PROJECT REPORT

Consumers, Vehicles and Energy Integration Project

Deliverable 8.1 - Final Project Summary Report

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Amy Woodward	Project Manager	Neale Kinnear	Technical Reviewer

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Authors

The following individuals have contributed to the development of this report:

Stephen Skippon (TRL), Neale Kinnear (TRL), George Beard (TRL), Hannah Al-Katib (TRL), James Greenleaf (Baringa), Natalie Bird (Baringa), and Tristan Dodson (Element Energy).

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Abbreviations

AER	All-Electric Range
BaU	Business as Usual (Narrative)
BEV	Battery Electric Vehicle
City	City Led (Narrative)
Comp	Composite (Narrative)
CP	Customer Proposition
CPAT	Commercial, Policy and Accounting Tool
CVC	Commercial Value Chain
CVEI	Consumers, Vehicles, and Energy Integration
DM	Demand Management
DNO	Distribution Network Operator
ECCo	Electric Car Consumer model
ESME	Energy System Modelling Environment
ETI	Energy Technologies Institute
FCV	Fuel Cell Vehicle
GDP	Gross Domestic Product
GHG	Greenhouse Gas
GOEM	Guided Original Equipment Manufacturer (Narrative)
GW	Gigawatt
H2P	Hydrogen Push (Narrative)
ICE	Internal Combustion Engine
ICEV	Internal Combustion Engine Vehicle
kW	Kilowatt
MaaS	Mobility as a Service
MC	Managed Charging
MCA	Multi-Criteria Analysis
MPF	Market and Policy Framework
OEM	Original Equipment Manufacturer
PHEV	Plug-in Hybrid Electric Vehicle
PiV	Plug-in Vehicle
PSC	Physical Supply Chain
PV	Present Value

RCT	Randomised Controlled Trial
REEV	Range-Extended Electric Vehicle
RtZ	Road-to-Zero
SMC	Supplier-Managed Charging
SOC	State-of-Charge
TNO	Transmission network operator
ToD	Transport on Demand (Narrative)
ToU	Time of Use
UK	United Kingdom
ULEV	Ultra-Low Emission Vehicle
UMC	User-Managed Charging
VED	Vehicle Excise Duty
VKT	Vehicle Kilometres Travelled
WACC	Weighted Average Cost of Capital

Glossary of key terms

Item	Description
All-Electric Range	The maximum range (i.e. distance that can be travelled) of a vehicle achievable using electric propulsion only.
Building Blocks	Individual components that influence ULEV deployment and use within each Dimension. A selected subset of BBs and their respective values or states (e.g. technology costs) constitute the tangible components of each Narrative.
Business as Usual (Narrative)	A Narrative that acts as a baseline against which the other Narratives can be compared. Present trends continue; ULEVs remain as a premium or niche product, and lower ULEV deployment and use is expected as a result.
Battery Electric Vehicle	A vehicle powered solely by a battery, such battery being charged only by a source of electricity external to and not part of the vehicle itself.
Car Sharing	An example of Mobility as a Service: A transportation service in which the use of vehicles is shared, rather than individuals owning or leasing their own vehicles privately. Typically a car sharing service is booked online or via a smartphone app, and has vehicles located at distributed sites in the area where its customers need them.
Centralised-Chooser Fleet	A Fleet User whose vehicles are selected by the Fleet Operator at a centralised, corporate level.
Choice Experiment	A stated preference experiment in which analysis of participants' discrete choices is performed, based on Random Utility Theory.
Commercial and Policy Accounting Tool	The tool, developed as a component of the Whole-System Analysis, to enable analysis of business models throughout the energy system, under specific policy and market frameworks.
Connected and Autonomous Vehicles	Vehicles equipped with communications technology and/or technology that enables part or all of the driving task to be carried out automatically by the vehicle itself.
Consumer	A private, domestic, individual driver who owns or leases his/her own vehicle.
City Led (Narrative)	A Narrative in which city regions drive the transport agenda, focussing on local environmental issues such as air and noise pollution and congestion. Consumers use multiple modes of transport as an integrated service including cars, but these are provided more through short-term rental and car clubs. Urban car rental fleets are charged at public / work locations. Outside of urban areas vehicles are still owned predominantly as assets by their users.

Item	Description
Composite (Narrative)	A Narrative developed to reflect a combination of some of the more desirable features for encouraging ULEV uptake and use. Its purpose was to combine some the 'best' aspects of Narratives identified in the Stage 1 analysis, with the aim of achieving a similar level of uptake to the ULEV Narrative but at a lower cost to government.
Customer Proposition	One of four dimensions of the ULEV market/energy system that is modelled in the Whole-System Analysis; what the customer sees at the point of interacting with a ULEV, e.g. is the customer buying or leasing the vehicle?
Commercial, Policy and Accounting Tool (CPAT)	A tool used in the Whole-System Analysis to represent the flows across the Commercial Value Chain, which acts as a two-way interface between the demands placed on the Physical Supply Chain by the uptake and use of ULEVs, and the prices seen by the end ULEV-consumers as part of the Customer Proposition.
Commercial Value Chain	One of four dimensions of the ULEV market/energy system that is modelled in the Whole-System Analysis. The commercial entities (and their business models) that sit across one or more parts of the PSC to collectively deliver the CP that the consumer sees, i.e. that are involved in the manufacture or sale of ULEVs, the building and operation of infrastructure and the supply of energy. Specifically the charging point operators, hydrogen refuelling station operators, localised hydrogen producers, hydrogen distributors (who may use tankers and/ or pipelines), Demand Management (DM) aggregators, electricity suppliers, and Distribution Network Operators (DNOs).
Demand Management	The modification of one or more energy consumers' demand for energy through various methods including financial incentives, time of use tariffs and education. The purpose is to encourage the consumer(s) to use less energy, in particular (but not exclusively) during peak hours, or to move the time of energy use to off-peak times, to reduce the need for investments in networks and/or power plants for meeting peak demands. For the purposes of the CVEI Project, Demand Management includes Managed Charging and other mechanisms which enable Vehicle Users and Fleet Operators to maximise their own benefits (for example by financial incentives for off-peak charging) and which may, as a result, reduce peak aggregate demand, enable optimal use of assets, etc.

Item	Description
Demand Management Aggregator (DM Aggregator)	An organisation providing Demand Management services to network operators and/or energy suppliers, by aggregating the charging requirements (and potentially V2G capabilities) of a number of plug-in vehicles; a Demand Management Aggregator may either be a separate service provider or be integrated within an energy supplier, distribution network operator or other organisation.
Demand Response	Changes in electricity usage by end-users from their normal patterns in response to changes in the price of electricity or to incentive payments, that are designed to induce lower electricity use to better match supply and demand.
Distribution Network Operator	A company licenced to distribute electricity in Great Britain by the Office of Gas and Electricity Markets.
Dynamic Time of Use	An energy tariff in which the price is not fixed in bands but varies dynamically.
Electric Car Consumer model	The tool used in the Whole-System Analysis to represent consumer and fleet choices of vehicles.
Energy System Modelling Environment (ESME)	The ETI's whole energy system model, which gives a consistent picture of how the UK can meet its greenhouse gas targets in a feasible manner, for both transport and the wider energy system.
Fleet	A fleet of vehicles (being a number of vehicles greater than one), owned and operated by a Fleet Operator.
Fleet Operator	A commercial, public sector or other organisation (whether large or small) which owns and operates a Fleet in the pursuit of its business or service.
Fleet User	An individual driver of a fleet vehicle.
Fuel Cell Vehicle (FCV)	A vehicle that uses an on-board fuel cell that generates electricity to power an electric motor. A Hydrogen FCV uses oxygen from the air and Hydrogen stored on-board.
Greenhouse Gas	A gas that contributes to the greenhouse effect by absorbing infra-red radiation. Carbon Dioxide is the major greenhouse gas.
Gross Value Added	The measure of the value of goods and services produced in an area, industry, or sector of an economy.
GigaWatts	Unit of power, equal to one billion (10^9) Watts.

Item	Description
Guided Original Equipment Manufacturer (Narrative)	A Narrative in which vehicle OEMs make ULEVs attractive to consumers by increasing desirability and enhancing functionality through integrated digital services which facilitate use of the vehicle (e.g. real-time access to maps of public charging stations and electricity prices at these stations). Proprietary motorway charging networks complement the dominant mode of home charging. Limited ongoing government support for consumers is used to supplement action by the OEMs.
Hydrogen Push (Narrative)	A Narrative in which central government makes a decision to deliver the *Road to Zero* strategy through mass transition to hydrogen, supporting both infrastructure deployment, and consumers purchasing hydrogen vehicles.
Innovator	Vehicle Users whose times to adoption of a new Ultra-Low Emission Vehicle type (e.g. Battery Electric Vehicle) lie earlier than two standard deviations before the population mean time to adoption; the first segment to adopt in Rogers' (2003) diffusion model.
Internal Combustion Engine	An engine that generates motive power by burning gasoline or diesel fuel inside the engine, the hot gases produced being used to drive pistons as they expand.
Internal Combustion Engine Vehicle	A vehicle propelled by an internal combustion engine.
kiloWatts	Unit of power, equal to one thousand (10^3) Watts.
Light Duty Vehicle	Any type of light vehicle including cars, vans, minibuses, ambulances and, for the avoidance of doubt, Light Commercial Vehicles.
Mainstream Consumers	Vehicle Users whose times to adoption of a new Ultra Low Emission Vehicle type (e.g. Battery Electric Vehicle) lie later than or equal to two standard deviations before the population mean time to adoption, i.e. all those other than the "Innovator" segment in Rogers' (2003) diffusion model.
Managed Charging	The management of vehicle charging in such a way as to control the timing and/or extent of energy transfer to provide Demand Management benefits to the energy system and the Vehicle User or Fleet Operator.

Item	Description
Market and Policy Framework	One of four dimensions of the ULEV market/energy system that is modelled in the Whole-System Analysis; government and regulatory intervention in the form of setting the overarching market framework for commercial entities (e.g. regulatory incentives for network infrastructure) or more direct policy intervention (e.g. in terms of taxes or subsidies at the point of the consumer).
Mobility as a Service	Transportation service in which the use of vehicles is shared, rather than individuals owning or leasing their own vehicles privately.
Multi-Criteria Analysis	A decision making approach used to evaluate problems where there are multiple alternatives, expectations, and wants, and different, often conflicting, goals.
Narrative	A set of plausible alternative futures constructed in the Whole-System Analysis to explore the consequences of a range of policies, strategies, and trends.
Original Equipment Manufacturer	Term used in the automotive industry to denote a vehicle manufacturer.
Parc	The set of all registered vehicles within a defined geographical region. The CVEI project was concerned with the UK light duty vehicle parc, i.e. all cars and vans registered in the UK.
Plug-in Hybrid Electric Vehicle	A vehicle that is equipped so that it may be powered both by an external electricity source and by liquid fuel (and which for the avoidance of doubt is similar to a REEV except that a REEV generally uses the engine solely to charge the battery and/or provide power directly to the electric motor, whereas a PHEV generally uses the engine for direct propulsion). PHEVs and REEVs are treated together in CVEI.
Plug-in Vehicle	Any vehicle which is powered, wholly or in part, by a source of electricity that is external to and not part of the vehicle itself, including PHEVs, REEVs and BEVs.
Physical Supply Chain	One of four dimensions of the ULEV market/energy system that is modelled in the Whole-System Analysis; the technologies and infrastructure required to deliver the vehicles and their energy requirements, e.g. plug-in vehicles and charging points.
Present Value	The value in the present of a future sum of money or stream of cash flows, given a specified rate of return. Future cashflows are discounted at a discount rate; the higher the discount rate, the lower the present value of future cashflows.

Item	Description
Randomised Controlled Trial	An experimental design that aims at minimising bias when testing for effects. Participants are randomly allocated either to one or more experimental groups or to a control group and inter-group differences are compared. The design enables causal inferences to be made about the observed effects.
Range-Extended Electric Vehicle	A vehicle that is equipped so that it may be powered both by an external electricity source and by liquid fuel (and which for the avoidance of doubt is similar to a PHEV, except that a REEV generally uses the engine solely to charge the battery whereas a PHEV generally uses the engine for direct propulsion). In CVEI, REEVs and PHEVs are treated together.
Road to Zero	UK government strategy outlining how the government will support the transition to zero emission road transport and reduce emissions from conventional vehicles during the transition.
Social Discount Rate	The discount rate used in computing the value of funds spent on social projects.
Supplier Managed Charging	A Managed Charging scheme in which a Vehicle User delegates control of charging, once plugged in, to a charging supplier who ensures that the Vehicle User's charging event goals are met at an advantageous average cost of charging by providing benefits to the energy system.
State of Charge	The percentage of a battery's maximum capacity that it currently holds.
Static Time of Use	A Time of Use tariff for electricity that has several price bands, for instance a lower price band overnight and a higher price band in the early evening. In a static ToU tariff the price and timing of the bands are fixed.
Success Metrics	Metrics used to determine what 'good' looks like for each Dimension as part of the assessment of a Narrative. These are divided into quantitative metrics, which are quantifiable via the Analytical Tools, and qualitative metrics.
Transport on Demand (Narrative)	A Narrative in which central government identifies widespread social benefits in delivery of *Road to Zero* through a smaller, more intensively used vehicle parc. Intervention provides a common standards and widespread infrastructure enabling vehicle fleets to offer an on-demand transport service to consumers.
Time of Use (ToU)	A form of tariff for electricity in which the price of electricity varies with time, being higher when demand is high and lower when demand is low.
Transmission Systems Operator	An entity entrusted with transporting energy in the form of natural gas or electrical power on a national or regional level.

Item	Description
Ultra-Low Emission Vehicle	A car or van that emits 75 g/km of CO_2 or less, measured using the NEDC test cycle, as well as very low levels of other air pollutants and low noise levels. For the avoidance of doubt, it is noted that other definitions exist that suggest 50g CO_2/km is a more appropriate threshold, but the 75 g/km threshold applies for the purposes of the CVEI Project.
ULEV Enabled (Narrative)	A Narrative in which, to support delivery of its *Road to Zero* strategy[1], government provides a supportive regulatory environment for charging and hydrogen infrastructure, reducing consumer anxiety in choosing a ULEV, and enabling a free choice between hydrogen and electrical energy sources.
User-Chooser Fleet	A Fleet where individual vehicle users select their own individual vehicles (within constraints set by the Fleet Operator, rather than having a vehicle selected by the Fleet Operator at a centralised, corporate level).
User Managed Charging	A Managed Charging scheme under which a Vehicle User directly controls the time of charging, once plugged in, to take advantage of periods of lower cost electricity, typically under a tariff band structure, thus providing benefits to the energy system.
Vehicle to Grid	The use of vehicle batteries as a controllable demand or storage asset to support the electricity grid (in return for payment).
Vehicle Kilometres Travelled	The total distance travelled (in kilometres) by all vehicles within a specified area or on a given highway over a specified time interval.
Vehicle User	An individual driver of a vehicle, being either a Consumer or a Fleet User; for the avoidance of doubt, the term Vehicle User excludes Fleet Operators since Fleet Operators are not individual drivers.
Weighted Average Cost of Capital	The rate that a company is expected to pay on average to all its security holders to finance its assets.
Whole-System Analysis	The conceptual approach and associated set of models and other tools, used to facilitate the detailed analysis throughout the CVEI Project.

