and drivers. As this analysis is forecasting toward the future, batteries lower than 45kWh are discounted since EV manufacturers are continually introducing larger batteries, and this trend endures. Hence, the modelling must consider the advent of 45kWh to more than 110kWh batteries, notwithstanding the onset of new generation superchargers such as 150kW to 350kW. By focusing on the popular family EV segment in which batteries average 50kWh net, this study discounts larger capacity batteries' charging characteristics. Moreover, overarching technical control features suggest it is the capability of the car to receive and control the delivery of power, rather than the sole ability of the charger to deliver and control power. This engineered hierarchy determines power delivery from charge point to EV and the time taken to provide the charge.

Competences in range and the ability to accept higher charge rates are already emerging in some EVs, and in-car Battery Management Systems (BMS) efficiencies improve. High voltage DC systems are now the emerging choice of some manufacturers, such as Porsche, Audi, Hyundai, and Kia, doubling the standard EV voltage from 400V to 800V. This enables much higher charge rates and lower currents, lower heat transfer, smaller battery cabling and charge delivery cables [5.9]. Furthermore, the modelling used is infinitely adaptable and scalable, providing the ability to introduce variables such as ultra-rapid charging speeds, currently up to 360kW, but additionally capable of future charger calculation as the sector heads toward hyper charging speeds - above 1MW. In theory, hyper-charging (1MW+) can charge an average EV battery in less than six minutes [5.10], thus negating the need for ever-larger EV batteries and their incremental weight. The main obstacle to true Hyper Charging [5.31] is EV battery capability, which is currently a maximum of 270kW speed across a small percentage of all EVs.

The large-scale deployment of pure EVs, combined with the government mandate that prevents all UK sales of petrol and diesel-engined cars by 2030, requires a sustainable rapid charging infrastructure for all classes of EVs, thus reducing range anxiety and charge point trauma [5.10]. There has not been a viable model to determine what rapid charging network is necessary to support the considerable forecast growth of EVs up to 2030. This will be founded on acknowledged assumptions and identified variables. Leading up to 2030 and beyond, vehicle charging equipment technology improvements will develop at pace. The charging behaviours of EV drivers are still materialising based on variables, such as payment and power delivery models. This study calculates the present UK situation based on theoretical rapid charge delivery. Further understanding that may assist in future predictions could be derived from investigating other similarly deployed technology networks, such as AC charging posts, or visual advertising cabinet networks, focussing on location, volume, and contiguous distribution modelling.

It must be noted that this investigation, comparable to mobile telecom development and growth of Compact Discs (CDs) in the eighties, is to a certain extent entering unknown territory. The transition to EVs is being attempted on a scale without precedent. The variables are tangible given that business processes, considering both EV charging protocols and payment technology [5.10], are evolving rapidly. The EV user is confronted with ongoing upgrades and field trials of payment choices testing the market. Additionally, CPOs and manufacturers must decide what charging rate is satisfactory and determine what ROI (return on investment) will be necessary to strike a balance between OEM and CPO investment versus an acceptable charge rate for the consumer. Notably, the deployment of unregulated rapid charge points by developing a non-contiguous network that only satisfies and meets the needs of EV users in and around major conurbations. This strategy could isolate potential EV users and purchasers by creating a barrier to growth due to the lack of rapid charging infrastructure. Some areas like the Southwest of the UK are provided with rapid chargers on most motorways and A-class road networks [5.29], adequate for the off-peak tourist-focused winter months. However, recent research in 2021 [5.10] suggests that the design and planning of the UK's Southwest rapid charging network has not considered the vast transient tourist population growth in summer months, and is thus wholly inadequate as an all-year-round public rapid charging network. It is clear from this current research that there is no strategic link between real-world usage [5.10] and desktop forecasting, suggesting that the UK's current energy policy regarding supporting EV growth to 2030 is not linked to reality and is out of step with real EV user's needs.

