Plugging the Gap: An Assessment of Future Demand for Britain's Electric Vehicle Public Charging Network

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SUMMARY OF FINDINGS

PLUGGING THE GAP: AN ASSESSMENT OF FUTURE DEMAND FOR BRITAIN'S ELECTRIC VEHICLE PUBLIC CHARGING NETWORK

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

EXECUTIVE SUMMARY

Overview

This report sets out the findings of new analysis of the optimal Electric Vehicle (EV) public charging infrastructure needed to meet future growth of EVs in Great Britain to 2030. Future scenarios for EV uptake are in line with scenarios developed by the Committee on Climate Change (CCC) in its 2015 advice to Government on the Fifth Carbon Budget. We explore the impact of a number of important factors on the optimal type of EV charging infrastructure likely to be required to 2030, such as: increased battery range, the number and pattern of trips taken using EVs, the availability of different types of rapid chargers and their associated charging speeds and times, as well as the behavioural consideration of 'range anxiety'.

The project is the result of a competitive tender issued by the Committee on Climate Change in 2017. As part of the project, SYSTRA together with Next Green Car and Cenex developed tools to analyse the supply and demand for two categories of public EV charging:

- Long distance *en route* charging on the strategic road network (i.e. motorways and major A roads) across mainland Great Britain.
- Parking-based charging at the destination of trips, often around local towns and regions. Charging for these trips takes place while a driver is using local facilities, such as shops, using chargers at on-street parking spaces or public car parks.

The outputs from the two tools have been combined to give an overall estimate of Britain's current (2016 base year) and future public EV infrastructure requirements. The key findings under the CCC 'Central scenario' uptake, which envisages EVs accounting for 60% of new car and van sales (approximately 30% of the total fleet) by 2030 are:

- To meet long distance *en route* rapid charging requirements, and maximise carbon emission reductions, the number of rapid chargers located near the major roads network needs to expand from 460 in 2016 to 1,170 by 2030.
- This is a relatively modest increase of 2.5 times 2016 provision compared with the increase in the number of electric vehicles in the UK car fleet which rises by a factor for 72. This can be explained by:
  - An increase in the range of future EVs, which means that many fewer trips will require a charge en route. In 2016 around 27% of trips need to charge en route; with increased battery range; this falls to less than 1% by 2030.
  - An increase in the proportion of EVs able to use faster chargers, which reduced overall charging times and increases charger utilisation rates i.e., there are more charging events per charger.
- The number of public chargers required to meet the 2016 level of demand for 'top-up' charging during parking-based charging around towns and local areas is estimated to rise from 2,700 in 2016 to over 27,000 by 2030.
  - This is a much larger increase than for longer distance en route charging.
  - It reflects a continued demand for 'top-up' charging, despite the increase in battery size and range, and reduction in range anxiety.

- Overall nearly 29,000 charging points are needed across Great Britain by 2030 to meet future EV charging needs. Around 85% of these are fast (22kW) or rapid (43+kW) chargers. There are uncertainties around this estimate as the analysis relies on some key simplifying assumptions:
  - The analysis takes account of differences in range anxiety between new and experienced BEV users, but the precise assumptions around how this reduces over time are uncertain.
  - Simplifying assumptions were made for the average time that drivers are prepared to wait for a charge. In practice, there is likely to be a distribution around these, and if EV users cannot continue their journey without re-charging they will be prepared to wait longer than this average.
  - The current (2016 base year) pattern of charging behaviour is also assumed to continue in the future which may not be the case as EV driver experience and familiarity grows.
  - The analysis of *en route* charging assumes that trips are spread evenly over the course of the day. However in reality, when there are peaks in travel demand, additional chargers may be required.

These will need to be monitored as the public EV infrastructure develops to ensure that it does not act as a barrier to the EV uptake required to meet the CCC scenarios.

The study also assessed the costs of installing chargers. It found that to meet the central EV uptake scenario requirement of around 25k additional chargers would cost around £530m based on current capital costs. This could be met through a mix of private and public investment.

- The vast majority of this, £500m, is for chargers around towns and local areas rather than on motorways and major roads. Rapid chargers installed on the major roads network would cost approximately £30m.
- Many chargers are likely to be installed by companies wanting to attract customers to their services (e.g. supermarkets, leisure centres etc.), and the growing EV market presents an opportunity for commercial investors. However, councils may need to assist with on-street chargers, chargers located in council-owned car parks and park and ride sites. In practice a mix of public and private investment is likely to be needed.
- There may also be additional costs if the electricity grid needs to be reinforced to support this number of chargers, but this will be dependent on the location where they are installed.

The modelling also considered the geographical distribution of the optimal EV charging infrastructure:

- The geographical distribution of chargers used for ‘topping-up’ during parking-based charging loosely reflects population density as well as current car use and provision of public transport services. Lancashire, the midlands and to the counties to the west of London are expected to require a high number of new chargers.
- The region which requires the highest number of additional motorway chargers is Lancashire, reflecting the importance of the M6 in journeys between the north and south of Britain.
- Located around the centre of the country, Derbyshire & Nottinghamshire and Leicestershire & Northamptonshire also require a high number of additional motorway chargers to serve numerous north-south and east-west routes.

The rest of this overview covers:

- The methodology used to assess the demand for long distance *en route*, e.g. motorway, and parking-based public charging infrastructure;
- The key findings from these models;
- Uncertainties and sensitivities; and
- Conclusions.

Methodology

(a) Long distance *en route* charging model

This model assesses re-charging required *en route* for long distance trips between urban areas. The model looks at travel demand between a set of zones (for example North Wales to London) on the Strategic Road Network and major roads and estimates the expected demand for charging *en route*.

Route demand across Great Britain as a whole is estimated using the relationship between the populations of and distance between two areas. This total route demand is calibrated using a combination of DfT travel diary data and station-to-station rail travel patterns in GB. Applying a scenario for future EV take-up, the result is a predicted matrix of the future long distance EV travel demand between the 50 mainland GB regions/zones considered.

The analysis takes into account the distribution of battery range of the EV fleet and likely charging rates in future year(s). This allows consideration of which trips will require a charge and where, and how this charge can be achieved based on the relevant *en route* charging infrastructure. The most cost-effective infrastructure improvements needed to create the optimal charging network to meet future demand for charging can then be estimated. The modelling takes account of the miles of electric range that can be driven in current (2016 base year) and future EVs, evidence on range anxiety and current preferences for EV charging.

The analysis considers three different CCC scenarios for the future take-up of EVs ('Barriers', 'Central' and 'Max'), based on its Fifth Carbon Budget advice (2015)[1]. Three types of rapid chargers are explored: 43kW, 150kW and 350kW ('ultra-fast' chargers available from 2020). Typical charging times are around 30 minutes or 15 minutes for ultra-fast chargers, and demand is spread throughout the day. The analysis assesses current (2016 base year) and potential charging locations to determine where it may be cost effective to build more chargers, e.g. where there are long waits for charging or the potential to serve a greater amount of demand.

The analysis considers different priorities when calculating the optimal network as follows. Each option will have a different impact on the experience of EV drivers:

- Do-Nothing, where no additional chargers are added to the en route charger network provision existing in the 2016 base year;
- Carbon-focussed, where the priority is to provide chargers to maximise the number of long distance journeys which can be made by EVs;
- Driver-focussed, which aims to provide chargers to improve a combination of factors that EV drivers are likely to be concerned about. These include the time taken to divert off-route to access a charger, the time spent waiting to gain access to a charger, the duration of charging and the monetary cost of a charge; and
- Commercial-focussed, where the main objective is to maximise the net income for the providers of the charging infrastructure.

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[1] CCC (2015) 'Sectoral Scenarios for the 5th Carbon Budget'

(b) Parking-based charging model

This analysis covers charging which occurs while EVs are parked at or near their destination, for example in shopping and leisure centres or in Park and Ride car parks. Drivers undertaking these trips may use public charge points to top up their battery before their next journey. Others may not have access to private charging facilities and, therefore, must use an on-street charger near their home or make a special trip to a charger further away. The types of charging events covered are:

- Public on-street home charging;
- Parking-based charging where EV users are undertaking other activity at a location close to the charging point (e.g. shopping);
- Specialist fleet charging – e.g. public sector vehicles/taxis that may take the opportunity to charge using public charge points;
- Park and ride charging; and
- People choosing to access a charger just to charge (i.e. comparable to making a specific trip to top up at a petrol station in a petrol/diesel vehicle).

Workplace and home off-street charging are excluded as these are generally assumed to be part of the private charging network.

The types of chargers considered include all standard (7kW) and fast (22kW) chargers in public places, and publicly-available rapid (43kW) chargers. They exclude those on the trunk road network (which are assumed to be predominantly used for *en route* recharging). Chargers at locations such as car dealership forecourts and hotels, which are primarily provided for the private use of customers, were excluded from the 2016 supply network used in the model.

Demand for charging during these trips is derived from the forecast total number of trips within each of the 50 mainland GB zones based on the Department for Transport (DfT)'s projections to 2030. This was then adjusted to take account of the forecast future-year EV ownership within the geographic region. The likelihood of an EV requiring a charge on a given trip was calibrated using observed charging behaviour based on 2016 data from zap-map (a map of UK electric vehicle charging points, which includes live data of their usage).[2] The analysis considers a large number of permutations of additional charging infrastructure within each zone, including different combinations of additional 'Standard', 'Fast' and 'Rapid' charging infrastructure.

The modelling tool uses the outputs from these simulations to assess the most cost-effective combination of new charging infrastructure needed to meet future growth in EV ownership for different CCC scenarios, both on a zone-by-zone basis and as an aggregated service level across all of mainland GB.

Key findings

(a) The long distance *en route* charging model

In 2016 there were around 460 rapid charge points on majors roads in Great Britain which have been considered by this study as part of the long distance *en route* charging network. This number of charge points, with the numbers of EVs with 2016 battery ranges, supports around 55% of potential long distance travel. The remaining long distance travel is not undertaken in electric vehicles as drivers choose alternative options due to a combination of there currently being no suitable rapid charging

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[2] www.zap-map.com

locations to complete certain routes or the wait times being longer than drivers are prepared to endure at the charging locations.

In 2030, if the existing (2016) EV recharging network is not improved, we estimate that that the proportion of potential long distance EV miles which will be 'lost' due to the insufficient supply of rapid chargers rises to around by 83% of the potential demand. This assumes that the maximum acceptable wait time for an EV driver is approximately 12 minutes, compared with the 2016 average of 7 minutes. The next sections set out the optimal charging network required in order to meet a range of different objectives.

Carbon-focussed objective

In order to meet future demand for charging and to maximise the number of miles that are undertaken in EV mode, the long distance rapid charging network needs to expand from 460 in 2016 to 1,170 by 2030 in the carbon-focussed scenario under the CCC central EV uptake scenario (Table 1). This is an increase of 2.5 times 2016 provision, and is relatively modest compared with the increase in the EV fleet which rises by a factor of 72. As the number of chargers increases, the amount of demand (in miles) met rises from 55% in 2016 to 90% by 2020 and 99% by 2030. There are several reasons for these results:

- The average range of a new EV is expected to increase from around 50 miles (80km) in 2016 to over 250 miles (400km) in 2030. Although there will still be vehicles with shorter ranges in the fleet in the 2020s, over time they will make up a smaller proportion of the fleet.
- Increased battery range means that many fewer trips will need to charge *en route*. In 2016 around 27% of trips need to charge *en route*, this falls to less than 1% by 2030. As a result, the number of trips requiring a charge only increases by a factor of ×1.3 over this period.
- An increase in the proportion of EVs able to use faster chargers reduces overall charging times by around one third. This means that charger utilisation rates rise and there are more charging events per charger. The average number of charging events per day increases by a factor of around 3.6.
- Average wait times rise, but are still close to the acceptable limit estimated from current 2016 base year data.

Table 1 also shows the number of chargers needed for different EV uptake scenarios. The CCC central EV uptake scenario corresponds with 60% of new car sales being EVs by 2030 compared with the max scenario of 65% and the barriers scenario of 40% by this time. With fewer EVs predicted to be on the road, we estimate a requirement for 710 chargers in the barriers scenario and the max scenario requires 1,300 by 2030.

Table 1. Optimal EV Rapid Charging Infrastructure Needed for Long Distance En Route Charging

	2016*	2020	2025	2030
Carbon-focussed Scenario, central EV uptake:				
Number of EV chargers	460	650	920	1,170
Demand met (%)	55%	90%	97%	99%
Average wait time (minutes)	7	4	10	13**
Other EV uptake levels:				
Max uptake – no. of chargers	460	650	920	1,300
Barrier uptake – no. of chargers	460	540	590	710
Other optimisation scenarios:				
Driver-focussed – no. of chargers	460	480	640	850
Commercial-focussed – no. of chargers	460	460	485	485

Notes: Results shown use the 'straight to year' optimisation methodology, as described in section 5.1 of the main report.

** 2016 is the base year for the model – this column represents the current situation, without any optimisation carried out. Note that this means the chargers listed here have not been checked for commercial viability, but are assumed to remain in the network in all future years and scenarios.*

*** The arrival rate cut-off is estimated for sites with >3 chargers, and so some sites may end up with a wait time of a little over 12 minutes, which pulls up the overall average.*

Other model runs: driver and commercial focussed results

As outlined in the methodology section, the long distance model is capable of considering the optimal EV infrastructure needed to meet objectives other than minimising carbon emissions.

In the driver-focussed runs, the main purpose is to assess the number of chargers needed to minimise the time and money a driver spends on charging (including diverting to a charger, waiting for a charger to become available and waiting for the charge to finish). The commercial objective aims to maximise value for installers – i.e. to make a financial return from the operation of their rapid chargers (i.e. ignoring any other benefits from attracting EV drivers to their charging locations) assuming current infrastructure costs and monetary charging rates are retained. The results from these are also shown in Table 1.

Assuming that EV drivers are willing to wait the same amount of time as they do currently, the driver-focussed scenario requires 850 chargers on long distance routes by 2030. This is lower than the number needed to maximise carbon saved, and less than twice the number of chargers in the 2016 base year. In this scenario, wait times are reduced to less than 6 minutes compared with 13 for the carbon-focussed scenario, and in both cases, 99% of *en route* charging demand can be met. The main difference between this scenario and the carbon-focussed scenario is the upgrade of a large number of 150kW chargers to 350kW ultra-rapid chargers, which enable quicker charging and reduce wait times, the primary objective of this scenario.

The focus of the commercial objective is to look at the charging infrastructure that might be developed from a purely commercial perspective – i.e. that maximises net income for installers and operators. It takes into account the predicted increase in revenue, increase in running costs (electricity supply and maintenance) and capital cost. It assumes that both base year charging rates apply to the future and that capital costs remain the same. In practice, it is likely that economies of scale and other learning would bring down capital costs so this is likely to be a cautious assumption. The scenario indicates that very few (less than 30) additional rapid chargers would be provided for purely commercial reasons.

The overall cost of installing additional chargers for long distance *en route* charging is around £30m for the carbon and driver-focussed scenarios (as the driver focussed scenario has fewer chargers overall but a higher proportion of the more expensive 350kW chargers). These are likely to need a mix of public and private financing:

- Private investment is likely to occur where this is profitable for operators. This is lower than the level needed to maximise carbon benefits or to reduce wait times.
- Public investment will therefore be needed to bridge the gap between type of infrastructure that would be installed from a private commercial perspective and what is needed to maximise carbon benefits.
- In practice we would expect some economies of scale to bring down capital costs such that chargers at more locations could become profitable.
- Installers are likely to invest in chargers for other reasons for example to attract users to existing service station facilities, in which case private investment could be higher than that modelled.

(b) Parking-based charging modelling

There are currently around 2,700 chargers across Great Britain, which have been considered by this study as part of the public parking-based charging model, serving demand for charging whilst cars are parked during periods when drivers are undertaking other activities. The modelling of these parking-based charging events suggests that drivers are able to choose to charge 58% of the maximum charge they could potentially demand given the base year battery ranges. The remaining potential demand is not taken up due to either no charger being available or the duration of the required charge exceeding the duration of the underlying trip. This could be because:

- The modelling assumes people like to top up whenever they can, which may not always be the case.
- Although batteries may not be completely full, people may still have sufficient charge to get to their next destination.

Using the CCC's Central EV uptake scenario, it is estimated that if there is no further improvement to the base year charging network the proportion of potential demand that could be satisfied will drop from 58% to 6% by 2030.

Under this 'Central' EV uptake scenario, the number of chargers required to meet the base year's 58% level of charging for parking-based charging is predicted to rise from 2,700 publicly-available chargers in the 2016 base year to over 5,600 chargers by 2020, almost 12,000 by 2025 and to around 27,000 chargers by 2030 (see Table 2).

Table 2. Optimal Number of Chargers Needed for Parking-based Charging

NUMBER OF CHARGERS	2016*	2020	2025	2030
Central EV uptake	2,700	5,600	11,700	27,000
Max EV uptake	2,700	5,600	11,800	34,000
Barriers EV uptake	2,700	4,100	6,000	13,100

Notes: Estimates rounded to nearest 100.
** 2016 is the base year for the model – this column represents the current situation, without any optimisation carried out.*

This represents a substantially more rapid expansion than on the *en route* long distance journey network. There are two main reasons for this difference:

- The increase in battery range over time has a bigger impact on the demand for longer distance charging (which will only be used if the journey cannot be completed without it) than for parking-based charging (which will continue to be used for 'topping up').
- High levels of charger utilisation are not achieved as it is assumed ultra-rapid chargers are not available for parking-based charging at destinations.

The results suggest that 55% of chargers need to be fast, 29% rapid and 16% standard, to enable drivers stopping for varying amounts of time to top up.

The total installation cost of these chargers is estimated at £500m, assuming current EV charger costs. The cost-effectiveness of installing these chargers is not considered in this modelling as only those areas which have most need for additional parking-based charging infrastructure are identified. It is expected that goals other than direct profit could lead to chargers being installed in these areas, for example retailers wishing to attract business to their shops.

Uncertainties and Sensitivities

There are several uncertainties and assumptions which could affect the results. Underlying the model are assumptions around range anxiety, current charging behaviour and average times EV drivers are prepared to wait for charging. These are based on current evidence, and assumed to hold in the future. Other uncertainties that we tested were: the proportion of EV owners with access to off-street charging; assumptions around charging behaviour for those without off-street home charging; and the reliability of chargers. The key results of these were:

- The proportion of EV owners who have access to off-street home charging. Evidence suggests that 93% of base year EV owners have off-street charging and this is assumed to continue to 2030. If this reduces to 80% by 2030 (in line with a reduction to 70% overall proportion of home owners with off-street charging by 2040), this leads to a 1% increase in chargers needed, or 290 by 2030.
- The assumptions relating to charging for EV owners without off-street parking. It is currently assumed that EV owners without off-street parking will charge during their normal activities as characterised by the parking-based charging modelling. If instead all of these require overnight charging using public chargers, this leads to a 20% increase in demand for chargers by 2030, or around 6,000 chargers.
- Reliability and availability of chargers. Some public chargers are only available to specific customers (e.g. Tesla super-fast chargers). Our central assumption is that these are available to all EV owners. To test the sensitivity of this, all manufacture-specific chargers

were taken out of the supply network and the results re-run. This resulted in fewer 150kW chargers and 20% fewer chargers overall, as well as an increase in efficiency in terms of charge delivered per charger, as supply and demand are matched more efficiently.

- There is uncertainty about how long people will be willing to wait for a charger. If drivers' tolerance of waiting time is less than what has been estimated in the model then additional chargers and a higher proportion of 350kW chargers may be required in order to keep waiting times down to acceptable levels.
- Charging on the long distance *en-route* network is assumed to be spread evenly across daytime hours. However this could be incorrect, with, for example, people planning their recharging stops to coincide with lunchtime, resulting in a lunchtime peak in charging demand. In this case, more chargers than indicated by these results may be required in order to serve a sufficient amount of this peak demand.

Conclusions

The above sections have detailed the results for *en route* charging along motorways and major roads, and 'top-up' parking-based charging separately. Selecting from these the carbon-focussed en-route model solution, and a solution which maintains the base year percentage level of service for parking-based charging, we determine that a total network of nearly 29,000 chargers will be needed across Great Britain in 2030. To achieve this from the base year charging network will require the installation of over 25,000 new chargers (Figure 1). This is estimated to cost around £530m (excluding potential grid connection costs) and is likely to need a mix of public and private investment to be delivered.

Without continuing financial support or a change to current charging regimes, providers of charging infrastructure are unlikely to see significant financial benefit from providing chargers in isolation. The private sector is therefore likely to focus on providing chargers at locations where they are also providing other services to the EV users (shoppers, hotel guests, leisure facilities etc). This means that these chargers are unlikely to be provided in optimal locations from the perspective of cost-effectiveness and efficiency in meeting the total charging demand of all EV users, rather than specific customers' needs. It will be important to monitor the future development of EV infrastructure to ensure it is consistent with delivering the EV uptake scenario. It may be necessary to offer additional financial support if this level of infrastructure is insufficient to give potential EV owners confidence that they will be able to charge as needed.

Figure 1. Total Chargers Required to Meet the CCC Central EV Uptake Scenario, Selected Solution Approaches

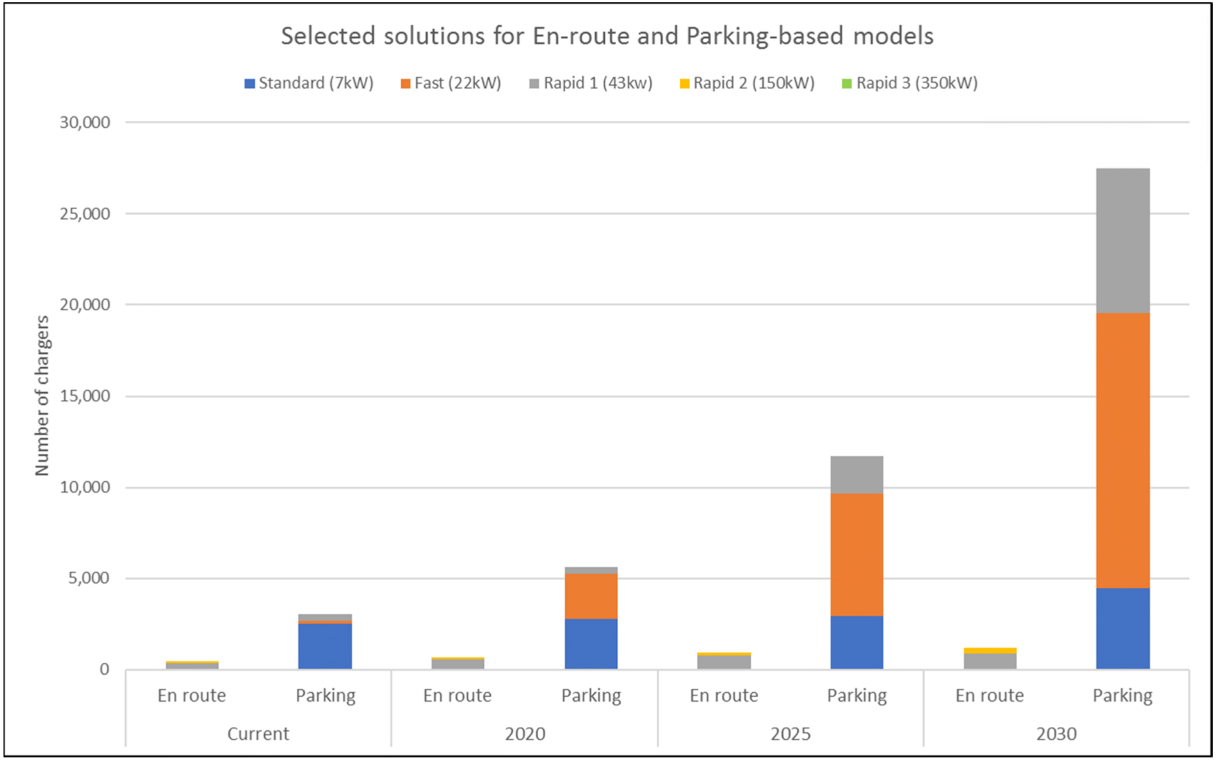

Figure 2 and Figure 3 show the regional breakdown of the number of chargers required in these solutions for the long distance *en route* and parking-based modelling respectively.

Figure 2. **Total Number of Chargers Required by Zone for Long Distance *En Route* Charging by 2030 (Carbon-Focussed Optimisation; CCC Central Uptake Scenario)**

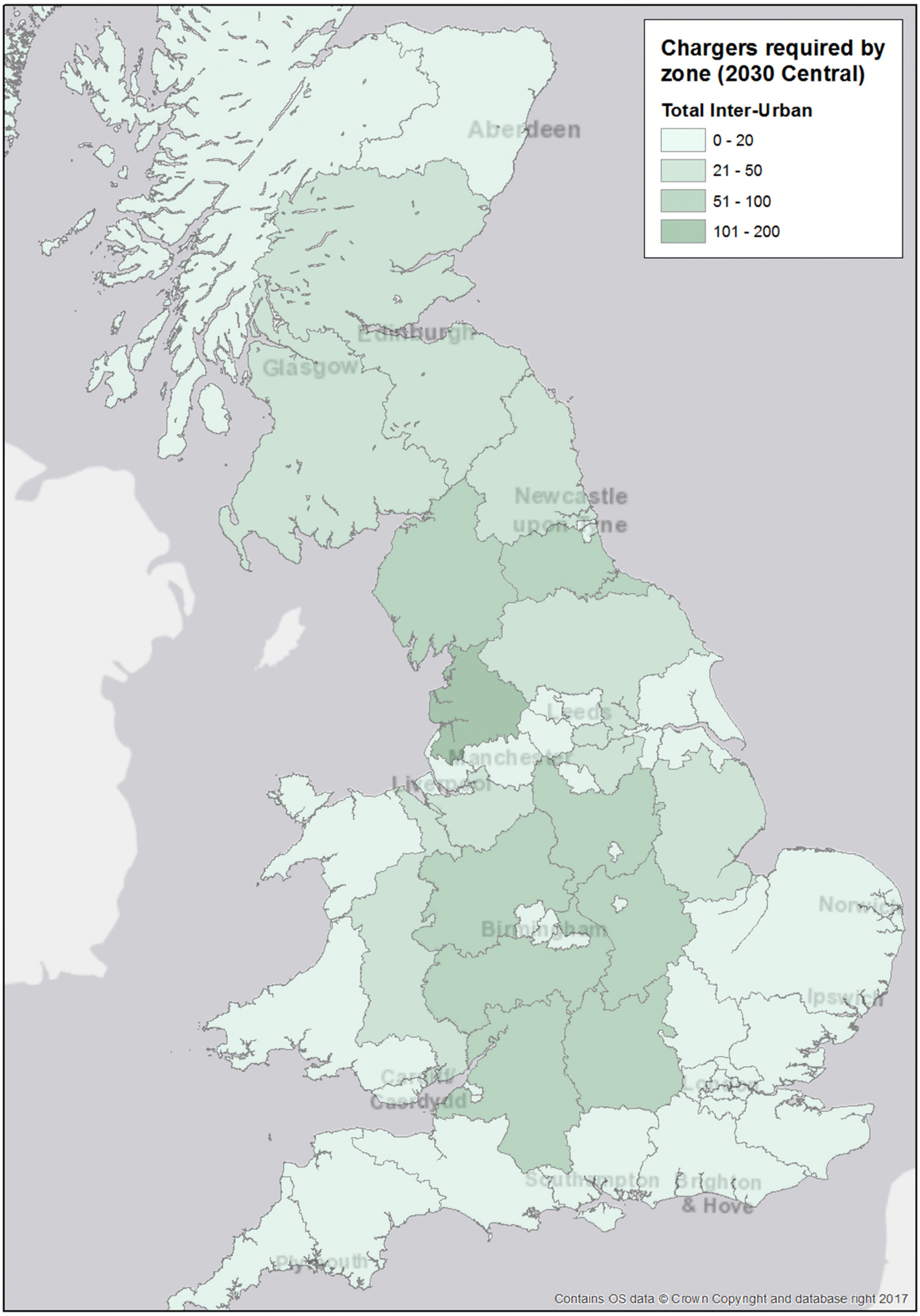

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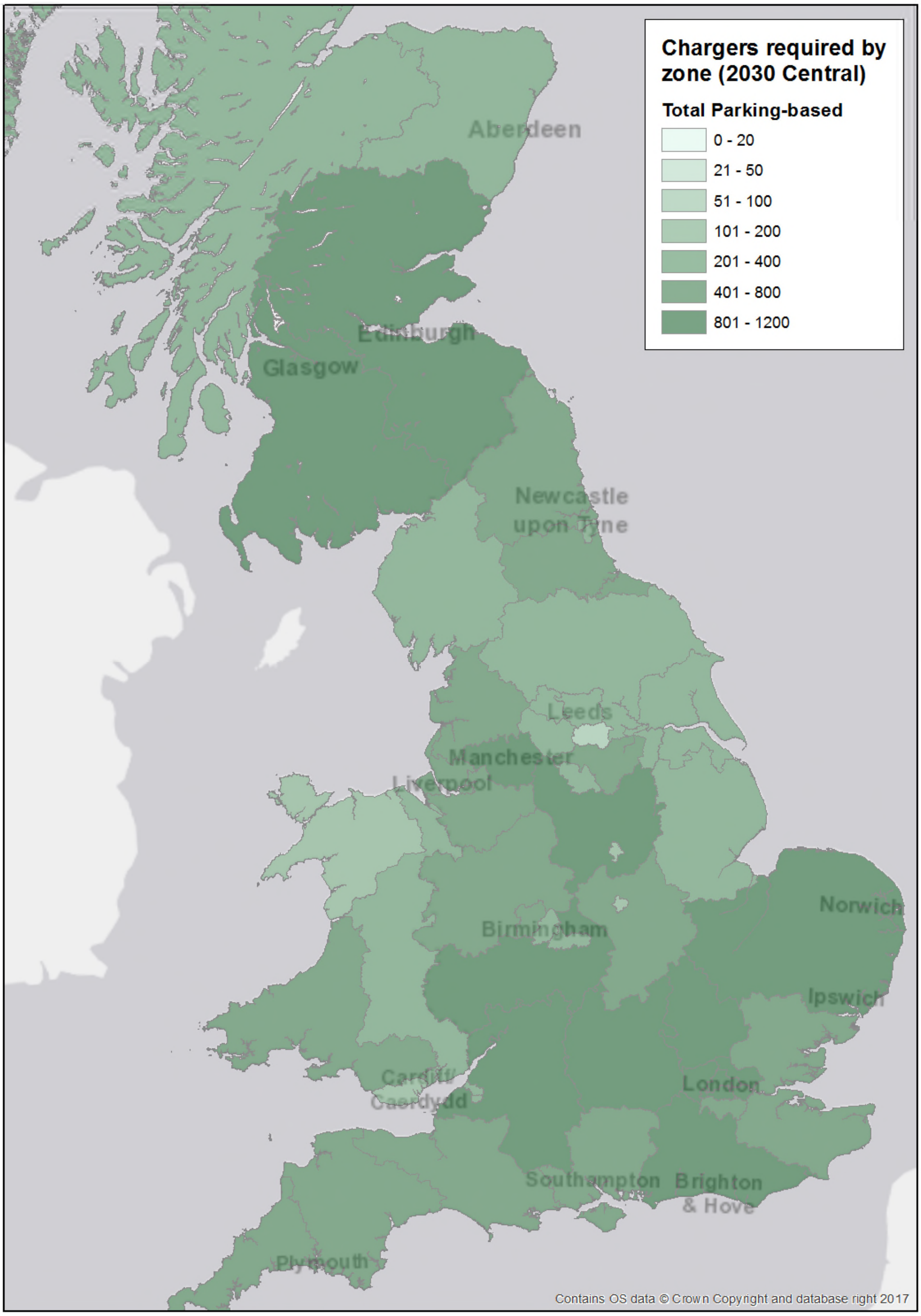
Figure 3. Total Number of Chargers Required by Zone to Meet Demand for Parking-Based Charging in 2030 (CCC Central Uptake)



1. INTRODUCTION

1.1.1 This document reports on the development of two Electric Vehicle charging infrastructure optimisation tools by a SYSTRA-led study team for the Committee on Climate Change (CCC), and provides a commentary on the results emerging from a set of agreed scenarios and sensitivity tests.