[1] *The Road to Zero* was published by HM government in July 2018, and outlines an ambition to achieve near-complete decarbonisation of the British light vehicle parc by 2050, along with a range of policy measures to facilitate that process.

D8.1. CVEI Final Report – Summary of Project

Background

The Consumers, Vehicles and Energy Integration (CVEI) project investigated the challenges and opportunities involved in transitioning to a secure and sustainable low-carbon light duty vehicle fleet. The project explored how integration of cars and vans with the energy supply system can benefit vehicle users, vehicle manufacturers and those involved in the supply of energy. The objective was to inform UK government and European policy, and to help shape energy and automotive industry products, propositions and investment strategies. In addition to developing new knowledge and understanding, the project developed an integrated set of analytical tools that can be used to model future market scenarios in order to test the impact of future policy, industry and societal choices.

Analytical approach

A Whole-System Analysis was undertaken to provide a representation of four 'Dimensions' that categorise all of the key issues that could impact the deployment of Ultra Low-Emission Vehicles (ULEVs), their use, and their interaction with the energy system. These were: **(A) Customer Proposition (CP)** – what a ULEV or a charging scheme offers the user; **(B) Physical Supply Chain (PSC)** – infrastructure that delivers ULEVs and their energy requirements; **(C) Commercial Value Chain (CVC)** – commercial entities that deliver the CP; and **(D) Market and Policy Framework (MPF)** – government and regulatory intervention.

The Whole-System Analysis was used to explore a range of possible light duty transport and energy supply futures, assuming the UK meets an 80% reduction in greenhouse gas emissions by 2050. These were mapped by defining two axes that frame important themes that could shape the evolution of the light duty transport sector: Organic Change vs. Co-ordinated Action, and Mobility as an Asset vs. Mobility as a Service. Seven **Narratives** (self-consistent descriptions of plausible light duty road transport futures) were defined, each incorporating different assumptions and parameter values for the Whole-System Analysis.

Although comprehensive, it was recognised that there were gaps in knowledge that created uncertainties in the analysis, particularly around the choices and behaviours of Mainstream Consumers in relation to Plug-in Vehicles (PiVs). Accordingly the CVEI project set out to generate new evidence to fill these gaps, through real-world trials of PiVs with Mainstream Consumers.

The Consumer Uptake Trial

The Consumer Uptake Trial was designed to provide up-to-date insight into the likely uptake of PiVs by Mainstream Consumers in the near future and over the coming decades. Two hundred Mainstream Consumers were given experience with a Battery Electric Vehicle (BEV), a Plug-in Hybrid Electric Vehicle (PHEV), and a conventional petrol-engine vehicle, all variants of the same vehicle model.

After this experience, around 50% of participants indicated they were fairly or very likely to choose a PHEV as a main or second household car, or a BEV as a second car in the next five years. Fewer (around 25%) indicated the same for a BEV as a main car. **These findings are very positive at this stage in market development and reflect the substantial development of PiVs over the five years preceding the CVEI project.**

Participants' willingness to consider a PiV increased with its electric range. Half would consider a BEV as a main car if its range was 320km (200 miles), and 90% if its range was 480km (300 miles). For PHEVs (which can also run on a conventional engine) the figures for electric range were 80km (50 miles) for 50%, and 160km (100 miles) for 90%. **These findings indicate the further development needed for PiVs to become mass-market products.**

The Consumer Charging Trials

In the Consumer Charging Trials 127 participants were provided with a BEV, and 121 participants were provided with a PHEV, for eight weeks. Participants were randomly allocated to one of three charging groups: (1) User-Managed Charging (UMC) in which participants were incentivised to charge at times of day when the electricity supply-demand balance is favourable, through a structured tariff; (2) Supplier-Managed Charging (SMC) in which participants specified the charge they required and the time they required it by, and allowed the supplier to control the timing of charging to maximise cost savings; or (3) a Control group who did not experience a Managed Charging (MC) scheme and were not incentivised to charge in a particular way.

Control group participants tended to start charging their vehicles in the late afternoon/early evening, the time when other electricity demands also peak. If there is mass uptake of PiVs, charging behaviour like this could make supply-demand balancing more difficult and demand may exceed the capacity of local distribution networks. **However, both UMC and SMC were effective at shifting the start of charging to late evening or overnight, and were preferred by a majority of participants over charging without such schemes.**

Key Findings and Conclusions from Whole-System Analysis

The analysis was used to identify potential elements of a solution to drive ULEV uptake and use that is robust in a range of transport futures, taking into account impacts across customers, commercial entities, infrastructure, and public finances. The elements were categorised into those likely to be essential (i.e. no or low regret), desirable (i.e. positive impact under most circumstances) and provisional (i.e. a positive case may exist but extent or timing depends on the reduction of uncertainty in the basis of the analysis). These elements were combined into a roadmap (see main body of the report). The essential elements include:

- Upfront cost mitigation for ULEVs: Crucial to driving enhanced uptake, however, the proportion of low carbon vehicle km can be significantly increased by 2050 versus today through use of modest subsidies for a limited period only.
- EU emissions regulations: Current 2020 EU targets for average CO_2 emissions for new car and van sales must be kept in place to encourage innovation and learning in the near-term that consequently reduces the cost of ULEVs.
- Appraisal of the role of hydrogen: Major decisions on government support for fuel cell vehicles (FCVs) and the associated infrastructure can be postponed until the mid-to-late 2020s to allow time for uncertainty over long-run costs to reduce.
- New tax on conventional and low emission vehicles: Likely to be required as simply extending the taxes that apply today, e.g. Vehicle Excise Duty (VED) and fuel duty, will likely lead to a gap in public finances between the net revenues from light duty transport sector and an assumed target.
- Support for on-street charging: To unlock ULEV uptake for those without access to off-street parking and to support the high levels set out in the Road to Zero.
- Support for rapid charging: To give certainty of access to charging outside of the home, a widespread network of rapid charging points is essential in the near to medium-term.

Executive Summary

The Consumers, Vehicles and Energy Integration (CVEI) project

The Consumers, Vehicles and Energy Integration (CVEI) project was designed, commissioned, and funded by the Energy Technologies Institute to investigate challenges and opportunities involved in transitioning to a secure and sustainable low-carbon UK parc of light duty vehicles (i.e. cars and vans). The project explored how integration of vehicles with the energy supply system can benefit vehicle users, vehicle manufacturers and those involved in the supply of energy. Widespread electric vehicle charging could mean that the peak demand on the grid will increase substantially, with a need for auxiliary storage solutions to enable excess electricity to be made available at peak times, or reserve generating capacity that can be brought on stream quickly, and potentially a need for reinforcement of local distribution networks. Its objective was to inform UK government and European policy, and to help shape energy and automotive industry products, propositions and investment strategies.

The CVEI Consortium, led by TRL, included a range of industry experts from the transport, energy and policy sectors.

The project developed a unique Whole-System Analysis of consumer propositions, the physical supply chains and commercial value chains for vehicles and energy, and the relevant market and policy frameworks. It carried out the most scientifically rigorous research to date into the potential uptake of Plug-in Vehicles (PiVs) by UK Mainstream Consumers who were given direct experience of using both BEVs and PHEVs. It also carried out the first large scale field study of PiV charging behaviour by UK Mainstream Consumers, rather than PiV Innovators, that included a rigorous randomised control trial of the effectiveness of Managed Charging as a means of shifting the timing of PiV charging to periods when other demands on the electricity supply are lower.

This report summarises the CVEI Project, focussing on its key findings. More detailed descriptions of experimental methods, results, and the Whole-System Analysis are available in the other project reports listed in the Bibliography.

Consumer Uptake Trial

The Consumer Uptake Trial was designed to provide up-to-date insight into the likely adoption of PiVs by Mainstream Consumers in the near future and over the coming decades, as features such as All-Electric Range (AER) and recharging time are improved.

It had a number of key methodological features that distinguished it from prior research:

1. This was the first trial in which the attitudes of **Mainstream Consumers**[2] (rather than PiV Innovators) towards **both BEVs and PHEVs** were measured after they had **experienced the use of each.**
2. Each participant was given four days of **real-world experience** with a BEV, PHEV, and an equivalent petrol vehicle (ICEV) (all VW Golfs), to reduce their psychological distance from PiVs and enable them to give responses based on their experiences of these vehicle categories. Their own cars were removed during these trial experiences.
3. Self-reported attitudes and likelihood to choose responses were collected **before and after** their experience of using the vehicles.
4. Participants completed a **choice experiment** following their experience of using the vehicles, to characterise the importance of various PiV attributes.

Figure 1 shows participants' self-reported likelihood to choose a PHEV or BEV as a main or second car in their household in the next five years[3].

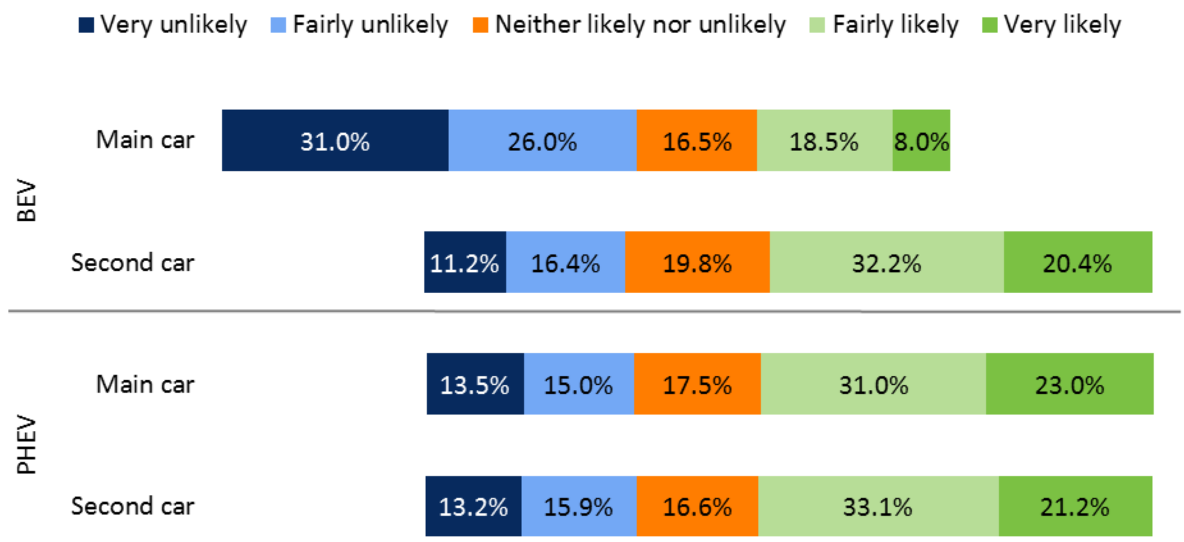


Figure 1: Likelihood to choose a BEV or PHEV as main and second car in the next five years, after experience with these categories of vehicles (no range specified in question)

Around 50% of participants indicated that they were fairly or very likely to choose a PHEV as a main or second household car, or a BEV as a second car. Many fewer (26.5%) indicated the same for a BEV as a main car. Thus, at present, PHEVs tend to be preferred over BEVs. Overall, the appeal of PiVs in this study appeared to be greater than in previous studies. Reduction of psychological distance in the trial is likely to have contributed to this.

[2] The sample was self-selected from Mainstream Consumers able to have a chargepoint fitted at home, so did not include people who could not do this, e.g. those living in apartments or other premises without access to off-street parking, or those unwilling to participate in research.

[3] In the interests of space this summary report does not discuss statistical analysis or inferential testing of the data; this information can be found in the detailed reports on the Consumer Trials listed in the Bibliography.

Participants were more familiar with BEVs and PHEVs (after the trial) than most Mainstream Consumers today; though it is reasonable to assume that familiarity with these vehicle types will increase as the market develops. Other contributing factors might include greater public awareness of PiVs, and improvements in the vehicles currently available.

The percentage of participants willing to consider owning a PHEV or a BEV increased with increasing perceived electric range (see Figure 2).

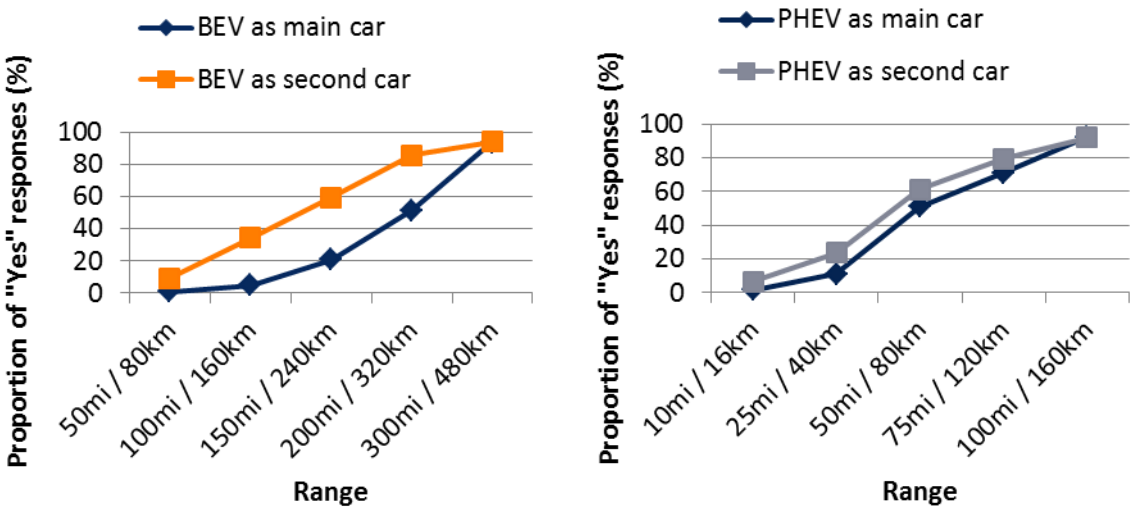


Figure 2: Proportion of participants who would choose a BEV (left) or PHEV (right) at each level of perceived electric range (responses after experience)

For PHEVs, an electric range of 80km (50 miles) is needed for around 50% of participants to consider owning one as a main household car, and around 60% as a second car. Increasing the electric range to 160km (100 miles) increases the share of participants willing to consider a PHEV to about 90% (for both main and second cars).

About 60% of participants would consider owning a BEV as a second household car if its electric range was 240km (150 miles). Electric range would need to be substantially higher, 320km (200 miles), before 50% of participants would consider owning a BEV as a main car. Increasing the electric range to 480km (300 miles) would result in more than 90% of participants considering a BEV, as either a main or a second car.

Participants' responses to these survey questions will have depended on their own perceptions of what "electric range" means; this will have been influenced by their direct experience of using the vehicles, including their experience of the rate at which the charge depleted, during the trial. Electric range here is therefore not necessarily the same as manufacturers' claimed range. Since participants had direct experience of BEVs and PHEVs to draw on, they are likely to have understood that real-world electric ranges are shorter than manufacturers' claimed ranges.

Consumer Charging Trials

The Consumer Charging Trials were designed to:

- provide data on the charging behaviours of Mainstream Consumers using PHEVs or BEVs;
- provide data on how those charging behaviours were altered by participation in Managed Charging schemes;
- identify how readily Mainstream Consumers would engage with Managed Charging schemes, and;
- identify what factors would influence that engagement.

Two alternative Managed Charging (MC) concepts were tested: **User-Managed Charging[4] (UMC)** and **Supplier-Managed Charging[5] (SMC)**. These differed in terms of who managed the timing of charging.