The data output of this research reveals that the current UK motorway charging network requires reinforcement and deployment of additional charging devices to cope with peak and current utilisation in known pinch-points. Furthermore, as more EVs enter the UK car sector with higher capacity charge rate specifications, greater focus should be targeted at reinforcing the local grid to allow and achieve the installation of ultra-rapid chargers. This practical approach will shorten charging times at the point of delivery and allow greater throughput of EV users per charge point, thus reducing waiting and queuing times, providing a greater overall customer experience and acceptance of this new technology. A further investigation should build on the work of this investigation by monitoring traffic flow and EV driver behaviour at the charge point level rather than using prediction techniques and charting transient motorway seasonal peaks over twelve months. Although the usage figure of less than 5%, if accurate, indicates sufficient infrastructure from a commercial outlook, location and peak usage data have not previously been considered, implying a deficit in available rapid charging for some EV users at peak times.

For ICE drivers to make the transition to EVs, the process of charging an EV, such as time at a charge point, delivery of charge, ease of payment, price parity between EV and ICE vehicles, and convenient location are all essential factors for this significant transformation to happen. Furthermore, there is a business investment case versus the need for contiguous coverage, not just in the lucrative urban conurbations but also in less densely populated areas.

This study’s results point to a need for greater government intervention and funding to enable the planning and deployment of nationwide infrastructure. Future traffic predictions should be utilised to forecast and plot infrastructure requirements. Another issue is the total infrastructure deployment cost, including grid reinforcement, connection, and appropriate equipment specification. While the grid's impact through rapid charger expansion is recognised, grid reinforcement and deployment costs have not been considered. Furthermore, while the EV population could benefit the grid through V2G (Vehicle to Grid) application, this future technology has not been considered. However, it is accepted that the UK national grid must preserve an operating baseload, which must form part of any overall future electric transport strategy.

However, as EV batteries increase in capacity and EV user's confidence grows through newer usable infrastructure deployed, additional long-distance commutes might increase per user. What is certain from the investigation is that as CPOs have made charging an EV more practical, simple to use and quick to charge, then one element guaranteed to increase is the overall demand on the

UK's national grid. Previous studies [5.9, 5.10] established that additional grid load could be mitigated by green energy in combination with grid-scale Battery Energy Storage Systems (BESS).

## 5.8 Chapter Conclusion

The data output from this chapter reveals that the current UK motorway rapid charging network requires reinforcement and deployment of additional devices to manage peak utilisation. Greater focus should be targeted at reinforcing the local grid to allow the installation of ultra-rapid chargers. For ICE drivers to make the transition to EVs, the process of charging, such as time at a charge point, delivery at charge, ease of payment, price parity between EV and ICE vehicles, and convenient location, are all essential factors for this significant transformation to materialise. Further research may focus on siting clean energy production and storage systems close to the rapid charging stations. This may include grid-scale solar farms, BESS to capture off-peak grid, solar power, or wind power, which can be exploited to benefit all rapid charge stakeholders, now and in the future. Finally, future research would benefit from a larger sample and mix of electric vehicles, deeper research into ever-improving in-car battery management systems (BMS), and new battery technologies yet to be exploited.

# Chapter SIX

# 6 CONCLUSIONS

## 6.1 Thesis Summary

Despite electric vehicle's many advantages over ICE vehicles, EV growth has remained lacklustre within the UK market [1,26]. A literature review shows that an explanatory factor for the slow adoption rate that has thus far received limited attention from the scientific community, is the contribution of tangible charge-point barriers. Previous studies have focussed on users' range anxiety; this study goes further by exploring the experiential dimensions of sociotechnical EV growth barriers in the UK.

To the best of my knowledge, this study is the first to demonstrate the impact of distress or trauma at the charge point on EV drivers, a factor which informs the three barriers to EV growth investigated in this thesis. An extensive set of field case studies of drivers covering more than 2250 miles were employed, together with structured surveys of new and experienced EV users to examine how non-standardisation of charge points affects sector growth (Ch.3). The study then evaluates how Charge-point Trauma (CPT) contributes to this barrier by carrying out a national survey of EV drivers at motorway service stations to produce and analyse data on existing rapid chargers (Ch.4) as a foundation for current and future charge point deployment modelling in (Ch. 5).

The output from this study can be employed to stimulate policy shifts and enforced regulation of EV charging infrastructure to meet targeted UK demands. These measures will assist in reducing greenhouse gases and promote a cleaner, more energy-efficient transport system for future generations.