1.2 Background

The Committee on Climate Change & the Fifth Carbon Budget

1.2.1 The Committee on Climate Change (CCC) is an independent, statutory body established under the 2008 Climate Change Act. The CCC is tasked with:

- Providing independent advice to Government on setting and meeting carbon budgets and preparing for climate change; and
- Monitoring progress in reducing emissions and achieving Carbon Budgets.

1.2.2 The UK is legally bound by the Climate Change Act to reduce its emissions by at least 80% below 1990 levels by 2050. In some sectors of the economy, such as agriculture and industry, it is more challenging and costly to reduce emissions than in others, such as power. Some sectors, including transport, must reduce emissions by up to 90% to achieve an economy-wide 80% reduction. This implies that in the road transport sector, the car, van, bus and HGV fleets would need to be almost entirely zero or ultra-low carbon by 2050.

1.2.3 The CCC have provided recommendations on the level of five carbon budgets, covering the period to 2032. These recommendations are based on a set of scenarios demonstrating how emissions reductions can be achieved in each sector of the economy, through deployment of technologies to reduce greenhouse gas emissions on the path to the 2050 target. The CCC has a statutory duty to advise the Government on the most cost-effective path to decarbonisation, taking account of the range of criteria in the Climate Change Act.

1.2.4 For its advice on the Fifth Carbon Budget period (2028-2032), the CCC developed a central scenario (the Medium Abatement scenario) for road transport emissions. This scenario is designed to be consistent with the objective of delivering car, van, bus and HGV fleets that are almost entirely zero or ultra-low carbon by 2050.

Electric Vehicles & Chargers

1.2.5 As noted above, Ultra-low emission vehicles (ULEVs) will be key to delivery of emissions reductions. ULEVs are vehicles with zero or near-zero tailpipe emissions which make use of electricity from an increasingly decarbonised power sector. Two types of ULEV are plug-in hybrid electric vehicles (PHEVs) or battery electric vehicles (BEVs), collectively referred to as electric vehicles (EVs). PHEVs have both an electric motor and an internal combustion engine. They can be recharged using a plug or refuelled using petrol or diesel. BEVs only use electric motors and derive all power from battery packs, which are recharged using a power cable connected to some form of charging infrastructure.

1.2.6 The ability to charge these vehicles, via charge points, is a major factor in the potential uptake of EVs. A survey of public attitudes towards electric vehicles by the Department for Transport (DfT) in 2016 identified recharging as the most important factor deterring people from buying an electric car or van. 45% of driving license holders surveyed reported charging as a deterring factor. These license holders listed concerns about the availability of charging points, including lack of charging points in their area and lack of knowledge of where charging points are.

1.2.7 Currently available electric vehicle chargers can broadly be classified in 3 main categories: Slow chargers, Fast chargers and Rapid chargers. The naming scheme is indicative of the amount of time it would take each type of charger to charge a vehicle, with rapid chargers delivering the most power in the shortest time. Cheaper slow chargers tend to be installed in places where cars are likely to be parked for long periods (i.e. home or workplace). Rapid chargers are significantly more expensive, but offer a valuable decrease in charging time, making charging *en route* a practical option.

Previous Work Undertaken by the CCC

1.2.8 In 2013 the CCC undertook work to develop a model to identify the optimal number of rapid chargers across the UK. The model was based on a number of assumptions, notably that a driving range of 300km would be achieved for larger models by 2030. However, recent developments by manufacturers suggest that a driving range of this extent will be achieved significantly earlier.

1.2.9 Latest information on driving ranges shows that the Tesla Model 3 has a minimum electric range of 346 km (EPA) and the latest Renault Zoe has a range of 400km (NEDC). Both of these vehicles are likely to be available in 2017. The Chevrolet Bolt has a range of 383km (EPA) or 500km (NEDC) and is currently being sold in the US. The new Nissan Leaf was announced in September 2017 with a range of 400km, while the Hyundai IONIQ is also planned to have an electric range of greater than 300km by 2018.

1.2.10 Even with the gap between the test cycle and real world driving range, it seems that a 300km electric range will be reached significantly before 2030 for most electric cars.

1.2.11 Electric vans also fall within the definition of 'Electric Vehicles', and the expected range and usage of these are included in the analysis. It is assumed that electric vans exhibit the same travel pattern as electric cars.

1.2.12 As range is a key factor in terms of determining the appropriate type, number, and optimum combination of chargers to meet requirements with the greatest efficiency in terms of investment required, the CCC looked to update their analysis of the required supply of rapid chargers.

1.3 This Study

1.3.1 In February 2017 the CCC issued a brief for work to update their previous analysis to take account of developments in terms of range and other factors to ensure recommendations are predicated on the latest available information and available data. They were also keen to explore whether any enhancements could be added to the modelling and optimisation processes.

1.3.2 In March 2017 SYSTRA Ltd, supported by Cenex Ltd and Next Green Car Ltd, responded to this brief and proposed the development of two models to meet CCC's requirements:

- An **long distance *en route* charging model** of Great Britain (GB) – a flexible Excel macro-based tool, allowing the testing of a wide range of alternative scenarios for future years. The scenarios, built around EV market penetration and battery range assumptions, will provide a clear identification of areas where additional EV charging is most required on the motorways and major roads network.
- An extended version of SYSTRA's Optimising the Provision of On-street Recharging Infrastructure (OPOSRI) model – an Excel macro-based tool, which can be used to optimise charging activity at the destination of trips for various purposes such as shopping or business. This is referred to as the '**parking-based' charging model**.

1.4 Purpose and Structure of this Report

1.4.1 The remainder of this document includes the following sections:

- **Chapter 2. Types of EV Charging Events:** describing the various circumstances under which an Electric Vehicle may wish to charge, and explaining how each of these are dealt with in our two models.
- **Chapter 3. Model Development: Long Distance *EN route* charging Model** – describing how the *en route* charging model was developed, including the geography and zoning system, the underlying assumptions of the model, and how the model was calibrated to existing data.
- **Chapter 4. Demand Modelling:** describing the process of generating a demand matrix between different regions for the long distance *en route* charging model.
- **Chapter 5. Modelling Results: Long Distance *En route* charging Model –** setting out the results of various test scenarios which were run through the model.
- **Chapter 6. Model Development: Parking-Based Charging Model** – describing how the parking-based charging model was developed as an extended version of SYSTRA's OPOSRI model, including the geography and zoning system, the underlying assumptions of the model, and discussions of applications at both a national and local level.
- **Chapter 7. Modelling Results:** setting out results of sample tests on both a national and local scale, including two local-level case-studies.
- **Chapter 8. Summary and Conclusions**

2. TYPES OF EV CHARGING EVENTS

2.1.1 In order to develop suitable modelling for this study, a range of potential types of EV charging event were considered. Following discussion with CCC and the Office for Low Emission Vehicles (OLEV) at project inception, the charging of EVs has been assumed to fall into one of the following categories for the purposes of this modelling commission:

- Private off-street home charging;
- Public on-street home charging;
- 'True Destination' parking-based charging – public;
- Work-place charging;
- Park and Ride charging;
- Specialist fleet charging;
- 'Charge-as-Destination'; and
- Long distance *en route* charging.

2.1.2 These scenarios are described below, along with the rationale for their inclusion or exclusion from either the extended OPOSRI parking-based charging model or the long distance *en route* charging model. The detailed assumptions underlying the treatment of these types of charging are outlined in Chapters 3 and 6.

Private Off-street Home Charging

2.1.3 This is defined as charging undertaken by EV users at their residence, using a private charger that is off-street, or in a private space that is not accessible to the general public. These charges can be undertaken at the EV user's convenience (typically overnight), with no need to book and usually a slow charger would be sufficient for this type of charging.

2.1.4 As these are not publicly available resources, this charging scenario is not considered directly as an output of either model developed in this study. This type of charging is, however, used as an input assumption within the parking-based charging model, as a factor to determine the proportion of the EV fleet that will require access to public charging facilities. This assumption is outlined in Chapter 6 but is essentially determined by the proportion of EV owners who have access to relevant off-street facilities.

2.1.5 Model treatment: excluded from direct modelling*, but included as a modelling input assumption within the extended OPOSRI parking-based charging model.*

Public On-street Home Charging

2.1.6 This is defined as charging undertaken by users at their residence using publicly available 'on-street' chargers. Typically these users will be those who do not have a drive, garage, or dedicated parking space that could host private charging facilities. These EV users will generally look to access a charger somewhere near their home for overnight charging – again, a slow charger would usually be sufficient for this type of charging.

2.1.8 This charging scenario has been included as one of the main elements of the parking-based charging model. In the model, all arrivals will in the first instance try to connect with the cheapest available device which will fully charge the battery within the desired parking duration. This means the model will prioritise serving an overnight charge from one of the standard-speed devices rather than a fast or rapid charger.

2.1.9 ***Model treatment:*** *included in the extended OPOSRI parking-based charging model as a core function.*

'True Destination' Parking-based Charging – Public

2.1.10 'True destination' charging occurs during trips where the EV user is undertaking some other activity at a location close to the potential charging point and seeks to charge their vehicle while it is parked during this activity, e.g. charging in a shopping centre car park while shopping. This parking-based charging is the core function of the parking-based charging model.

2.1.11 In order to optimise the number and type of chargers required to satisfy this demand, the important factors are the duration of the charge required and the hour by hour distribution of the vehicle arrivals. The duration of the charge will be largely determined by the time people will be parked for a particular activity e.g. 30 minutes for food shopping, 2-3 hours for a business trip. The availability of parking spaces with chargers will be determined by the previous (random) arrival and departure of other EV users. The trip durations and distributions used in the model have been calculated by the study team, using DfT's National Travel Survey (NTS) data.[3] The model selects the most appropriate charger type for the user based on the cost and the recharge rate for that trip duration. For example, short trips require a faster charging rate to ensure the vehicle is topped up before it needs to leave. Further details of this process are described in Chapter 6.

2.1.12 Model treatment: included *in the extended OPOSRI parking-based charging model as a core function.*

'Work-place' Charging

2.1.13 For the purposes of this study, work-place charging facilities have been assumed to be provided and managed for a specific group of EV users (e.g. provided via workplace travel planning) and as such are not available for the general public. These chargers have therefore not been included in the optimisation of the public 'on-street' network.

2.1.14 To reflect this in the modelling, commuter trips are excluded from the calculation of parking-based charging demand which is considered by the parking-based charging model.

2.1.15 Model consideration: excluded from direct *modelling.*

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[3] Department for Transport. (2017). National Travel Survey, 2002-2016: Secure Access. [data collection]. 4th Edition. UK Data Service. SN: 7559, http://doi.org/10.5255/UKDA-SN-7559-4

Park and Ride Charging

2.1.16 When charging at Park and Ride sites, the owner usually does not return to the vehicle for a number of hours, reducing the need for expensive 'rapid charging' at these Park and Ride locations, but also increasing the time spent at the charger to just under one day per vehicle.

2.1.17 This scenario is captured as an optional facility within the parking-based charging model, to be used where park and ride demand data is available (for example at a local city-specific level, where a multimodal transport model, including park and ride, is available).

2.1.18 Model treatment: included in the extended *OPOSRI parking-based charging model as an optional function.*

Specialist Fleet Charging

2.1.19 In general, similar to work-place trips, specialist fleets (buses, council vehicles, taxis etc.) are likely to make use of infrastructure that is not available to the general public, where the relevant supply and demand is controlled by the owners/managers of the relevant fleets (and therefore does not need to be included in the core public parking-based charging optimisation process within the model).

2.1.20 However, there is a chance that the specialist fleet will use public chargers for opportunistic charging (i.e. not as their core charging option, meaning the vehicle is not reliant on this charge, but instead is topping-up where possible). To reflect this possibility, the parking-based charging model has been developed to include the optional facility to consider opportunistic specialist fleet EV drivers who seek a charge at a public charger while travelling between their origin and destination. To reflect the opportunistic charging nature of these trips, the 'relative importance' factor of these trips is lower compared to the core car fleet within the parking-based charging model. The trip duration is determined by the time taken to charge and therefore increases the overall general demand for rapid chargers across the network. Further details are provided in Chapter 6.

2.1.21 Model treatment: included in the extended OPOSRI *parking-based charging model as an optional function.*

'Charge-as-Destination'

2.1.22 'Charge-as-Destination' represents EV users who travel to a charger location specifically for the purpose of obtaining a charge. These users charge their vehicle without necessarily wanting to travel to this location for other purposes. In contrast to the 'True Destination' parking-based charging, where trip patterns by purpose can by analysed, this makes this group of users difficult to model within the parking-based charging model. They are also not covered by the long distance *en route* model.

2.1.23 These trips have therefore been modelled in the specialist fleet charging scenario, and are included with a trip duration determined by the time taken to charge if the user was able to connect to a rapid charger. This is on the assumption that charge-as-destination users will not wish to spend any longer than necessary on their charging trip.

2.1.24 Model treatment: included in the *extended OPOSRI parking-based charging model as an optional function.*

Long Distance *En Route* Charging

2.1.25 This type of charging considers EV users who are travelling from an origin (A) to destination (B) for a long distance trip and who need (or choose) to recharge at an intermediate location (L). At a basic level, for this type of charging the critical factors are the distance between A and B, the (perceived) range of the vehicle, the diversion and charging time at each alternative location, and the monetary cost of the charge required at these locations.

2.1.26 For some vehicle types, the perceived range will be insufficient to complete some longer trips even with a charge *en route* – two or more charges may in some instances be required. This can, at the user's discretion, also be taken into account by the model – more details on this can be found in section 4.3.

2.1.27 Modelling of this scenario therefore includes the full pattern of trips in the modelled area (mainland GB), the distribution of battery ranges (including factors such as range anxiety) in the fleet in the relevant modelled year, and the distribution of charging time (including any delay waiting to gain access to a rapid charger). Further details of the assumptions used within the long distance *en route* charging model are provided in Section 3.

2.1.28 Model treatment: this *type of charging is captured in the interurban en route charging model.*

3. MODEL DEVELOPMENT: LONG DISTANCE *EN ROUTE* CHARGING MODEL

3.1 Overview and Purpose of the Long Distance *En Route* Charging Model

3.1.1 The long distance *en route* recharging model is a Microsoft Excel macro-based tool which considers the optimisation of current (2016 base year) and potential EV charger locations on the strategic road network across mainland Great Britain.

3.1.2 The model looks at vehicle travel demand patterns between different regions (e.g. North Wales to Central London) and will calculate expected demand and waiting times at each of the current and potential charger locations that are defined in the model. Route demand is estimated using a gravity model, where the demand between two areas is proportional to the product of their populations divided by a power of the distance between them. More details on this can be found in Appendix A.

3.1.3 The model also takes into account CCC scenarios for EV ownership in future years, as well as the location of existing charging points; number of chargers at each location; and the expected distribution of charging times in the future years.

3.1.4 There are three types of chargers, characterised by charging speed, although all would be termed ‘Rapid’ chargers. The three categories are:

- Rapid 1 – with a speed of 43kW[4], chargers of this type are currently present in the long distance *en route* charging network;
- Rapid 2 – with a speed of 150kW, chargers of this type are a more recent addition to the long distance charging network; and
- Rapid 3 – with a speed of 350kW, these chargers are expected to be available for installation in 2020.

3.1.5 The outputs of the model provide an understanding of:

- The supply and demand for long distance recharging in different travel corridors across mainland GB; and
- How these change as demand levels and the makeup of the EV fleet evolve over time.

3.1.6 These results, alongside budget considerations, provide a basis to make recommendations relating to the number, type, and location of additional charging points required on the network, in order to:

- Support decision makers when planning where to install recharging stations;
- Identify the most cost-effective number and type of chargers for each zone; and
- Help decision makers examine how the optimal budget allocation changes under different mixes of priorities such as minimising cost to drivers, maximising carbon reduction, or maximising developers’ revenue.

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[4] Representative of all 43kW and 50kW charger types.

3.1.7 In summary, the long distance *en route* recharging model takes account of:

- the pattern of demand for trips between different regions across mainland GB;
- the distribution of EV ownership in each of these regions;
- different forecast scenarios for EV ownership in future years;
- the current and potential mix and location of the different types of rapid chargers easily accessible from the major road network;
- the makeup of the EV fleet in terms of vehicle age, compatibility with the different rapid chargers, expected charging time and expected driving range in practice.

3.2 How the Long Distance *En Route* Model Optimises the Charger Network

3.2.1 The travel demand pattern for GB is subdivided into battery *range distribution 'buckets',* that represent the composition of the future-year GB EV fleet in terms of battery technology, e.g. vehicles with ranges of 100km, 100-200km, 200-300km and so on. The assumed effective range of each bucket of vehicles includes additional factors such as range anxiety, as described in Section 3.8.

3.2.2 By analysing the distance of the journey that the EV wishes to undertake in relation to the assumed range of its range bucket, the model can calculate a subset of routes for which EV users will require one or more charges during their journey.

3.2.3 Journeys which require more than one charge for a given vehicle range can be split into sub-journeys, allowing the model to consider charging demand purely in terms of single-charge trips. The model offers the functionality that if the model user believes that multi-charge trips are less desirable to drivers, restrictions can be placed on the amount of demand from these multi-charge trips considered in the calculations.

3.2.4 For each origin (e.g. Lancashire) and destination (e.g. Kent) combination, the journey between the two regions is allocated a set of in-range candidate charging locations. A logit-based charging location choice model[5] is then used to distribute the demand for charging among the candidate locations, based on the 'generalised cost' of each location for the given route. More detail on this can be found in section 4.4.

3.2.5 The result of this logit-based allocation process is a demand at each location, which is calculated by adding demand from journeys between all possible origins and destination regions and all range buckets of vehicles in the fleet, which can then be used to estimate the waiting time at that location. This is done using a calculation from queuing theory based on arrival rates, charging times, and number of chargers at the location. This calculation relies on the assumption that vehicles on average can be served at a faster rate than they arrive (otherwise, over time the expected queue length will increase indefinitely). However, even before vehicles start to be served at the same rate as they arrive, we find that the wait times produced are greater than what an EV user would expect to wait in practice. Therefore we allow the model user to specify a maximum acceptable wait time, and use this to calculate a cap on arrivals. Demand at a location over and above this cap is considered to be discouraged by the excessive wait time and is 'lost' – i.e. the journey will be made by petrol or diesel vehicle instead. This 'lost' demand may come back later in the optimisation process if new devices are added at or near the

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[5] Logit-based models use a specific mathematical formula to split demand between discrete choices.

oversubscribed locations. Further details of the queuing model and the arrival rate cap are provided in Appendix B.

3.2.6 The waiting time feeds back into the generalised cost calculation, which in turn means the demand can be re-allocated based on these new costs. This process of demand allocation and wait time calculation continues until acceptable convergence is reached.

3.2.7 The process will then identify the current and potential locations for which there may be a benefit of providing additional chargers. The benefit is calculated according to the following priorities (which can be turned on or off within the model):

- potential time savings for drivers (driving time, waiting time or charging time);
- potential costs savings to drivers;
- potential additional revenues for developers;
- potential additional costs incurred by developers; and
- the value of the reduction in greenhouse gas emissions achieved by allowing the long distance journey to be made by EV.

3.2.8 The optimisation process will then add the chargers with the best benefit per unit cost of installation, taking into account that the cost of installing the 'first' charger at a new site may be more than providing additional chargers at existing sites. Chargers will be added at a number of sites, up to a user-defined step of budget spend, before the demand allocation process is re-run for this new supply scenario.

3.2.9 This 'hill-climbing' approach to adding new charging infrastructure will continue until no additional cost-effective chargers can be identified, a user-defined budget ceiling is reached, or an alternative objective is fulfilled (e.g. reducing waiting times to a minimal level). Setting this budget ceiling at £0 will allow the tool to show the predicted level of service on the base year charger network in the relevant future modelled year. Otherwise, the model will show the most cost-effective way to optimise the network to meet the user-specified objective.

3.2.10 The tool is flexible, in that it allows the user to test a wide range of alternative scenarios for future years, EV uptake levels, vehicle range assumptions and charging cost structures.

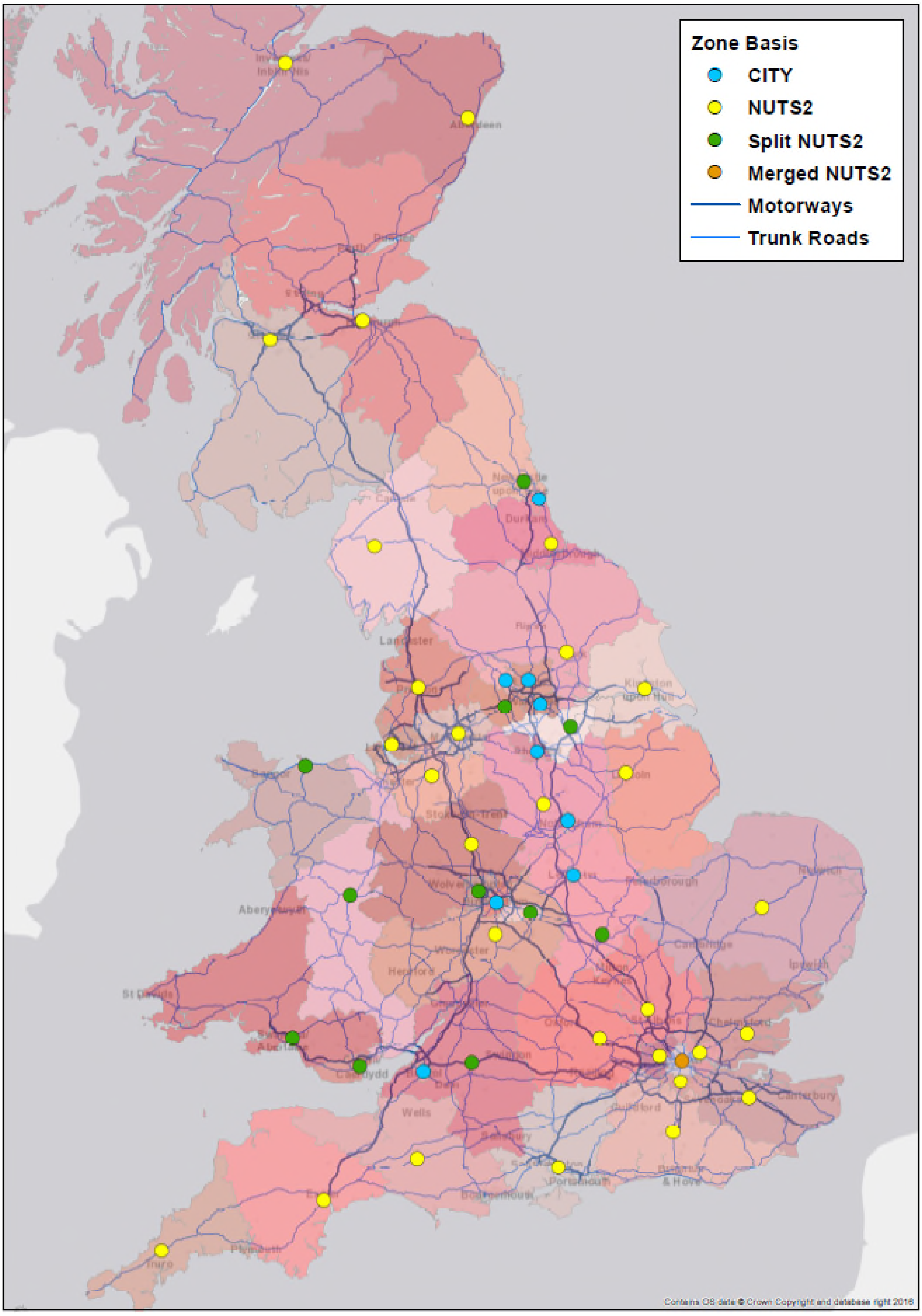
3.3 Geography and Model Zoning System

3.3.1 For the purposes of examining long distance demand, the mainland of Great Britain was divided into 50 zones. These were based on the 39 Nomenclature of Territorial Units for Statistics level 2 (NUTS2) which are the statistical unit building blocks for pan European Union statistical analysis. From these NUTS2 zones, the 17 largest cities (excluding London which is already represented by multiple NUTS2 areas) in terms of population (>250,000 residents) were split out, with some other zones being divided or merged so as to better represent the relationship between population centres and the strategic road network.

3.3.2 The resulting 50 zones, along with their associated centres, are shown in Figure 4, with different zone types identified as follows:

- 'CITY' centres represent where a city-area zone has been adopted;
- 'NUTS2' centres represent where an unedited NUTS2 zone has been adopted;
- 'Split NUTS2' centres represent where a NUTS2 zone has been split;
- 'Merged NUTS2' centres represent where NUTS2 zones have been spatially joined (as per London).

Figure 4. Zone System Adopted for GB-Wide Modelling



Contains OS data © Crown Copyright and database right 2016

3.3.3 The zone centres shown are positioned based on the centres of population in the zones, and the travel distance between two zones is taken to be the distance by road (using the long distance strategic network, including B roads where necessary) between the two zone centre points.

3.4 Modelling Period

3.4.1 The model was developed based on the requirement to explicitly model the following years:

- 2016 Base year;
- 2020;
- 2025; and,
- 2030.

3.4.2 Where possible, model input data has been interpolated for intermediate years, to allow the model user to run the model for each year between the base year and up to 2030.

3.5 Modelled Time Periods

3.5.1 The standard modelled day is 12 hours in length, with arrivals spread evenly over this period. Therefore when hourly demand is being considered, this is calculated by simply dividing daily demand by 12.

3.5.2 The model represents an average hour or day, each of which are considered to be independent. Therefore, any unmet demand during one day will not affect recharging demand on the next day.

3.6 Charging Point Network

3.6.1 The default optimisation mode of the models is to start from the existing charging network (as provided by Zap-Map data) and supplement this to produce the optimum network in future modelled years by adding new chargers at candidate charger locations to meet extra demand and changes in technology and behaviour e.g. range and range anxiety.

Existing Charging Point Network

3.6.2 Data for the existing public charger network was provided by Zap-Map (owned by Next Green Car), a UK charging point digital platform with data for more than 5,000 charging locations and 13,000 connectors (as of July 2017). Zap-Map is the UK's leading consumer brand for EV charging, with over 50,000 cross-platform users per month and 40,000 app downloads (iOS and Android) to date.

3.6.3 Zap-Map has been selected by key industry players such as OEMs (Nissan, BMW) and Government (GoUltraLow) for charging information and market insights. The platform has also integrated real-time data from several major networks covering more than 50% of UK public charging devices – unique in the UK market.

3.6.4 Data provided for the project from Zap-Map included a static data export of all current devices (monthly archive from 2013 to the start of 2017), including:

- device and connector type;
- location type (including public/private);
- geolocational data (geocodes and postcodes); and
- date added/removed to/from database.

3.6.5 Dynamic network data and Zap-Chat status user updates were also provided for several participating networks across a three-month period including:

- number of charge events per device/connector
- total time of charge events per device/connector

3.6.6 In all cases, the charge point data provided to the project was anonymised to protect commercial confidentiality relating to networks and device ownership.

3.6.7 It was necessary to determine which chargers (of those known to ZapMap) were most appropriate to the long distance *en route* charging model and which chargers were most appropriate for the parking-based charging model. A filtering process identified 457 chargers as being part of the long distance *en route* network. The following filters were used to select this site list:

- Rapid Chargers at Service Stations;
- Rapid Chargers at Public Estates;
- Rapid Chargers at 'Other' classifications; and
- Each of the above have been filtered to ensure there is no physical access barrier and no customer access restriction to use – examples of excluded sites include educational establishments and hospitals.

3.6.8 An ArcMap GIS database was used to analyse, map, and allocate relevant chargers to the 50 modelled zones for use in each of the optimisation modelling tools.

Future Charging Point Network – Candidate Locations

3.6.9 To ensure it is feasible to install chargers at suggested additional charge point locations coming out of the optimisation, the long distance *en route* model selects sites at which to place chargers using a set of 'candidate locations'. The following sources of candidate locations were used within the long distance *en route* model for future year optimisation:

- The existing base year long distance *en route* rapid charger network sites, as described above; and
- all petrol stations in mainland GB categorised as a 'service station'.[6]

3.6.10 Note that no consideration has been given here to any possible restrictions on the supply of electricity to a particular location.

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[6] Data source provided by the CCC via a data-sharing agreement the Department of Energy and Climate Change (DECC).