These Charging Trials had two key methodological features that distinguished them from prior research on charging behaviour:

1. **248 Mainstream Consumers** were recruited, rather than the PiV Innovators who have participated in UK PiV charging trials to date.
2. **Each trial (BEV and PHEV) had a Randomised Controlled Trial design** in which participants were randomly allocated to one of three charging groups: UMC, SMC, and Control (no Managed Charging).

Other key design features of the trials were:

- Participants were provided with either a PHEV or a BEV for **eight weeks**.
- Participants were provided with a **smartphone app** to enable them to interface with their MC scheme, or in the case of the Control group, to monitor their vehicle's state of charge (SOC) and charging status.
- Participants were provided with a **dedicated 3.6kW 3G network enabled chargepoint** at their home. Data on home charging events were collected via the chargepoint and vehicle telematics. Participants also had access to the Polar Plus network of public chargers. Data on charging events away from home were collected via vehicle telematics.
- The key dependent variables were a series of measures of **home-charging behaviour** such as the frequency of home charging, the distributions of plug-in time, and charge-start time. Telematics data on **journey patterns**, **away-from home charging events,** and **self-reported attitudes (before and after the trial experience) and willingness to choose** MC schemes were also collected.

[4] In UMC the user directly controls the time of charging under a tariff structure with different price bands at different times of day.

[5] In SMC the user delegates control of charging to a charging supplier who ensures that the user receives a specified State-of-Charge (SOC) by a specified time, seeking to charge at times of lowest cost within a time window defined by the user.

- Participants completed a **choice experiment** following their experience of using and charging the vehicles, to characterise preferences for MC schemes and the relative importance of MC scheme attributes.

Participants in the control groups (who were not incentivised to charge at particular times) usually started charging at home in the late afternoon/early evening (15:00 to 20:00), with 18:00 being the most common starting time for BEV users and 17:00 the most common for PHEV users, as shown in Figure 3. These timings were in line with the typical end of the working day. Median control group charging durations were approximately 3.7 hours for BEV users and 1.8 hours for PHEV users. Thus without MC, peak demand from BEVs extended to around 21:00, and from PHEVs to around 19:00, on average.

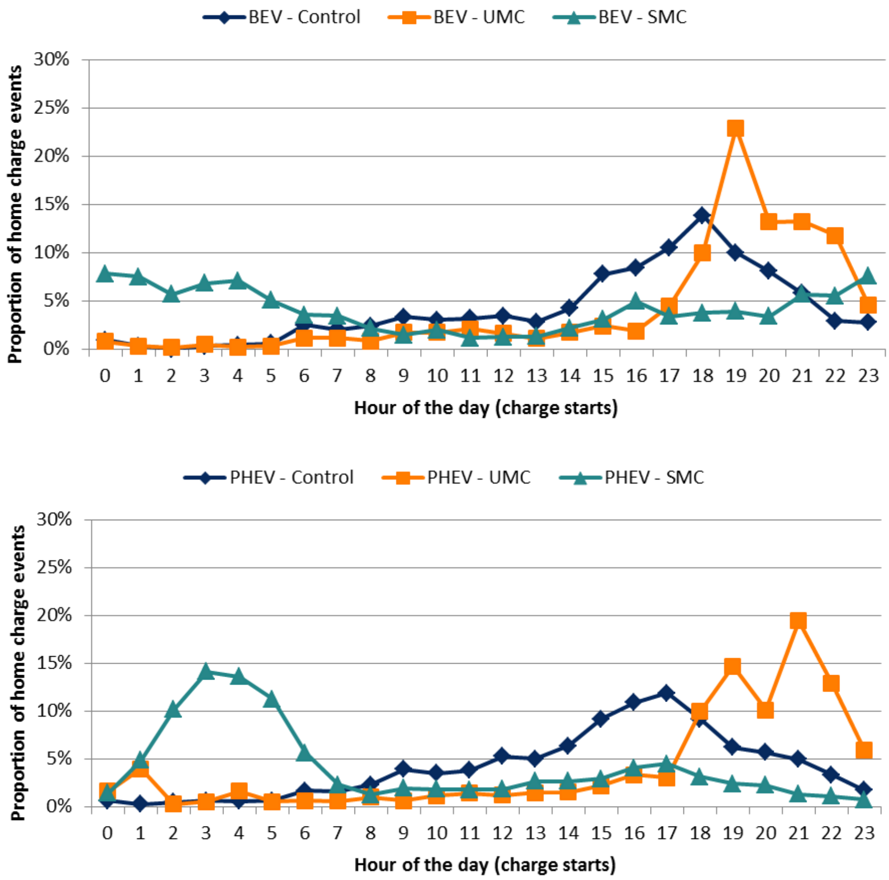


Figure 3: Percentage of home charge events starting in each hour of the day for Control, UMC and SMC participants (Top – BEV, Bottom – PHEV)

Both UMC and SMC were effective at shifting the time at which PiV charging started to later in the evening (UMC) or overnight (SMC) when other electricity demands are less. This effect was observed for both BEV and PHEV participants.

The majority of participants in both the UMC and SMC groups were either satisfied or very satisfied with the MC scheme they had experienced in the trial. Participants from all groups, including both the Control groups (who had not experienced MC during the trial) expressed a preference for MC over non-managed charging. This suggests that the basic concept of MC has appeal to PiV users even when they have not experienced it for themselves. Control group participants were substantially more likely to choose UMC over SMC, resulting in UMC being preferred to SMC by a majority of the participants taken as a whole. However, BEV users who had direct experience of SMC were more likely to prefer an SMC scheme. This suggests that experience with SMC is important for adoption of that type of MC scheme.

Whole-System Analysis

The CVEI project conducted the first comprehensive Whole-System Analysis of the potential development of the UK light duty vehicle market and energy system. The Whole-System Analysis explored how these would develop in a number of plausible alternative futures, and was used to make recommendations for action.

The Whole-System Analysis had two main elements:

1. A series of "Narratives" that represented plausible alternative transport futures[6]. These Narratives differed in terms of their positioning in terms of the two key factors that emerged from early analysis and expert workshops as important discriminators of possible future pathways for the future of light duty road transport:
    - how far future mobility is based on individual assets (e.g. owned or leased cars and vans) vs. asset sharing (e.g. Mobility as a Service), and;
    - how far decarbonisation was driven by organic change (commercial product development and consumer choice) vs. coordinated action (policy-driven incentives and market frameworks)
2. A set of inter-linked modelling tools that represented the major dimensions of the ULEV market and energy systems[7]:
    - **Customer Proposition (CP)** – what a ULEV or a charging scheme offers the user
    - **Physical Supply Chain (PSC)** – the tangible assets and skills that deliver ULEVs and their energy requirements
    - **Commercial Value Chain (CVC)** – the commercial entities that deliver the CP
    - **Market and Policy Framework (MPF)** – government and regulatory interventions

The modelling tools were used to provide a holistic Multi-Criteria Analysis (MCA) of how the ULEV market and the energy system would develop under each Narrative, in order to understand the aspects that may facilitate better successful mass-market deployment and use of ULEVs. A set of conclusions and recommendations was developed from this assessment that is robust in a range of possible transport futures.

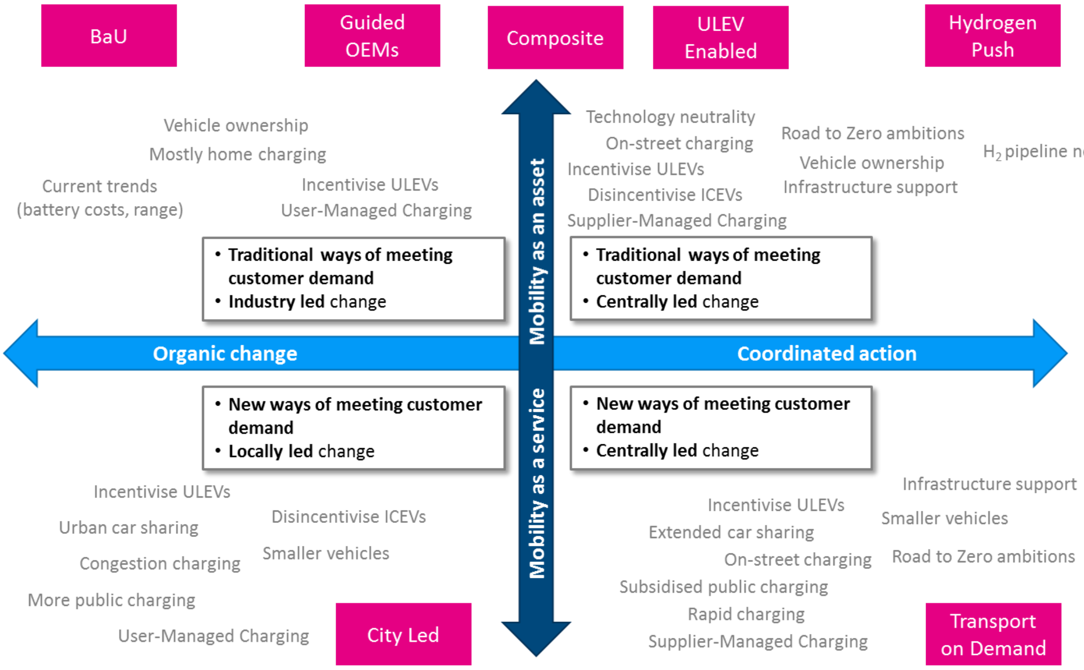
The modelling tools, Narratives, and analyses are described in full in other CVEI reports listed in the Bibliography. In this report we shall focus on outlining the key findings of the Whole-System Analysis and the conclusions and recommendations that follow from it.

[6] The Narratives used in CVEI are somewhat analogous to "scenarios" in other work (e.g. National Grid's Future Energy Scenarios). The term "Narrative" is used here to indicate that they represent the evolution of a particular plausible future over the pathway from the present (2019) to 2050 and to retain consistency with other CVEI reports.

[7] Full details of the modelling tools are available in the CVEI reports listed in the Bibliography, particularly D1.3.

Narratives

The key Narratives (i.e. future scenarios) used in the project are summarised in boxes around the outside of Figure 4. The three Narratives that reflect the Co-ordinated action theme (ULEV Enabled, Hydrogen Push, and Transport on Demand) also reflect the government's Road to Zero (RtZ) aims to end the sales of conventional petrol and diesel vans by 2040 and that almost all cars and vans should be ULEVs by 2050.



Note: BaU = Business as Usual, OEM = Original Equipment Manufacturer.

Figure 4: Summary of the seven Narratives

Composite Narrative

An additional *Composite* Narrative was developed for the final analysis to reflect a combination of some of the more desirable features in the initial Narratives for encouraging ULEV uptake and use. Its aim was to achieve a similar level of uptake to the ULEV Narrative but at a lower cost to government. In contrast to the other Narratives, which have stark distinctions in order to explore possibilities in the analysis, the Composite Narrative was intended to combine elements of these to create a potentially cheaper pathway.

Roadmap and recommendations

The Whole-System Analysis identified potential elements of a good solution and set these out on the roadmap shown in **Error! Reference source not found.**. In this project, a good solution is defined as one that attempts to strike an appropriate balance of decarbonisation in transport versus the wider system at a low overall cost, in a manner that successfully engages Private Consumers and fleets to achieve critical mass-market uptake and use of ULEVs at the appropriate points in time (e.g. balancing the need for anticipatory investment as an enabler versus the risk of stranding from making key decisions too early).

Broad timing guidelines are provided, both for when government intervention is required and when key industry participants should act in order to achieve efficient ULEV deployment and use.

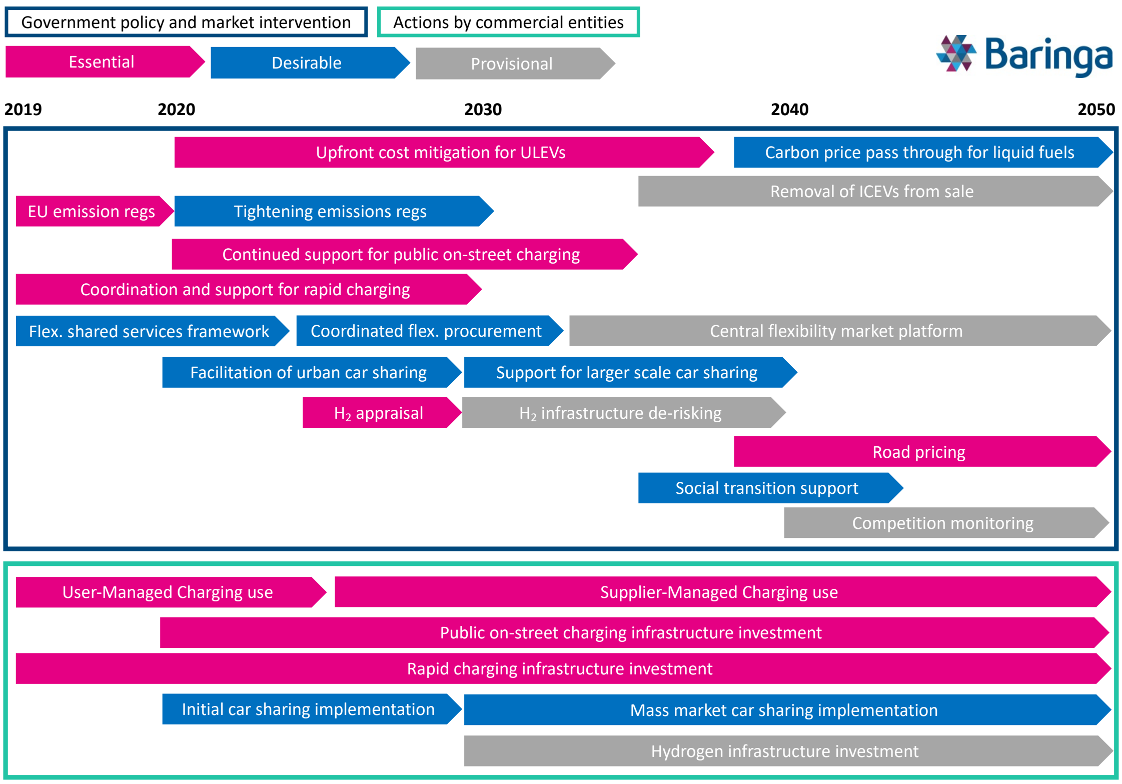


Figure 5: Roadmap for efficient ULEV deployment and use

The key elements of a ‘good’ solution across all four Dimensions were identified and prioritised by categorising them as Essential, Desirable, or Provisional (i.e. dependent upon other factors). These are shown in Table 1.