## 6.2 Research Findings

This research set out to identify and quantify barriers to EV adoption in the UK market. To reitterate from chapter one, the study follows the theoretical framework illustrated in figure 1.3 below:

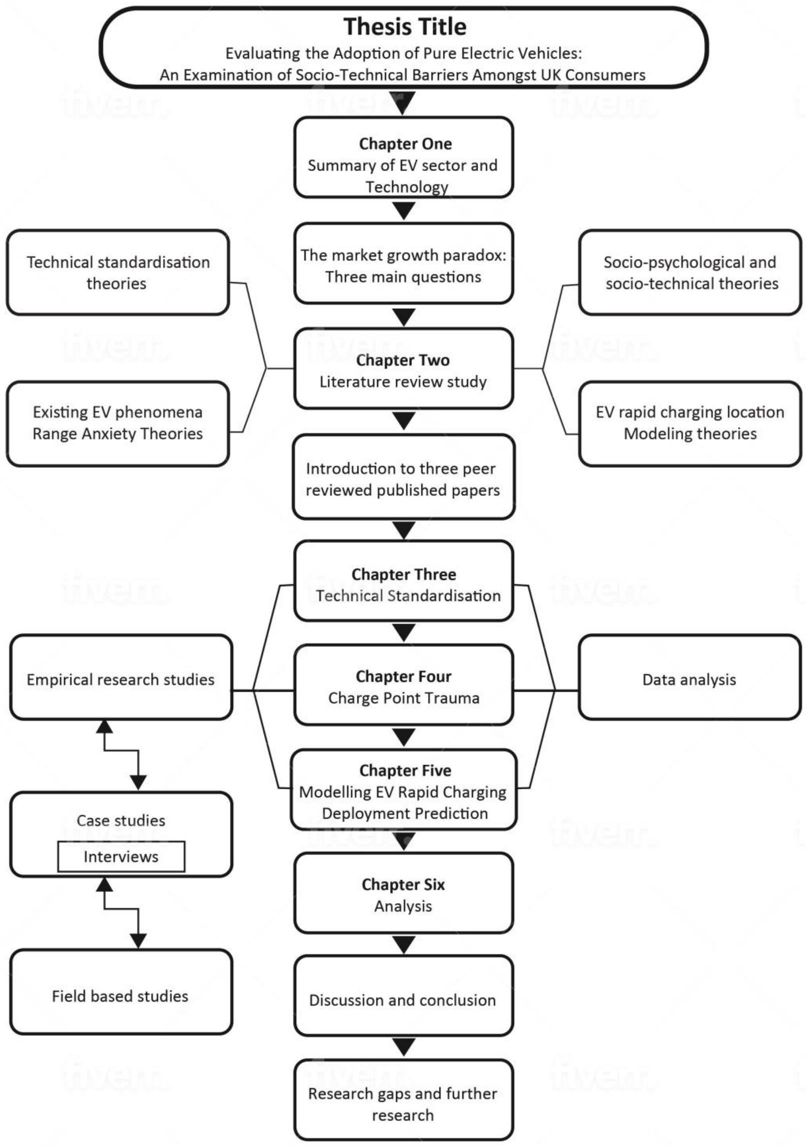



**Figure 1.3.** Theoretical framework

The combined investigations described in this thesis illustrate the tangible barriers to growth in market share that exist among prospective and inexperienced EV drivers despite an environment which encourages a substantial market share for EVs. The literature review identified nineteen acknowledged barriers to EV market growth (see Chapter 2, Table 2.1); five of these fundamental barriers developed into substantial fears and anxieties for UK drivers transitioning between ICE vehicles and EVs. This study uses the five most cited barriers in post-2018 research articles in order to reduce technological progression bias. The five most cited barriers are: the elevated price-point of EVs; poor availability or lack of public charging stations; range anxiety due to battery capacity and lack of rapid chargers; battery durability concerns; and the time taken to charge an EV. Whilst the most recent research found that the availability and operability of public charging stations is still a significant concern, a 2022 study indicates that one of the five barriers may have begun to fall away: price parity now exists between many equivalent EV models and their equivalent ICE vehicles [6.1]. Other significant barriers to EV adoption and growth included the payment process at the point of charging delivery and worries about ease of operability, maintenance, service and repair for downstream charging infrastructure.