Capital Cost of Network Improvements

3.6.11 A standard installation cost was assumed for each of the three charger categories. These costs applied to all current locations in the charging network, regardless of geographic location or other characteristics of the site.

3.6.12 Special consideration had to be given to installation costs at sites which do not currently have chargers installed. For these sites it was assumed that an additional cost would apply to install the first charger at a particular location, with the standard installation cost applying to any recommended additional chargers at the site thereafter.

3.6.13 The installation costs used were as follows:

Table 3. Assumed Standard Installation Cost of New *En Route* Charging Infrastructure

CHARGER CATEGORY	COST OF ADDITIONAL CHARGER AT SITE	COST OF FIRST CHARGER AT SITE
Rapid 1 (43kW)	£34,000	£52,000
Rapid 2 (150kW)	£64,000	£82,000
Rapid 3 (350kW)	£94,000	£112,000

Knowledge of the Network

3.6.14 It is assumed that drivers know the location of the recharging facilities, and that they know the expected waiting time at each of these locations. This allows us to predict the effect of changes to the network, such as placing additional devices and the effect this will have on waiting time.

3.7 EV Fleet Assumptions

3.7.1 As noted, travel demand for GB is subdivided into battery *range distribution 'buckets'*, that represent the composition of the future-year GB EV fleet in terms of battery technology and additional factors such as range anxiety, as described in Section 3.8.

EV Uptake Scenarios

3.7.2 CCC maintain three trajectories of the size of the EV fleet in future years. These include a 'Central' scenario, which represents the CCC's best assessment of uptake required to meet the 5th carbon budget; and two other scenarios, one representing unfavourable conditions for EV technology and behaviour (referred to as the 'Barrier' scenario), and one representing a higher but still feasible level of uptake ('Max' scenario).

Fleet Range Buckets Calculation

3.7.3 CCC provided the numbers of 'small', 'medium' and 'large' BEVs and PHEVs registered in each year from 2015 to 2030 under each of the uptake scenarios (Barrier, Central and Max).

3.7.4 Using vehicle registration data and information about the different vehicles currently available, namely the size and the expected driving range, it is then possible to represent the current base year fleet in terms of 'range buckets'.

3.7.5 These range buckets are defined such that the average vehicle in each bucket will have a maximum range of 100km, 200km, 300km, 400km or 500km.

3.7.6 Using this base year split of the fleet into range buckets, and the fleet scenarios provided by CCC, the projected number of vehicles in each range bucket for future years is calculated. This calculation includes a projection of new registrations and the scrappage rate of old vehicles, which is necessary for evaluating the age of the fleet for estimating the compatibility with newer charger types.

Base Year Zone by Zone Fleet

3.7.7 The percentage BEV ownership in each zone was calculated by taking the ratio of the number of BEVs in the zone to the total number of cars in the zone.

3.7.8 The number of BEVs in the zone is calculated from the OLEV plug-in car registration data. This was provided at a local authority level, and was aggregated up to give the number of BEVs in each of the 50 zones used for this model.

3.7.9 The number of cars registered in each zone was calculated from Vehicle Licensing Statistics produced by the Department for Transport. This was also given at a local authority level and was aggregated up to give the number of vehicles registered in each of the 50 model zones.

Future Year Zone by Zone Fleet

3.7.10 The zone by zone EV ownership for future years depends on the uptake scenario being used. For each of these – Barriers, Central and Max – CCC has provided a forecast total number of BEVs for each model year.

3.7.11 If we begin by assuming that the distribution of EVs across zones stays constant, then we can apply this proportion to the total forecast number of EVs to give a projection of the number of EVs in each zone in future.

3.7.12 Similarly, we assume the total number of cars in each zone will remain in the same proportion as in 2016. Therefore we can use proportions calculated from the DfT statistics described in 3.7.9 multiplied by the forecast total car fleet for each future year to predict the number of cars in each zone in each future year.

3.7.13 Taking the ratio of these two forecast numbers will give a proportion of EVs in each zone for each future year and uptake scenario.

3.7.14 This forecast number however is very sensitive to unusually high or low EV numbers which might be present in the base year, amplifying these differences into the future. For this reason, an additional 'smoothing' calculation is used. Here, the percentage for each zone is modified, setting the value instead to the midpoint between the calculated zone percentage and the national average for that year, thereby dampening extreme percentage values.

3.8 Driver Behaviour

3.8.1 Driver behaviour is reflected by grouping users into three behavioural groups, and making a range of assumptions about these groups for each of the modelled years:

- new BEV users;
- experienced BEV users; and,
- PHEV users.

3.8.2 The main driver behaviours considered to change across these groups include range anxiety, charging tariff effects, and the time they are willing to spend charging. Published research and observed data, provided by Cenex and Next Green Car Zap-Map, is used to calibrate these behaviours to represent observed recharging behaviour as described below.

Range Anxiety

3.8.3 The model assumes all vehicles in a given range bucket to have the same expected range, and that the users will display the same profile of 'range anxiety' – i.e. the distance they are willing to drive before they feel the need to recharge, which will be less than the actual expected range of the vehicle.

3.8.4 To account for this a range anxiety factor is applied to each range bucket. A 'range anxiety factor' (%) was defined as the percentage of the vehicle's operational range that the user would consider a minimum before seeking to charge the vehicle. Factors were set for new and experienced EV users across five buckets defined by EV range (0-150 kms, 150-250 kms, 250-350 kms, 350-450 kms, 450 kms+).

3.8.5 For example, for an average range of 100 km (bucket 1), a 20% range anxiety factor would equate to 20 km off the max range so that the user would seek to charge within 80 km as a maximum.

3.8.6 To populate these range anxiety factors, a short literature review was conducted to quantify the extent to which range anxiety was an issue for drivers of fully electric vehicles. Observations from a selection of papers and reports include:

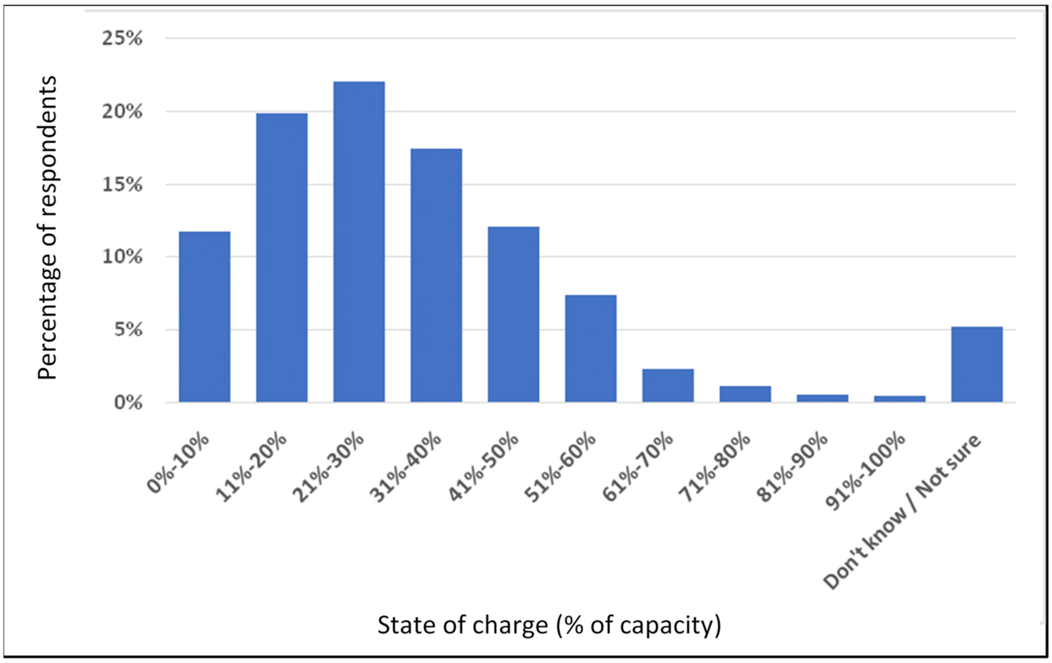
- Drivers' range comfort zone (i.e., comfortable range) is on average only about 80% of their actual available range (paper cites an EV with range of 150 km) (Franke and Krems 2013; Franke, Neumann et al. 2012);
- Most driving range adaptation seems to occur within the first three months of BEV use (Pichelmann et al. 2013; Franke, Cocron, et al. 2012);

- Experienced BEV drivers are as challenged as inexperienced drivers by the critical range situation but not as stressed by it (Rauh et-al. 2014);
- On average people would consider a range of 60 miles “adequate” for an EV but that an “ideal” range of 206 miles would be necessary to enable them to meet all their travel needs (Carroll et al. 2013); and
- Range anxiety felt in any locality can be correlated to about half the driving range (Bonges and Lusk 2016).

3.8.7 While useful in identifying the key issues affecting range anxiety, the literature review was unable to directly provide detailed estimates for the range anxiety factors in question. Quantitative data was therefore sourced from a Zap-Map survey completed by 1,460 EV drivers conducted in March 2017.

3.8.8 One question in the survey asked respondents to self-report on their vehicle’s state-of-charge (SOC) when starting a charging session – a value which can be used as a proxy for the range anxiety factor. While a range of SOC values is apparent (as one would expect) the results show an average SOC of 32% for all charger types and 26% where only rapid chargers are considered – see Figure 5.

Figure 5. State-of-Charge at plug-in – All charger Types



3.8.9 Analysing the survey data in more detail, the average SOC values at the start of charging varies according to vehicle usage, with business users showing lower range anxiety (19%) by driving further before charging their vehicles. Assuming that business users are likely to be more experienced in driving and charging EVs, the model therefore uses the following range anxiety factors: 30% for the average driver and 20% for the most experienced group. A value of 40% is also inferred for new EV drivers, as per Table 4.

Table 4. State-of-Charge at Point of Charging

AVERAGES	STATE-OF-CHARGE AT START	PROXY	STATE-OF-CHARGE AT START
Personal use only	32%	Average EV driver	30% (rounded)
Personal & business use	31%		
Business use only	19%	Experienced driver	20% (rounded)
		Inexperienced driver	40% (rounded)

3.8.10 Given that 70% of the vehicles used by survey participants have a real driving range of 150-250 kms, these central values were used for this range bucket. While no correlation was found in the survey data between vehicle range and anxiety factors, the value for other range buckets are assumed to vary linearly with lower anxiety factors for EVs with larger vehicle range, while maintaining a ratio of two between factors of inexperienced and experienced EV drivers – see Table 5 below for the values used.

Table 5. Range Anxiety Factors Applied

REAL WORLD RANGE		RANGE ANXIETY FACTOR (%)		
Bucket (km)	**Bucket (Miles)**	**New BEV user**	**Experienced BEV user**	**PHEV users**
0-150kms	0-95 miles	44% (40 miles)	22% (20 miles)	0% (no effect)
150-250kms	95-155 miles	40% (50 miles)	20% (25 miles)	0% (no effect)
250-350kms	155-220 miles	36% (68 miles)	18% (34 miles)	0% (no effect)
350-450kms	220-280 miles	32% (80 miles)	16% (40 miles)	0% (no effect)
450kms+	280 miles +	28% (98 miles)	14% (49 miles)	0% (no effect)

3.8.11 Note that because PHEV users have the option of switching to petrol when their battery is discharged, we assume that their range anxiety is 0%. This means that PHEV users will not feel the need to charge until their battery has been fully used, and will not actively seek to charge before this point. Indeed, once they have switched to petrol they may wish to drive for some time in this mode before recharging the battery.

3.8.12 For BEVs, the 'new' and 'experienced' user range anxieties are combined into a single aggregated factor for each range bucket. To do this, we assume that the increase in vehicles in a given range bucket from one year to the next (see 3.7.6 for further discussion of this calculation) represents new users switching to driving an EV for the first time. These are 'new' users, while we assume all other EVs in the fleet are owned and driven by 'experienced' users. The range anxiety for the range bucket in a given year is then the average for the two user groups, weighted according to the percentage of new versus experienced users in the bucket for that year.

Tariff Effects

3.8.13 Tariff effects are represented in the model by including a charging event cost at each charging location. This is then considered in conjunction with car occupant time when making predictions about charging behaviour. In order to make the times and costs comparable on a single scale the charging cost is converted into a time value. For this, the values of occupant (driver and passenger) time are provided by WebTAG[7] for both in-work and non-work trips. For a given future year, the in-work and non-work trip values of time are aggregated according to the projected proportions of in-work and non-work trips to obtain a single value per unit of time. This can then be used to convert charging cost.

3.8.14 The cost of EV charging was taken directly from base year network tariffs reflected in the Next Green Car Zap-Map data. For all devices in the data set defined to be on the long distance *en route* network, the base year standard network pricing was applied according to: annual card/ subscription fee, charging connection fee, per kWh energy fee and any penalties for exceeding maximum permitted charging period. In cases where networks offer multiple tariffs, an average tariff was calculated based on equal shares of customers using each long distance *en route* pricing structure. The cost of using each device is assumed to remain the same in future years.

3.8.15 For all device records in the database, pricing data provided to the project was anonymised, to protect commercial confidentiality relating to networks and device ownership.

Time Involved in Charging

3.8.16 When considering the different reaction of PHEV and EV users, we must consider the impact of waiting time and service time on the decision to charge.

3.8.17 For BEV users, charging is a necessity, and they will select the charger which will cost the least in terms of time and money out of those available to them. However, as PHEV users have the option of switching to petrol, it seems reasonable to assume that they will not be prepared to wait an undue length of time to charge or go too far out of their way to obtain a cheap or quick charge.

3.8.18 We therefore assume that PHEV users will exhibit a more opportunistic attitude to charging, and may charge during a routine stop if there is no queue for the charger at that time. This prevents us from considering PHEV charging behaviour explicitly; however, as described in section 4.5 their demand is still included in the long distance *en route* charging model.

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[7] see https://www.gov.uk/government/publications/webtag-tag-data-book-july-2017, table A1.3.2

4. DEMAND MODELLING

4.1 Overview

4.1.1 Demand modelling is carried out in three stages, as discussed below:

- Estimation of total demand;
- Finding the proportion which require a charge; and
- Distributing this demand between charging locations.

4.2 Overall Demand Patterns

4.2.1 Travel demand patterns are estimated using a gravity model, where the trip demand (using all surface modes) between two areas is proportional to the product of their populations divided by a power of the distance between them. This means that more trips will be generated between areas with large populations than areas with smaller populations, as trips 'gravitate' from one to the other. The power-of-distance parameter represents the rate at which long-distance travel becomes undesirable as the distance between locations increases. More details on this can be found in Appendix A.

4.2.2 SYSTRA had already calibrated a similar long distance travel demand model for Ireland which provided a starting point for calibrating the power-of-distance parameter for this model. An alternative to this was to develop a distance parameter using travel diary data from the DfT's National Travel Survey (NTS) [8], available for England and Wales only.

4.2.3 A scale parameter also had to be determined, in order to produce a daily person-trip demand. As described in Appendix A, this was calibrated against railway journey data from the Office of Rail and Road (ORR) and using SYSTRA's knowledge of expected road and rail mode shares for journeys on key long-distance corridors. During this process, it was found that the Irish-based distance parameter resulted in a better level of calibration to the rail journeys than the NTS-based parameter.

4.2.4 Once a daily trip demand was obtained from this calibration, the railway journey figures were deducted to achieve a road trip demand. This in turn was discounted using an average car occupancy value to obtain a matrix of daily *vehicle* trips which can be fed into the long distance *en route* model.

4.3 Demand for Recharging by Origin-Destination pair

4.3.1 The vehicle trip demand pattern described above can be converted into an EV trip demand by considering the percentage of the vehicle fleet which is electric in the Origin and Destination zones. The arithmetic average of these two percentages for a given O-D pair gives the percentage of vehicles making this journey which are EVs.

4.3.2 This EV demand is separated into battery range distribution 'buckets', as described in Section 3.7. These range distribution buckets are then compared with the distance between A and B for each Origin-Destination (O-D) pairs for each of the modelled zones. Routes will fall into three categories for a given range bucket:

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[8] Department for Transport. (2017). National Travel Survey, 2002-2016: Secure Access. [data collection]. 4th Edition. UK Data Service. SN: 7559, http://doi.org/10.5255/UKDA-SN-7559-4

- The route can be driven without needing to stop and charge by an EV in this range bucket;
- The route can be driven with a single stop to charge by an EV in this range bucket; or
- The route is more than two charges long for an EV in this range bucket, and therefore multiple stops to charge up would be required in order to complete the journey.

4.3.3 Demand on routes falling into the first category need not be considered by the long distance *en route* charging model, since no *en route* charge is required.

4.3.4 Demand which requires a single charge will be allocated to suitable charging locations for that O-D route – this is described in section 4.4 below.

4.3.5 Demand which requires more than one charge may be ignored or downscaled by the user, to reflect the negative effect on journey desirability of the need to stop more than once to charge. If the demand is considered, the O-D route will be broken down into two further O-D pairs, the charging locations for which will approximate to charging around one third and around two thirds of the original distance.

4.3.6 This process can, if necessary, be applied iteratively to journeys which would require three or more charges to complete the distance in a vehicle of this range.

4.3.7 Once this analysis has been carried out, the demand pattern will have been converted into a collection of single-charge trips, for vehicles of varying ranges, which will be considered by the model.

4.4 Demand for Recharging at Specific Charging Locations

4.4.1 Journeys between each Origin-Destination pair are allocated a set of in-range candidate charging locations, which would be used to charge *once* between O and D (as described above).

4.4.2 The in-range charging locations are selected on the principle of minimising the longest leg of the journey between Origin and Destination. If a charging location L is used to charge between O and D then this creates two legs: O to L, and L to D. For each OD pair, the locations are then ordered according to the distance of the longest of these two legs, and the best of these selected as in-range charging locations. A maximum of 20 will be selected, subject to restrictions such as ignoring any locations for which the longest leg is further than from O to D direct.

4.4.3 For each OD route, this will give a set of locations which in most cases will be near to the mid-point of that route. It should be noted however that, depending on the density of locations between points O and D, some 'in-range' locations may in fact be some distance from the mid-point. Consequently, not all 'in-range' locations for a given OD route will be suitable for all vehicles, as the longest leg for some may be further than the range of the smaller range bucket vehicles.

4.4.4 Given that the 'in-range' charging locations are known for each route, a logit-based charging location choice model[9] can then be used to distribute the demand for charging

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[9] Logit-based models use a specific mathematical formula to split demand between discrete choices.

among these locations, based on the 'generalised cost' of each location for the given OD route. This generalised cost is made up of a combination of:

- the diversion time needed to drive to and from the charging location (i.e. the deviation from the shortest route between the O and D);
- the average waiting time to gain access to the charger (which will vary as a function of the supply and demand at each location);
- the charge time (based on the average charging rate at each location); and
- the (monetary) cost of the charge at each location (calculated as a combination of flat connection charge, cost per kilowatt-hour of charge delivered, and any additional cost of connecting for longer than an hour if relevant).

4.4.5 A weighted average of the standard in-work and non-work values of time, taken from WebTAG, is used to convert the components of the generalised cost between time and monetary values.

4.4.6 The logit-based location choice model takes these generalised costs for each charging location and uses them to distribute the demand to the locations. Locations with relatively high generalised cost will receive little or no demand, while lower cost locations will take the majority of demand. If there are two locations with similar generalised costs then the demand will be split quite evenly between them. A shape parameter, which determines the precise shape of the logit curve, is used to determine the sensitivity of the demand to differences in the generalised cost.

4.5 Demand for 'Long Distance' Charging for Plug-in Hybrids, Local Residents and Other EV Users

4.5.1 As described above, the logic of the demand forecasting is essentially based round the predicted behaviour of battery electric car drivers who need to obtain a charge to complete their longer journeys and who are assumed to revert to a fossil fuel trip if a suitable charging facility is not available or incurs too much time or cost.

4.5.2 However, the base year demand for long distance charging has been calibrated using all current charging behaviour at a subset of the base year long distance rapid charger locations, including any charging by plug-in-hybrid vehicles, vans, 'charge-as-the-destination' charging by local residents etc.

4.5.3 Therefore, provided the relative frequency of these 'other' types of charging events using the long distance rapid charging network does not change significantly over time (i.e. it grows in line with the corresponding growth in pure electric vehicle ownership which we have used to define the EV growth scenario), then it is reasonable to claim that the long distance charger tool is taking account of these other 'other' types of charging behaviour.

4.6 Demand Summary

4.6.1 Using the steps described above we have a method which can be used to generate the EV charging demand at each location on the base year or future long distance network. Starting from the total vehicle trip demand between each zone, this demand is adjusted firstly according to the relative size of the EV fleet in these zones, and then according to the calibrated proportion of these EVs which will actually make the trip. This gives the number of EV trips on each route, which is then broken down by the range of the EVs.

Those able to make the journey without charging need not be considered, while those for which the journey is too long to be made with a single *en route* charge may at the user's discretion also be excluded, or a percentage be allocated to shorter routes in order to approximate the charging behaviour. The remaining demand, now considered only in terms of single-charge journeys, can then be allocated between the charging locations according to the logit-based choice model to give a demand at each location.

5. MODELLING RESULTS: LONG DISTANCE *EN ROUTE* CHARGING MODEL

5.1 Introduction

5.1.1 In this section we describe the key themes emerging from use of the long distance optimisation model to test a number of alternative approaches to 'optimisation' applied to a number of different EV Uptake scenarios.

5.1.2 Three different 'EV Uptake' scenarios governing the proportion of EV's in the UK fleet in each of the future years from 2017 to 2030 have been tested here, as follows:

- The 'barrier' uptake scenario, which is the lowest uptake scenario;
- The 'central' uptake scenario; and
- The 'max' uptake scenario, which is the same as the central to 2025 but then predicts a higher uptake of Electric Vehicles from 2026 onwards.

5.1.3 A set of four different approaches to the design of the future-year infrastructure network are reported here, as follows:

- A 'Do Nothing' approach (in which only the base year charging infrastructure is assumed in all future years);
- 'Carbon-focussed' – an optimisation based on minimising 'lost' carbon, i.e. emissions caused by journeys being made by petrol or diesel car because of an insufficient supply of *en route* EV charging facilities;
- 'Driver-focussed' – minimising the cost and inconvenience of diverting to a charger, waiting for a charger to be available, and waiting for the charge to complete for a driver; and
- 'Commercial-focussed' – maximising the net income for the provider of the charging infrastructure.

5.1.4 The optimisation process can also be applied in a number of different ways, as follows:

- 'Straight to year' optimisation: optimising the future year as a 'stand-alone' optimisation, by starting from the current (2016) infrastructure;
- Year by year optimisation: optimising iteratively, by optimising the 2017 demand using the 2016 network as the starting point, then using this 2017 solution as the base to optimise for the following year's demand, and so on, through to 2030; and
- 'Five-year Plans', optimising iteratively , but just considering 3 future years (2020, 2025 and 2030), with each solution providing the starting point for the next target year.

5.1.5 The various combinations of approaches to the optimisation process are described in more detail in Section 5.2 below.

5.1.6 A number of other parameters were set for these test runs and remained fixed throughout. These were:

- The maximum acceptable waiting time for an EV user was set at 12 minutes – this value was chosen as it had been found to limit the demand in line with the number of observed charge events at our calibration subset of sites;
- The maximum number of chargers permitted at a site was set to a limit of 100 for an individual charger type, or 300 of all types in total – in practice, this has the effect of placing no real limit on the number which can be at the site in these test runs, since this number is greater than any amount we would expect to see added under any of the setting combinations used here; and
- The smoothing of zone-level EV percentages (as described in 3.7 above) was activated, in order to dampen potential extreme percentage values which can arise from anomalously high or low EV numbers in the base year data.
- Journeys which could only be made using two or more charging stops were excluded completely.

5.1.7 The key indicators which we have used to evaluate the effectiveness of the solutions are as follows:

- The overall installation cost of the solution;
- The number of chargers required in the solution (including those already in the network);
- The predicted number of charge events per day;
- The GB-wide average waiting time for vehicles wishing to charge;
- The mean charging time per vehicle; and
- The amount (and % amount) of 'lost demand' (in kilometres) of trips which failed to find an acceptable charger (or set of chargers) or would have required waiting too long for a charger to become available.

5.2 Optimisation Approaches

5.2.1 This section gives more detail on the objectives considered in the optimisation phase of the model, and the extent to which the constraints of previous years' solutions are taken into account during the test runs.

Objectives Applied

5.2.2 The first objective applied is the 'Do Nothing' approach. This models future demand on the existing network, but does not attempt to make any improvements by adding chargers. The results give an indication of how the existing network will cope with the changing demand of future years, and can be used as a comparison with results obtained using other approaches to the optimisation.

5.2.3 The 'Carbon focussed' scenario finds solutions which will reduce the estimated amount of lost EV demand in the network. If electric vehicles on a given route would want to charge but cannot charge (either because there is too much demand at their desired charging location, or because no suitable charging locations are within range of the route), then we consider that this journey will be made by petrol or diesel car instead, meaning the potential carbon saving from the EV is 'lost'. The optimisation algorithm attempts to add chargers at locations which will minimise the amount of demand that is lost, by considering locations which have more demand than they can serve and other locations which could 'take the pressure off' these overloaded sites.

5.2.4 For the 'Driver focussed' scenario, maximisation of driver/passenger benefit takes into account both the costs associated with charging and the total time taken to do so. The time taken to charge also includes additional driving to reach the charger, and time spent queueing. A monetary value for this time is obtained for the purposes of calculating possible 'generalised cost' savings for the vehicle occupants. The optimisation algorithm evaluates the effect of adding a charger to a location, and whether the changes in demand allocation will lead to a net saving of time and money to the network users.

5.2.5 Because driver/passenger benefit can always be improved, even fractionally, by the addition of another charger, it is necessary to set additional stopping criteria, specific to the 'Driver focussed' scenario, to determine the budget spend required to 'optimise' this objective.

5.2.6 We therefore tested three alternative stopping criteria, as follows:

- Stop the optimisation when the future supply achieves the current base year level of service (average wait time) in each modelled zone;
- Stop the optimisation when the GB-wide average wait time is less than 1 minute and no zone has an average wait time greater than 5 minutes; or
- Calculate the 'theoretical optimum' wait time which could be achieved if all vehicles desiring a charge were able to access the fastest compatible charging device and terminate the optimisation if a solution is found which has a GB-wide average charge time which is close enough (within 25%) to this theoretical minimum.

5.2.7 Finally, for the 'Commercial focussed' scenario, the maximisation of developers' net income takes into account the predicted increase in revenue (from additional charging costs) that would result from installing a new device, and balances this against the running costs (electricity supply and maintenance) and capital cost of the installation. A required timescale for return on investment is used to convert the capital cost into an annual value, allowing it to be combined with the revenue and running costs into a single annual profit or loss figure. If this amount is a profit for a given location then the algorithm will consider installing a device here. This approach is essentially attempting to predict what level of supply the (commercial) market might deliver, if left to its own devices.

Constraints on the Starting Solution

5.2.8 As described in Section 5.1 above, three different starting solutions for the optimisation can be chosen in the model: 'straight to year' optimisation for a specific year, year by year iterative optimisation, and five-year iterative optimisation.

5.2.9 The first of these is to constrain only by the base year network (as provided by Zap-Map data), and to optimise for relevant future year from this starting point. This allows us to see the solutions (and their cost) under each of the objectives if our only concern was to undertake a 'stand-alone' optimisation to meet the relevant future year's demand.

5.2.10 An alternative to this is to optimise iteratively, year by year. This begins by optimising based on the 2016 demand taking the current network as the starting point. The 2016 solution then becomes the starting point for the 2018 optimisation, and so on. This means that chargers installed in the earlier future years may become partially redundant &/or sub-optimal in later years. Although the spend for each individual year may be less (because it is starting from a point of more chargers in the network), we would expect the aggregate spend for a given year's demand to be greater under this method than using the 'stand-alone' optimisation from a 2016 starting point as described above.

5.2.11 A third 'Five-year Plan' approach is to optimise iteratively, but in five-year steps. Under this method, we firstly find a solution for the year 2020 taking the base year network as the starting point. This 2020 solution then becomes the initial network to optimise from in 2025; and the 2025 solution is then used as the starting point to optimise for 2030. The expectation here would be that there will be some redundancy of additions, but fewer than in under the year by year iterative optimisation, and that therefore the cost of the solutions obtained by this method will lie between those of the other two approaches described here. This method also reflects a more realistic investment strategy which could be implemented in practice.

5.3 Results

5.3.1 A large number of results were produced by testing each of the objectives with each of the starting solutions described above. In this section we summarise a number of the main conclusions implied by these results, presented with selected graphs. A full collection of results graphs can be found in Appendix C.

The 'Do Nothing' Case

5.3.2 Firstly, we look at the Do Nothing case, where no chargers are added (and therefore no budget spent), under the Central uptake scenario – see Appendix section C.2 for all graphs. This case acts as a useful point of comparison against the other scenarios. As might be expected, lost demand increases fairly steadily as a percentage of the total demand considered (see Figure 6), from 45% in the base year to 83% of the total demand by 2030.

5.3.3 The expected wait time is predicated to stay fairly steady around six or seven minutes up until 2024, but increase considerably in the last few modelled years (see Figure 7). We note here that the graph shows that in 2030 the wait time reaches just above the defined acceptable wait time limit of 12 minutes – this is because of an approximation in the calculation of the arrival rate cap (as described in section 3.2) for sites with more than 3 charging devices, which results in a small number of sites with a greater than 12 minute wait time.