Table 1: Recommendations for government policy and market intervention

(actions grouped into Essential, Desirable, and Provisional categories as in Figure 5)

Element	Commentary
Essential	
Upfront cost mitigation for ULEVs	▸ **Reducing upfront ULEV costs is crucial to driving enhanced ULEV uptake, however, the proportion of low carbon vehicle km can be significantly increased by 2050 versus today through use of modest subsidies for a limited period only.** The results from this analysis show that a Narrative with no further subsidies after the current Plug-in Grant schemes end in 2020 resulted in the proportion of vehicle kilometres (vkm) that are low carbon being 42% by 2035 (compared to around 1-2% currently), whereas in a Narrative with limited subsidies for an interim period[8], the low carbon vkm accounted for 48% by 2035[9]. ▸ **Stronger incentives will be needed to reach RtZ ambitions.** ▸ The results of this analysis suggest that getting the remaining few vehicle users to switch to zero-emission vehicles (i.e. in the post-2040 period) will be difficult, even with a continuation of ULEV grants. Thus, the removal of conventional vehicles from sale may also be necessary in line with the government's current commitment to its RtZ strategy.
EU emissions regulations	▸ **Current 2020 EU targets for average CO_2 emissions for new car and van sales must be kept in place to encourage innovation and learning in the near-term that consequently reduces the cost of ULEVs.** The Narrative results show carbon emissions of 62 to 92 gCO_2/km as the new car average by 2020, below the target of 100 gCO_2/km, and 142 to 144 gCO_2/km as the new van average, below the target of 147 gCO_2/km. As a result, there is a case for tightening these further over the medium term (see later entry in this table).
Hydrogen appraisal	▸ **Major decisions on government support for FCVs and the associated infrastructure can be postponed until the mid-to-late 2020s to allow time for uncertainty over long-run costs to reduce.** ▸ FCVs appear to be important in the longer-term to reach the RtZ ambitions, particularly for the van sector, which is less suited to

[8] £500 per ULEV car and £1000 per ULEV van from 2025 to 2035 versus current Plug-in Car and Van grants offering up to £3,500 and £8,000 reduction on eligible cars and vans, respectively.

[9] It may be possible to reach similar levels of ULEV uptake in the medium-term with a shorter period of subsidies by conducting further analysis on different subsidy levels and timings.

	PiVs due to the duty cycle restrictions and current expectations about BEV range[10]. However, uptake of FCVs is expected to be relatively slow until the purchase price decreases substantially, around 2030[11], and in the long-term it depends on the level of access to on-street charging for competing BEV alternatives.
New tax on ICEVs and ULEVs (road pricing)	▸ **A new tax that applies to both ICEVs and ULEVs is likely to be required because it appears that simply extending the taxes that apply today, e.g. Vehicle Excise Duty (VED) and fuel duty, will lead to a gap in public finances between the net revenues from light duty transport sector and an assumed target.** The analysis evaluated the impact of different subsidies and taxes on public finances versus an assumed target net position for road transport[12], finding that measures that differentiate ULEVs from ICEVs can only go so far in driving ULEV uptake without causing long-term revenue cannibalisation[13], thus a technology neutral tax is necessary. This could be applied equally to equivalent ICEVs and ULEVs but still differentiated between vehicle segments and it does not need to be completely neutral; it could incorporate a low carbon discount. In the Narratives, the price for road usage ranges from 0.8 to 1.6 p/km on average across the pathway to 2050, assuming the gap in public finances is applied equally to all light vehicles. This represents between 3% and 8% of the actual cost of transport[14]. An alternative would be a per-vehicle annual tax, which ranges between around £145 and £345 in the Narratives and would be a substantial increase on the current VED tax[15]. It is noted that, assuming no change to current taxation, long-term revenue cannibalisation may happen without PiVs if the efficiency of ICEVs improves or if UK mileage growth declines as fewer people

[10] The result is that by 2050, around 25% to 95% of vans in the parc are FCVs depending on the Narrative.

[11] On a total cost of ownership (TCO) basis, consumer car segment B FCVs reach parity with petrol ICEVs in 2029 and petrol PHEVs in 2030 at the earliest (across the Narratives), including subsidies. The assumption about FCV cost reduction is dependent on investment by the automotive sector in the technology and its production.

[12] This project has explored options to meet the target revenue for road transport from within the road transport sector although the government could use other routes to bring down spending or obtain tax receipts from elsewhere in the economy.

[13] E.g. a higher tax on ICEVs may result in less use of ICEVs and less tax collected.

[14] The overarching cost of delivering the underlying transport service for car users, i.e. the total fixed and variable costs of the vehicles and fuel per year spread across the vkm travelled.

[15] Current VED rates are applied uniformly across all non-zero emission vehicles from the second year at £140/year.

	learn to drive or own cars. However, this analysis assumes that no OEMs transition to developing electrified powertrains and there are no further ICEV efficiency measures deployed beyond 2020.
Support for public on-street charging	▸ **The majority of charging occurs overnight at home for consumers and home-based fleet drivers during the horizon to 2050, assuming current expectations about charging behaviour and technologies. Thus deployment of on-street residential charging points is necessary to unlock ULEV uptake for those without access to off-street parking and to support the RtZ strategy.** The analysis tested implementation of on-street residential charge points, finding that the proportion of low carbon vkm in 2050 rises from around 86% when on-street residential charge points are not available to 91% when they are available. This suggests that to reach levels consistent with RtZ ambitions, on-street charging will probably be needed. However, the impact is lower than expected given that around 20% of new car buyers and 50% of new van buyers, who keep their vehicles at home, do not have access to off-street parking (but this is because some PiV drivers switch to FCVs instead in the absence of on-street charging). However, providing overnight access to those without off-street parking in the near term is important for social solidarity and also because ULEV uptake is initially likely to be higher in cities where the availability of off-street parking is lower, although these consumers may have lower than average mileage and could potentially be better served by integrated transport services. The analysis showed that direct support for on-street residential charging providers may be necessary, for example, if investment ahead of need is required[16], or if drivers' perception of access to charging is likely to lag behind the actual infrastructure available.
Coordination and support for rapid charging	▸ **To give certainty of access to charging outside of the home, a widespread network of rapid charging points is essential in the near to medium-term[17] and this may require some de-risking and direct support[18] to encourage investment[19].** As the battery size of BEVs increases, overnight charging with some

[16] Tested in the analysis via faster deployment of charging points based on the total ULEV uptake than the demand at those charging points.

[17] i.e. 50kW and greater.

[18] For example, from the £400mn Charging Infrastructure Investment Fund that the government is currently in the process of constructing to support non-home infrastructure development.

[19] Further sensitivity testing would be needed to establish the relative importance of rapid versus on-street residential charge points.

	top-up from rapid charging is likely to be able to meet the vast majority of charging demand requirements. The analysis indicated that a modest amount of direct government support may be needed whilst charging point businesses are still in their initial loss-making periods[20], especially as investment is particularly important in the near-to-medium term in order to reduce the range anxiety associated with access to charging, which remains a key barrier to uptake. By comparison, there is a more limited long-term role for standard public destination and workplace charging (except where the former is needed to facilitate car sharing); demand at these locations declines after 2025 and around 2030 respectively[21].
Desirable	
Carbon price pass through for liquid fuels	▸ **In the longer-term a well-designed support scheme would then switch the emphasis of policy intervention from incentivising ULEVs towards dis-incentivising ICEVs, for example through a long-term carbon tax[22].** After a competitive position for ULEVs has been established economically and in terms of their convenience, which is expected to be in the mid to late 2020s for segment B cars (most popular small cars, like Ford Fiesta), it appears to be worth implementing a carbon tax on liquid fuels as an effective way of dis-incentivising conventional vehicles whilst increasing the net position of public finances (i.e. as opposed to trying to drive ULEV uptake through further subsidies). However, policymakers should carefully consider any dis-incentives applied on ICEVs in the longer-term to avoid targeting people on lower incomes who are likely to be disproportionately the owners of these vehicles. ▸ **The push for decarbonisation from ULEVs needs to be considered together with decarbonisation of other sectors such as industry, building heat and power generation in order to reduce emissions as efficiently as possible.** In the nearer-term the higher costs of ULEVs versus conventional

[20] For context, the Commercial Value Chain subsidy required for rapid CPOs is around £10mn to £100mn, which is small when compared to total capital expenditure over the pathway.

[21] The share of workplace charging decreases over time as PiV ranges increases and consumers focus can meet the majority of their needs through a combination of home or on-street residential charge points and rapid charging.

[22] The system-wide CO_2 price refers to the marginal cost to the system to decarbonise the system by 1 ton CO_2. In some Narratives this marginal cost has been passed through to the petrol and diesel retail prices as a tax at different levels depending on the Narrative (i.e. 100% pass through level transfers the full carbon cost).

	vehicles may result in a relatively high cost of decarbonisation of road transport; however, it may be easier to generate momentum with ULEVs than with other forms of abatement (e.g. heating or efficiency measures) depending on the relative barriers to adoption. On the other hand, while progress with ULEVs is essential, it may prove harder to deliver decarbonisation than the Narratives imply and action on other sectors should not be neglected. In particular, decarbonisation of PiVs is closely linked to decarbonisation of power and it will be problematic if the large added load for charging is met from high carbon sources.
Further tightening of vehicle emissions regulations	▸ **It appears desirable to further tighten national CO_2 limits on new cars and vans beyond the values already set by the EU for 2020/21, as both a backstop measure to enforce decarbonisation and as stimulus for manufacturer innovation.** Across the Narratives, average emissions are between 7 and 41 gCO_2/km for new cars and between 17 and 75 gCO_2/km for new vans, both much lower than targets agreed by the European Parliament in December 2018 of a 37.5% reduction for cars and 31% for vans by 2030 versus 2021[23]. In order to encourage innovation and support ULEV uptake post 2020/21, vehicle emissions targets that are much more stringent than those already agreed could be implemented without subjecting vehicle manufacturers to large penalties[24]. Possible alternative mechanisms to encourage innovation and emissions reduction could be taken forward for further consideration, such as the effectiveness of incentives as opposed to penalties.
Support for the provision of flexibility (flex. shared services framework &	▸ **Wider market arrangements need to evolve to ensure that there are clear routes-to-market that enable the use of flexibility provided by Managed Charging (MC).** This could include, for example, a Flexibility shared services framework, which would aim to establish coordination between the

[23] Current targets are 95 gCO_2/km by 2021 for new cars and 147 gCO_2/km by 2020 for new vans, based on the New European Driving Cycle test procedure, which is in the final stages of being replaced with the Worldwide Harmonized Light Vehicle Testing Procedure. The reduction percentages should be equivalent to 59 gCO_2/km by 2030 for cars and 101 gCO_2/km for vans versus modelled targets of 65 gCO_2/km by 2030 for cars and 100 gCO_2/km for vans.

[24] If the current targets were to be reduced substantially to 25 gCO_2/km by 2030 for cars and 75 gCO_2/km by 2030 for vans then manufacturers would likely end up paying penalties (although these only appear in 2030-2031 and 2039 for cars and 2024-2025 for vans, of around £1bn in total). In the analysis the new car average reduces from 31 gCO_2/km to 27 gCO_2/km in 2030 and the share of low-emission car sales increases from 66% to 71%.

coordinated flex.procurement)	entities that have an active interest in flexibility, setting out how this resource could be shared between Distribution Network Operators (DNOs) and the Electricity System Operator (ESO). This could be followed by co-ordinated flexibility procurement (e.g. with an entity such as the ESO responsible for contracting services and then selling them on to other entities when they need them), which would represent a more substantial change to the market framework requiring, for example, reconsideration of price control frameworks. Further down the line, a central flexibility market platform could be developed, operated and regulated, allowing demand and/or generation to be optimised across all sellers and buyers of flexibility services for all purposes, including those with specific locational needs. ▸ **MC propositions result in substantial cost reductions for the ESO and the DNOs.** The two schemes modelled in this analysis (using data on charging behaviour from trials with around 240 participants, conducted as part of this project) are User-Managed Charging (UMC)[25] and Supplier-Managed (SMC)[26]. The benefits of MC are substantial, accounting for £1.1bn to £4.4bn in Present Value (PV) terms across the pathway to 2050 for the ESO[27], and £1.6bn to £2.1bn in avoided network reinforcement costs for the DNO[28]. These would account for £7 to £22 per PiV per year for the ESO and £39 to £56 per PiV per year for the DNO (both on average from 2020 to 2050). Incremental savings from SMC are greater towards the middle-to-end of the pathway. A more in-depth analysis of Demand Management (DM) aggregator[29] cash flows in the nearer term was also carried out as part of the CVEI project, using data from the trials[30]. This indicated that the value of flexibility (without Vehicle-to-Grid, V2G, technologies) that the aggregator could monetise would be in the order of 5% of the annual electricity cost for charging a PiV in 2030,

[25] I.e. consumer shifting of charging load to cheaper periods in response to static Time of Use tariffs.

[26] I.e. more complete load shifting in which a third-party such as an aggregator optimises the charging profile against prices across the available plug-in window provided by the driver.

[27] These are the long-run avoided costs of (more expensive) energy balancing and peaking plant, covering part of the balancing market, short term operating reserve and additional peaking plant.

[28] Note that savings for the transmission network operator (TNO) appeared to be negligible.

[29] A Demand Management Aggregator is a third party company specialised in demand management. It aggregates demand from its customers (industrial, commercial, PiVs etc.) and provides flexibility as a service to the system.

[30] The results of which can be found in the Deliverable *D7.3 DM Aggregator Framework.*

	but noting that the current market arrangements do not always sufficiently reflect the underlying system value of flexibility, in particular with respect to the avoided cost of reinforcement on the distribution network.
Support for car sharing (facilitation of urban car sharing)	▸ **The economics of car sharing appear positive and policymakers should support a role for shared cars that leads to efficient use of vehicles (i.e. does not increase total mileage through shifting demand away from public transport). For example, policymakers could avoid support for vehicle purchase where access to integrated transport services would be better for consumers[31].** Car sharing reduces the overall cost of transport by around 20% to 30% versus the cost of using a privately-owned consumer car[32], depending on how widespread the car sharing is[33]. With no 'dead miles', widespread car sharing reduces the cost of transport to 11 to 17p/vkm for shared cars and to 11 to 24p/vkm for privately owned consumer cars taking into account the costs across the pathway to 2050. Shared cars may result in shifting of vehicle demand away from public transport; however, if this reduces cost to consumers overall it could be left to the market to decide how this could evolve.
Social transition support	▸ **From a social policy perspective support could be targeted towards lower priced models and/or the second-hand market to help tackle transport poverty issues as part of a widespread transition to ULEVs.** ▸ The exact policy options would need to be carefully considered as, for example, providing grants to the second-hand market may not be effective if this is then indirectly priced into new car sales. An alternative could be to drive fleet decarbonisation harder to increase the supply of PiVs, on the basis that greater supply could reduce the costs of used vehicles.
Provisional	
Removal of ICEVs from sale	▸ **Meeting the 2050 RtZ ambition of 100% of new vehicle sales being zero-emission vehicles may require policy mechanisms that are more interventionist than financial incentives, such as preventing the sale of carbon emitting vehicles.** Several of the Narratives aimed to reach the 2050 RtZ ambition and

[31] E.g. With a transport package offering a monthly fee or pay as you go charge to access multi-modal transport.

[32] Comparing the average cost across 2019 to 2050.

[33] This analysis tested 'urban' car sharing, in which shared cars account for around 30% of total mileage in 2050, and extended car sharing when shared cars account for 75%. Note that this does not account for any modal shifting which was out of scope for this project; although reaching 75% of mileage in shared cars may require CAVs to capture the proportion of drivers that will not walk to pick up a shared car.

	demonstrated the difficulty in getting the residual proportion of vehicle users to switch to zero-emission vehicles without very high subsidies. This suggests that the removal of conventional vehicles from sale may also be necessary, although the analysis showed that this type of action might only be needed when sales of ICEVs or PHEVs have already fallen to very low levels[34].
Competition monitoring	▸ **Market supervision and regulation may become necessary to ensure fair treatment of consumers and avoid formation of natural monopolies as this nascent market evolves, for example, with respect to ownership of non-home charging infrastructure.**

Conclusions

The CVEI project has provided the first Whole-System Analysis of the transition towards a low-carbon future for light duty transport in the UK. This approach has generated unique insights into the elements needed for a successful transition to low-carbon light duty road transport in the UK.