My initial pre-thesis hypothesis that the complexity and variety of possible concerns should be limited to five growth and adoption barriers proved to be useful. I initially discounted it however, because I anticipated that barriers to growth would be multi-dimensional and interdependent [6.2]. Research for chapters three to five confirmed that most respondents in the survey cited numerous barriers to adoption rather than one isolated issue.

The empirical field-based study and analysis in chapter three reinforced this proposition; it found that all barriers included one of two observed characteristics, or both: technical uncertainty at the point of delivery and traumatic sociotechnical issues. In both sets of studies, I measured the fundamental emphasis on driver trauma against the field test data in Chapter 4. In the controlled field studies, the data revealed that trauma is directly connected to concerns over the reliability and serviceability of charge-point technology. This included concerns about monetary expense, vehicle-to-charger communication, battery range durability, ability to recharge on par with an ICE vehicle, ease of repair or future resale values of EVs.

Subsequent data analysis revealed more subtle relationships between the variables of range anxiety, charge-point operability, charge-point availability and location. This novel phenomenon is described for the first time in this thesis as Charge-Point Trauma (CPT). CPT emerges as a more significant barrier for novice EV drivers than experienced drivers. This is to be expected, given that novel technology users tend to be more anxious regarding technical operation and protocol ‘know-how’ during the early stages of adoption; this can occur whenever novel technology replaces long-established incumbent technology [6.3]. The second strong association emerging from the research in chapters three to five is that multifaceted charge-point uncertainty as a barrier directly correlates with increased EV driver heart rate and indicative anxiety or trauma, influencing the driver's behaviour (Chapter 4). Conversely, the links between concerns and behaviours linked to a lack of awareness, especially for less experienced EV drivers, were also evident in this research evaluation.

The research analysis implied that, to a certain degree, the sociotechnical barrier to adoption is a more critical issue for women than for men [1.26, 1.27]. The robust statistical evidence in this investigation for the five-barrier factorisation is enlightening and highlights a strong demand perspective-based issue facing the EV sector. Several government statements between 2017 and 2022 announced bans on the sale of new diesel and petrol-powered vehicles after the deadline of 2030 for migrating entirely to EV sales only [1.22, 5.3]. This deadline indicates how administrations successfully seek to propel EVs into mainstream transportation supply chains. Numerous OEMs have declared that from 2030 novel diesel and petrol cars will no longer be available in their model line-up. Although issues of supply and production receive much attention outside the automotive circles, there is far less policy intervention to mitigate the EV adoption barrier issues highlighted in this study. This comparative oversight is epitomised in the UK government-published EV infrastructure strategy [6.4], in which the critical demand-side enterprises provided an additional £100m toward ‘plug-in car' grant schemes, committing to 25% of central government department fleets being electric by the end of 2022. This was implemented independently of a separate £400m grant for charging infrastructure [6.5].

Originating from the five-factor barrier description and data analysis in chapters three and four, the data in this study shows that barriers to EV growth are complex and multi-dimensional. A new study [6.6] supports this hypothesis, suggesting that barrier factors are not easily explained through individual issues, and demand a broader holistic approach by strategy and policy creators.

In response to sociotechnical concerns such as CPT, such holistic strategies can include, for example, supply-side investment within the broader EV ecology such as relevant and effective charging infrastructure, parking hubs, and networks (both inter and intra-urban); at the same time, R&D investment in improved battery durability and performance should continue in order to support manufacturing. Reliable and consistent information is vital to refuting biased and fabricated information from traditional transport sector stakeholders such as oil companies and legacy car manufacturers. Disinformation can proliferate mistrust of novel technology among consumers [6.7]. The literature to date has not investigated or resolved issues of disinformation sufficiently, nor has it emphasised the importance of interventions based on gender. My investigation has shown for the first time that gender is a major factor in differences in user's and potential adopter's sociotechnical awareness about EVs. It is essential to note here that mainstream policy stakeholders involved in the national-level EV debate are predominantly male [6.8], which raises the possibility of unintentional bias in existing interventions. Interestingly, research by Statista [4.40] shows that 80% of men are licensed drivers as against 71% of women; therefore, further research is needed to investigate why a disproportionately higher number of men to women drive EVs.