Figure 6. ‘Do Nothing’: Lost Demand

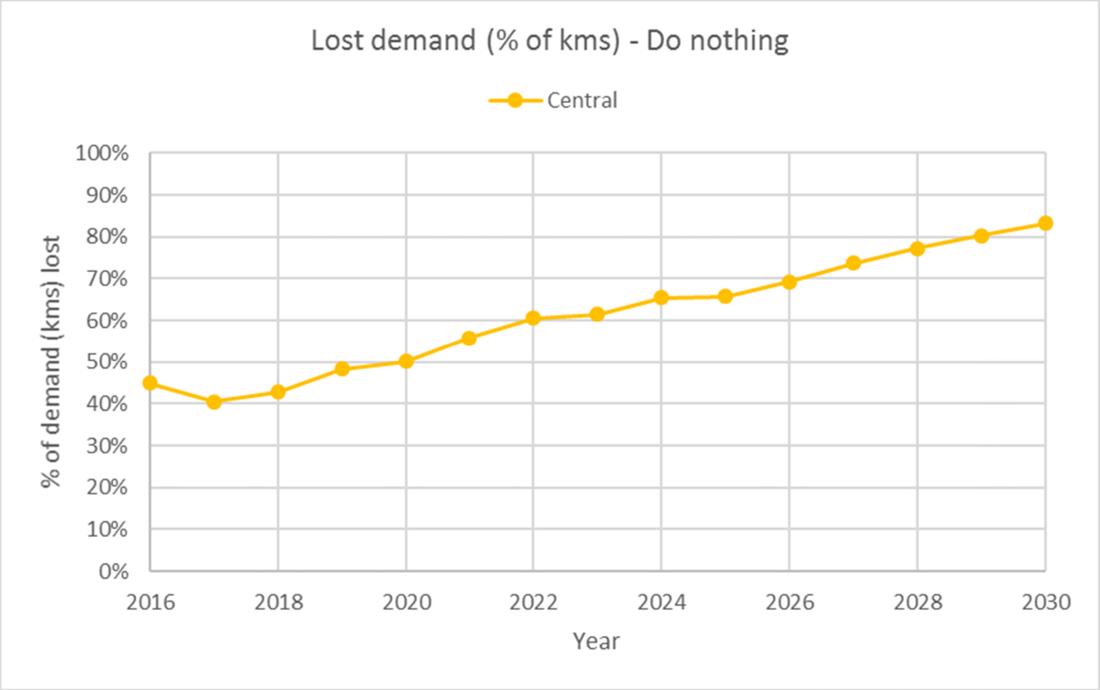
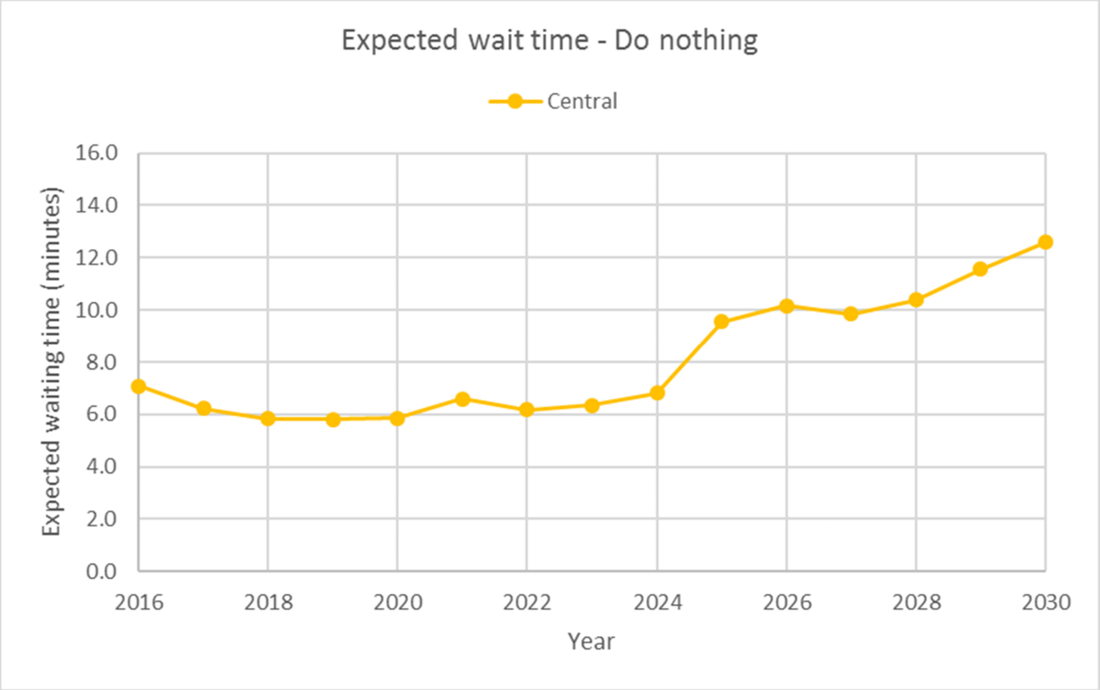


Figure 7. ‘Do Nothing’: Expected Wait Time



5.3.4 The results focus on optimisation of each year separately, under the Central uptake scenario, for each of the objectives detailed above. See Appendix section C.3 for all graphs relating to these. Results from the two iterative optimisation methods are also presented below for comparison.

Optimising for 'Straight to Year' Solutions

Carbon-focussed Scenario

5.3.5 Taking the carbon-focussed optimisation, we see that there is a steady increase in the number of chargers required to achieve the objective over time (Figure 8). Including the 457 present in the base network, around 650 chargers are required in 2020, increasing to 1170 chargers in 2030. Meanwhile the percentage of lost demand remaining in these future years decreases over time (Figure 9), from 45% in the 2016 'do nothing' scenario to 10% by 2020 and just 1% by 2030. This comes at a cost of around £7.2m for the 2020 network, and about £30.2m to construct the 2030 network.

5.3.6 Wait times however can be seen to increase over time (Figure 10), and in fact from 2020 do so at a greater rate than under the Do Nothing scenario. A possible explanation for this is that the additional chargers provide more capacity, allowing more vehicles to charge at more sites. The more popular sites will still have higher wait times, and if they are now serving more vehicles this will increase the weighting given when calculating the national average.

Figure 8. Carbon-focussed Optimisation: Chargers Required

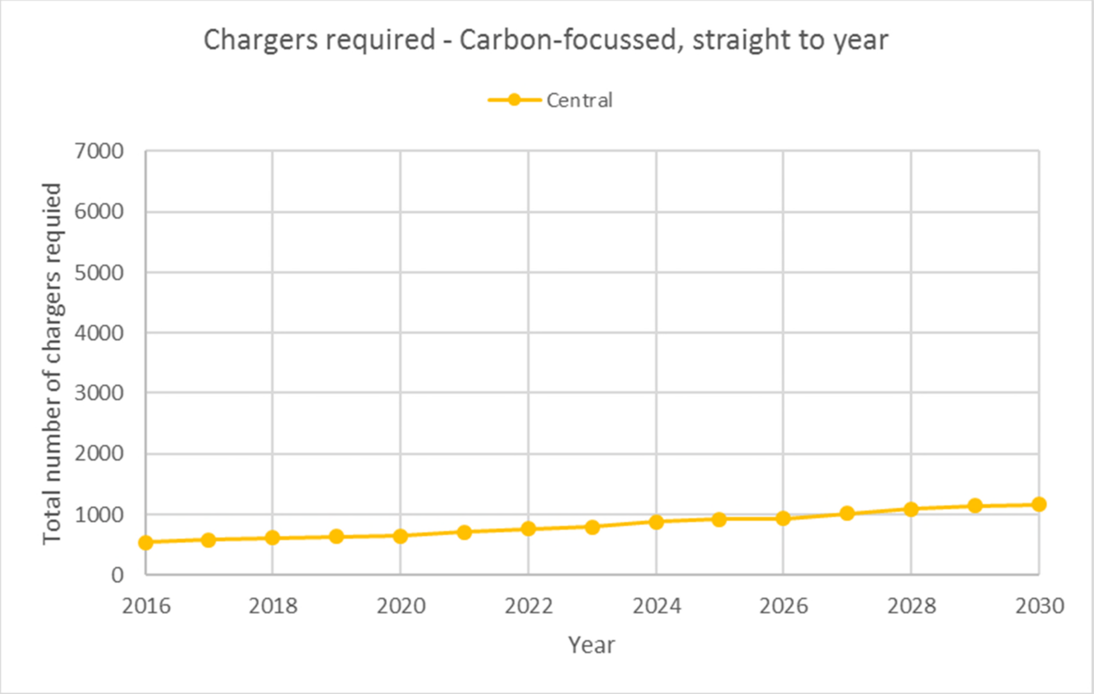


Figure 9. Carbon-focussed Optimisation: Lost Demand

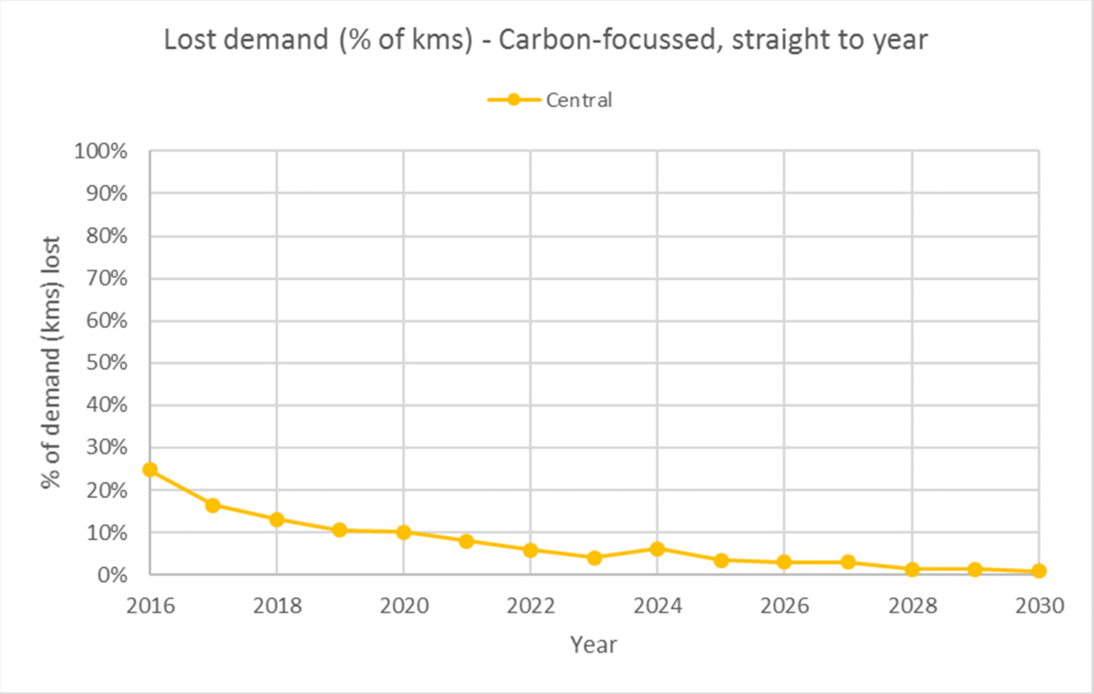
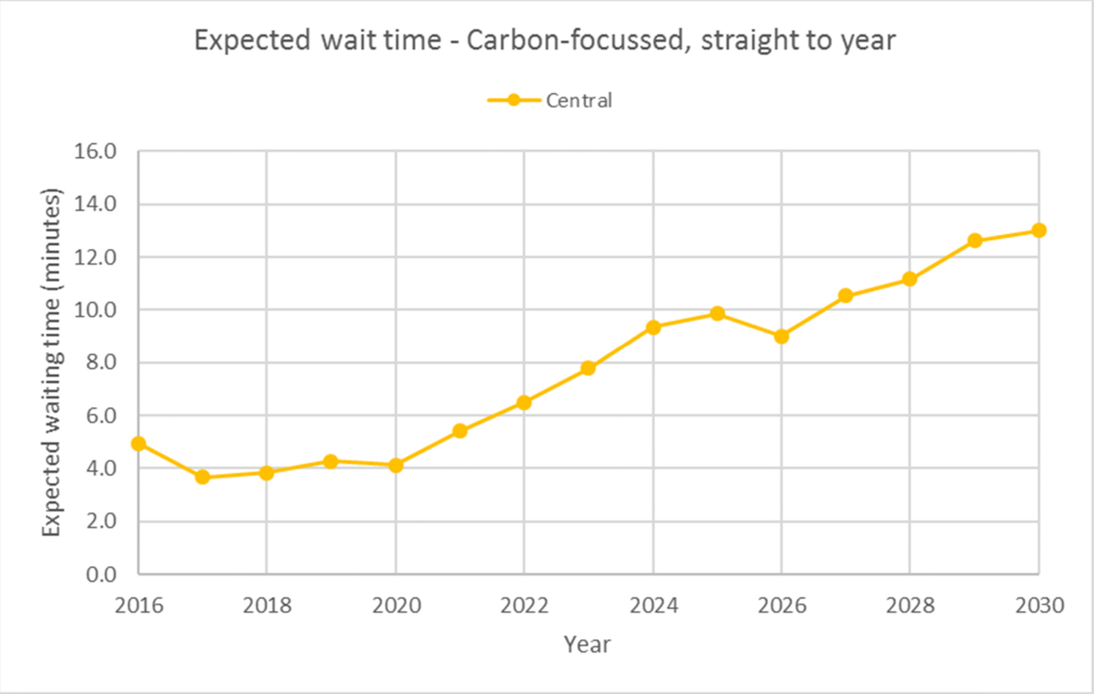


Figure 10. Carbon-focussed Optimisation: Expected Wait Time



5.3.7 It can be seen from these results that the number of *en route* chargers required in future years does not increase at the same rate as the forecast increase in EVs on the road. This is due to a combination of factors.

5.3.8 Firstly, while the number of trips made by EVs is expected to increase by a factor of ×72 between 2016 and 2030, the increase in range of vehicles over this period will mean that many fewer trips will need an *en route* charge. The average range of an EV is expected to increase from approximately 80kms in 2016 to over 400kms in 2030. Since the frequency of longer trips is much lower than shorter trips, the impact of this increase in range is to significantly decrease the number of trips which need a charge when starting with a full battery, from 27% of trips in 2016 to less than 1% in 2030. As a result, the number of trips requiring a charge only increases by a factor of ×1.3 over this period.

5.3.9 In addition, the increase in the proportion of vehicles able to make use of the faster charging rates more than offsets the increase in battery size over time. As a result, the average time of a charging event is reduced by 32% (based on the 2030 driver-focussed solution). This means that each charger is able to provide charge to a greater number of EVs over the course of a day, with the average number of daily charge events per charger increasing by a factor of ×3.6 (again, based on the 2030 driver-focussed solution).

5.3.10 This means that despite such a large increase in EV numbers from 2016 to 2030, only a comparatively modest increase in the number of chargers is required on the *en route* network to meet the 2030 objectives.

5.3.11 Breaking down the number of chargers required in 2030 by zone, we see that the zones requiring the most chargers to achieve this solution are: Lancashire (129 chargers); Berkshire, Buckinghamshire & Oxfordshire (98); and Leicestershire & Northamptonshire (79). In terms of the number of chargers which must be added to the base year network to achieve this, the zones in which the most work is required are: Lancashire (104 additional chargers); Derbyshire & Nottinghamshire (64) and Leicestershire & Northamptonshire (62).

Driver-focussed Scenario

5.3.12 For the driver-focussed scenario, there are three different stopping criteria used to obtain the results. The first, stopping when a solution is found with a GB-wide mean waiting time no greater than the current mean of seven minutes, seems relatively easy to achieve. In each year, fewer chargers are required to achieve this than under the carbon-focussed scenario (Figure 11), with only around 480 chargers needed in 2020 and around 850 in 2030, an increase of only 85% on the current number of *en route* chargers in the network.

5.3.13 The percentage of lost demand (Figure 12) increases slightly under this stopping criterion up to 2021, but drops quite sharply thereafter. Similarly to the carbon-focussed optimisation, it reaches just 1% by 2030. The main difference between this scenario and the carbon-focussed scenario is the upgrade of a large number of 150kW chargers to 350kW ultra-rapid chargers, which enable quicker charging and reduce wait times, the primary objective of this scenario.

Figure 11. Driver-focussed Optimisation (Existing Wait Time Target): Chargers Required

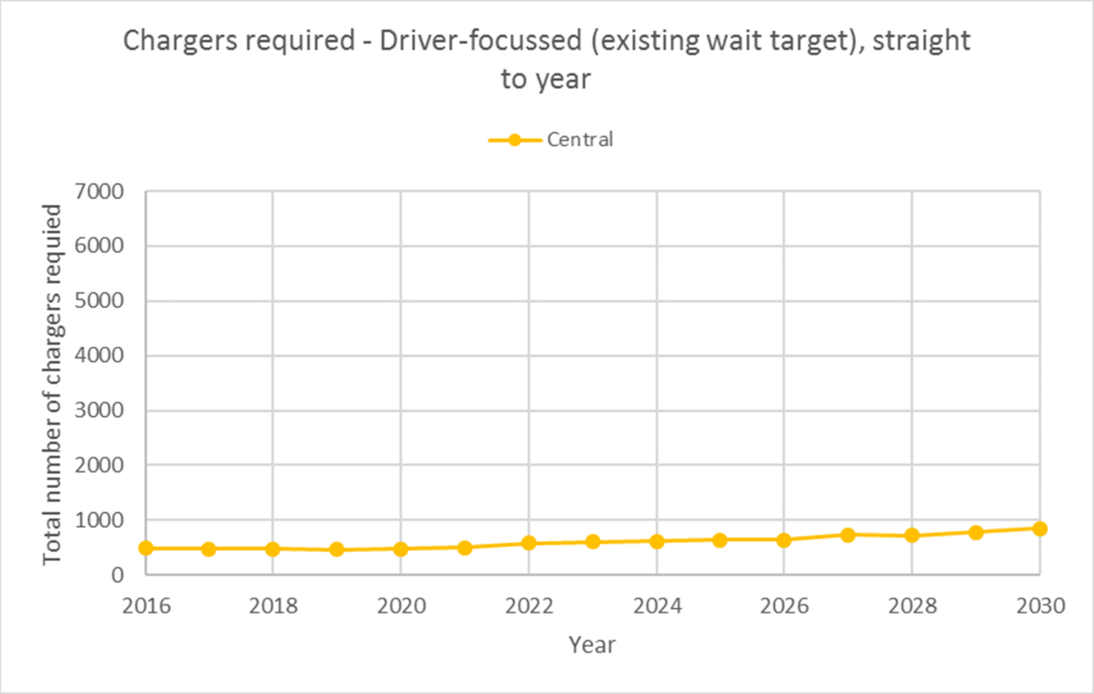
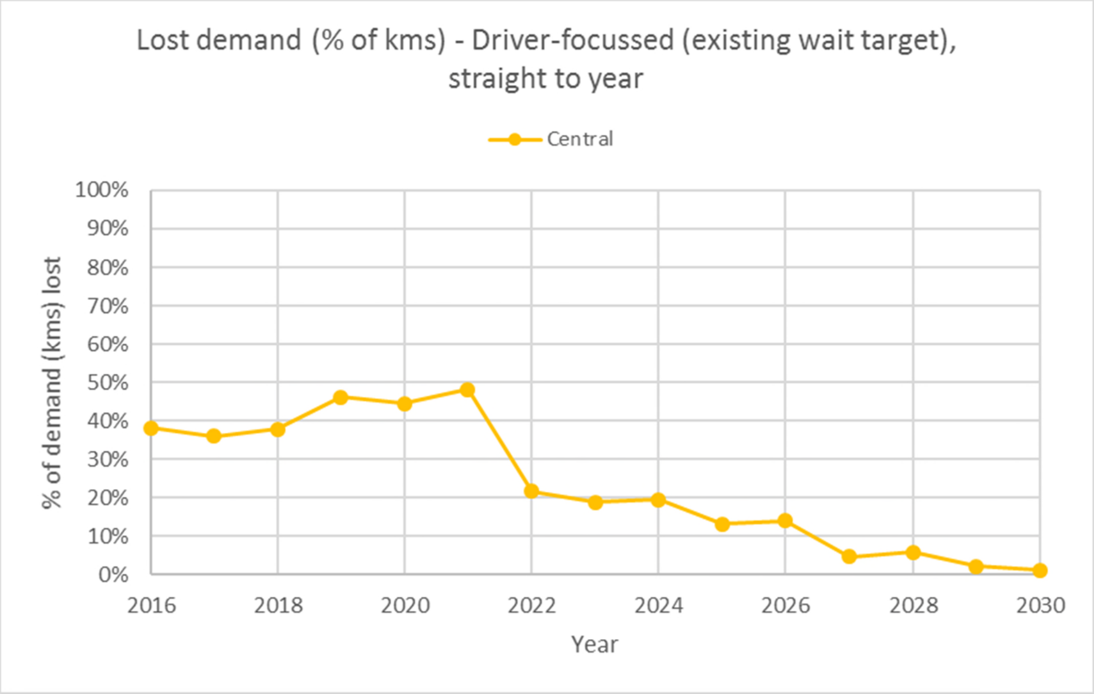


Figure 12. Driver-focussed Optimisation (Existing Wait Time Target): Lost Demand



5.3.14 For the next stopping criterion, the driver-focussed optimisation is run until a lower specified wait time (a GB-wide average of less than 1 minute, with no zone having an average wait greater than 5 minutes) is reached. Doing so, we see that this is possible for all years except 2030. In the case of 2030, the model could not converge to a solution meeting a 1 minute average wait within the specified maximum run-time of the model. This can be seen in Figure 13, where the expected wait time in the 2030 scenario is 1.2

minutes. We can also say that the budget spend, as shown in Figure 14, for this scenario is at least £100m. In addition, it can be seen from this graph that the budget spend is increasing over time as more chargers are required to meet the target in future years. As a result of the additional chargers added, we also see (Figure 15) that the percentage of lost demand is very low, similar to under the carbon-focussed objective.

Figure 13. Driver-Focussed Optimisation (Lower Wait Time Target): Expected Wait Time

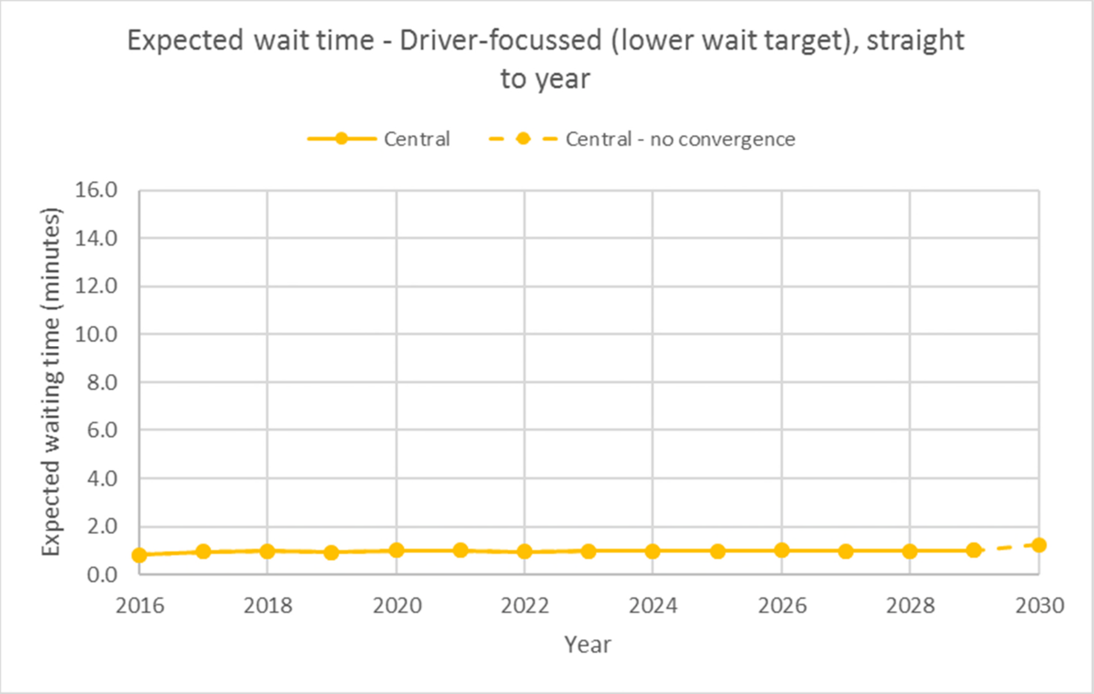


Figure 14. Driver-focussed Optimisation (Lower Wait Time Target): Estimated Budget

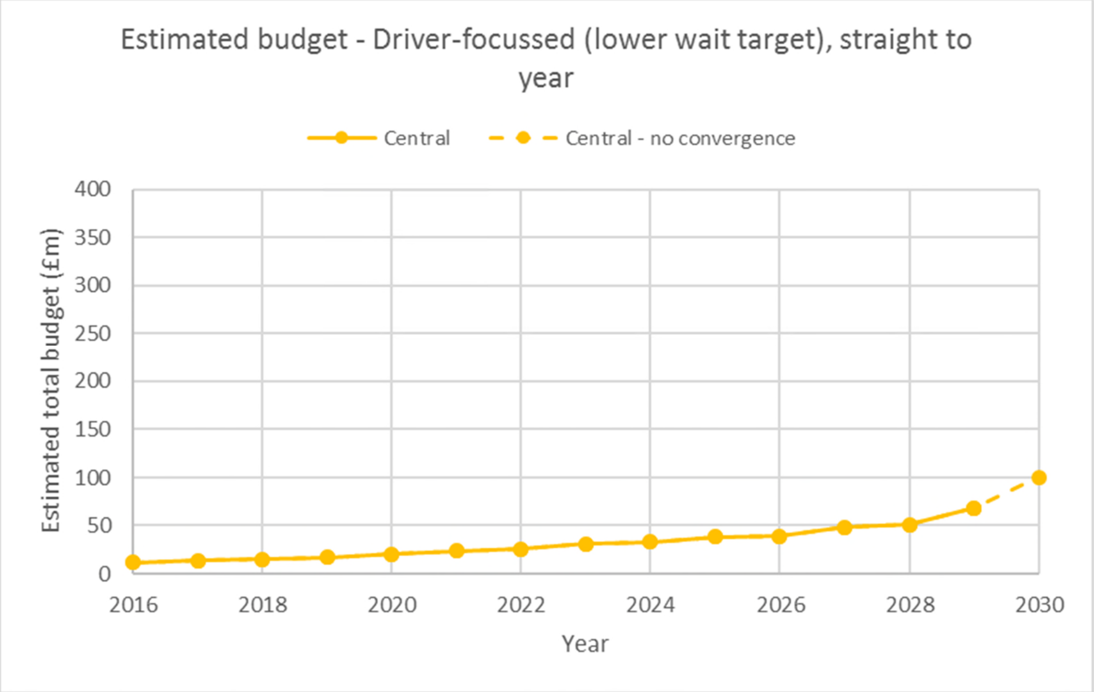
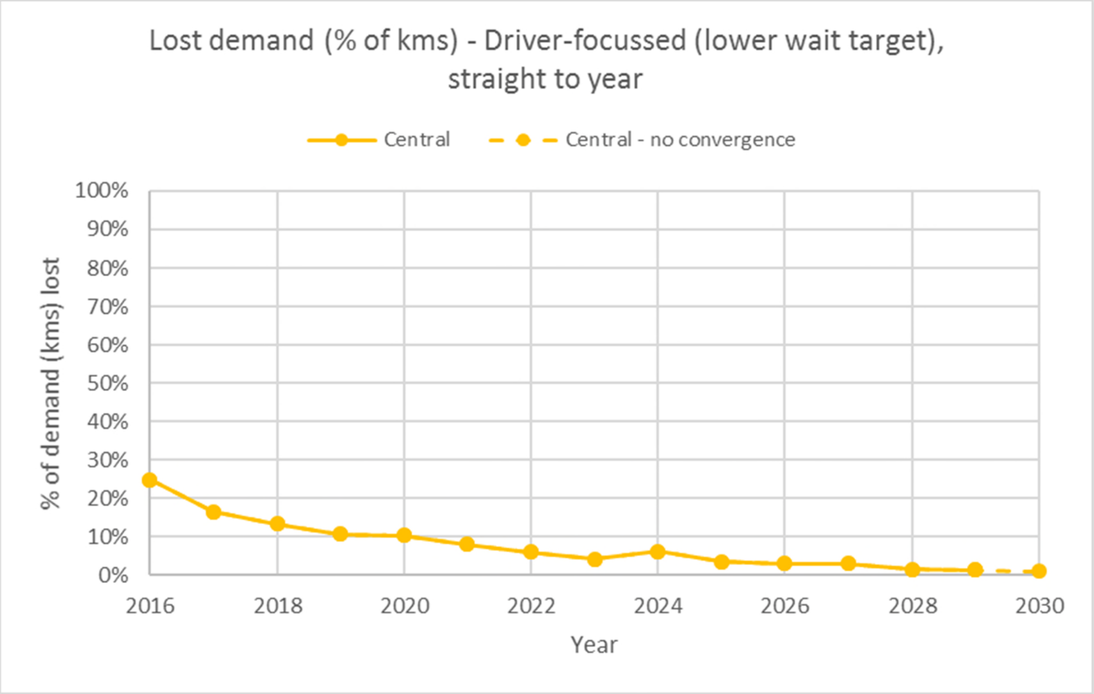


Figure 15. Driver-focussed Optimisation (Lower Wait Time Target): Lost Demand



5.3.15 The third stopping criterion to use when optimising driver and passenger benefit is when a target value is reached for the mean charging time of each vehicle. As described in section 5.2 above, this target is calculated as being within 25% of a theoretical minimum charging time. This target changes over time as the EV fleet and charger availability changes, with the target decreasing from around 75 minutes in 2016 to under 45 minutes in 2030. Consequently, the target is met relatively easily (with a similar number of chargers as under the carbon-focussed optimisation) up to 2024, but the model is unable to keep average charging/service time within the target while optimising from 2025 onwards. If the model could find a suitable solution, the budget required would be over £100m (see Figure 16) and the number of chargers required would be over between 1878 (for the 2030 scenario) and 1991 (for the 2025 scenario).

5.3.16 Meanwhile, a consequence of a larger number of chargers being required for 2025 onwards is a sharp reduction in the percentage lost demand (which was already showing a downward trend in 2016-2024 – see Figure 17) and the expected wait time, which had been holding fairly steady at around 6-7 minute for the 2016-2024 period (see Figure 18).