The validity of the analysis has been underpinned by original, scientific research using rigorous experimental design to minimise findings being confounded by learning effects or uncontrolled external variables.

- The project undertook the first research on potential uptake of PiVs with Mainstream Consumer participants who have had direct experience of using both BEVs and PHEVs. The Mainstream Consumer sample means that findings are generalisable to the whole driving population rather than restricted to PiV Innovators who have special motivations.
- The project also undertook the first research on the charging behaviour of Mainstream Consumers when using PHEVs and BEVs; and the first research with Mainstream Consumer participants investigating the effectiveness of both User-Managed Charging ("Time-of-Use" tariffs) and Supplier-Managed Charging as means of mitigating the impacts of PiV charging on the electricity supply system.
- Case studies with fleet operators have also provided new understanding of the factors that influence the potential uptake of PiVs by fleets.

Key conclusions from the project include:

- Empirical data from the Consumer Uptake Trial indicates that, over the next five years, PHEVs are likely to be adopted more quickly in the mass-market than BEVs.

[34] In Narratives in which the RtZ ambitions are implemented, it is assumed that manufactures will remove conventional petrol and diesel powertrains from sale once their market shares, within their segment, fall below 5%. This does not necessarily assume a government ban and could instead be the response of manufacturers to falling profit margins as production volumes fall, and their unwillingness to invest in the continued development of these powertrains in anticipation of unfavourable policy conditions post-2040. However, ultimately a ban may still be needed to prevent the laggard consumers from buying an ICEV and policymakers should signal this far in advance.

- Ranges of 200 miles would enable BEVs to appeal to 50% of Mainstream Consumers as main household cars; ranges of 300 miles would enable them to appeal to over 90%. BEVs with ranges of 150 miles would appeal to 50% of Mainstream Consumers as second cars in households. These findings indicate what needs to be achieved in terms of BEV development in order to achieve the UK government's RtZ ambitions.
- Mainstream Consumers who are not participating in formal Managed Charging schemes are likely to undertake most of their charging at home in the late afternoon/early evening (15:00 to 20:00), particularly on weekdays. These timings coincide with peak demands from other sources, confirming that additional energy demand from PiVs could lead to supply-demand balancing, local network capacity issues and an increase in higher carbon generation.
- Managed Charging schemes have the potential to shift the timing of charging to the late evening and overnight, substantially alleviating these issues for the energy system at grid and local network levels. Managed Charging schemes also have substantial appeal to Mainstream Consumers.
- UMC schemes ("Time-of-Use" tariffs) have more a priori appeal to Mainstream Consumers, but SMC has similar appeal when those consumers are familiar with it.
- The Whole-System Analysis showed that 'Business as Usual' would result in a lower fraction of low-carbon Vehicle Kilometres Travelled (VKT), a higher cost of car transport, higher residual carbon costs, higher light duty road transport CO_2 emissions, and lower uptake of ULEVs than other Narratives considered. However, the gap between government transport-related tax and spend would be lower than in other Narratives.
- The greatest fractions of low-carbon VKT and reductions in light duty road transport CO_2 emissions by 2050 would be achieved under the 'ULEV Enabled' and 'Transport on Demand' Narratives. The cumulative reduction in CO_2 emissions would be substantially greater under the Transport on Demand Narrative, as reductions in annual emissions would be made substantially earlier in the pathway to 2050.
- The Whole-System Analysis indicates that PHEVs initially are adopted at slightly higher or similar rates to BEVs early in the pathway in all Narratives, but as the range of BEVs improves the uptake of PHEVs peaks and then stabilises or declines (the timing and magnitude of the peak depending on the conditions represented in each Narrative). The Consumer Uptake Trial findings suggest that this analysis may underestimate the adoption of PHEVs in the first five years, while confirming that BEV uptake will increase as the range of BEVs increases.
- Uptake of hydrogen FCVs increases steadily in all Narratives, particularly in consumer/fleet segments driving longer distances for whom limited battery ranges are more prohibitive, but is substantially less than uptake of BEVs, except in the 'H_2 Push' Narrative where a concerted effort is made to drive a transition towards FCV deployment.
- Based on the experimental findings and the Whole-System Analysis, a number of policy choices are recommended that are likely to be effective across a range of circumstances (as represented in the various Narratives plus the additional

sensitivity analyses). The most important of these, that should be applied early in the pathway, are:

- Upfront cost mitigation for ULEVs.
- Maintenance of EU emissions regulations or equivalent UK-specific regulations to encourage innovation and learning that increases the CO_2 emissions reduction potential and decreases the cost of ULEVs. Further tightening of emissions regulations is also desirable.
- Support for on-street charging to encourage uptake of PiVs by the large proportion of households that do not have off-street parking, and by fleets where vehicles are based at users' homes where those homes do not have off-street parking.
- Early support for a network of rapid chargers to provide reassurance of opportunities to charge away from home until BEV ranges increase substantially beyond present (2019) levels.
- Managed Charging propositions offer substantial benefits to the Electricity System Operator and Distribution Network Operator, and the regulatory and market environment should ensure that both UMC ("Time-of-Use" tariff) and SMC can be made available to users.
- Policymakers should support an early transition towards Mobility as a Service (MaaS) as this has the potential to yield greater reductions in cumulative light duty transport CO_2 emissions early in the pathway. For example, policymakers could avoid support for vehicle purchase where access to integrated transport services would be better for consumers[35]. Such a transition should encourage movement from private to shared cars (whilst discouraging movement away from Public Transport).

The introduction of a new fiscal mechanism to close the gap between the government's road transport-related tax and spending that will emerge as fuel tax revenues decline will also be essential. The need for this will develop somewhat later, as ULEV uptake increases. The mechanism should be neutral with respect to the powertrain technology of light duty vehicles (i.e. it should apply equally to ICEVs, PiVs, and FCVs).

Major decisions on government support for FCVs and the associated infrastructure could potentially be postponed until the mid-to-late 2020s to allow time for uncertainty to reduce over long-run costs of FCVs, particularly the fuel cell stack within them. At present, there is far less certainty over manufacturers' future commitments to developing and producing these in large volumes compared to PiVs. In addition, this support needs to consider the associated hydrogen supply and distribution needs.

The CVEI project was an ambitious study that blended multiple market and knowledge disciplines within the delivery Consortium, building on prior work including, among others, the ETI's previous Plug-In Vehicles project, and using high-quality scientific research to fill identified gaps in knowledge. The CVEI Whole-System Analysis has shown that there are no easy answers that lead to straightforward success across all metrics. It has, however,

[35] E.g. With a transport package offering a monthly fee or pay as you go charge to access multi-modal transport.

identified what a good solution that is robust in a range of transport futures could look like, and has provided a set of evidence-based, prioritised recommendations for policymakers and other stakeholders. If followed, these will substantially improve the chances of a transition to widespread adoption of ULEVs, integrated with the wider energy system through Managed Charging, and contributing to its efficient operation at lower cost than would be possible without that integration. The CVEI project's findings are relevant to stakeholders including the UK government, the transport sector including vehicle manufacturers, and the energy sector including the Energy System Operator, electricity retailers, and Distribution Network Operators.

1 Introduction

The UK Climate Change Act (2008) makes it the duty of the government to ensure that the net UK carbon account (for the six greenhouse gases recognised in the earlier Kyoto international agreement) is 80% lower in the year 2050 than it was in 1990. In June 2019, the UK became the first major economy in the world to pass laws to end its contribution to global warming by 2050. This more ambitious target will require the UK to bring all greenhouse gas emissions to net zero by 2050.

Transport (including domestic, but not international, aviation and shipping) is one of the major contributors to greenhouse gas emissions worldwide. In the UK, transport accounted for 27.3% of all emissions of greenhouse gases in 2017[36]. Light duty road transport (cars and vans) is the biggest source of UK transport CO_2 emissions, because of the predominance of gasoline and diesel Internal Combustion Engines (ICEs) as their powertrains.

The UK government is committed to encouraging the uptake of Ultra-Low Emission Vehicles (ULEVs) with alternative, low-carbon powertrains. The most promising candidate ULEV powertrains are Plug-in Vehicles (PiVs, powered in whole or in part by electricity stored in on-board batteries), and hydrogen Fuel Cell Vehicles (FCVs). The former are at a more advanced stage of market introduction, though the latter may still have an important role to play in decarbonising the whole UK light duty vehicle parc.

In September 2013 a report by the UK's Office of Low Emission Vehicles (OLEV)[37] set out a vision that by 2050 almost every car and van in the UK will be a ULEV. In October 2017, as a part of the government's Clean Growth Strategy, the UK pledged to spend £1bn to enable the transition away from ICE vehicles (ICEVs). By 2040, the government intends that the sale of new conventional petrol and diesel cars and vans in the UK will cease. To support the uptake of PiVs, a £400 million Charging Infrastructure Investment Fund has also been announced by the government to support the expansion of the PiV charging network by 2020 (including home, on-street, workplace, and wireless charging).

The Energy Technologies Institute (ETI) has been active in exploring potential pathways to a low-carbon future for light duty road transport, including sponsoring major research on the potential development of the PiV market in a previous PiV research project, and publishing its report *Transport: An affordable transition to sustainable and secure energy for light vehicles in the UK* (ETI, 2013). Since publication of that report there have been further developments in the field, suggesting that a fresh look would be valuable. In addition, it has become clearer that the potential system-wide impacts of PiV charging demand merit a more in-depth study. The CVEI project was developed in response to these needs.

[36] Source of information about transport CO_2 emissions: UK National Statistics: https://www.gov.uk/government/statistics/provisional-uk-greenhouse-gas-emissions-national-statistics-2017

[37] Office for Low Emission Vehicles (OLEV): https://www.gov.uk/government/publications/driving-the-future-today-a-strategy-for-ultra-low-emission-vehicles-in-the-uk

1.1 System implications of PiV electricity demand

Large scale replacement of ICEVs by PiVs has multiple implications for the UK's energy systems. Mass deployment of PiVs would result in a decline in gasoline and diesel demand, and consequent decommissioning of some existing gasoline/diesel supply, distribution, and retail infrastructure. There are also concerns that PiV energy demand resulting from mass uptake would add substantially to the overall and peak demand for electricity, at a time when increasing deployment of renewable supply sources will make supply-demand balancing more difficult (Greenleaf, Chen, & Stiel, 2014; Hardman *et al.*, 2018). Given the need for national electricity infrastructure to be built around peak demand rather than average demand, this presents major infrastructural challenges, particularly as decarbonisation of the country's electricity supply progresses. Unlike other plants, which can provide electricity on-demand, renewable sources such as solar and wind are intermittent and dependent on external conditions (such as length of daylight hours and cloud cover for solar). Solutions are needed to match supply and demand when supply is more variable than it has been in the past.

The electrification of the transport network could make this problem worse, or it could contribute to solving it; the difference will depend largely on consumer behaviour and mechanisms used to influence it. Experience in the early market for PiVs suggests that users tend to charge PiVs in the early evening, already a time when electricity demand is high. If this behaviour is replicated by mainstream consumer PiV users in a more mature PiV market, this could mean that the peak demands on the grid will increase substantially, with a need for auxiliary storage solutions to enable excess electricity to be made available at peak times, or reserve generating capacity that can be brought on stream quickly to cope with peaks in demand. Both of these are costly and likely imply high life-cycle CO_2 emissions in their own right.

It may be possible to mitigate supply-demand balance issues by using Managed Charging (MC), in which mainstream consumers who are PiV users are incentivised to charge their vehicles at times when other electricity demands are low. The CVEI project's Consumer Charging Trials were designed to test the effectiveness of two alternative forms of MC. High charging demand from PiVs could also pose problems at a local level by increasing loads on local electricity distribution networks beyond their existing capacity, thus necessitating investment in network reinforcement. MC may also be a useful tool for deferring the need for such reinforcement, helping to keep local loads within local network constraints. Accordingly, the CVEI project has paid particular attention to the potential uptake of PiVs by the mass market in the UK, the likely impacts of such uptake on the electricity supply and distribution systems, and the potential for mitigating these impacts through MC.

1.2 The potential role of hydrogen FCVs

Although substantial progress has been made in developing practical FCVs, there remain significant barriers to a transition to a hydrogen-based light duty mobility system. Mass deployment of FCVs would require a whole new infrastructure of hydrogen manufacture and distribution, including a network of hydrogen fuelling stations. Investment in this infrastructure in the early stages is potentially high-risk because it initially needs to be built in an environment where there are few FCV vehicles to refuel. As such, these infrastructure changes would likely happen later than in the case of PiVs. Nevertheless, if this hurdle can be overcome, FCVs have advantages (such as refuelling times and ranges equivalent to those of present ICEVs, together with the driving experience delivered by an electric powertrain) that mean that it is plausible that they will play a substantial role, though somewhat later than that of PiVs. Ultimately, mass deployment of PiVs and FCVs would result in a decline in gasoline and diesel demand, and might result in decommissioning of some existing supply, distribution, and retail infrastructure, though parts of the retail infrastructure might be repurposed for hydrogen retail and rapid charging. FCVs are included in the CVEI Whole-System Analysis.

1.3 Policy challenges

The ETI (2013) report highlighted a range of policy challenges in delivering an efficient transition to a low-carbon vehicle fleet:

- Optimising the combination of interventions (e.g. grants, subsidies, tax instruments, fuel pricing and other ownership incentives) to promote an efficient uptake of ULEVs by fleets and private consumers within an affordable and politically acceptable policy framework.
- Creating effective incentives to promote investment and innovation in ULEV manufacturing supply chains.
- Creating market frameworks that enable a level playing field for market competition between options and technologies for managing supply and demand for light vehicle energy (e.g. different combinations of pricing, Demand Management (DM), MC, range flexibility, energy storage, etc.)
- Creating regulatory and market frameworks to incentivise efficient and responsive investment in electricity, liquid fuel and hydrogen distribution infrastructure.
- Managing the distributional and fiscal impacts of policy change in ways that are politically and socially acceptable.

The next section outlines how the CVEI project addressed these challenges.

2 CVEI's Whole-System Analysis

The primary objective of the CVEI project was to characterise the market and policy frameworks, business propositions, and the integrated vehicle and infrastructure system and technologies best suited to enabling a cost-effective UK energy system for ULEVs.

To address this objective the CVEI project conducted the first comprehensive Whole-System Analysis of the potential development of the UK light duty vehicle market and energy system. The Whole-System Analysis explored how these would develop in a number of plausible alternative futures, and was used to make recommendations for action.