A holistic solution for mitigating the economic uncertainty barrier should involve numerous stakeholders, including EV car dealerships, OEMs and policymakers. Diverse business models are appropriate, particularly in the short term; the data explored in chapter three shows that this is particularly important as long as the retail purchase price-point remains excessively high for most potential EV adopters. The analysis presented in this thesis advocates for the widespread adoption of diverse retail models and their standardisation, a process which can be accelerated by pursuing those market elements for whom the risk of economic uncertainty is already less of an issue. One such element is younger drivers, for whom EV dealers have moved away from loans for outright purchase or hire purchases toward subscription models of ownership [6.9] This method of consumption is consistent with other types of purchases made by young adults, such as mobile phones; it allows comparison and management of monthly whole-life costs and removes the negative consequences of high initial acquisition costs by transferring a portion of anxiety and decreasing second-hand device values onto sellers [6.10]. Similarly, supplementary ownership models such as access to an EV through a car club or monthly subscription may influence the development and growth of a shared ownership economy amongst younger EV adopters; this would put the EV economy in line with younger consumers' diminishing desire to acquire and own physical assets such as homes and cars [6.10]. Additionally, such ground-breaking models of EV ownership can assist those facing mobility challenges, reducing economic insecurity by reducing the risk and subsequent cost involved, compared to a traditional ICE driver moving to an EV [6.9].

Equally, policy-makers can resolve high economic insecurity among mature drivers and encourage EV purchasing behaviour by shifting discourses away from the purchase costs of EVs to the total cost of ownership over time.

EVs' main economic benefits for purchasers are their considerably reduced running costs, that can compensate over time for higher initial purchase prices [6.10]. Equally, research published by the ECF (European Climate Foundation) [6.11] maintains that the added cost over a four-year whole-life cycle of owning an electric Nissan Leaf® compared to a C-segment ICE car such as the petrol Vauxhall Astra®, reduced from circa €2000 in 2015 to roughly €1000 in 2020; the costs of owning the two types of vehicles are predicted to converge by 2030. If battery costs fall rapidly over the following seven years, this may accelerate price parity between ICE vehicles and EVs.

### 6.3 Significance of this study

The three novel studies in this thesis are capable of affecting policy and practice in the fields of EV rapid charger strategy, planning and deployment; their implications are important for policymakers, regulators, EV and charging equipment OEMs, and rapid charge-point operators. Better policy and regulation would stimulate higher growth in the sector by reducing the barriers to EV adoption examined in this thesis. Higher EV growth is likely to lead to improved vehicle connectivity and, coupled with an open data-sharing policy, is expected to lead to innovative charging strategies. Two-way connectivity such as vehicle-to-load (V2L) and vehicle-to-grid (V2G) is already a standard specification on some EVs [6.12] and is becoming more common in a fully connected EV ecosystem. Without significant growth in the EV sector, this vision may be delayed for several years.

The concept of CPT (Charge Point Trauma) is a significant innovation in this study. CPT describes the user's experience of trauma or anxiety at the charge-point for any of a number of reasons such as the charge point being out of service or not accepting payment, every charge point being busy, or the charge point being subscription only without a mobile phone signal to download the subscription application.

### 6.4 Contribution to new knowledge

This study considerably enriches extant literature by providing both empirical and theoretical contributions. Field-based research on EV drivers and a review of existing literature on mass-market EV drivers have been used to identify and minimise the complexity of present EV market growth barriers. The three significant studies at the core of this thesis (chapters 3, 4 and 5) focus on a number of critical human relationships with EV technology and its supporting infrastructure. The study names and reveals anxieties including the novel phenomenon designated Charge Point Trauma, which all contribute to EV sector growth barriers and hamper EV adoption.

The field-based analysis presented in chapter 3 and 4, is intended to provide a structured and practical guide which policymakers from similar European and North American settings to the UK may use to erode barriers to EV sector growth and enable evolution toward extensive EV acceptance. Chapter 5 examines the lack of a contiguous charging network in the UK and evaluates the deployment and effectiveness of currently existing rapid charge stations by using their locations, rate of charge and time-of-day charging data. This study is intended to provide a foundation for further research focusing on rapid charger location based on usage, traffic flow and physical location.