Figure 16. Driver-focussed Optimisation (Charge Time Target): Estimated Budget

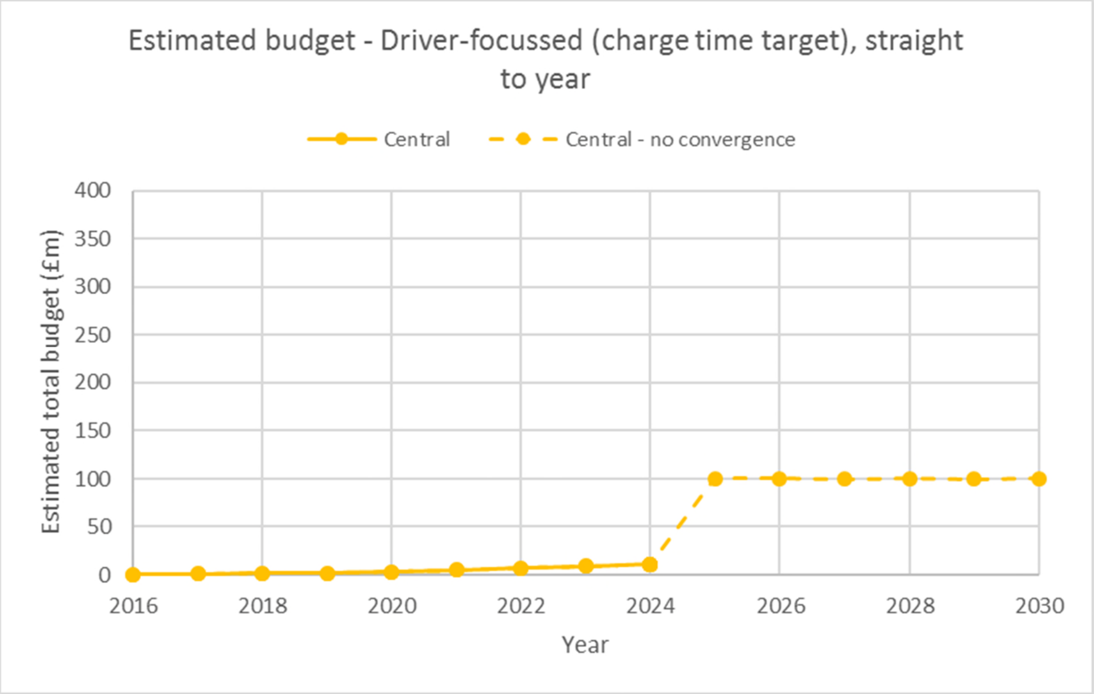


Figure 17. Driver-focussed Optimisation (Charge Time Target): Lost Demand

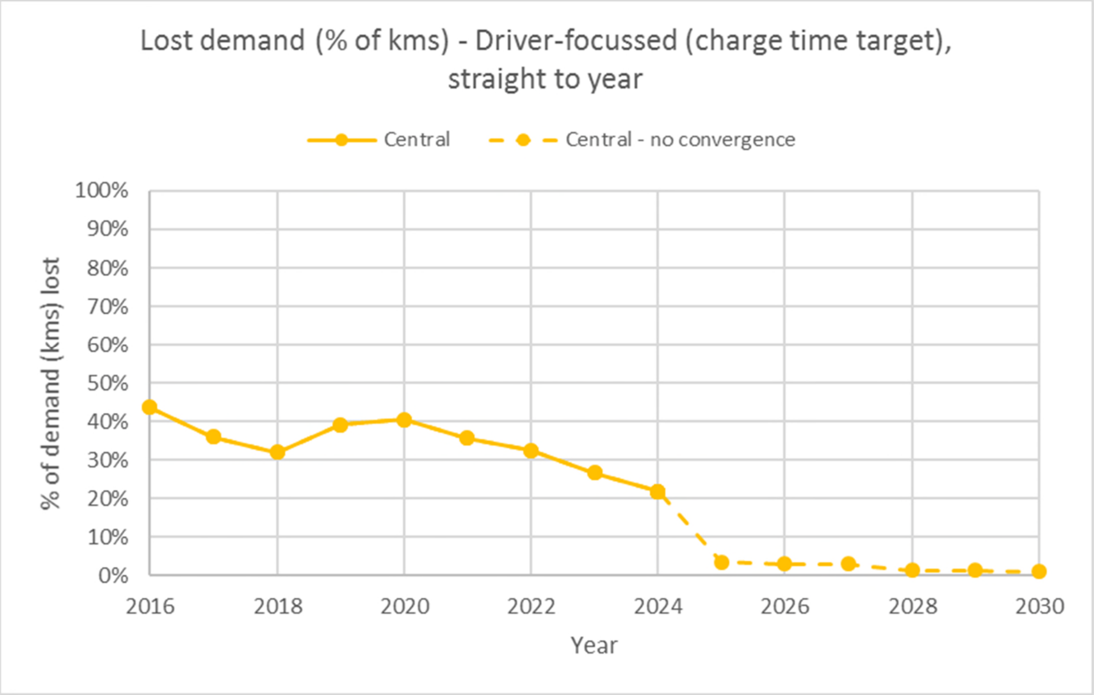
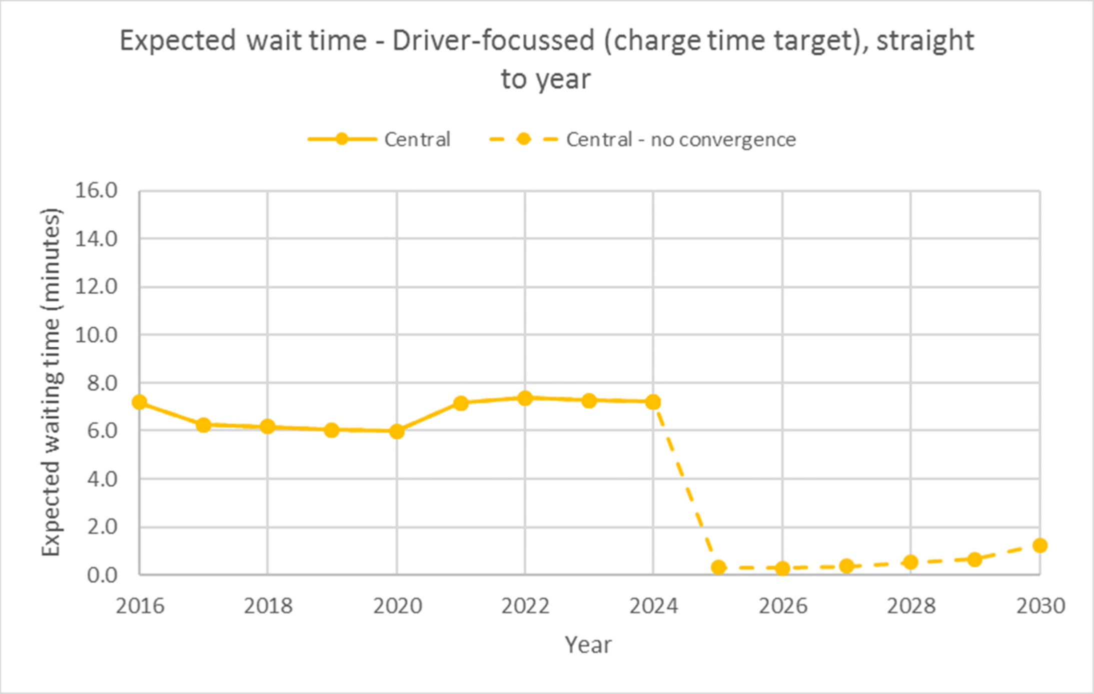


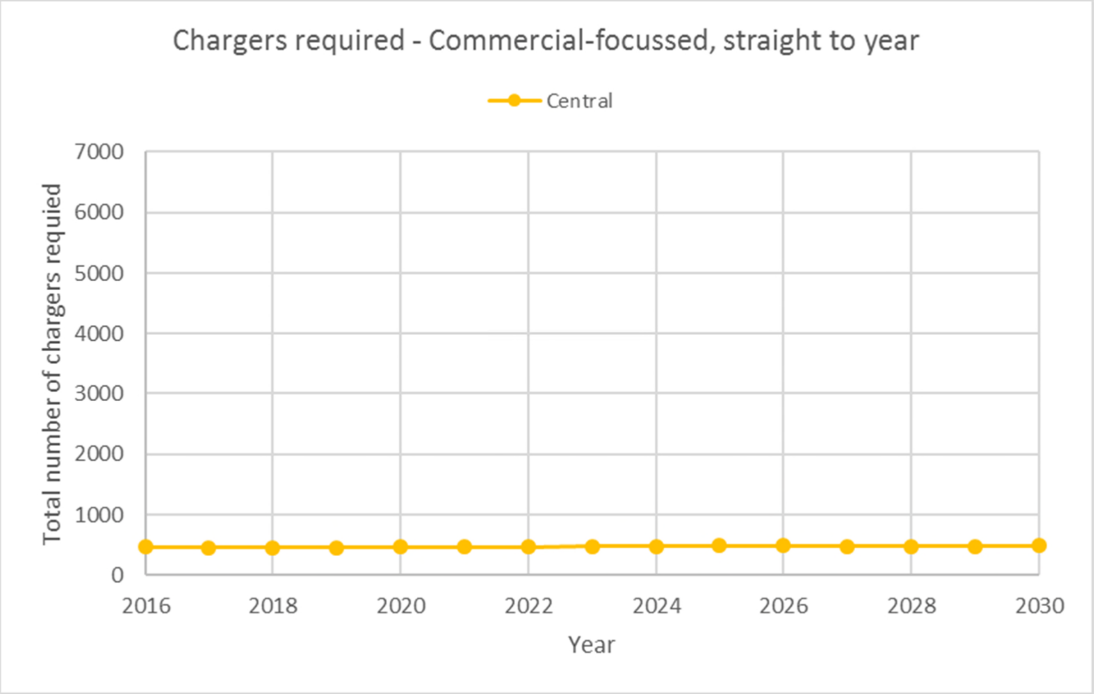
Figure 18. Driver-focussed Optimisation (Charge Time Target): Expected Wait Time



Commercial-focussed Scenario

5.3.17 In the case of the ’commercial-focussed’ scenario, the model identifies very few locations where it is cost-effective (from a provider’s perspective) to add additional chargers, with the 2030 solution comprising fewer than 30 additions. As a result, the required number of chargers remains very close to the starting baseline number (see Figure 19), the budget spend remains close to zero (the maximum spend for the Central uptake is for 2030 at just over £2m), and the lost demand and expected wait times closely resemble the Do Nothing case.

Figure 19. Commercial-focussed Optimisation: Chargers Required



5.3.18 This raises a question of what makes a site a desirable one from a developer's point of view. The interactions between vehicle types and the various generalised cost components are complex, but it is possible, by making certain assumptions about a charge site, to estimate the number of charges per day which would be required for the installation of a device to make a return on investment over the required period.

5.3.19 We will in this case consider the base year 2016, and assume a typical 43kW charger, with connection cost of £3 plus a rate of 17p per kWh, and assume all arrivals are from the 0-150km range bucket (with charge time 1.3 hours). This can be used to calculate a profit generated of £4.29 per charge event, once deduction of the supply cost of the electricity has been made.

5.3.20 For a ten year return on investment, this would mean to cover the installation and running costs of a 'Rapid 1' charger at a new site the location would require an average of between 5 and 6 charges per day. Unfortunately, the acceptable wait time limit of 12 minutes means that arrivals in this case have to be restricted to just over 2 per day (see Appendix B for details on how this cap is calculated), and consequently the breakeven point cannot be reached under these assumptions.

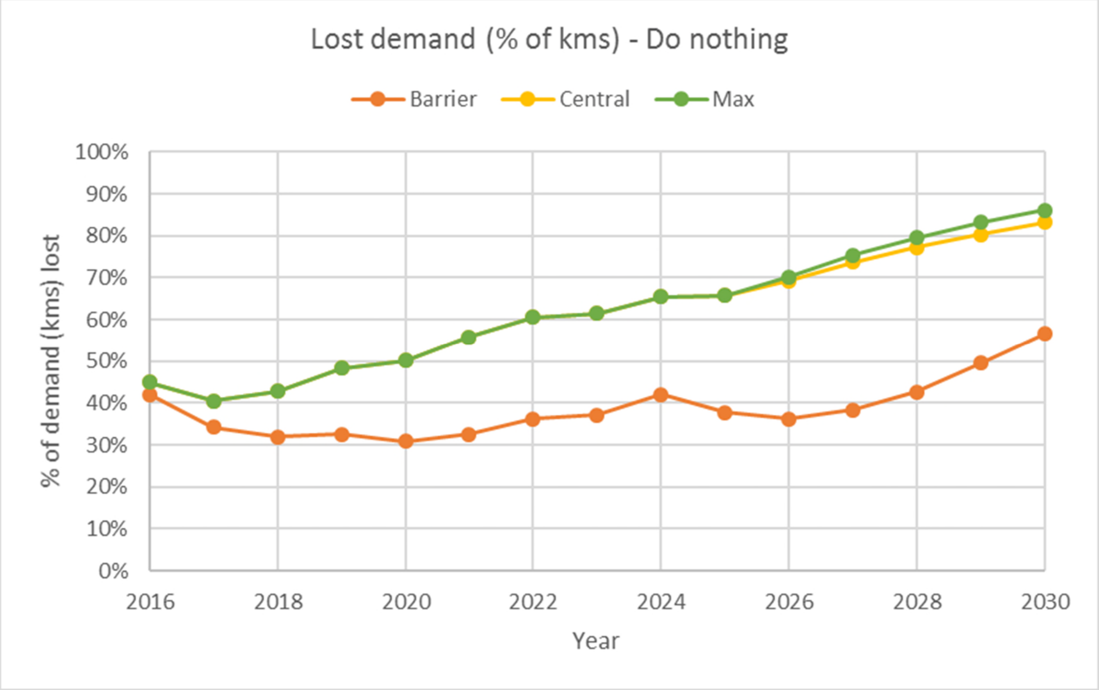
5.3.21 However, under the same conditions, the number of daily charge events required to cover the installation and running costs of a second ('Rapid 1') charger at an existing site is less, at just over 4 per day. Meanwhile, with a second charger at the site the queuing model allows for up to 9 arrivals per day at the site, approximately 7 per day more than a saturated single charger. This means installing a second charger at the site could potentially break even under the right conditions.

Other Uptake Scenarios

5.3.22 We now extend our analysis to consider when the EV uptake in future years is less ('Barrier' scenario) or greater ('Max' scenario) than in the Central scenario discussed above.

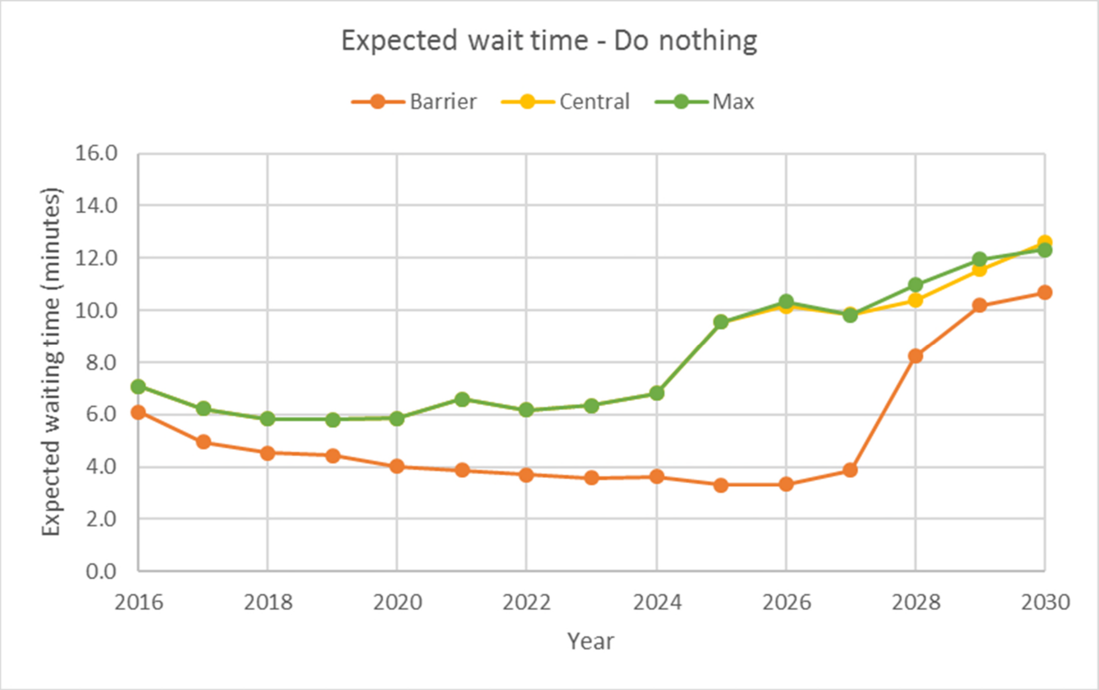
5.3.23 As before, looking firstly at the Do Nothing case, we see from the Figure 20 that the lost demand is greater under the Max uptake, as might be expected. Similarly, the lower Barrier uptake scenarios show a much lower percentage of demand being lost, although the trajectory is a little more surprising. Under this scenario, the impact of the increasing range of the vehicles actually offsets the growing size of the EV fleet, so that the percentage of demand lost actually decreases slightly from around 40% in the early future years, and then remains between 30% and 40% until 2024; it is only after 2026 that a steeper increase in lost demand is predicted with the Barriers uptake scenario.

Figure 20. 'Do Nothing': Lost Demand, All Uptakes



5.3.24 Figure 21 shows that the Max scenario produces very similar results to the Central scenario in terms of the expected wait time in the Do Nothing scenario. However, as above, the Barrier scenario not only produces a lower wait time, it also exhibits a less expected pattern – following a downward trend through to 2020, and only significantly increasing after 2026. This can also be attributed to the changing range of the vehicle fleet over time, meaning a different set of journeys are being carried and will use different charging locations in future years. It would appear then that from a waiting time perspective the 2016 network is in fact better placed to handle demand in, say, 2024 under Barrier-level uptake than the demand today.

Figure 21. 'Do Nothing': Expected Wait Time, All Uptakes



5.3.25 The general trend observable in the graphs (see Appendix section C.4) shows that for the Max level of EV uptake more chargers will be required to meet any of the objectives in question. Similarly, the Barrier level uptake will require fewer chargers and therefore less budget to meet the objectives. An example of this can be seen in Table 6, which shows the number of chargers required to meet the Carbon-focussed objective in several future years under each of the three uptake scenarios.

Table 6. Number of chargers to meet Carbon-focussed objective in selected years for difference EV uptake Scenarios

	2020	2025	2030
Barrier scenario – no. of chargers	540	590	710
Central scenario – no. of chargers	650	920	1,170
Max scenario – no. of chargers	650	920	1,300

5.3.26 For the most part, the targets set for wait time can be achieved. However, as with the Central scenario, the model is unable to find a solution with the 1-minute wait time stopping criterion for the 2030 Max uptake in the Driver-focussed scenario. In this case, the best solution found has an expected wait time of 1.4 minutes (see 0).

5.3.27 Figure 23 shows the number of chargers which are required to find a solution with this wait time, with 1879 in total required for the 2030 Max uptake scenario. This is a sharp rise from two years before, with only 1172 chargers require to meet the 1.4 minute wait time target for the 2028 Max uptake.

5.3.28 Similarly, the service time target (i.e. within 25% of the theoretical minimum average charging duration) cannot be reached by the model for any uptake scenario, even the Barrier case, for the years 2025-2030.

5.3.29 Meanwhile, for the commercial-focussed objective, there is only a marginal increase in the number of chargers which it is economical to add from a developers perspective when we consider the Max scenario. For the latest model year 2030, only an extra £304,000 capital expenditure is predicted if the EV uptake level is at its maximum.

Figure 22. Driver-focussed Optimisation (Lower Wait Time Target): Expected Wait Time, All Uptakes

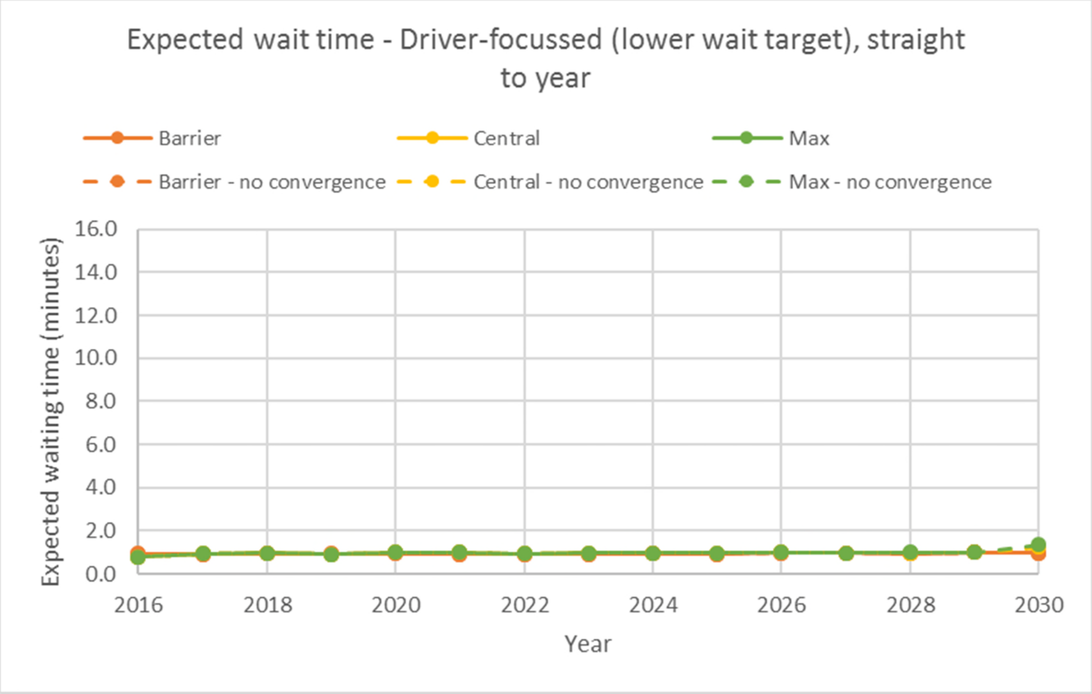
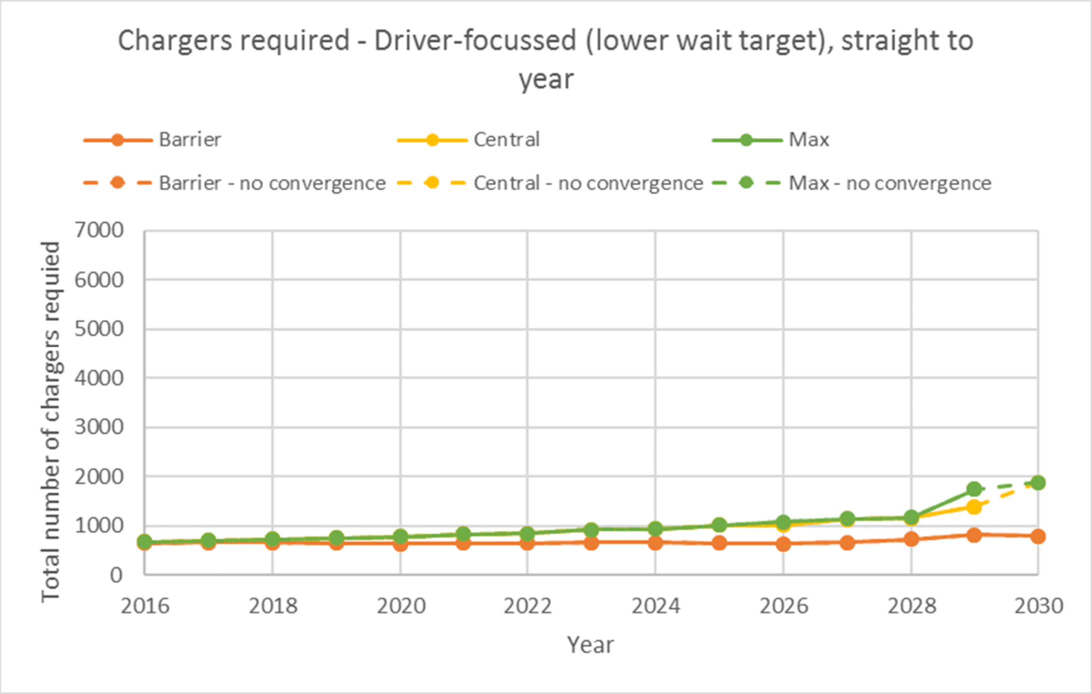


Figure 23. Driver-focussed Optimisation (Lower Wait Time Target): Chargers Required, All Uptakes

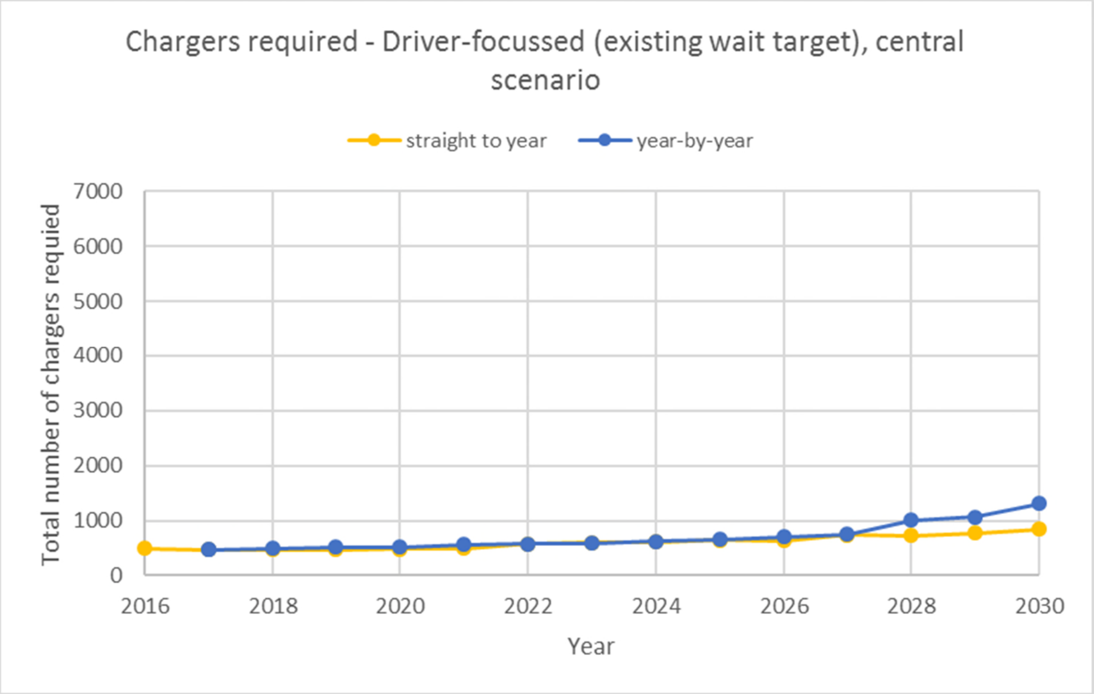


Other Optimisation Approaches

5.3.30 In general, optimising by building year-by-year on the previous solution leads to a number of redundant additions in earlier years. An example of this can be seen in Figure 24, giving the number of chargers required to maintain the current seven-minute wait time target. In this case there are up to 500 chargers more in the 2030 solution using this method as opposed to optimising 2030 separately, direct from the 2016 network. This equates to an approximately 50% increase in the number of chargers required. Overall, fewer chargers are needed to reach the same target in 2030 when using standalone optimisation than when using year-by-year iterative optimisation.

5.3.31 Other trends, such as more chargers being required in future years, and more chargers being required to meet targets under the higher uptake scenarios, are generally consistent through these other optimisation approaches.

Figure 24. Driver-focussed Optimisation (Existing Wait Time Target): Chargers Required, Approach Comparison



Uncertainties and Sensitivities

5.3.32 There are uncertainties and assumptions about the data inputs to the model which could affect the results. The key assumptions were investigated further to better judge their influence.

5.3.33 One uncertainty arises from the unknown reliability and availability of the chargers. A charger may, for example, be offline for maintenance, or may have its parking space blocked by a petrol/diesel vehicle. The true reliability rate of the *en route* chargers is not known, but since the model is calibrated to observed charging behaviour the reliability will be incorporated into the calibration factor. It is assumed that the reliability will remain constant over the future years covered in the model. No formal sensitivity test has been carried out on this; however, it can be predicted that if the charger reliability were to improve in the future, this would mean the recommended solutions would be able to achieve better service levels and shorter waiting times (or that fewer chargers would be required to meet the same targets).

5.3.34 The key uncertainty in the *en route* charging model related to the availability to the general public of certain manufacturer-specific 150kW charging sites on the strategic road network. The optimisation tool does not allow for different monetary charges to be applied to different subsets of EV owners, and we have therefore considered two extremes. In the first 'Best Case' scenario, these 150kW chargers are assumed to be available (free of charge) to all vehicles which are compatible with them (which is assumed to be all vehicles purchased after 2016). This scenario represents the assumption under which the results above have been produced. In the 'Worst Case' the existing single-manufacturer 150kW chargers are excluded from the supply network and any new 150kW chargers provided at these locations are assumed to apply the default monetary charging regime to all EV users, regardless of the make and model of their vehicle. A sensitivity test under this assumption showed that the driver-focussed solution for 2030 (Central Uptake scenario) had fewer 150kW chargers, and 20% fewer devices overall, than under the 'best case' above. The total charge delivered drops by only 4% in this 'worst case', and in fact this solution is approximately 10% more efficient in terms of charge delivered per pound spent on installation. This is as a result of the demand being spread around sites more efficiently in this 'worst case', rather than a high number of vehicles being drawn towards these attractive 150kW sites in the 'best case' base network.

6. MODEL DEVELOPMENT: PARKING-BASED CHARGING MODEL

6.1 Overview and Purpose of the Parking-based Model

6.1.1 The parking-based charging model (developed as an extension to SYSTRA's OPOSRI tool) predicts the demand for public 'on-street' and park-and-ride EV charging. This prediction takes into account parking-based charging at retail and leisure locations, on-street home charging, and charge-as-destination and specialist fleet charging, and is used to optimise the number and type of EV chargers across a set of locations.

6.1.2 The MS Excel macro-based tool simulates how well different infrastructure scenarios meet the predicted future-year demand for on-street recharging. Base demand is derived from existing transport models and the tool takes account of the likely future demand for on-street recharging; location of charging points; number of chargers at each point; number of parking bays each charger serves and the duration of both the charge and the underlying trip. It also takes into account number of uncertainties by allowing the CCC to evaluate the impact of variations and sensitivity of different parameters.

6.1.3 The outputs of the tool provide an understanding of:

- the locations and numbers of chargers of different types which minimises the level of unmet demand for a given level of capital investment; and/or
- the level of investment required to achieve a given level of service in different future years.