The Whole-System Analysis had two main elements:

1. A series of "Narratives" that represented plausible alternative transport futures[38]. These Narratives differed in terms of their positioning in terms of two key factors that emerged from early analysis and expert workshops as important discriminators of possible future pathways for the future of light duty road transport:
    - how far future mobility is based on individual assets (e.g. owned or leased cars and vans) vs. asset sharing (e.g. Mobility as a Service), and;
    - how far decarbonisation was driven by organic change (commercial product development and consumer choice) vs. coordinated action (policy-driven incentives and market frameworks)
2. A set of inter-linked modelling tools that represented the major dimensions of the ULEV market and energy systems[39]:
    - **Customer Proposition (CP)** – what a ULEV or a charging scheme offers the user
    - **Physical Supply Chain (PSC)** – the tangible assets and skills that deliver ULEVs and their energy requirements
    - **Commercial Value Chain (CVC)** – the commercial entities that deliver the CP
    - **Market and Policy Framework (MPF)** – government and regulatory interventions

The modelling tools were used to provide a holistic Multi-Criteria Analysis (MCA) of how the ULEV market and the energy system would develop under each Narrative, in order to understand the aspects that may facilitate better successful mass-market deployment and use of ULEVs. A set of conclusions and recommendations was developed from this assessment that is robust in a range of possible transport futures.

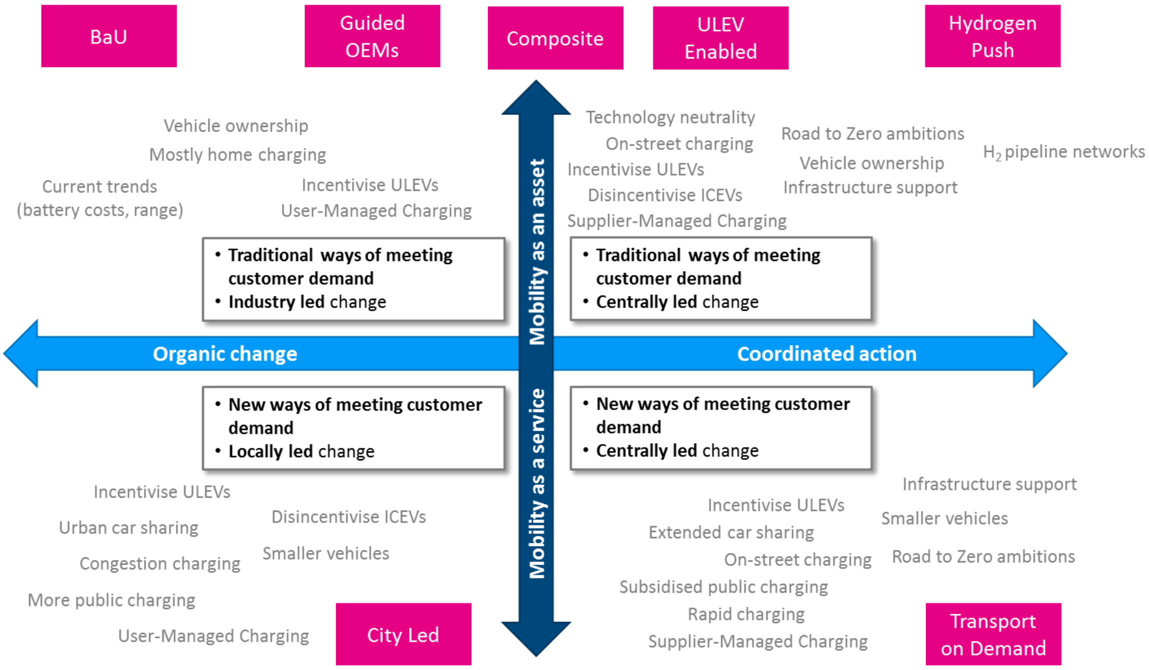
The modelling tools, Narratives, and analyses are described in full in other CVEI reports listed in the Bibliography. In this report we shall focus on outlining the key findings of the Whole-System Analysis and the conclusions and recommendations that follow from it.

[38] The Narratives used in CVEI are somewhat analogous to "scenarios" in other work (e.g. National Grid's Future Energy Scenarios). The term "Narrative" is used here to indicate that they represent the evolution of a particular plausible future over the time interval out to 2050; and for consistency with other CVEI reports.

[39] Full details of the modelling tools are available in the CVEI reports listed in the Bibliography, particularly D1.3.

2.1 Narratives

The key Narratives (i.e. future scenarios) used in the project are summarised in boxes around the outside of Figure 6. The three Narratives that reflect the Co-ordinated action theme (ULEV Enabled, Hydrogen Push, and Transport on Demand) also reflect the government's Road to Zero (RtZ) aims to end the sales of conventional petrol and diesel vans by 2040 and that almost all cars and vans should be ULEVs by 2050



Note: BaU = Business as Usual, OEM = Original Equipment Manufacturer.

Figure 6: Summary of the six Narratives (these are brief summaries of them; full details can be found in D7.4, listed in the Bibliography)

2.1.1 Composite Narrative

An additional *Composite* Narrative was developed for the final analysis to reflect a combination of some of the more desirable features in the initial Narratives for encouraging ULEV uptake and use. Its aim was to achieve a similar level of uptake to the ULEV Narrative but at a lower cost to government. In contrast to the other Narratives, which have stark distinctions in order to explore possibilities in the analysis, the Composite Narrative was intended to combine elements of these to create a potentially cheaper pathway, and to explicitly reflect the UK government's RtZ strategy ambitions to cease sales of new ICEV cars and vans by 2040 and that almost all cars and vans in the UK parc should be zero emission by 2050. It included:

- A pull towards ULEVs led by vehicle cost and performance improvements and a gradual increase in access to charging, with a particular focus on on-street charging for those without access to off-street overnight charging.
- A focus in the medium-term on maintaining momentum in ULEV uptake through incentives such as vehicle grants, albeit at low levels and for a limited period, whereas later on a carbon tax on liquid fuels (in addition to fuel duty) is a disincentive for ICEVs.

- Consumers being able to choose to shift the timing of their charging demand through participation in a User-Managed Charging scheme.
- On-street charging points providing access for those without off-street parking.

2.2 Multi-Criteria Analysis: Metrics

A set of quantitative Metrics was defined in order to conduct a Multi-Criteria Analysis (MCA) that compared and contrasted the key outcomes under the various Narratives. Metrics are shown in Table 2. In this table, "pathway" refers to the period from the present (2019) to 2050 over which the Narratives develop.

These quantitative metrics were supplemented by two qualitative metrics that describe outcomes that cannot readily be quantified:

- **Transport Utility**: The material impact of mass deployment of ULEVs on consumers' transport utility (considering factors such as convenience, choice, certainty and flexibility of travel patterns).
- **Wider impact on UK economy**: Potential impact on e.g. jobs, innovation, competitiveness, the developing domestic supply chain.

2.3 Sensitivity analyses

Several sensitivity analyses were conducted to test how resilient the outcomes of the various Narratives, or of various possible ULEV strategies, might be to changing external conditions, particularly those that are outside of the direct control of UK entities. Sensitivities to the following changes were explored:

- Higher and lower ULEV costs.
- Earlier and later pass-through of carbon tax onto liquid fuels.
- Lower certainty of access to charging (primarily through absence of residential on-street charging points[40] limiting access to those without off-street parking).
- Manipulation of the key levers that reflect the UK government's RtZ strategy (as included in the Narratives that are framed by the "Coordinated Action" theme).

Full details of the sensitivity analyses can be found in the Deliverable D7.4 report which is listed in the Bibliography.

[40] Given lack of data on how much on-street overnight infrastructure each consumer needs, conservative assumptions were made i.e. one on-street charge point for every consumer needing it overnight.

Table 2: Quantitative Metrics

Metric	Description	Unit	Rationale
Low-carbon Vehicle Km Travelled (VKT) in ULEV use	– Maximises proportion of total (tank to wheel) low carbon vehicle km (vkm) (of consumers and fleets covered by the scope of this study) that is undertaken with an ULEV (i.e. in electric only mode for PHEVs)	%	Are the aspects of the Customer Proposition (both price and others such as refuelling availability) sufficiently attractive to spur uptake and use by consumers and fleets?
Car user transport costs	– Overarching cost of delivering the underlying transport service for car users (i.e. including Consumers, Fleet Car Sharing, Fleet User Choosers and Fleet Non-User Choosers)	p/km	Understand the combined impact of vehicle, wider system energy costs, car sharing, taxes on the costs of transport. Upfront vehicle grants are excluded from this metric.
Residual CO_2 cost	– Present Value at Treasury Social Discount Rate of transport carbon emissions over pathway, assuming UK meets its overarching greenhouse gas targets (carbon budget and 2050) and is technically feasible, i.e. tCO_2/year multiplied by the system-wide carbon price from ESME in each year, which is the price necessary to achieve the targets for the UK as a whole	£bn	The level of abatement across the physical energy system both within and outside of transport (including the delivery of fuels) must be consistent with the UK's overarching targets and be cost-effective given balance of abatement options across the wider energy system, i.e. when contrasted with other Narratives and the government spending metric, does the additional decarbonisation through transport appear more/less expensive compared to other options?
	– Undiscounted cost of residual carbon emissions in 2050 only	£bn/yr	This metric allows a comparison with abatement over the pathway, by understanding the cost-effectiveness of the abatement position at the end of the pathway only, as this level is likely to be maintained going forward

Metric	Description	Unit	Rationale
Commercially viable?	– Present Value of the total upfront subsidy needed to ensure that all Commercial Entities modelled meets their required rate of return given the assumed WACC (weighted average cost of capital) or margin over the pathway, noting that there may be missing money as WACC is normally applied to an enterprise and does not reflect different levels of risk for each investment	£bn	Commercial entities should be viable over the pathway to 2050 (potentially with government support) to deliver the required Customer Propositions and supporting infrastructure (e.g. given risks of asset stranding).
'UK Plc.' appropriate spending	– Present Value (at Treasury Social Discount Rate) of the gap over the pathway between direct transport related income (revenues less subsidies) and a target share for road transport related net income[41] associated with cars and vans.	£bn	Government net tax and spend directly associated with transport are hard to separate from wider government objectives as not all revenue is hypothecated. This metric reflects a proxy for the broad maintenance of existing revenues.
	– Undiscounted gap in revenue in 2050 only	£bn/yr	This metric allows a comparison with the revenue gap over the pathway, by understanding at the end of the pathway only, as this level is likely to be maintained going forwards.

[41] The target share for transport related income was based on the 2015 share of ~2% given the coverage of consumer/fleet vehicle policy measures modelled, assumed to grow in line with the latest GDP/capita forecast.

3 Filling the knowledge gaps

It was clear from the outset that there were a number of substantial knowledge gaps that, left unaddressed, would lead to significant uncertainties in the analyses. The key uncertainties concerned consumer responses to ULEVs:

- Under what circumstances would Mainstream Consumers and fleets be willing to adopt BEVs, PHEVs, or FCVs?
- How would Mainstream Consumer and fleet PiV users recharge their vehicles, and in particular, what would be the temporal profiles of daily charging demand?
- Assuming some form of Managed Charging could in principle be used to mitigate negative system impacts of PiV electricity demand, would Mainstream Consumers and fleets be willing to engage with it, and would they in fact respond to it in ways that benefitted the wider system?

3.1 Mainstream Consumer uptake of PiVs

The term ‘Mainstream Consumer’ is used throughout this report and in other CVEI reports to mean all private consumers who may adopt PiVs except for the Innovator segment as defined in Rogers’ (2003) diffusion model for the adoption of innovations[42]. The segments in Rogers’ model are defined statistically, as shown in Figure 7.

Mainstream Consumers include the Early Adopter, Early Majority, Late Majority, and Laggard segments defined by Rogers; all those whose times to adoption are later than two standard deviations before the mean time to adoption. The segmentation study carried out in the ETI’s earlier PiV project (Anable, Kinnear, Hutchins, Delmonte & Skippon, 2011) showed that the attitudes towards PiVs held by Innovators (termed “Plug-in Pioneers” in that study, representing 2% of the sample) were unrepresentative of those of the other segments, being much more favourably disposed towards both BEVs and PHEVs. This means that findings from research with Innovator samples cannot be used to infer conclusions about the Mainstream Consumer population.

The literature review conducted in Stage 1 (Kinnear, Anable, Delmonte, Tailor & Skippon, 2017) found that much of the research on consumer attitudes to uptake of PiVs has been conducted with people who already had a PiV, or who acquired one as part of a trial (e.g. by leasing a vehicle at their own expense); these participants were all Innovators in diffusion model terms. Their attitudes are informative if we are interested in the establishment of the early PiV market, but they can tell us little about PiV uptake by Mainstream Consumers.

[42] Assuming an eventual full transition to PiVs, the present (2019) population of PiV users in the UK are all Innovators.

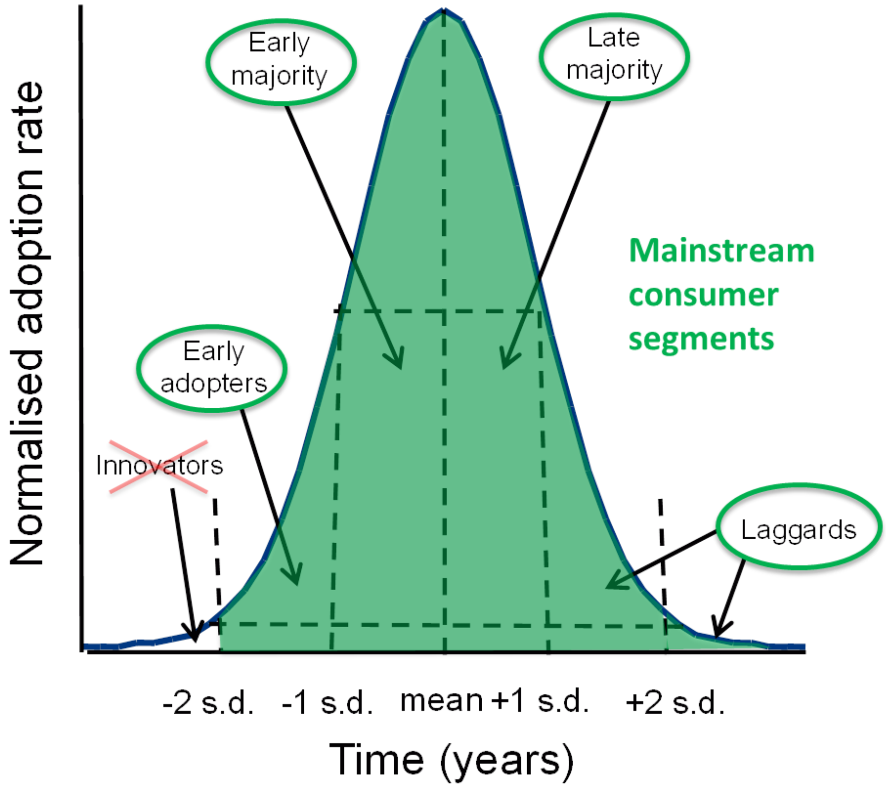


Figure 7: Consumer segments in Rogers' (2003) model for adoption of innovations. Mainstream Consumers (circled in green) are defined in CVEI as all segments except Innovators. The horizontal axis is time relative to the mean time to adoption

There has also been research with Mainstream Consumer samples, for instance choice experiments to explore the relative value of PiV attributes (Kinnear et al., 2017). However, this kind of research is subject to another form of uncertainty due to the participants' lack of experience with PiVs – leading to a theoretical concept known as psychological distance (Eyal, Liberman & Trope, 2009). Psychological distance increases the weight a person attaches to high-level construals (*why* that person might choose and use an object), and psychological closeness increases the weight given to lower-level construals (*how* that person might choose and use the object). Also, the "pros" of an object are generally higher-level constructs than its "cons". Psychological distance thus generates systematic biases in participants' responses.