The findings from the field studies and surveys in this thesis have highlighted a fragmented network of disparate rapid charging stations located on major trunk routes and motorways in the UK. This line of analysis raises significant issues about existing studies of EV rapid charging, nearly all of which focus on the speed of charge delivery rather than contiguous network location, availability and operability. Both the empirical data presented in this thesis and the data-driven evidence from the literature cited, support the value of a novel scientific model to analyse and predict public rapid charge post-requirement on UK motorway routes. Emerging seminal studies have produced important insights into EV rapid-charging network deployment observation, and conclude that further infrastructure development is required to satisfy the growing demand for EVs. This is corroborated in a recent 2022 article by La Monica et al. [6.13] which states that rapid charging infrastructure is costly to deploy. Government support is needed to build charging infrastructure on less busy trunk routes in order to ensure a contiguous national network, with costs and infrastructure shared by operators through both roaming agreements and payment of deployment costs [6.13].

Furthermore, a recent study by Herron et al. [5.3] suggested that as of 2018 the number of rapid chargers was adequate to service the number of UK-registered EVs. However, findings from the study above problematise this analysis based on the assumption of 24/7 usage of all calculated rapid chargers. La Monica et al. [6.13] scrutinises other facets of rapid charger deployment by examining how major charging infrastructure is funded, citing that rapid charging should be regulated using the same process applied to the delivery of electricity. This, it is argued, would encourage ease of roaming with one single contract for users and clear access to interoperable infrastructure. La Monica et al. [6.13] further contend that this arrangement would enforce ease of charger access and encourage a highly competitive market, although this will almost certainly require government intervention through regulation and subsidies.

However, while there is an emerging consensus on the elements and policies necessary to create a contiguous national charging network, there is less agreement from both the literature and among actors in the sector, about whether such a network will actually come into existence. This is especially true in light of predictions of current and future demand and the possibility of technological advancements such as growing EV battery capacity. My own experience as an EV owner since 2016 provided the initial impetus and motivation for this investigation, which focused on many unanswered questions that had not been explored in previous studies.

The findings of this study have revealed that at present, the UK has a barely adequate number of rapid chargers to satisfy overall EV charge demand; further, the public rapid-charging national network is poorly designed from a locational and operational perspective and is not effectively exploited. This study provides a framework and foundation for accurate prediction forecasting, thus reducing the inefficiency resulting from the current ‘scattergun’ approach created by the absence of a national planning strategy by the authorities and the relevant regulators [6.14].

### 6.5 Limitations of the study

Firstly, although the structured survey in chapter 3 comprised 242 EV drivers, only 16% of those interviewed identified as female (the remainder identified as male). The study took place during the Covid pandemic, at a time when many people opted to remain at home and video calling significantly reduced the need to travel long distances. This is substantiated in a general transport study by Borowski et al. [6.15] in 2021. They noted that the number of women drivers travelling on major trunk routes through the pandemic was significantly lower than during the period after Covid restrictions were lifted.

Secondly, while the survey in chapter 3 was significant in terms of participant numbers given the restrictions imposed at the time, the number is still insufficient to represent all commuting stakeholders. Therefore, one must be cautious in making generalisations based on the results of this study.

Thirdly, as battery prices fall and power and energy density increase, new battery technology may accept much higher charge rates. This would allow EVs to run on a charge similar to an ICE vehicles range that have been refuelled. This may slow rapid charge-point use, creating a need for new subject research.

Finally, this study has taken place entirely within the UK. Although some comparative data were employed and discussed in the analysis, more research data might be used to compare experiences in mainland Europe, China and the US. Whilst the current research results provided a solid basis for identifying barriers to the adoption of EVs in the UK, the analysis looked mainly at the external elements. Hence further research is needed to complete a full-circle audit of barriers to adoption by looking deeper into the technical and operational issues relating to EVs. The results of this study identified sociotechnical barriers to adoption of EVs such as lack of standardisation and the novel psychological phenomenon of Charge-Point Trauma (CPT) due to current technical and operational constraints.