6.1.4 The chargers in the parking-based charging network are classified into three types, based on charging speed. These are:

- 'Standard' – with a speed of 7kW;
- 'Fast' – with a speed of 22kW; and
- 'Rapid' – with a speed of 43kW.

6.1.5 This provides a basis for recommendations on the number, type and location of additional charging points and associated budget requirements. This will help:

- support decision makers when planning where to install recharging stations;
- identify the most cost-effective number and type of rechargers at each location;
- allow the CCC to visualise which overall investment strategies are efficient and which are not; and
- identify the optimal recharging infrastructure for a given level of investment or the investment required to (cost-effectively) deliver a given level of future-year level of service to EV users.

6.1.6 The main benefit of the tool is to support the decision-making process around the optimum EV charging infrastructure strategy for a given level of budget input.

6.1.7 The tool is therefore designed to support the provision of accessible, convenient and reliable EV charging.

6.1.8 The parking-based charging model takes account of:

- the distribution of EV ownership in a given area;
- the pattern of 'true destination' parking-based demand for travel to the various destination zones (having 'top-sliced off 'home-based private' and 'workplace' charging);
- the distribution of the durations the vehicle is parked, for all different trip purposes (which is needed to determine how long each vehicle occupies the parking bays at the recharger);
- the user-defined recharging rates and costs of three types of charger ('Rapid', 'Fast' and 'Standard');
- whether or not drivers arriving at a charger can unplug earlier-arrival vehicles which have completed their charge;
- whether the optimum pattern of chargers in the modelled area starts from a 'clean sheet' or from the current network of 'Rapid', 'Fast' and 'Standard' rechargers.

6.1.9 The tool however does not take account of any commercial objective – i.e. the cost-effectiveness – when evaluating the installation of chargers. Instead, only those areas which have most need for additional parking-based charging infrastructure are identified. It is anticipated that goals other than direct profit could lead to chargers being installed in these areas, for example retailers wishing to attract business to their shops.

6.1.10 The tool is flexible with respect to the level of geographic detail it requires, using a zoning system based on EV Recharging Areas (EVRAs) to group the chargers into clusters which can all be used by the trips travelling to that area. This level of zoning will work best when these EVRAs are 'walking distance-sized', but the underlying approach can also be applied at a more strategic level, to start to optimise the future level of EV 'parking-based' infrastructure at the 'whole city' level.

6.1.11 To demonstrate the flexibility of the tool, three versions of the model are presented here: a strategic-level model to provide guidance on parking-based charging provision across mainland Great Britain, and two local-level case studies focussing on the Glasgow and Sheffield-Rotherham areas.

6.2 How the Parking-based Model Optimises the Charger Network

6.2.1 Before starting the optimisation process, the model will take input data relating to the demand between and within zones and convert it into a demand rate for EV charging within each EVRA. This conversion is carried out differently for the strategic-level and local-level versions of the model, and is discussed in more detail in Section 6.4.

6.2.2 As was done for the long distance *en route* charging model, the EV fleet is divided into range distribution 'buckets'. Vehicles in each of these 'buckets' have an associated battery capacity, which is used in the determination of charging demand.

6.2.3 The model runs a series of simulations to firstly evaluate the performance of the base year network, and then to determine the likely impact on performance if additional devices are added. The simulation is run multiple times for each EVRA and each combination of chargers, in order to reduce the impact of random variation on the results.

6.2.4 During a simulation, the model will simulate a random 'typical' day in a charging zone. Random vehicle arrivals are generated using the distributions calculated (see section 6.4), with the (random) parking duration determined by the trip purpose – i.e. the EV is assumed to park for as long as is necessary for its driver to complete their business in the area.

6.2.5 Vehicles will park at a charger where possible, and select the most cost-effective device in order to obtain a full charge where there is a choice of chargers. If there are no chargers free in the area, the EV may choose to queue for a limited time; if the specified time limit is reached before the EV is able to plug in to charge, then this demand will be added to the total 'unmet demand' for this scenario. Similarly, if a vehicle is unplugged before it has received a full charge, i.e. when the user completes their trip quicker than the required recharge time, then the residual required charge is added to the tally of unmet demand.

6.2.6 Different types of unmet demand are given different weights within this tallying process. For example, the CCC can specify input parameters which ensure that drivers of vehicles with larger battery capacities are assumed to have less-urgent need of regular charging than smaller capacity vehicles. A 'relative importance' factor is used to define this scaling process; for the test cases considered in this report, this is set to 100% 'importance' for the shortest range bucket and then applied proportionately based on battery capacity, resulting in the longest range bucket having a 33.3% 'importance' factor. These factors are used to multiply the undelivered charge before it is added to the tally of unmet demand.

6.2.7 For each combination of chargers and each EVRA, the results of the simulation runs are averaged to obtain for that scenario a forecast of:

- total demand in kWh satisfied;
- total unmet demand in kWh; and
- total demand overall in kWh (which is simply a sum of the satisfied and unmet totals).

6.2.8 The budget spend required for the scenario is also known, allowing each scenario to be evaluated according to two criteria – the cost of the charger network and the level of service (i.e. total demand satisfied divided by total demand overall) that it delivers.

6.2.9 The tool can then construct a set of solutions which will provide the best service level (aggregated across all EVRAs) up to a budget limit set by the user. It does this in multiple budget steps. At each step it modifies the number of chargers in a zone which will give the best improvement in service level within the cost of that budget step. The size of the budget step can also be modified by the user.

6.2.10 From this, the CCC will be able to see not only the service level achievable for a given amount of spend, but also the EVRAs in which chargers should be installed to achieve each cost-effective solution. The CCC will then be free to make their own judgement on the trade-off between the cost of the charging network and the level of service it delivers.

6.3 Geography and Model Zoning Systems

6.3.1 Three versions of the model presented here:

- A strategic-level mainland GB model;
- A local-level case study of the Glasgow area; and
- A local-level case study of the Sheffield-Rotherham area.

6.3.2 Each of these models has their own zoning system, as described below.

The Mainland GB Model

6.3.3 The mainland GB model uses the same zoning system as that used for the long distance *en route* charging model (see Section 3.3 for details).

6.3.4 This zoning system was based on the 39 NUTS2 (Nomenclature of Territorial Units for Statistics level 2) zones, with some modifications made. After London, which is already represented by several NUTS2 zones, the 17 next largest cities by population (> 250,000 residents) were split out from the NUTS2 zones in which they lie. For the parking based charging model, this allows demand for parking-based charging within these cities to be considered separately from the demand in the surrounding area. In addition, the central London NUTS2 areas were merged to a single zone for this model. These modifications resulted in a 50-zone system for this model.

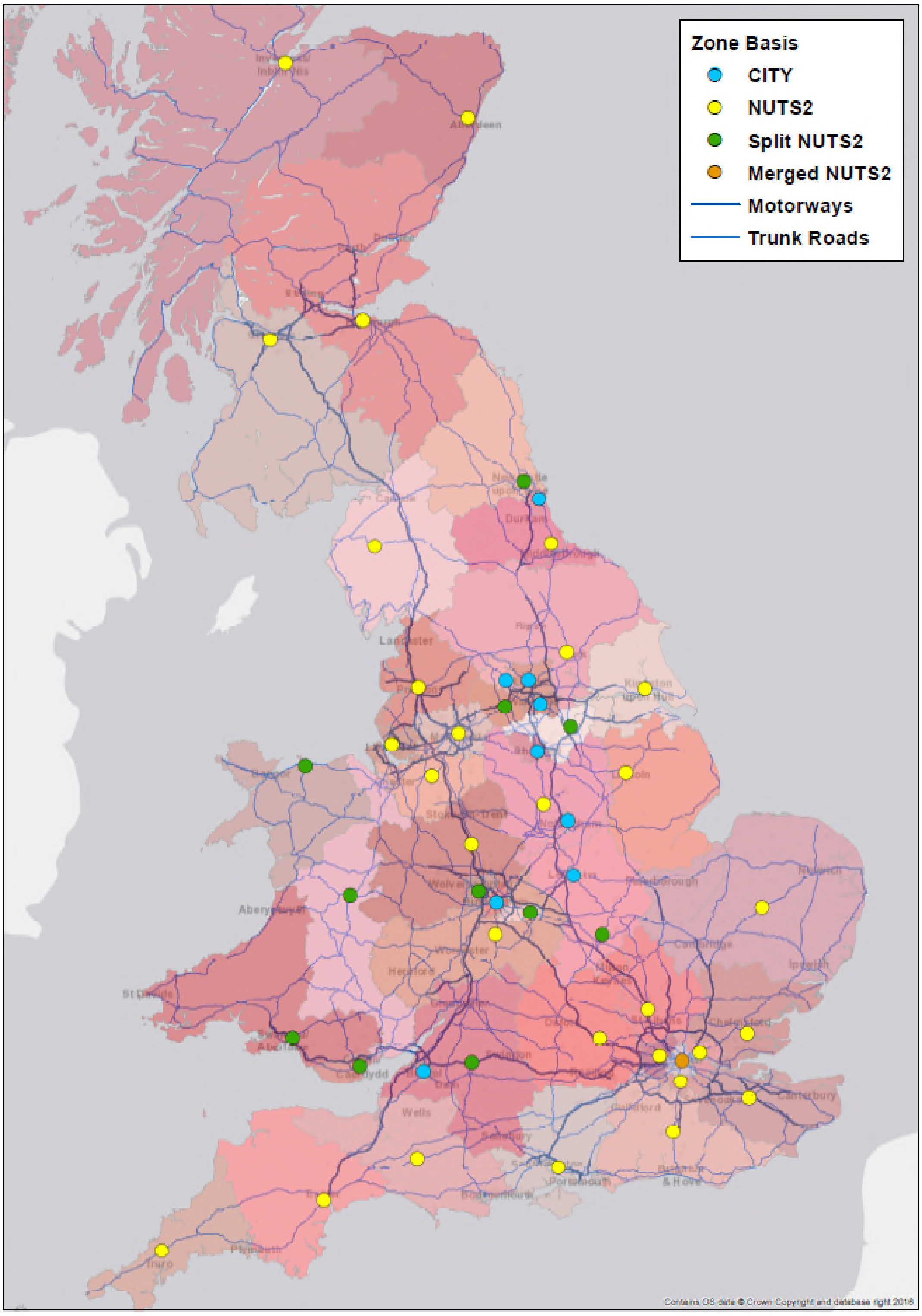
6.3.5 These 50 zones, along with their associated centres, are shown in Figure 25 with different zone types identified as follows:

- ‘CITY’ centres represent where a city-area zone has been adopted;
- ‘NUTS2’ centres represent where an unedited NUTS2 zone has been adopted;
- ‘Split NUTS2’ centres represent where a NUTS2 zone has been split;
- ‘Merged NUTS2’ centres represent where NUTS2 zones have been spatially joined (as per London).

6.3.6 Note that the zone centres shown are positioned based on the centres of population in the zones.

6.3.7 The size of the areas means that, especially in future years, there is a relatively high demand in certain zones, with a consequent effect on the running time of the model. An option is therefore provided to CCC to divide up each zone, either by a constant value across the whole model area, or proportionate to the size of demand in each zone. This ‘scaling factor’ has the effect of considering a representative sub-division of each zone, with the demand and number of available chargers sub-divided accordingly. This scaling factor divides each zone into a number of equivalent sub-zones, each of which is assumed to be consistent with the assumption that drivers will attempt to use an EV charging station within walking distance of their intended destination.

Figure 25. Zone System Adopted for GB-Wide Modelling



6.3.8 The zones used for the Glasgow case study model were based around the Local Authority areas within the Strathclyde region. These are:

- Argyll and Bute;
- East Ayrshire;
- East Dunbartonshire;
- East Renfrewshire;
- Inverclyde;
- North Ayrshire;
- North Lanarkshire;
- Renfrewshire;
- South Ayrshire;
- South Lanarkshire;
- West Dunbartonshire; and
- Glasgow City.

6.3.9 The zones can be categorised into three types:

- The external zone, used only to enable us to consider trips from further afield, is a composite of all locations beyond the Strathclyde region, along with the majority of the Argyll and Bute Local Authority;
- The 'buffer' zones, also used only for considering demand from beyond the EV Recharging Areas, represent the 11 Local Authorities within Strathclyde which surround Glasgow (note that only the South-east portion of Argyll and Bute is considered in this category, with the majority of this area being classified as being within the more-remote external zone);
- The main model zones, defined as nine EV Recharging Areas (EVRAs) making up the Glasgow City Local Authority area – each of these nine EVRA's have their own forecast EV demand forecasts;

6.3.10 The starting supply of chargers in each EVRA is based on the current base year network of publicly-available parking-based chargers.

6.3.11 Figure 26 below shows the buffer zones shaded in greyscale, with the Glasgow zones in colour in the centre. Figure 27 zooms in on the EVRAs within Glasgow City itself.

Figure 26. Zone System, Including Buffer Zones, for Glasgow Case Study Model

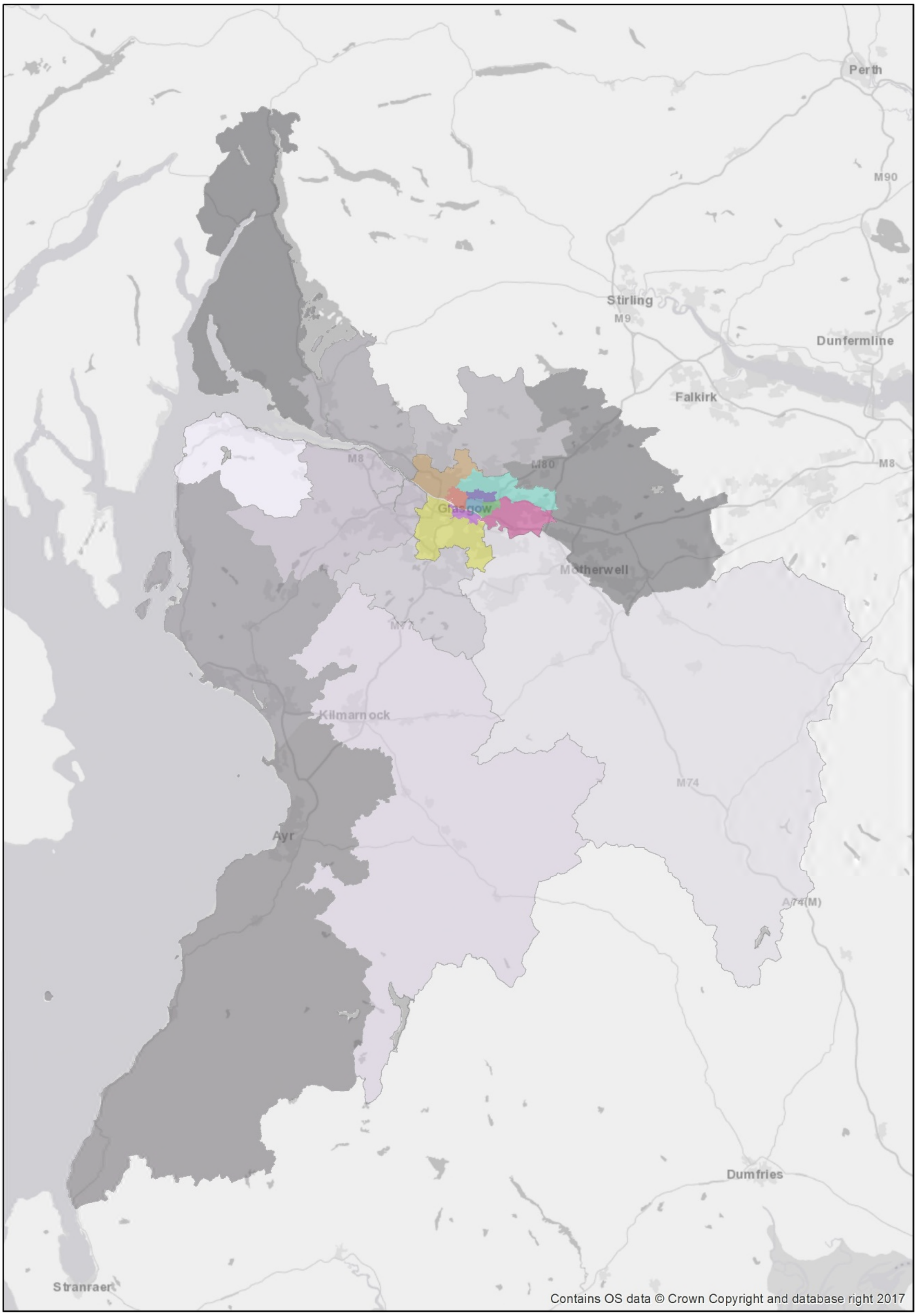


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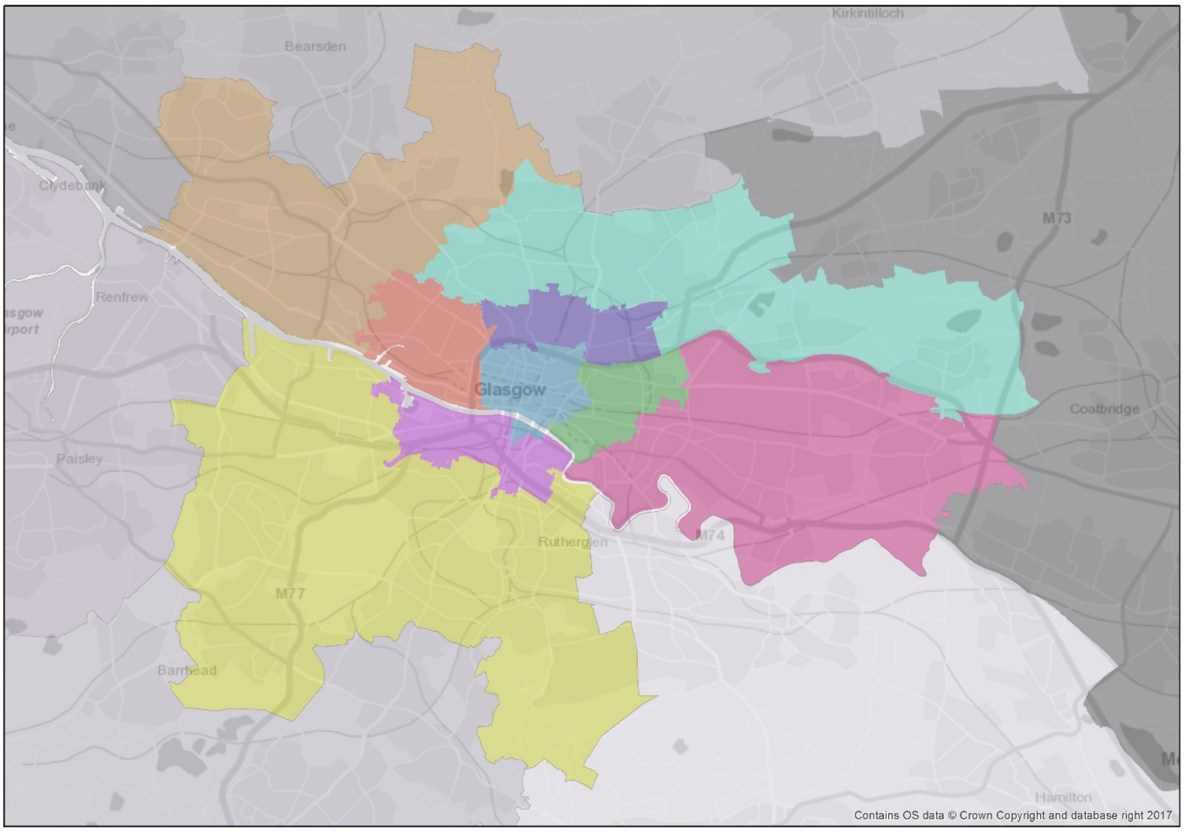
Figure 27. Main EVRA Zones for Glasgow Case Study Model



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6.3.12 The zones used for the Sheffield-Rotherham case study model were based largely on the GB-level model zones in and around the South Yorkshire area.

6.3.13 These zones can be categorised into three types:

- an external zone, used to enable us to consider trips from further afield, is a composite of all locations beyond the main model area and buffer zone.
- a buffer zone, used as part of demand considerations, covers an area surrounding Sheffield and Rotherham. It is divided according to the zones used in the national-level model, and includes:

    - the four zones comprising West Yorkshire;
    - the Barnsley and Doncaster districts of South Yorkshire;
    - the Selby and York districts of North Yorkshire;
    - the combined East Yorkshire and North and Northeast Lincolnshire zone;
    - the city of Nottingham; and
    - the combined Derbyshire and Nottinghamshire zone.

- The main model zones, defined to be EV Recharging Areas (EVRAs) within the model, comprise the Sheffield and Rotherham local authority districts of South Yorkshire. There are sixteen such zones (ten in Sheffield and six in Rotherham), each with their own forecast demands.

6.3.14 The supply of chargers in the EVRAs starts from the base year supply of publicly-available parking-based chargers.

6.3.15 Figure 28 below shows the buffer zone shaded in greyscale, distinguishing between the different zones used in the national level model. The Sheffield and Rotherham EVRAs are in colour in the centre, and can be seen more clearly in the zoomed in map in Figure 29.

Figure 28. Zone System, Including Buffer Zones, for Sheffield-Rotherham Case Study Model

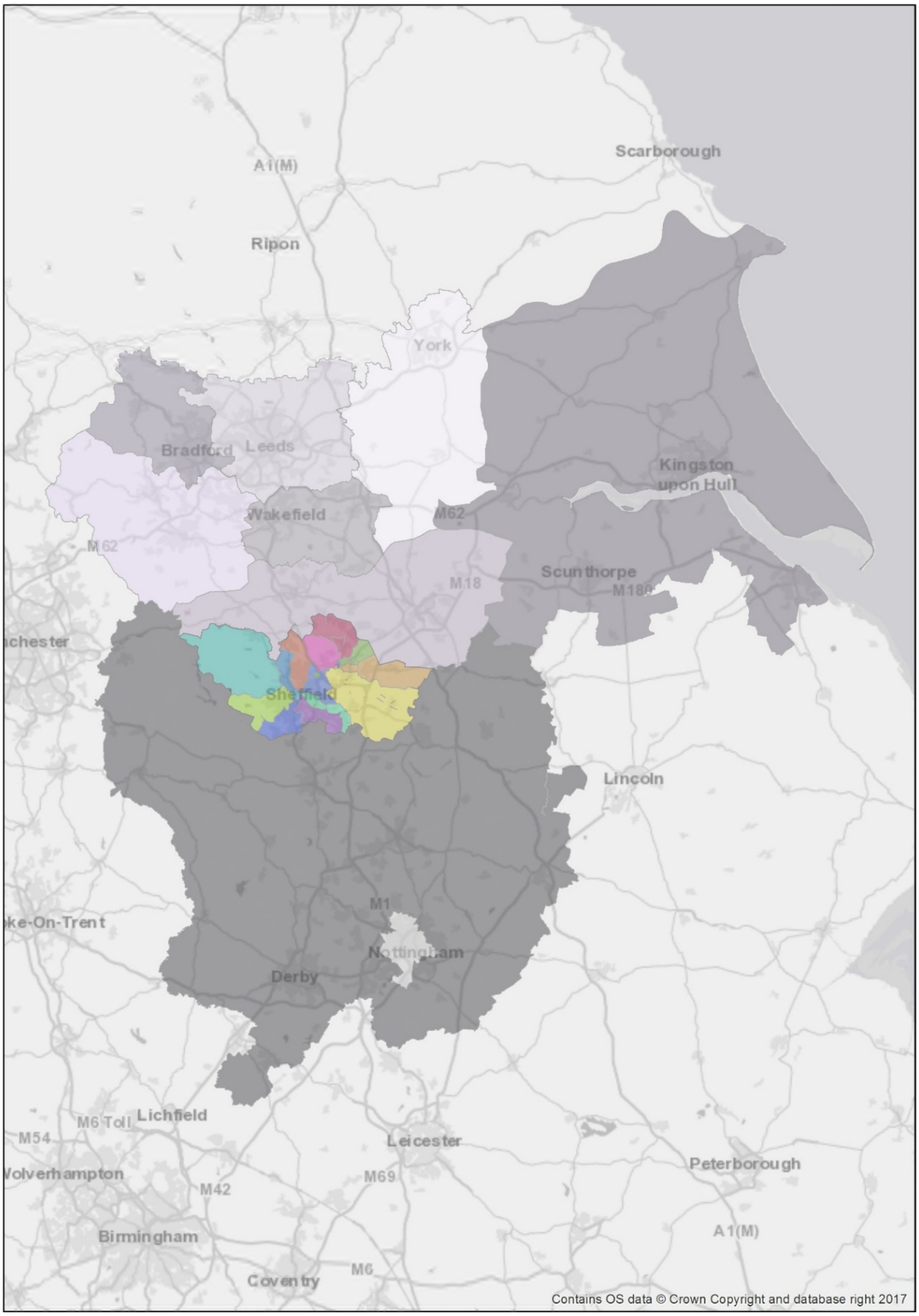

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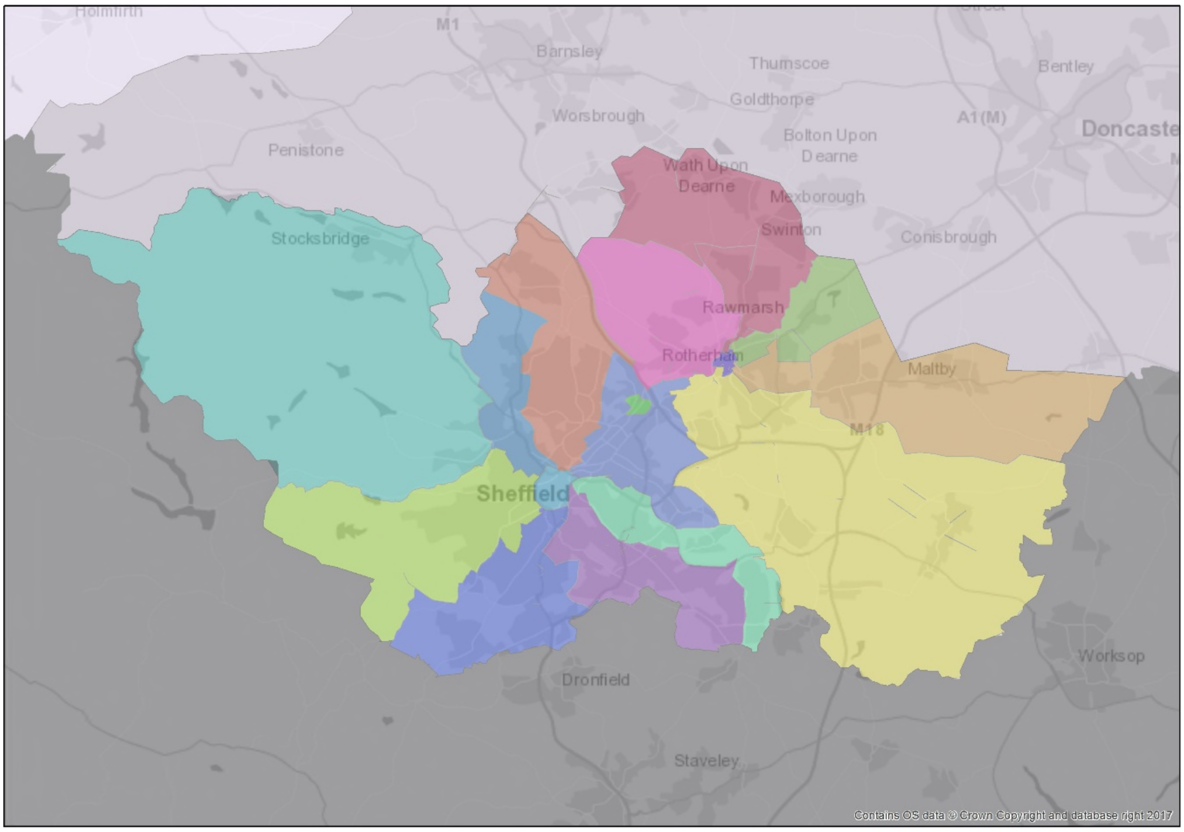
Figure 29. Main EVRA Zones for Sheffield-Rotherham Case Study Model



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6.4 Demand Inputs

6.4.1 Before starting the optimisation process, the model takes input data for the demand between and within zones and converts it into a demand rate for EV charging within each EVRA. The input data and associated conversion is different for the strategic-level model as compared to the local-level versions of the model. Both are discussed in this section.

Parking-based Charging Demand

6.4.2 The parking-based charging demand for the national-level model is derived from the DfT's TEMPro software, which provides a forecast of the number of car vehicle trips with parking destinations in each of our modelled zones for the required future years.

6.4.3 It is assumed that all these parking-based charging trips are intra-zonal, and therefore the arrivals given by TEMPro for each zone can be calculated using the percentage of the vehicle fleet in that zone which is electric to produce a forecast number of EV destination/parking arrivals in that zone for the required future years. The EV percentage of fleet by zones was also calculated for the long distance *en route* charging model, and details of this can be found in section 3.7.

6.4.4 How these arrivals are spread across the course of the day was derived from analysis of NTS Travel Diary data[10], from which hourly proportions of daily demand were determined.

6.4.5 Not all EVs arriving in a zone will wish to charge. This could be because the owner has access to lower-cost private off-street charging at home and will chose to use this instead, or because the car has sufficient residual charge that the owner can afford to wait until a future trip to recharge the vehicle. The number of EVs which charge is calibrated to observed data, with this calibration factor applied across all zones and all future years. Using this, we can adjust the EV arrivals described above to give a forecast charging demand for each zone.

6.4.6 For the local-level models, data from local transport models was used to provide the inputs. These were:

- For Glasgow, the Strathclyde Regional Transport Model (SRTM); and
- For Sheffield-Rotherham, the Sheffield and Rotherham Transport Model.

6.4.7 These models provide O-D matrices giving journey demand between each of the zones in the parking-based charging model. The matrices are broken down by time period, allowing the distribution of arrivals across the day to be extrapolated from the output.

6.4.8 The O-D matrices allow an EV percentage by zone to be applied to the trips according to their zone of origin. For these case studies, EV percentages can be calculated at a more detailed level than for the national-level zones, with EV registration data and total vehicle numbers available at a Local Authority level. The mechanics of the calculation is, however, the same as that described in Section 3.7.

6.4.9 As with the national-level parking-based charging model, there will be a percentage of EVs which will arrive on a trip but do not wish to charge on that particular occasion. We apply the same calibration determined for the national-level model from observed data to each of the case study model areas. This calibration factor can then be applied to the EV arrivals to produce a forecast EV charging demand for each zone.