These two weaknesses taken together meant that understanding of the conditions under which Mainstream Consumers would take up PiVs in substantial numbers was weak. In addition, the literature review indicated that research had largely focused on potential uptake of BEVs; there had been very little research on uptake of PHEVs.

To close this knowledge gap, the CVEI project conducted a field study (the Consumer Uptake Trial – detailed in Section 4) to provide a sample of Mainstream Consumers with the experience of using a BEV and a PHEV (and an ICE vehicle as a control) to reduce their psychological distance from these new vehicle categories.

3.2 Mainstream Consumer PiV charging behaviour and responses to Managed Charging

Similar arguments apply to research on PiV charging behaviour. First, the literature review showed that trials in which charging behaviour was measured were generally conducted with Innovator participants whose special pro-PiV motivations could lead to charging behaviours that were unrepresentative of those of Mainstream Consumers. Second, very limited data were available about charging behaviours with PHEVs. In addition, there were very little data available on responses to MC, and those data came from uncontrolled studies that did not enable causal attribution of behaviours to charging schemes. Accordingly, the project included two further field studies (the Consumer Charging Trials – detailed in Section 5) to close this knowledge gap[43].

3.3 Uptake of plug-in cars and vans by fleets

Uptake of PiVs by centralised-chooser fleets (those where vehicle choices are made by the organisation, for instance by the fleet manager or a procurement team) is modelled in the Whole-System Analysis as a rational choice based on total cost of ownership and operational suitability. However, PiV uptake modelled in this way over-predicts present uptake. Accordingly, a qualitative study based on in-depth case studies with five Fleet Operators was carried out to identify what other factors influenced their vehicle selection. This identified that strategic-level concerns such as corporate remuneration policy and corporate social responsibility could influence decisions away from straightforward rational choice, as could commercial concerns, and, in the case of fleets whose vehicles were based at users' homes, managerial perceptions that home charging would not be feasible at the type of accommodation their staff tended to live in.

These insights, however, were qualitative in nature, so not readily incorporated in the Whole-System Analysis. Rather, they were drawn on in interpreting the modelling outputs. The discrepancy between rational-choice predictions and present fleet PiV uptake was addressed in the Whole-System Analysis by including an "unfamiliarity" penalty for PiVs.

3.4 Potential Mainstream Consumer adoption of FCVs

There is a similar lack of knowledge about potential adoption of FCVs by Mainstream Consumers; indeed the knowledge gap is wider, since FCVs are not yet readily available on the UK market, and there is negligible refuelling infrastructure. This situation prevented field studies being used to reduce the knowledge gap. It is possible to extrapolate from some of the findings of the uptake trial and previous research (see Deliverable D2.1, listed in the Bibliography), that drivers are concerned about factors such as the cost of vehicles, the driving experience, and the availability and convenience of refuelling, to suggest that FCV uptake will depend on the a priori development of adequate refuelling infrastructure.

[43] The Consumer trials were preceded by a qualitative study using Innovator participants to investigate their responses to potential MC schemes, which was used to help design the main field study. The qualitative study is described in full in Deliverable D2.1, which is listed in the Bibliography.

4 The Consumer Uptake Trial

The Consumer Uptake Trial was designed to provide up-to-date insight into the likely uptake of PiVs by Mainstream Consumers in the near future and over the coming decades, as features such as range and recharging time are improved. Readers interested in the full details are referred to Deliverable D5.2, listed in the Bibliography.

4.1 Key methodological features

The trial recruited a stratified sample[44] of 200 Mainstream Consumers, giving them experience with three vehicles: a BEV, and PHEV, and an ICEV, all from the same model family (Volkswagen Golfs). The ICEV was included to control for the possibility that responses to the vehicles could be attributed to unfamiliarity, and to understand possible effects of simply participating in the trial. Apart from the powertrain differences, the three vehicles were very similar. The trial had a number of methodological features that distinguished it from prior research:

200 participants were each given a VW Golf BEV, PHEV and ICEV for four days each in succession. In total, the Uptake Trial recorded 11,000 journeys and 1,700 charge events.

1. Attitudes towards adoption of PHEVs were measured in addition to attitudes towards adoption of BEVs.
2. Mainstream Consumers were recruited rather than the Innovators who had participated in previous UK PiV trials.
3. Each participant was given four days of real-world experience with a BEV, PHEV, and an equivalent ICEV, to reduce their psychological distance to PiVs and enable them to give responses based on their experiences of these vehicle categories. Their existing cars were removed during the trial experiences.
4. Self-reported attitudes and willingness to choose responses were collected before and after their experience of using the vehicles.
5. Participants completed a choice experiment following their experience of using the vehicles, to characterise the importance of PiV attributes.

[44] The sample was recruited to meet quotas for key demographic variables to maximise representation of the target population. In this case quotas were set for age, sex, and urban vs. rural living, based on national driving licence and population statistics.

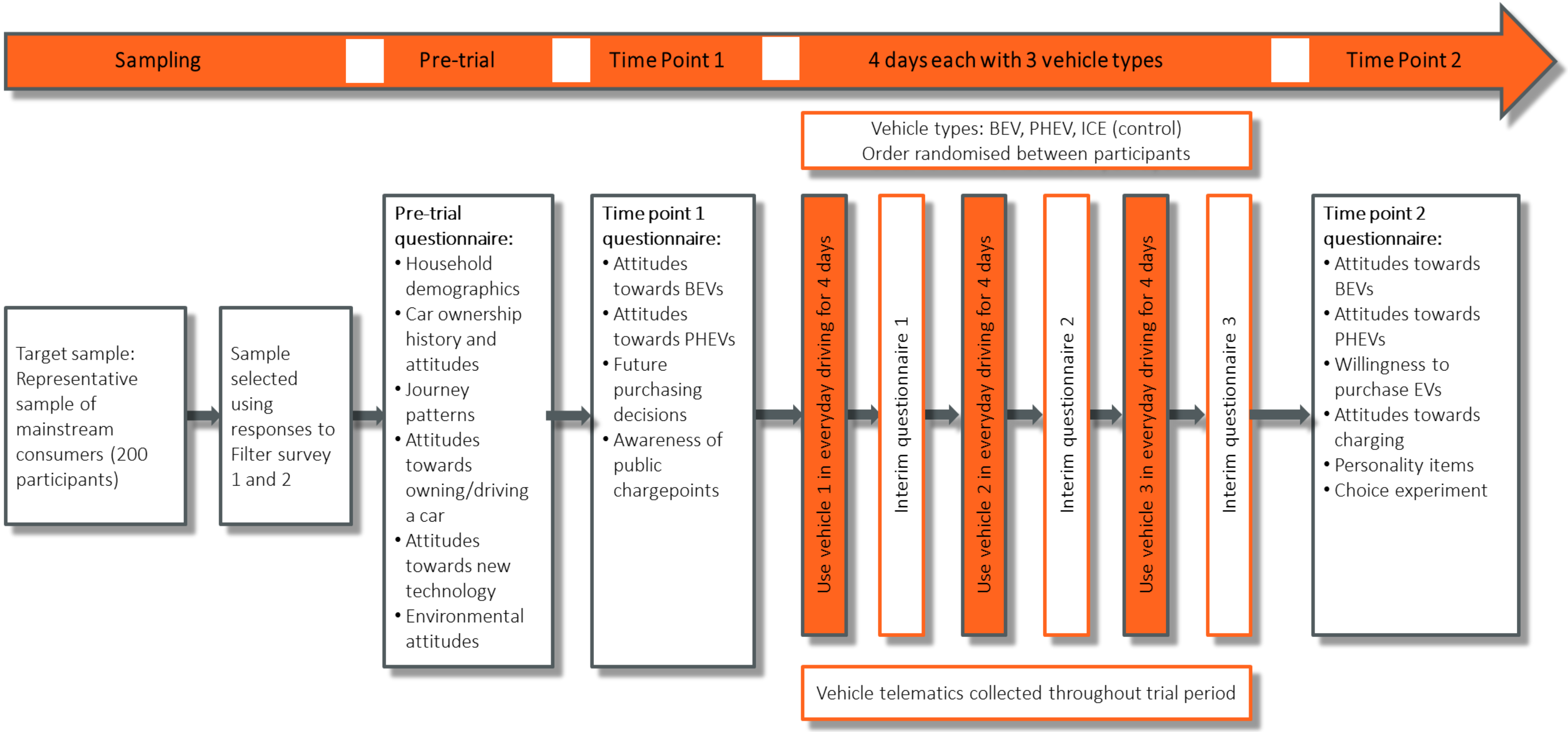


Figure 8: Overview of Consumer Uptake Trial method

4.2 Key findings

The Consumer Uptake Trial produced a wide range of detailed findings. Only those most relevant to the Whole-System Analysis are described here. Comprehensive reports on the findings are listed in the Bibliography.

4.2.1 Likelihood to choose a PHEV or BEV in the next five years

After experiencing the three vehicles, participants were asked to state how likely they were to choose either a PHEV or a BEV as the main car or second car in their household within the next five years. The results are summarised in Figure 9.

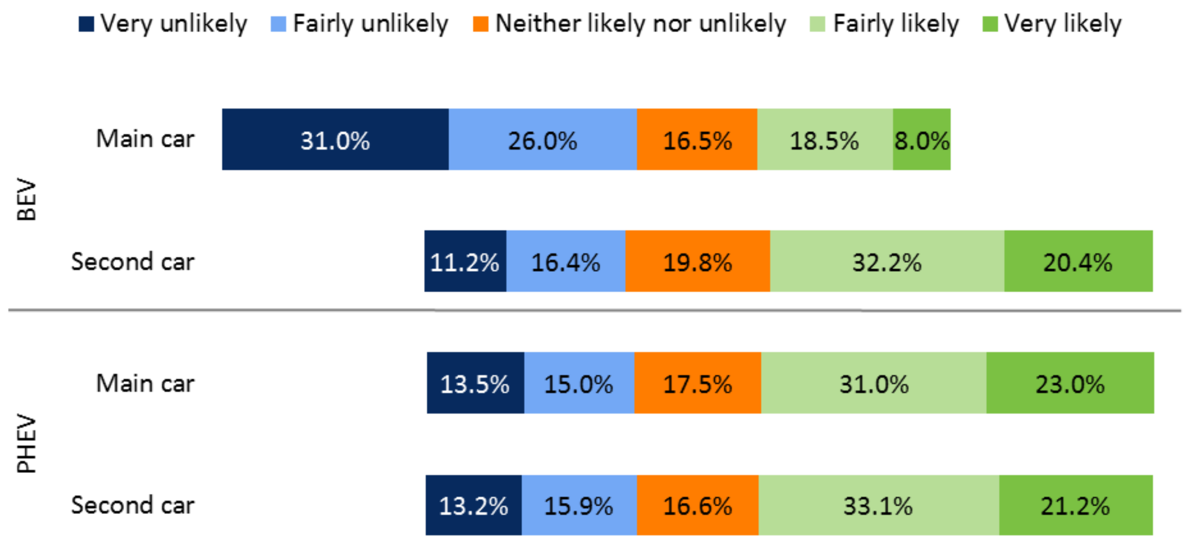


Figure 9: Likelihood to choose a BEV or PHEV as main and second car in the next five years, after experience with these categories of vehicles

Around 50% of participants indicated they were fairly or very likely to choose a PHEV as a main or second household car, or a BEV as a second car. Many fewer (26.5%) indicated the same for a BEV as a main car. Overall, the appeal of PiVs in this study appeared to be greater than in previous studies. This may be due to the reduction in psychological distance provided in the current study. It may also suggest greater awareness of PiVs in the population now, or more desirable models of PiVs appearing on the market. In addition, the influence of other differences between this and previous studies, for instance the use of a stratified sample in the Consumer Uptake Trial, cannot be ruled out.

Participants in the Consumer Uptake Trial were assigned to pre-defined consumer segments defined in the Electric Car Consumer model (ECCo). The original segmentation used responses to a questionnaire developed by Element Energy for the Department for

Transport (DfT) (Element Energy, 2015). Participants largely fell into three of these consumer segments, described in Table 3[45].

Table 3: Profiles of the three main consumer segments

Segment	Profile
Cost-conscious Greens **(25% of sample)**	Generally drive medium sized cars; average annual mileage, frequent long trips; strongly link cars to status; do not particularly like cars/driving; interested in new technology; relatively high interest in fuel economy; strong pro-environmental attitudes; positive attitudes to PiVs; young, medium income, 50/50 female/male.
Pragmatists **(50% of sample)**	Generally drive medium sized cars; average annual mileage, frequent long trips; strongly link cars to status; do not particularly like cars/driving; interested in new technology; relatively high interest in fuel economy; neutral attitudes to environment; negative attitudes to PiVs; young, low income, 50/50 female/male.
Uninterested Rejectors **(19% of sample)**	Generally drive medium sized cars; low annual mileage, few long trips; do not link cars to status; do not particularly like cars/driving; not interested in new technology; do not see benefits in changing from hydrocarbon fuels; negative attitudes to environment; negative attitudes to PiVs; older, low income, slight male predominance.

Figure 10 shows the responses for PHEVs broken down by consumer segment. Members of the Pragmatist segment reported being substantially more likely to choose a PHEV, as both a main or second household car, than members of the Cost-conscious Greens segment, who in turn were substantially more likely to choose a PHEV as both a main or second household car than members of the Uninterested Rejectors segment.

PHEVs provide a pragmatic compromise between the running cost, performance, and environmental benefits of a BEV, and the driving range and speed of refuelling of an ICEV, so it is unsurprising that the Pragmatist segment expressed greater likelihood to choose a PHEV. Likewise, it is to be expected that Uninterested Rejectors would be less likely to choose a PHEV than either of the other segments. It is interesting though that even among the Uninterested Rejectors, 11% were very likely to choose a PHEV as a main car, along with 26% who were fairly likely. This suggests that PHEVs can appeal to some extent even to the most sceptical of Mainstream Consumer segments.

[45] Note that the allocation of participants to pre-defined segments cannot be exact, so some discrepancies may arise: for instance, the CVEI participants tended to have higher mileages than members of the a priori segments as described in Table 3. For more information see Deliverable D5.2.