### 6.6 Recommendations for future research

Given that the current study has identified a number of interlinked barriers to EV adoption, a fully funded more extensive national survey of EV users should be carried out now Covid restrictions have been lifted and the country is reverting to normality. This survey should use a sample of at least two thousand participants, especially as the number of registered EVs on UK roads has more than trebled since the start of this research. Additional variables which should be investigated in future studies include the effects of marital status, ethnicity, vehicle type, housing type, home tenure and brand preference on EV adoption. The current study has been limited to the UK; future studies could examine the inter-relationship of growth barriers within the global EV environment.

Outside the discrete context of the three core studies in this thesis, it is anticipated that the methodology and approach will provide a framework for future researchers to investigate and examine how acknowledged barriers to sector growth and EV adoption can be mitigated, thus providing more beneficial justifications and remedies.

## 6.7 Final Reflections

### 6.7.1 Secondary data research development

Although I had good basic secondary research abilities before commencing this study, those capabilities have significantly developed as a result of completing this thesis. The secondary research skills I have gained while conducting this study will contribute enormously to my ongoing academic development in the years ahead and will allow me to evaluate and use publicly available data for business and research in more effective ways.

My competency increased significantly in two areas. The first was prioritising information among large amounts of secondary data. Throughout the literature review phase of the research, I developed the skill of prioritising secondary research data by using a clear set of significant criteria, such as the qualifications and academic status of the author, publication date, and the credentials of the journal or publisher. For example, there was an immense volume of secondary data relating to EV issues and zero-carbon topics closely allied to the EV sector; nevertheless, as a consequence of selecting secondary studies using the criteria, chapter 2 of the thesis examines only the most significant contributions to the research field. The skills I gained by selecting secondary data according to the criteria above provided significant advantages, such as efficient time management which improved the validity level of discoveries from secondary research.

The second area in which I increased my competency was the in-depth analysis of secondary data. I now adopt a critical approach to secondary data; before embarking on this research, I tended to view the perspectives expressed in non-fiction books as facts, assuming that the authors must deeply understand the subject they were writing about. The exercise of examining the available literature in my chosen field of research has transformed my understanding and my ability to access and assess others' knowledge. I can now better evaluate the limitations and weaknesses of the secondary literature I read.

### 6.7.2 Developing Primary Research Abilities

As a practising research engineer, I have acquired valuable primary research skills by carrying out this study. For me, it was an unparalleled experience of being engaged in research that required novel primary data collection, and field study analysis with minimal resources. The broad significance of choosing the most appropriate sampling method helped me gain in-depth awareness of a range of techniques from establishing sample size to critically analysing the various techniques available.

My involvement in primary data gathering and its analysis has significantly contributed to my maturity as a scholar and researcher. In the current highly competitive commercial environment, the significance of sector intelligence is more important than ever. Through developing my primary research skills and knowledge, I can now speak with authority in my market sector due to the work I have done during the course of this study and its outcomes.

### 6.7.3 Time Management Development

From a personal and a professional perspective, my time-management skills benefited enormously from this research experience. The process of fulfilling this study required extensive planning and preparation for each phase.

In addition, each stage of the thesis had to be limited in scope, whilst incorporating and achieving key milestones and deadlines.

I did encounter challenges in keeping to my schedule. These matters primarily surfaced at the literature review stage of the investigation, where I underestimated the amount of time necessary for secondary research. I consequently needed to prolong this phase of analysis but was able to remedy the issue by realigning my schedule of study. This resulted in greater focus in maintaining my research schedule. Moreover, the experience of writing this thesis has improved my time-management skills, providing considerable benefits to me academically, professionally, and personally.

### 6.7.4 Improvement in Self-Confidence

My level of self-confidence improved significantly during the process of this research, achieved mainly by overcoming self-doubt and believing in myself. This has been especially relevant when hosting lectures and conferences.

Finally, I would like to record valuable advice I received from three final year PhD candidates during my first year of this investigation.

1) Establish a routine in a dedicated workspace and treat it like a job.
2) Focus on your own research, but ask questions all of the time.
3) Expect continual change.

This advice proved invaluable throughout the progress of my PhD.

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