Park and Ride Charging

6.4.10 As the national-level version of the model is a strategic version of the tool, designed to deal with whole zones rather than specific local areas, park and ride charging is not considered in this case.

6.4.11 However, key park and ride areas are defined as separate zones in the two case study transport models, each with a predicted arrival and departure rate in each of the modelled time periods.

6.4.12 Discounting these to account for home charging and the proportion of EVs which will require to charge when the opportunity arises, we can obtain a forecast number of EVs desiring to charge in each park and ride zone over the course of a day.

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[10] Department for Transport. (2017). National Travel Survey, 2002-2016: Secure Access. [data collection]. 4th Edition. UK Data Service. SN: 7559, http://doi.org/10.5255/UKDA-SN-7559-4

On-street at-home Charging

6.4.13 It is assumed that on-street home charging (for EV owners who do not have access to their own drive or garage) will take place overnight, starting towards the end of working hours (from around 4pm) and continuing to around 8am the next morning.

6.4.14 The strategic GB-wide level model considers only daytime charging, and ignores any on-street home charging which may be required during this day-time modelled period.

6.4.15 For the local case study models, we assume that an increasing level of trips in the afternoon and into the evening period are travelling home for overnight charging, from 20% of trips from 4pm-5pm, to 100% in the 7pm-8pm hour.

6.4.16 These trips are discounted according to the percentage of vehicles which make use of private home charging, which Next Green Car estimates at 93% of the EV fleet – i.e. only 7% of the EVs arriving for overnight parking will wish to use on-street recharging facilities.

Special Fleet and Charge-as-Destination Charging

6.4.17 Data on special fleet and charge-as-destination trips is scarce, and so assumptions have to be made about the nature of these trips for the purposes of this model. However, it should be noted that this is for illustrative purposes and can be modified in sensitivity testing by the CCC.

6.4.18 In the local case study models we assume that there are no special fleet or charge-as-destination trips.

6.4.19 In the national-level strategic version of the tool, we assume that daily demand in this category is currently 10% of the daily parking-based charging demand. This percentage is assumed to be linked to the percentage of vehicles which make use of private home charging – if there are more vehicles which cannot charge off-street at home, this will increase the number of vehicles making charge-as-destination trips.

6.4.20 The demand for this category of trip is assumed to be spread predominantly over the daytime period from 10am to 4pm.

PHEV Users

6.4.21 Similar to the long distance *en route* charging model, the demand forecasting is based around the predicted behaviour of BEV car drivers who must charge regularly to be able to use their vehicle, as opposed to plug-in-hybrid users who have the option of reverting to fossil fuel if their electric battery runs out of charge.

6.4.22 However, the base year demand for the national-level parking-based charging model has been calibrated using all current charging behaviour at a subset of the current parking-based charging locations, including any charging by plug-in-hybrid cars or vans.

6.4.23 Therefore, provided the relative frequency of these 'other' types of charging events using the chargers does not change significantly over time (i.e. it grows in line with the corresponding growth in pure electric vehicle ownership which we have used to define the EV growth scenario), then it is reasonable to claim that the parking-based charging model is taking account of these other 'other' types of charging behaviour.

6.5 The Modelled Years

6.5.1 The model was developed based on the requirement to explicitly model the following years:

- 2016 Base Year;
- 2020;
- 2025; and,
- 2030.

6.6 Modelled Time Periods

6.6.1 The tool simulates arrivals and charging requirements over an average 12-hour weekday, from 8am to 8pm.

6.6.2 It is assumed that all overnight home-based on-street charging events finish by 8am the next day, and that consequently all parking bays and charging devices are unoccupied at the start of a new day (i.e. the start of the simulation period).

6.6.3 Each simulated day is considered to be independent. This means that any unmet demand one day will not affect the recharging demand in subsequent days.

6.7 The Charging Network

6.7.1 The default mode of operation for the parking-based charging is to start from the existing charging network (as provided by Zap-Map data) and supplement this to produce the optimum network in future modelled years by adding chargers to meet extra demand and changes in technology.

Existing Charging Point Network

6.7.2 'Zap-Map' data for the existing public charger network was provided by Next Green Car. Zap-Map is a UK charging point digital platform with data for more than 5,000 charging locations and 13,000 connectors (as of July 2017). It is the UK's leading consumer brand for EV charging, with over 50,000 cross-platform users per month and over 40,000 app downloads (iOS and Android) to date.

6.7.3 Zap-Map has been selected by key industry players such as OEMs (Nissan, BMW) and Government (GoUltraLow) for charging information and market insights. The platform has also integrated real-time data from several major networks covering more than 50% of UK public charging devices – unique in the UK market.

6.7.4 Zap-Map data provided for the project by Next Green Car included a static data export of all current devices (monthly archive from 2013 to the start of 2017), including:

- device and connector type;
- location type (including public/private);
- geolocational data (geocodes and postcodes); and
- date added/removed to/from database.

6.7.5 Dynamic network data and Zap-Chat status user updates were also provided for several participating networks across a three-month period including:

- number of charge events per device/connector
- total time of charge events per device/connector

6.7.6 In all cases, the charge point data provided to the project was anonymised to protect commercial confidentiality relating to networks and device ownership.

6.7.7 The chargers appropriate to the parking-based charging model were filtered from the list of chargers provided by ZapMap, with 2,721 devices being identified through this process. In general, this included all listed chargers which were not identified as appropriate for *en route* charging (see Section 3.3.3); however, there were some exceptions to this:

- Dealership forecourt chargers were not considered, as they were assumed to be for customers only;
- Hotel / Accommodation chargers were not considered, as they were assumed to be for customers only;
- Chargers at Park & Ride sites were not considered as part of the standard EVRA zone charger count, but would instead be included as a separate Park and Ride site when relevant to the model;
- Workplace car park devices were not considered, as they were assumed to be for employees only; and
- Any device which was located behind a barrier or did not operate 24/7 was not considered, as its availability could not be guaranteed.

The Charging Network by Zone

6.7.8 An ArcMap GIS database was used to analyse, map, and allocate relevant chargers:

- To the 50 NUTS2-based zones, for use in the strategic GB-level tool; and
- For the case study versions of the model, to the 9 main Glasgow EVRAs and to the 16 Sheffield-Rotherham EVRAs.

6.7.9 For input into the parking-based charging model, the numbers and types of charger in each zone is required. More specific detail of device locations are not required, since for the purposes of this model we assume that EVRAs are 'walking distance-sized' and that any device in an EVRA is equally convenient for access to a driver's underlying trip purpose.

6.7.10 As noted in Section 6.3, in order to maintain the assumption of the walking-distance-sized EVRAs, a user-defined scaling factor can be applied to the zones for the strategic-level model. This has the effect of scaling down the number of available chargers and the demand to create a representative sub-division in each zone, for which the area also can be considered to be factored down.

Capital Cost of Network Improvements

6.7.11 A standard installation cost was assumed for each of the three charger categories, as shown in Table 7. These costs applied in all zones regardless of geographic location or other characteristics of the zone. This allows a total cost to be estimated for each scenario generated for each zone.

Table 7. Assumed Standard Installation Cost of New Parking-based Charging Infrastructure

CHARGER CATEGORY	COST OF ADDITIONAL CHARGER
Standard (7kW)	£10,000
Fast (22kW)	£12,000
Rapid (43kW)	£34,000

Knowledge of the Network

6.7.12 It is assumed that drivers know the location and costs of the recharging facilities, and which ones (if any) are available at their time of arrival. This means they are able to go directly to their chosen device on arrival in the zone, or to queue nearby if necessary.

6.8 EV Fleet Assumptions

6.8.1 Assumptions made about the EV fleet for the purposes of the parking-based charging model are similar to those made for the long distance *en route* charging model, as described in Section 3.7 of this report.

6.8.2 The *range distribution* 'buckets' used are the same as defined previously, with the same future year splits of the fleet being used as those described in Section 3.7 of this report.

6.8.3 The method of forecasting the EV percentage by zone is the same for the GB-level model as that used for the long distance *en route* charging tool. Meanwhile, since OLEV's BEV registration data and DfT's Vehicle Licensing Statistics are both given at a Local Authority level, it is possible forecast the EV percentage at a more granular level closer to that of the Glasgow and Sheffield-Rotherham EVRAs for the case study models.

6.9 Driver Behaviour

6.9.1 There are a number of factors relating to driver behaviour on which assumptions have to be made, relating to such matters as the use of parking bays, the relationship between different EVRAs, and the duration for which an EV will plug in to charge.

Charging Bay Use

6.9.2 It is assumed that charging bays are only used by electric vehicles, i.e. conventional Internal Combustion Engine (ICE) vehicles are prevented from using these spaces.

Independence of Electric Vehicle Recharging Areas

6.9.3 We assume that demand arriving in a given EVRA will be served *only* from the bays and devices within that EVRA. In other words, if all bays are occupied when a vehicle arrives in a zone, the driver will not look to a neighbouring zone for a charge.

Plug-in Duration

6.9.4 The duration for which a vehicle is plugged in is dependent on the type of charging that is taking place – parking-based charging, on-street home charging, park and ride charging, specialist fleet or charge-as-destination charging.

6.9.5 For parking-based charging, the plug-in duration depends on the underlying purpose of the trip (e.g. length of time spent shopping). The average length of parking duration across the country was analysed from NTS Travel Diary data[11], with a different average calculated for each arrival hour (from 8am to 8pm). It is assumed that these durations are standard across all 50 of the NUTS2-based zones, and by extension that they apply in each of the EVRAs in the two case study models.

6.9.6 For test scenarios where the model user wishes to consider on-street home charging, this is assumed to be done overnight. Even if a vehicle arrives at, for example, 5pm it is assumed not to leave again that day if its purpose is to home-charge. Therefore all on-street home charges are assumed to have a parking duration of 8 hours.

6.9.7 Park and ride plug-in durations also depend on the length of time for which a vehicle is parked. This type of charging is not modelled in the strategic national-level tool, but is be used in the local case study parking-based charging models. In these cases, an average parking duration is estimated from the local traffic model data.

6.9.8 For each of these charge event types, the parking-based charging model has the functionality to allow a vehicle to be unplugged by another driver once it has been fully charged, even if its underlying trip purpose has not been completed. However, for the purposes of the three model versions discussed here, this option is not used here.

6.9.9 For the specialist fleet and charge-as-destination charging, the charge is the trip purpose, and therefore the plug-in time is related to the time taken to charge. We assume that the driver will not wish to take any longer than necessary to charge, and therefore the parking time will be calculated as the time which *would* be required to deliver a full charge *if* the fastest rate of charger is available. If a non-rapid charger is the first to become available, the vehicle will still park and connect for this time, with any remaining required charge being recorded as unmet demand.

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[11] Department for Transport. (2017). National Travel Survey, 2002-2016: Secure Access. [data collection]. 4th Edition. UK Data Service. SN: 7559, http://doi.org/10.5255/UKDA-SN-7559-4

6.10 Model Calibration

6.10.1 As described in section 6.4, it was believed that some drivers will not feel the need to charge during every trip. In order to test this, the number of charge events per charger across the 50 national-level zones was examined for the dynamic data from Zap-Map (provided by Next Green Car) and for the base year in the national-level parking-based charging model (with no additional chargers in the network). This comparison gave a calibration value of 88%, indicating that this percentage of all non-home-charging EVs will attempt to charge on arrival.

6.10.2 Note that for the purposes of calibrating the GB-level model, the zones were treated as complete areas rather than applying the scaling factor and working with representative subdivisions of the zones. This was in order to keep results as precise as possible so that the calibration could be carried out without potential rounding errors.

6.10.3 This calibration factor was assumed to also hold true for the two case study versions of the model.

7. MODELLING RESULTS: PARKING-BASED CHARGING MODEL

7.1 Introduction

7.1.1 In this chapter we set out a sample run of each of the three versions of the parking-based charging model described in Chapter 6. For these runs, a single set of circumstances was assumed, and the optimisation, with a specified objective, was carried out under these assumptions. The CCC have access to the parking-based charging model, and will therefore be able to carry out further tests using a similar approach to that described here.

7.1.2 For the purposes of these test runs, we have used the Central EV uptake scenario for future years and with the objective to find the most cost-effective means of improving the existing network such that the base year level of service is maintained when demand increases to expected 2030 levels.

7.1.3 It was also assumed that the wait time limit for EV drivers would be zero – i.e. if there are no available charging spaces when an EV arrives, then this EV will not wait and therefore not receive a charge on this visit.

7.2 Approach to Analysis

7.2.1 As stated, we work on the basis that there is a given level of service in the base year, and that we want to determine the size of budget that is required to be spent to maintain this level of service in the future modelled year, specified as 2030.

7.2.2 Firstly, needed to determine the current service level. To do this, we ran the model in the base year (2016) and restricted the number of devices to add to be zero. For the GB-level model, a relatively low scaling factor of 10, applied as absolute across the modelled area, was used. This had the effect of reducing each zone to a representative sub-division of one-tenth the size to allow the model to run efficiently, as discussed in Section 6.3.

7.2.3 Running with these parameters gave a value for service rate when no improvements were made to the base year. This became the target service level for our future-year optimisation.

7.2.4 We then moved forward to optimise for a given future modelled year. In this case, we set this year as 2030 and defined a maximum number of chargers to add in each zone. The model calculated how many chargers were required to maintain the same level of service as in the base year.[12] The results of the solution, to meet the base year level of service, are discussed in detail in Sections 7.3 and 7.4 below.[13]

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[12] Note that for further runs by the CCC it may be necessary for the model to be run by the user several times in order to determine how many chargers are required to be added in order to reach the target service level, however the recommended starting point is up to 5 of each type. It is also recommended, to keep the running time within manageable levels, to increase the scaling factor for the strategic-level model.

[13] When the target level of service cannot be achieved under these constraints (the level of the scaling factor and the number of chargers that the model can add), then it is likely that more devices are needed to meet the higher future demand. In this case, the numbers of charges to be added is increased, and the model is run again.

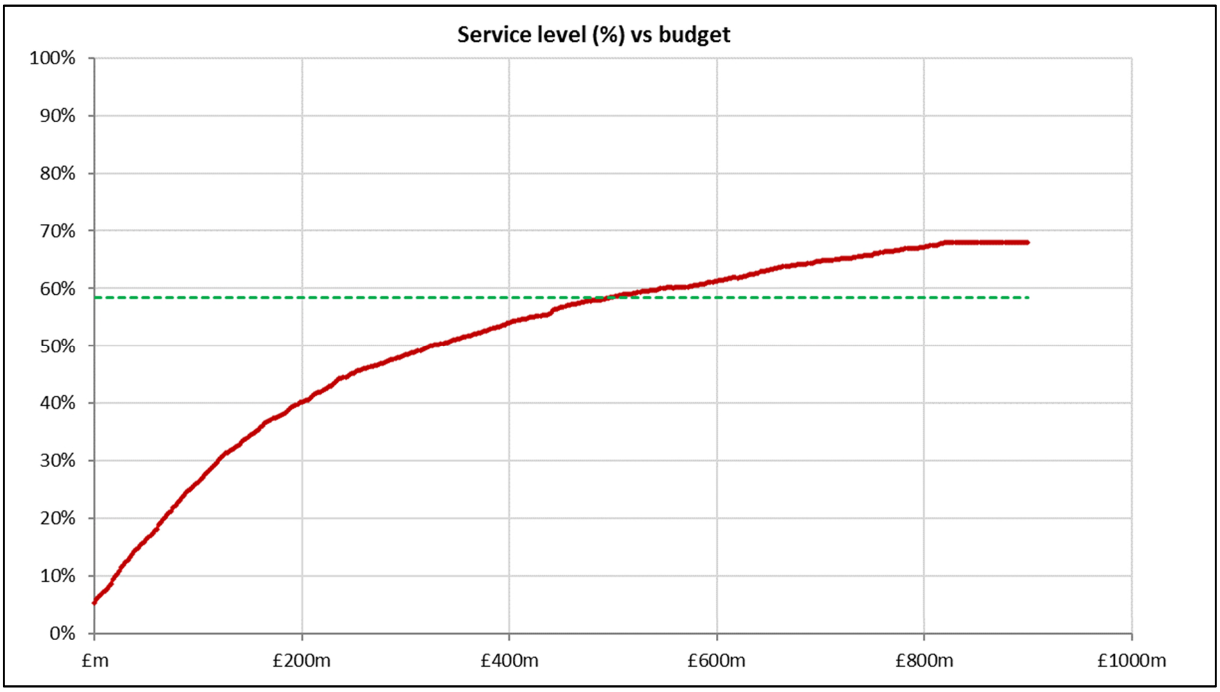
7.3 GB-level Strategic Model Results

7.3.1 Using the approach described in Section 7.1 above, the base year level of service was estimated to be approximately 58% of total demand, averaged across all zones.

7.3.2 An initial run of the 2030 scenario showed that restricting each zone to a maximum of 5 chargers (of each kind) did not allow for a sufficient increase in the service level. Therefore a second run, increasing the maximum number of chargers added per zone to 8 of each type, was carried out.

7.3.3 Figure 27 presents the service level against the budget across the whole model area, showing an estimate of the best service level which can be achieved for each amount of a hypothetical budget that is spent. The plot also gives a dotted line showing the 58% target service level.

Figure 30. Summary Chart for GB-level Model



7.3.4 This chart shows that the base service level, i.e. if no investment is made, was around 6% of the 2030 demand. This was increased to around 40% with a spend of £200m, and to around 50% if when £350m was invested. The target of 58% service level was reached at approximately £500m.

7.3.5 Figure 28 shows a more detailed breakdown of the solutions, and their associated service level. This gives the expected improvement in served demand and the service rate for every budget, and provides detail of how to invest in charging stations in each EV Recharging Area to achieve this.

Table 8. Summary Table for GB-level Model

Budget	Improvement (score)	Service level (%)	Total standard	Total fast	Total rapid	EV1	EV2	EV3	EV4	EV5	EV6
£ -	**4532859**	6%	2437	154	150	(37,0,0)	(0,0,15)	(79,0,0)	(0,0,0)	(32,0,0)	(38,0,0)
£ 2,000,000	14673	6%	2626	154	150	(37,0,0)	(0,0,15)	(79,0,0)	(0,0,0)	(32,0,0)	(38,0,0)
£ 4,000,000	27976	6%	2626	306	150	(37,0,0)	(0,0,15)	(79,0,0)	(0,0,0)	(32,0,0)	(38,152,0)
£ 6,000,000	41021	7%	2626	464	150	(37,0,0)	(0,0,15)	(79,158,0)	(0,0,0)	(32,0,0)	(38,152,0)
£ 8,000,000	53696	7%	2626	599	150	(37,0,0)	(0,0,15)	(79,158,0)	(0,0,0)	(32,0,0)	(38,152,0)
£ 10,000,000	65867	8%	2626	731	150	(37,0,0)	(0,0,15)	(79,158,0)	(0,0,0)	(32,0,0)	(38,152,0)
£ 12,000,000	77895	9%	2626	929	150	(37,0,0)	(0,0,15)	(79,158,0)	(0,0,0)	(32,0,0)	(38,152,0)
£ 14,000,000	89887	9%	2626	1089	150	(37,0,0)	(0,0,15)	(79,158,0)	(0,0,0)	(32,0,0)	(38,152,0)
£ 16,000,000	101726	10%	2626	1233	150	(37,0,0)	(0,0,15)	(79,158,0)	(0,0,0)	(32,0,0)	(38,152,0)

7.3.6 The first row is the base scenario, i.e. the rate if no money is invested. The value under 'improvement' in red is the total residual charge across all EVRAs under this scenario. Each subsequent row then displays (reading left to right) the following:

- the budget spent for this solution;
- the improvement made, in terms of extra demand served, on the next cheapest solution;
- the service level for this solution;
- the total number of standard, fast and rapid chargers required nationally by this solution; and
- the mix of (standard, fast, rapid) chargers required in each individual zone under each solution, with a cell highlighted where it differs from the previous solution – for example in row 2 for zone EV3 in Table 8 above.

7.3.7 From this table, we could find that the target service level was first achieved with a budget spend of £498m, which required a total of 4469 standard, 15105 fast and 7905 rapid chargers across the country. In percentage terms, the mix of chargers for this solution can be expressed as 16% standard, 55% fast and 29% rapid. By comparison, the base mix of chargers are 89% standard, with only 6% fast and 5% rapid in the base year network.

7.3.8 This same method was used to estimate the number of chargers required to maintain the current base year 58% service level in the intermediate years 2020 and 2025, and was also be replicated for the Max and Barriers uptake scenarios. Results for these runs are summarised in Table 9.

Table 9. Number of Chargers Required to Maintain Current 2016 Base Year Level of Service for Different Years and Uptake Scenarios

EV UPTAKE SCENARIO	NUMBER OF CHARGERS REQUIRED BY YEAR		
	2020	2025	2030
Central	**5,624**	**11,724**	**27,479**
Max	5,574	11,755	34,243
Barriers	4,069	6,042	13,104

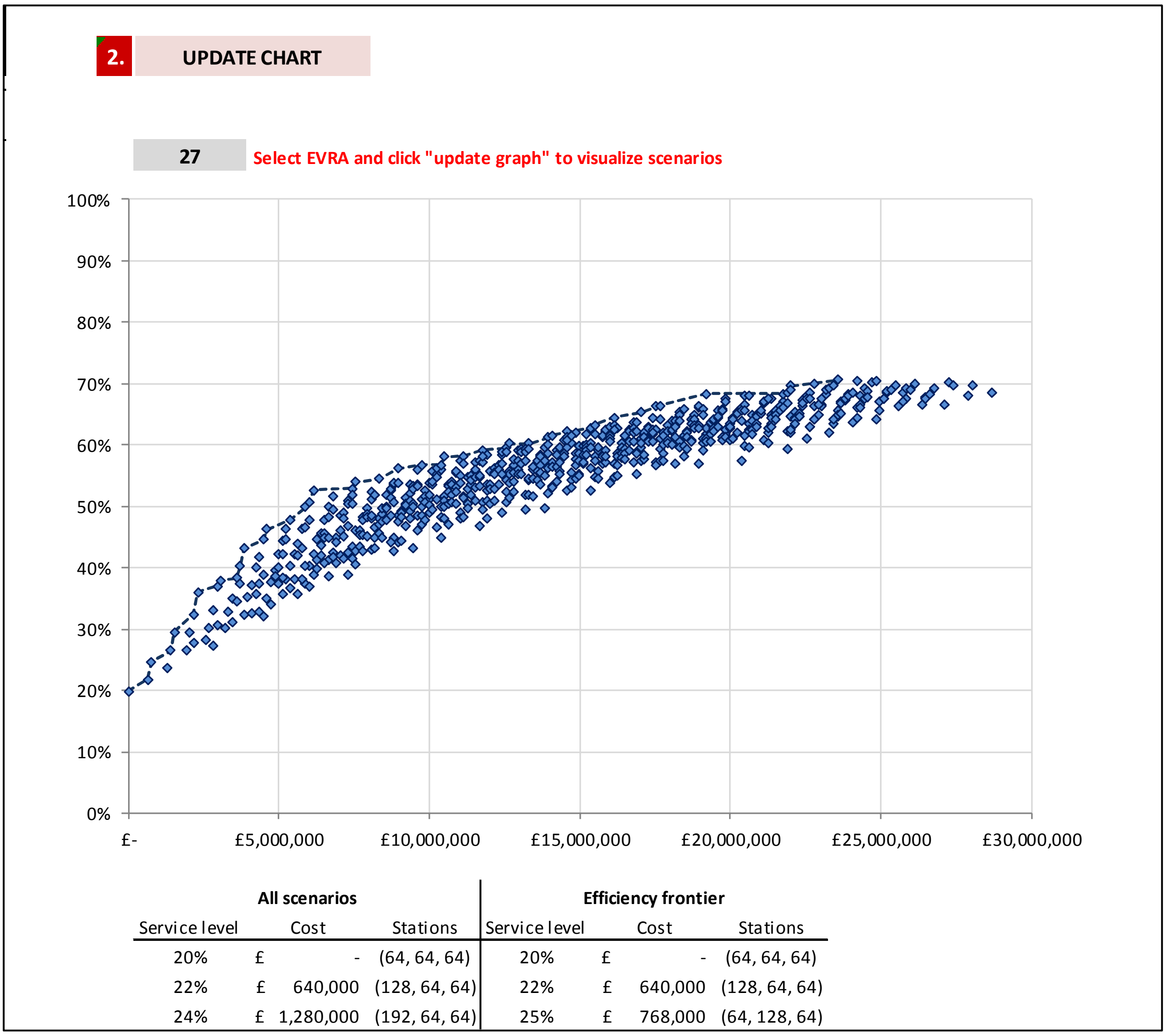
7.3.9 It can be seen that the requirements for the Central uptake scenario in 2030 represent a substantially more rapid expansion of the network than the equivalent results for the *en route* charging network. This difference can be explained by two main reasons which stem from the modelling assumptions:

- Firstly, the increase in battery range over time has a bigger impact on the demand for *en route* charging than for parking-based charging. This is because *en route* chargers will only be used if drivers cannot complete their journeys without them, whereas parking-based charging will be used whenever available; and
- Secondly, the model inputs used here have assumed that the ultra-rapid chargers are only available on the *en route* network and therefore the improvement in charging speed over time yield smaller improvements in the parking-based charging model than in the *en route* model.

Zone-level Results

7.3.10 The tool also allows the CCC to view results on a zone-level. In particular, efficient solutions on a zone-by-zone basis can be viewed on a chart – an example of this for one of the zones of the GB-level model can be seen in Figure 31.

Figure 31. Example Zone-level Chart for GB-level Model



Select EVRA and click "update graph" to visualize scenarios

All scenarios			Efficiency frontier		
Service level	Cost	Stations	Service level	Cost	Stations
20%	£ -	(64, 64, 64)	20%	£ -	(64, 64, 64)
22%	£ 640,000	(128, 64, 64)	22%	£ 640,000	(128, 64, 64)
24%	£ 1,280,000	(192, 64, 64)	25%	£ 768,000	(64, 128, 64)

7.3.11 The chart plots service levels scores for all scenarios against their budget. Every blue marker represents a tested combination of additional chargers. Those which are not located on the dashed line are not 'efficient', indicating a performance at least as good as this can be achieved with a lesser investment. Ideally, only these efficient combinations should be considered when planning to invest in charging stations.

7.3.12 Below the chart, two tables (also seen in Figure 31) are given. On the left, a table displays the service level, cost and number of stations of all scenarios in the area. On the right, the table displays only the 'efficient' scenarios, i.e. those who yield the best improvement for a given budget.

Uncertainties and Sensitivities

7.3.13 There are several uncertainties and assumptions about the data inputs to the model which could affect the results. The key assumptions were investigated further to better judge their influence.

7.3.14 The first of these uncertainties was the percentage of electric vehicles which make use of private off-street charging at home. As described in section 6.4, this is currently estimated to apply to 93% of all EVs, and in the main model runs it has been assumed that this early adopter pattern will continue until at least 2030. However, since this value has a direct influence on the number of EVs requiring overnight on-street parking, as well as those seeking 'charge-as-destination' during the day, a change to this assumption may have a significant impact on results.

7.3.15 A sensitivity run was therefore carried out on the 2030 Central uptake data using a value of 80%, calculated to be in line with a CCC estimate of private home-charging reducing to 70% by 2040. The solution providing the target 58% service level recommended the installation of a net 290 more chargers (up 1% on the results given above), with the mix now altered to 17% standard, 47% fast, and 35% rapid (compared to 16% / 55% / 29% when the higher home charging percentage was used).

7.3.16 The second of these arises from the use in the GB-wide parking-based model of representative zones to approximate the 50 large zones covering mainland Great Britain. This approach means that the zone is considered to be a 'typical' mix of the types of parking destination included in the modelling. In particular, this approach cannot distinguish between purely residential areas (where slow overnight charging may be required) and city centres (where day-time parking is the main demand). Care is therefore needed when interpreting results based on these typical zones. The main scenario reported for the GB level analysis therefore does not include a specific 'overnight' charging element, and instead this demand is catered for using the 'charge as a destination' demand. This provides a better representation of the rapid charger requirements at a GB level that are the main focus of this study.

7.3.17 A more accurate representation of overnight charging would be available using the local level parking-based charging model, for example at a city level. At a local level, the input data on which drivers can access which chargers would be more disaggregate and could distinguish between different mixes of demand in different areas of the city.

7.3.18 As a sensitivity test relating to this overnight charging element of the GB level parking-based charging results, a scenario has been considered whereby all users who do not have access to a home charger were assumed to desire a charge overnight, a distinctly modelled component of demand. This caused an increase in the estimated current base year service level from the 58% found previously up to 61%. Finding the solution which will maintain this current service level in 2030 under the Central uptake scenario indicated that around 20% more chargers will be required compared to the results reported previously, while around 10% more chargers would be required to meet the previous 58% service level. The mix of chargers in these results sees an increase in the proportion of Standard and Rapid chargers, but a decrease in the relative numbers of Fast chargers.

7.3.19 A further uncertainty arises from the unknown reliability and availability of the chargers. A charger may, for example, be offline for maintenance, or may have its parking space blocked by a petrol/diesel vehicle. The true reliability of a parking-based chargers is not known, but since the model is calibrated to observed charging behaviour from ZapMap, some measure of reliability is taken into account. It is assumed that the reliability will remain constant over the future years covered in the model. No formal sensitivity test has been carried out on this; however, it can be predicted that if the charger reliability were to improve in the future, this would mean the recommended solutions would be able to achieve better service levels and shorter waiting times (or that fewer chargers would be required to meet the same targets).

7.4 Local-level Case Study Model Results

7.4.1 We can also show the results of a similar analysis on each of the two case study areas, taking first the Glasgow area model and then the Sheffield-Rotherham area version.

Glasgow Area Case Study

7.4.2 For the base year, it was estimated that 31% of demand was being served given no improvements to the current base year network.

7.4.3 An initial run of the 2030 scenario shows that restricting each zone to a maximum of 5 chargers (of each kind) is insufficient for the service level to be increased as far as the 31% target. Indeed, additional runs adding 10 or 15 of each type are also insufficient, with the restriction of adding 15 of each type resulting in a maximum service level of 15%.

7.4.4 A subsequent test run with the restriction increased to a maximum of 30 chargers of each kind was still unable to reach a suitable solution, indicating that this was a particularly difficult problem to solve. In this case, the highest service level was reached at around £15m spent, but that even with this only around 23% of the demand is served.

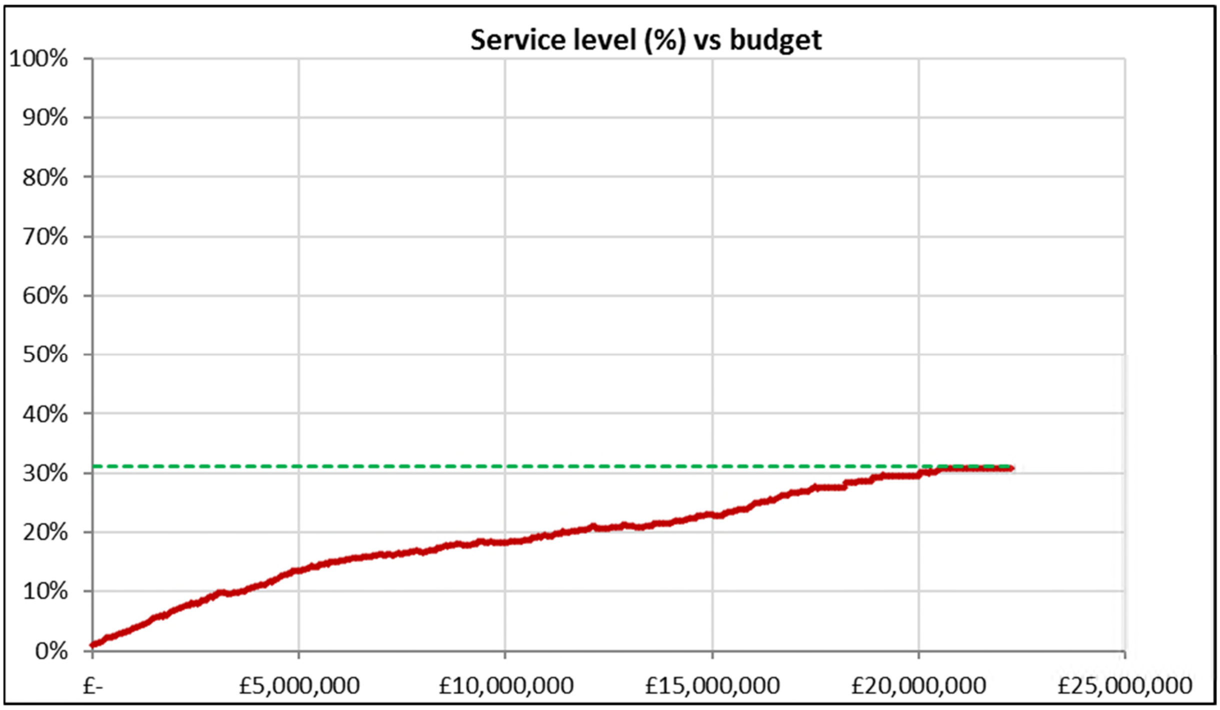
7.4.5 Further investigation showed that the inability to reach the 31% service level target was largely due to a very high demand in one particular zone (9: Glasgow South, which contains a number of large retail developments as well as residential areas). In this zone, at best only a 14% service rate be achieved. This brought down the average across zones substantially, with a service rate of almost 31% being achieved across the rest of the model area if this zone was ignored.

7.4.6 Additional steps were taken to generate more suitable scenarios for this individual zone. Firstly, a solution was built in stages, to meet the service level for 2020 and then 2025 using each solution as the ‘initial’ number for the following simulation. This allowed a more useful 2030 solution to be constructed, although did not in itself achieve the target service rate.

7.4.7 Further enhancement to the set of scenarios was made by selecting a good solution for each of the modelled zones and using this as the starting point for a new simulation. The practical effect of this is to cut out the generation of scenarios for which we know the solution would not be useful.

7.4.8 Figure 32 shows the summary chart after two iterations of building additional solutions in this manner. As can be seen, the 31% service level target is reached at a cost of £20.5m, entailing the installation of around 1,000 new charging devices.

Figure 32. Example Summary Chart for Glasgow Case Study Model



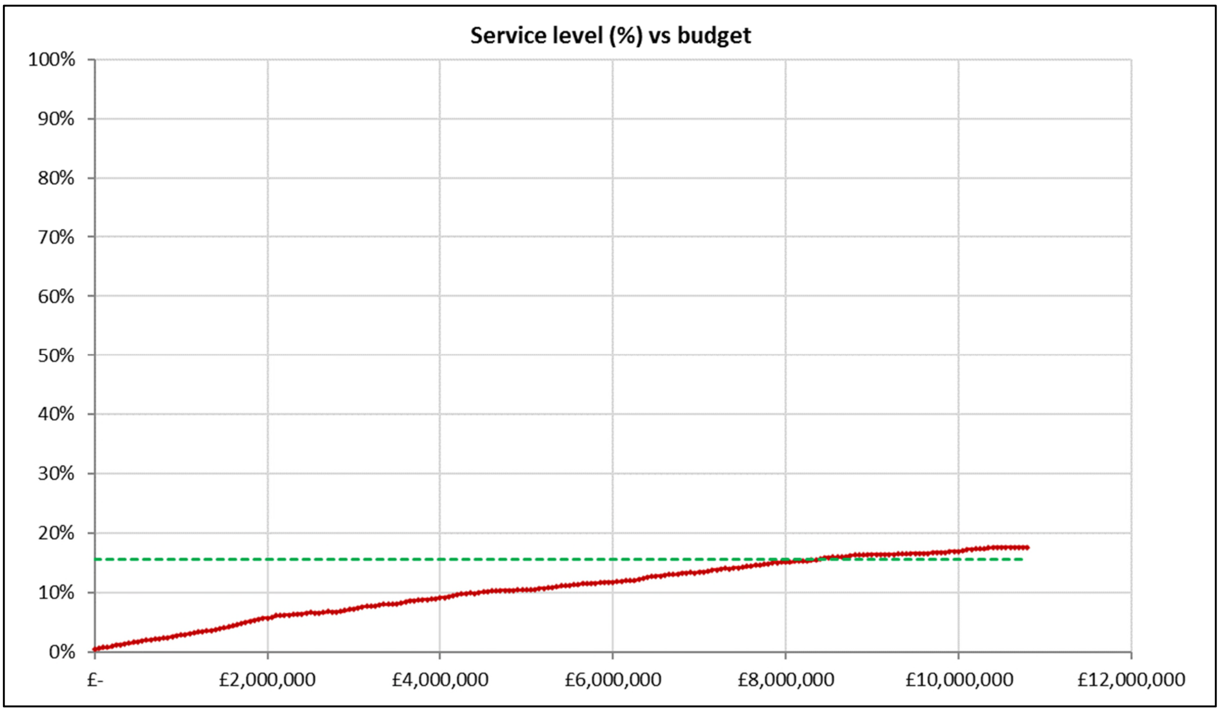
Sheffield-Rotherham Area Case Study

7.4.9 Due to the low number of charging devices available in the Sheffield-Rotherham area, it was found that the base year service level was just 16% of the arriving demand.

7.4.10 An initial run of the 2030 scenario showed that with no investment on improving the charging network the service level would be only 1% of that future year's demand, while restricting each zone to a maximum of 5 chargers of each kind would only allow this to be increased as far as 8%. A second run, increasing the maximum number of chargers added per zone to 8 of each type, was carried out, but this could only achieve a service level of 12%. A third run was therefore conducted, allowing a maximum of 12 chargers to be added in each zone.

7.4.11 Running the optimisation with this increased number showed that a 16% service level could be maintained for the 2030 demand with a spend of around £8.2m. Also, as can be seen in Figure 33, improvement can be made a little beyond this, for with service level reaching around 18% if £11m was invested in the network.

Figure 33. Summary Chart for Sheffield-Rotherham Case Study Model

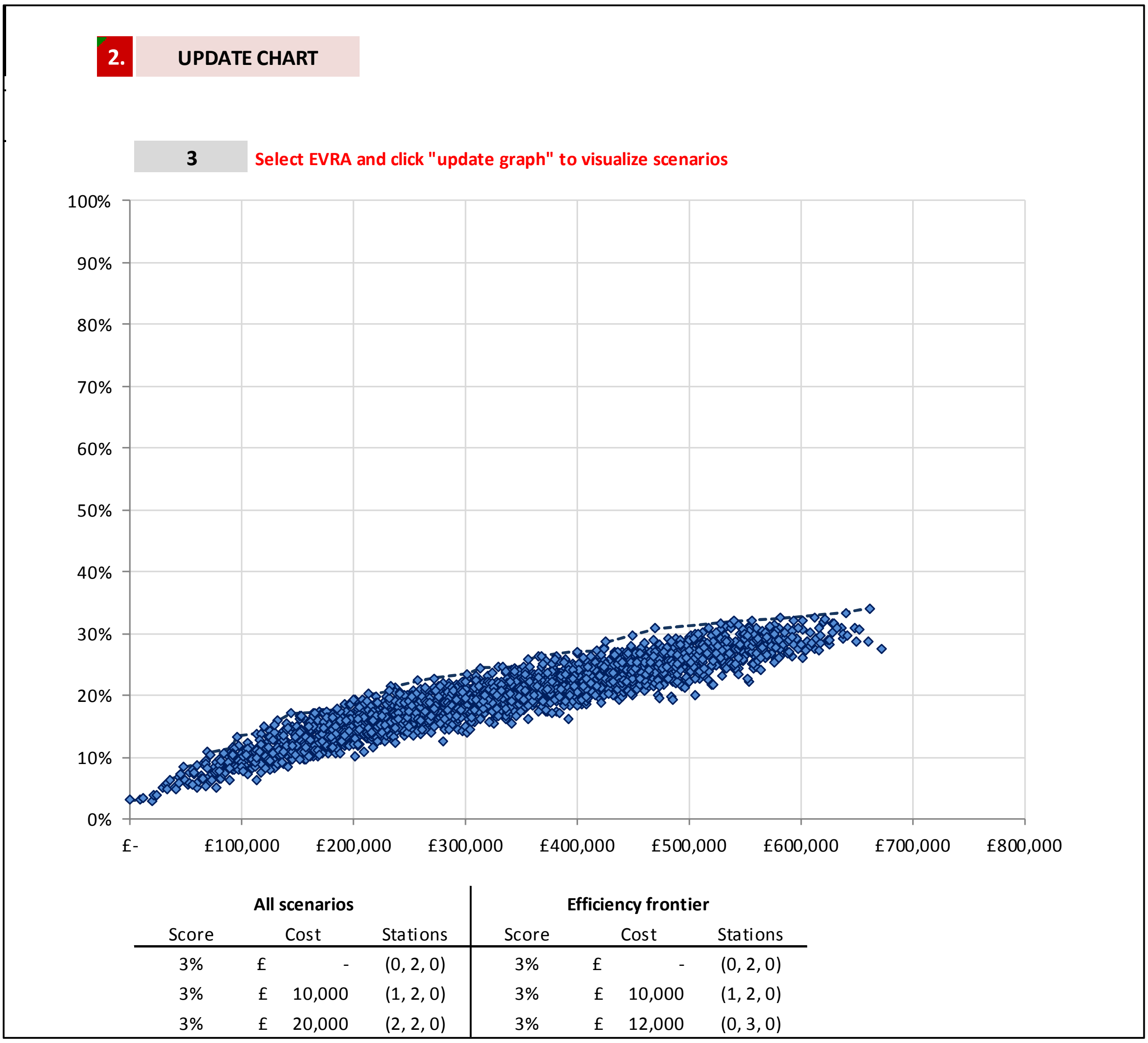


7.4.12 It was found that the target service level was in fact most efficiently reached at £8.45m, with a total of 146 standard, 171 fast and 145 rapid chargers required.

7.4.13 We can also highlight an example of the zone-level scatterplot which shows that higher service levels are achievable on this scale in some cases. Figure 34 shows the scatterplot of all tested combinations for the Rotherham Town Centre zone. From this, we see that the efficient frontier includes solutions with service levels of up to 34%, which can be achieved with a spend of £662,000.

7.4.14 Further solutions with higher service levels, in excess of the target chosen in this test case, would be achievable at both city and zone level if the model was run with a higher spend limit.

Figure 34. Example Zone-level Chart for Sheffield-Rotherham Model



Select EVRA and click "update graph" to visualize scenarios

All scenarios			Efficiency frontier		
Score	Cost	Stations	Score	Cost	Stations
3%	£ -	(0, 2, 0)	3%	£ -	(0, 2, 0)
3%	£ 10,000	(1, 2, 0)	3%	£ 10,000	(1, 2, 0)
3%	£ 20,000	(2, 2, 0)	3%	£ 12,000	(0, 3, 0)

8. SUMMARY AND CONCLUSIONS

8.1 This Report

8.1.1 This report has set out the findings of new analysis of the optimal EV public charging infrastructure needed to meet future growth of EVs in Great Britain to 2030. Future scenarios for EV uptake were considered in line with those developed by the Committee on Climate Change (CCC) in its 2015 advice to Government on the Fifth Carbon Budget.

8.1.2 We have explored the impact of a number of important factors on the optimal type of EV charging infrastructure likely to be required to 2030, such as: increased battery range, the number and pattern of trips taken using EVs, the availability of different types of rapid chargers and their associated charging speeds and times, as well as the behavioural consideration of 'range anxiety'.

8.1.3 SYSTRA together with Next Green Car and Cenex developed two models to analyse the supply and demand for two categories of public EV charging:

- **Long distance *en route* charging** on the strategic road network (i.e. motorways and major A roads) across mainland Great Britain.
- **Parking-based charging** at the destination of trips, often around local towns and regions.

8.1.4 This report has described the various applications of these models, including the flexibility they offer in terms of input assumptions and objectives used in the optimisation process. It was also described the results from a number of different scenarios to illustrate how the tools can be used to inform future EV investment strategies.

8.2 Key Results

8.2.1 The key results of the study are those of the CCC 'Central scenario' uptake, which envisages EVs accounting for 60% of new car and van sales (approximately 30% of the total fleet) by 2030.

8.2.2 The outputs from the two tools have been combined to give an overall estimate of Britain's current (2016 base year) and future public EV infrastructure requirements.

- To meet long distance *en route* rapid charging requirements, and maximise carbon emission reductions, the number of rapid chargers located near the major roads network needs to expand from 460 in 2016 to 1,170 by 2030.
- This is a relatively modest increase of 2.5 times 2016 provision compared with the increase in the number of electric vehicles in the UK car fleet which rises by a factor for 72. This can be explained by:
  - An increase in the range of future EVs, which means that many fewer trips will require a charge *en route*. Currently around 27% of trips need to charge *en route*; with increased battery range; this falls to less than 1% by 2030.
  - An increase in the proportion of EVs able to use faster chargers, which reduced overall charging times and increases charger utilisation rates i.e., there are more charging events per charger.

- The number of public chargers required to meet the 2016 base year level of demand for 'top-up' charging during parking-based charging around towns and local areas is estimated to rise from 2,700 currently to over 27,000 by 2030.

  - This is a much larger increase than for longer distance *en route* charging.
  - It reflects a continued demand for 'top-up' charging, despite the increase in battery size and range, and reduction in range anxiety.

- Overall nearly 29,000 charging points are needed across Great Britain by 2030 to meet future EV charging needs. Around 85% of these are fast (22kW) or rapid (43+kW) chargers. There are uncertainties around this estimate as the analysis relies on some key simplifying assumptions, as described in Section 8.3 below.
- The modelling also considered the geographical distribution of the optimal EV charging infrastructure:

  - The distribution of chargers used for 'topping-up' during parking-based charging loosely reflects population density as well as current car use and provision of public transport services. Lancashire, the midlands and to the counties to the west of London are expected to require a high number of new chargers.
  - The region which requires the highest number of additional motorway chargers is Lancashire, reflecting the importance of the M6 in journeys between the north and south of Britain.

8.3 Uncertainties and Sensitivities

8.3.1 As with all complex models, a number of assumptions have been made which could affect the results produced. As such, there are a number of uncertainties which must be considered when examining the results.

8.3.2 In relation to behavioural aspects, the model considers factors such as range anxiety, current charging behaviour, and the average time EV drivers are prepared to wait for charging. Assumptions related to these points were based on current evidence, and assumed to hold true in the future.

8.3.3 For other factors, a number of 'sensitivity test' model runs were undertaken, including: the proportion of EV owners with access to off-street charging; assumptions around charging behaviour for those without off-street home charging; and the reliability of chargers. The key results of these were:

- The proportion of EV owners who have access to off-street home charging. Evidence suggests that 93% of current EV owners have off-street charging and this is assumed to continue to 2030. If this reduces to 80% by 2030 (in line with a reduction to 70% overall proportion of home owners with off-street charging by 2040), this leads to a 1% increase in chargers needed, or 290 by 2030.
- The assumptions relating to charging for EV owners without off-street parking. It is currently assumed that EV owners without off-street parking will charge during their normal activities as characterised by the parking-based charging modelling. If instead all of these require overnight charging using public chargers, this leads to a 20% increase in demand for chargers by 2030, or around 6,000 chargers.

- Reliability and availability of chargers. Some public chargers are only available to specific customers (e.g. Tesla super-fast chargers). Our central assumption is that these are available to all EV owners. To test the sensitivity of this, all manufacture-specific chargers were taken out of the supply network and the results re-run. This resulted in fewer 150kW chargers and 20% fewer chargers overall, as well as an increase in efficiency in terms of charge delivered per charger, as supply and demand are matched more efficiently.
- There is uncertainty about how long people will be willing to wait for a charger. If drivers' tolerance of waiting time is less than what has been estimated in the model then additional chargers and a higher proportion of 350kW chargers may be required in order to keep waiting times down to acceptable levels.
- Charging on the long distance *en-route* network is assumed to be spread evenly across daytime hours. However this could be incorrect, with, for example, people planning their recharging stops to coincide with lunchtime, resulting in a lunchtime peak in charging demand. In this case, more chargers than indicated by these results may be required in order to serve a sufficient amount of this peak demand.

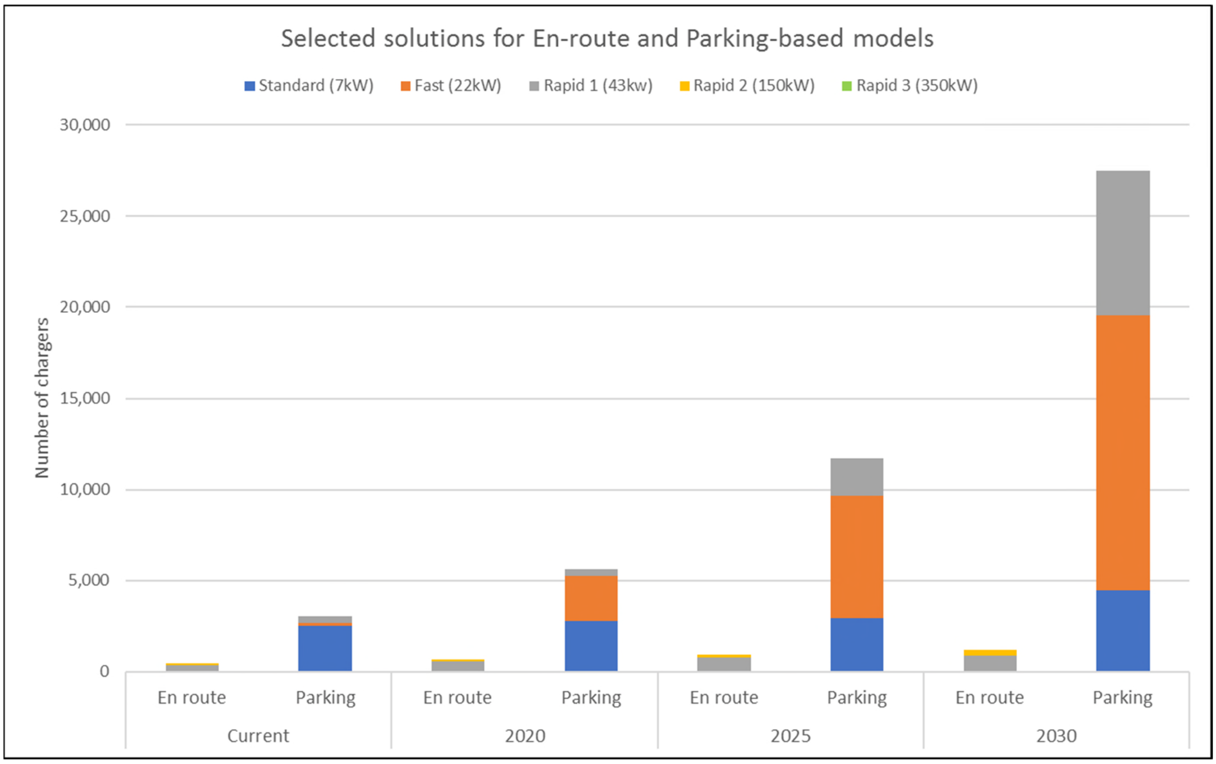
8.4 Conclusions

8.4.1 This report has detailed the results for *en route* charging along motorways and major roads, and 'top-up' parking-based charging separately. Selecting from these the carbon-focussed en-route model solution, and a solution which maintains the 2016 base year percentage level of service for parking-based charging, we determine that a total network of nearly 29,000 chargers will be needed across Great Britain in 2030. To achieve this from the 2016 base year charging network will require the installation of over 25,000 new chargers (Figure 35). This is estimated to cost around £530m (£500m parking-based and £30m long distance *en route*), excluding potential grid connection costs, and is likely to need a mix of public and private investment to be delivered.

8.4.2 Without continuing financial support or a change to current charging regimes, providers of charging infrastructure are unlikely to see significant financial benefit from providing chargers in isolation. The private sector is therefore likely to focus on providing chargers at locations where they are also providing other services to the EV users (shoppers, hotel guests, leisure facilities etc). This means that these chargers are unlikely to be provided in optimal locations from the perspective of cost-effectiveness and efficiency in meeting the total charging demand of all EV users, rather than specific customers' needs.

8.4.3 It will be important to monitor the future development of EV infrastructure to ensure it is consistent with delivering the EV uptake scenario. It may be necessary to offer additional financial support if this level of infrastructure is insufficient to give potential EV owners confidence that they will be able to charge as needed.

Figure 35. Total Chargers Required to Meet the CCC Central EV Uptake Scenario, Selected Solution Approaches



8.4.4 Figure 36 and Figure 37 show the regional breakdown of the number of chargers required in these solutions for the long distance *en route* and parking-based modelling respectively.

Figure 36. Total Number of Chargers Required by Zone for Long Distance *En Route* Charging by 2030 (Carbon-Focussed Optimisation; CCC Central Uptake Scenario)

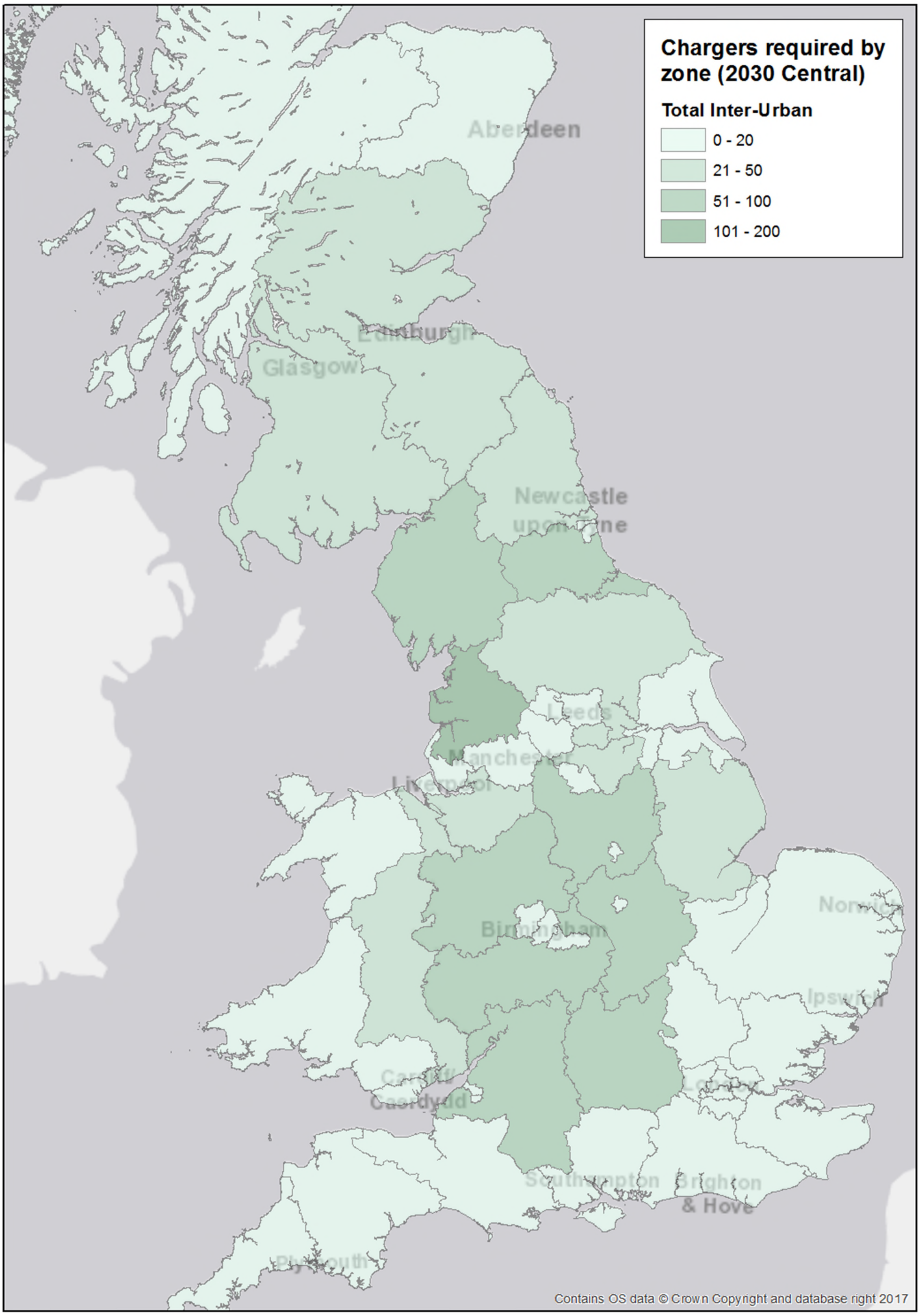
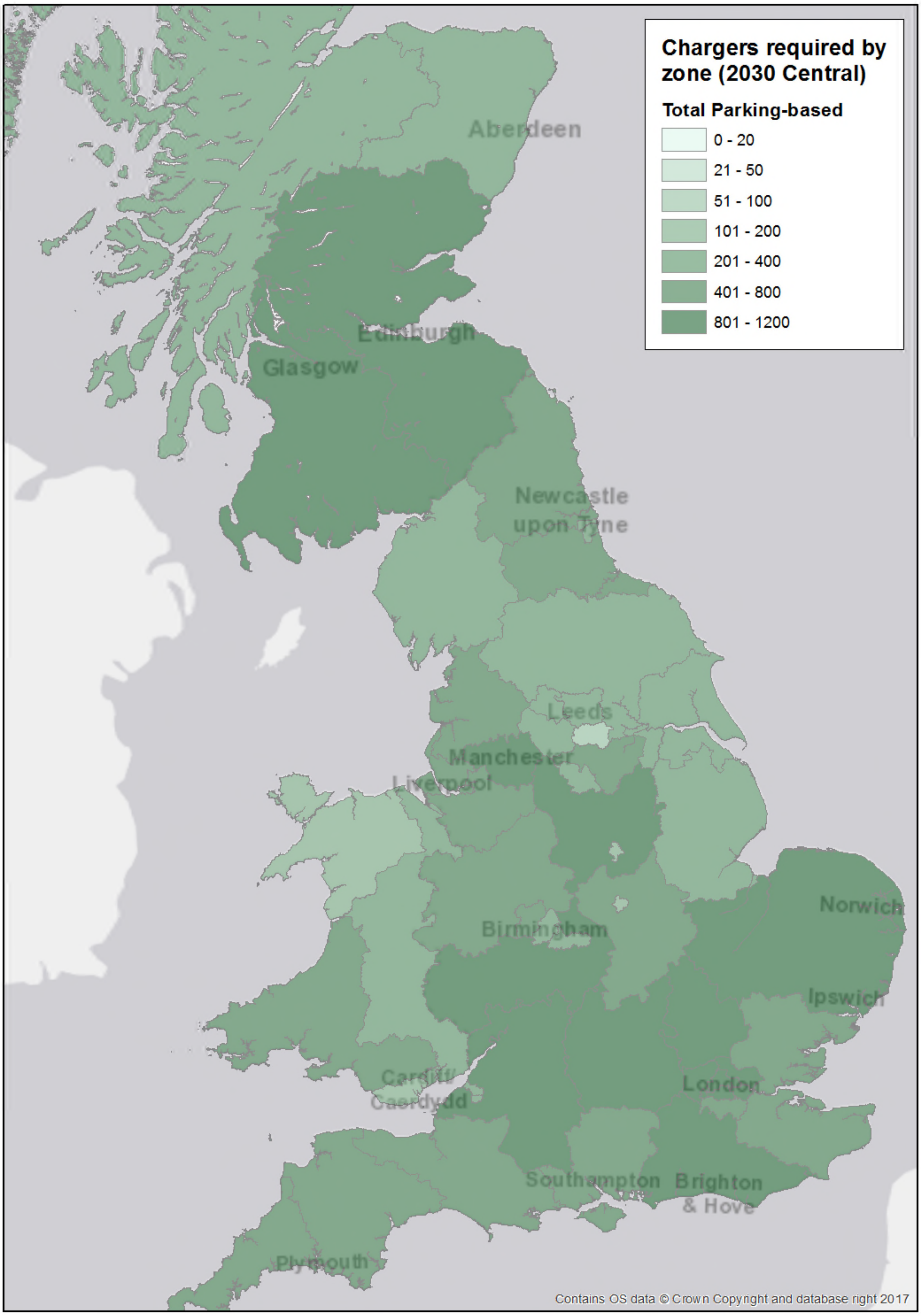


Figure 37. **Total Number of Chargers Required by Zone to Meet Demand for Parking-Based Charging in 2030 (CCC Central Uptake)**



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