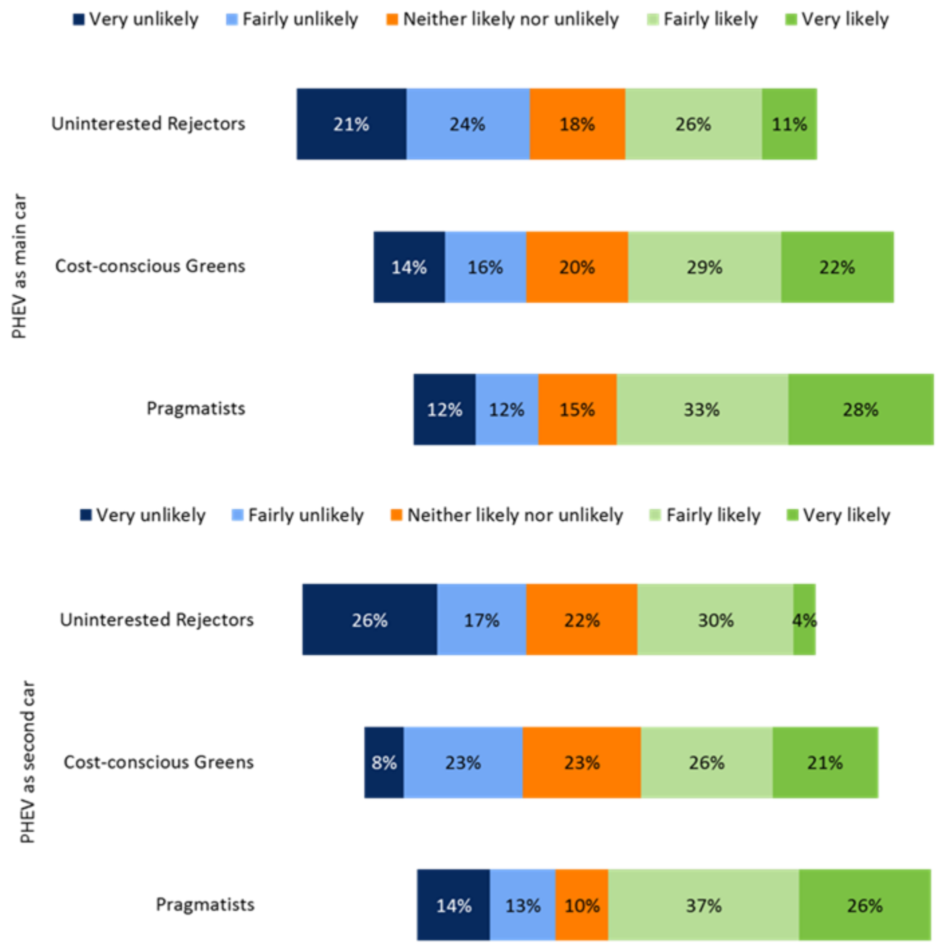


Figure 10: Likelihood to choose a PHEV as a main or second car in the next five years, by consumer segment

The segmented response to PHEVs as a second household car was similar, but the inter-segment differences were larger. Among Pragmatists, likelihood to choose a PHEV as a second car was similar to likelihood to choose a PHEV as a main car; but for the other segments it was lower. This effect requires further investigation through qualitative research that could explore the reasoning that underlies the pattern.

Figure 11 shows the responses for BEVs broken down by consumer segment. Likelihood to choose a BEV as a second car was similar for all three segments. Likelihood to choose a BEV as a main car, however, was substantially lower among the Uninterested Rejector segment than the other two: 40% of Uninterested Rejectors reported being very unlikely to choose one, as opposed to 29% of Pragmatists and 25% of Cost-conscious Greens. Uninterested Rejectors were much more rejecting of BEVs as a main car than as a second car. This was also the case for Pragmatists (though to a lesser extent) and for Cost-conscious Greens, to an even lesser extent.

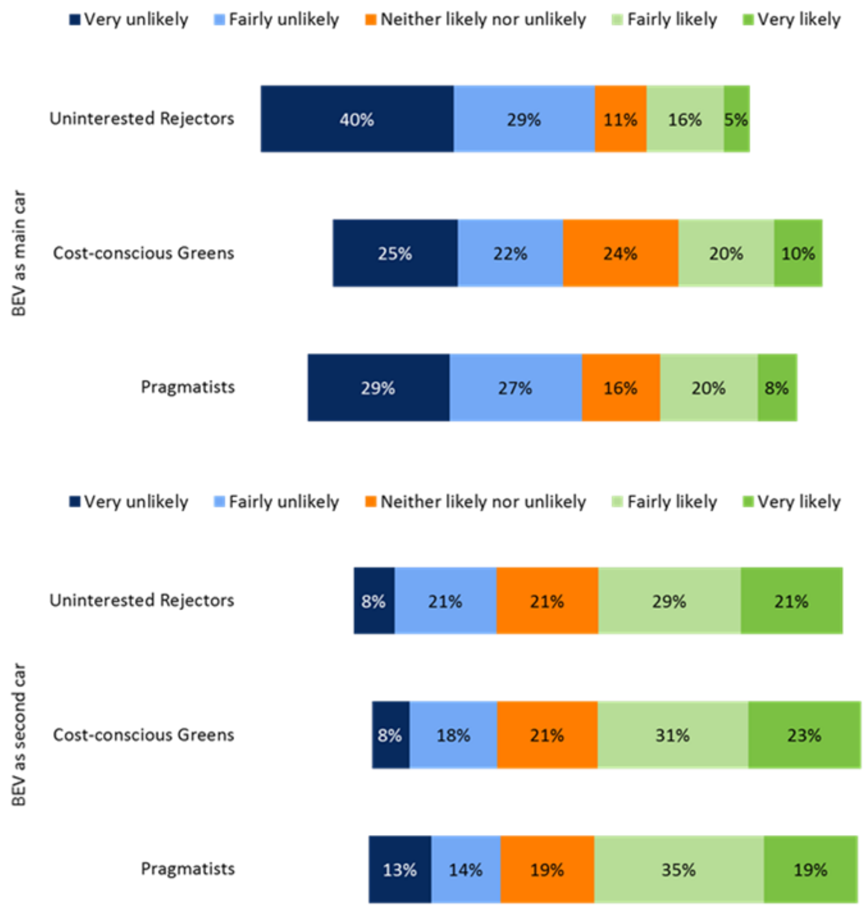


Figure 11: Likelihood to choose a BEV as a main or second car in the next five years, by consumer segment

4.2.2 Influence of electric range on willingness to consider owning a PiV

Figure 12 shows how willingness to consider owning a PHEV, as a main or second car, varied with the range of the vehicle. Participants' willingness to consider owning a PHEV increased with increasing range. Around 50% of participants would consider owning a PHEV as a main household car, and around 60% as a second car, if its range when fully charged was 80km (50 miles), rising to around 90% (for both main and second cars) if the range when fully charged was 160km (100 miles). The distribution of responses was similar across the segments. The Uninterested Rejectors segment was somewhat less willing to consider a PHEV whatever the range; but even in this segment more than 80% of them would be willing to consider one with a range of 160km (100 miles).

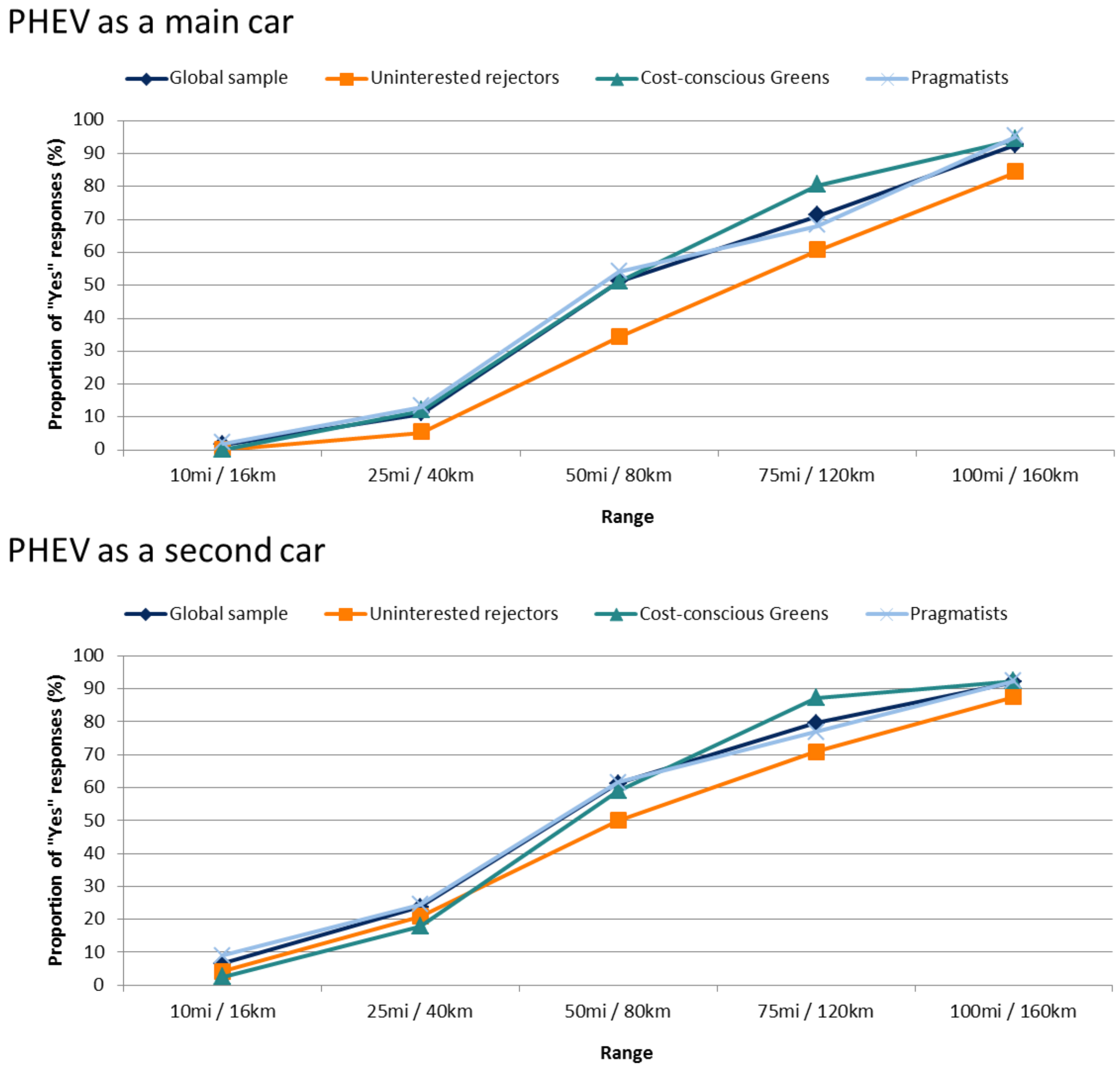


Figure 12: How willingness to consider owning a PHEV as a main or second car depends on range, by consumer segment ('Yes' response indicates they would choose a PHEV)

Figure 13 shows how willingness to consider owning a BEV, as a main or second car, varied with the range of the vehicle. Around 50% of participants would consider owning a BEV as a second household car if its range when fully charged was between 160km (100 miles) and 240km (150 miles); but range would need to be substantially higher, 320km (200 miles) before 50% of participants would consider owning a BEV as a main car. A range of 480km (300 miles) would be required for more than 90% of participants to consider owning a BEV as either a main or a second car. These findings are consistent with those of Skippon, Kinnear, Lloyd & Stannard (2016), and provide guidance to vehicle manufacturers as to the AERs required to achieve mass-market penetration by BEVs. It is plausible that consumers are reluctant (and possibly risk-averse) to accept the need to recharge part-way during long journeys; 480km (300 miles) may therefore represent a perceived maximum distance that the majority of participants would expect to drive in a day, even if only for irregular journeys.

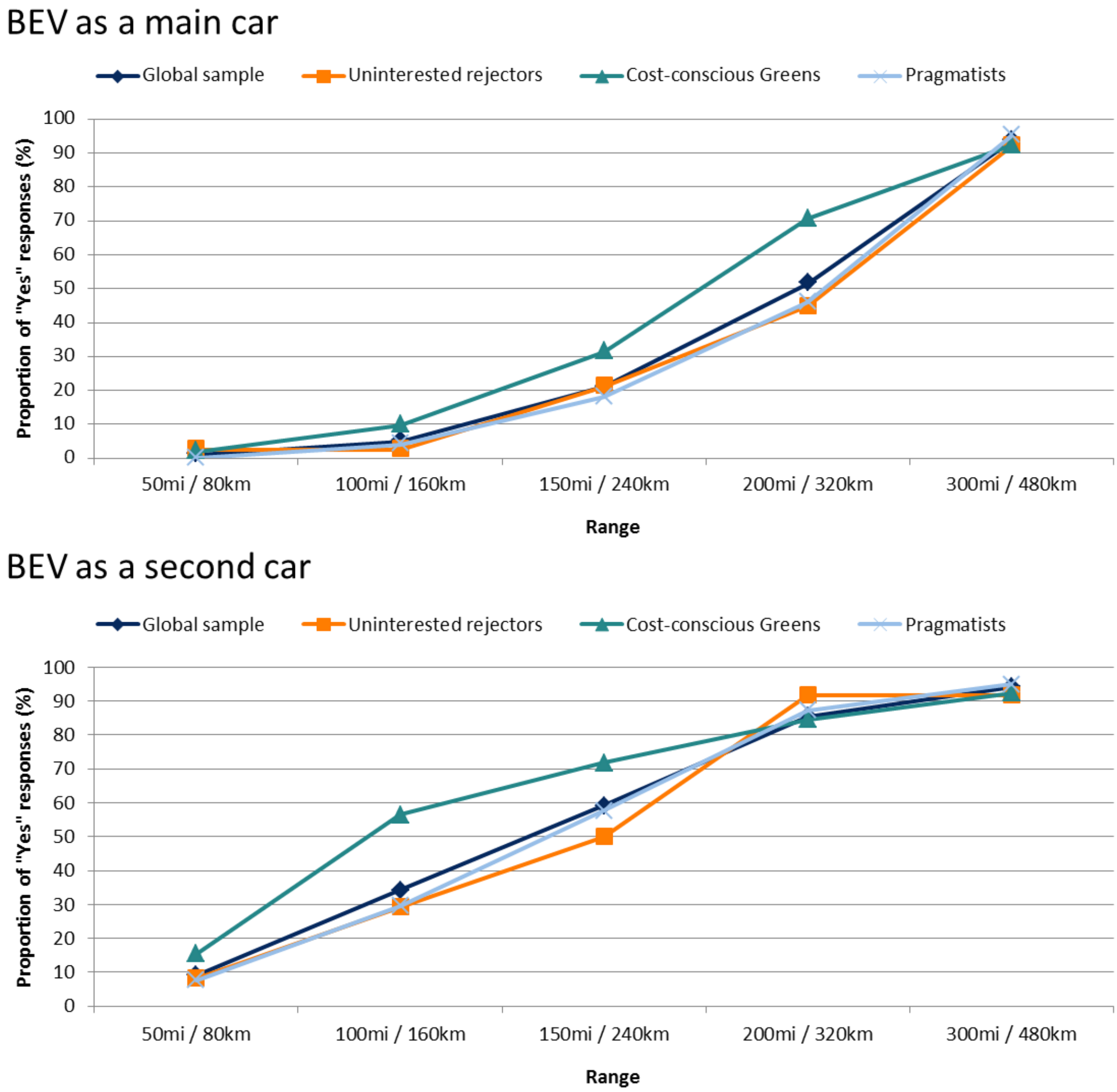


Figure 13: How willingness to consider owning a BEV as a main or second car depends on range, by consumer segment ('Yes' response indicates they would choose a BEV)

Participants' responses to these survey questions will have depended on their own perceptions of what "electric range" means; this will have been influenced by their direct experience of using the vehicles, including their experience of the rate at which the charge depleted, during the trial. Electric range here is therefore not necessarily the same as manufacturers' claimed range. Since participants had direct experience of BEVs and PHEVs to draw on, they are likely to have understood that real-world electric ranges are shorter than manufacturers' claimed ranges.

4.2.3 Effect of charging time on likelihood to choose a BEV or PHEV

Charging time impacted on likelihood of choosing a PHEV. Around 20% would be likely to choose a PHEV (as either a main or second car) if the time required to deliver 160 km (100 miles) of range was eight hours; but 50% would be likely to choose a PHEV if the time was four hours (about the time required with 7.2kW chargers).

Charging time also impacted on likelihood of choosing a BEV, which increased continuously as recharge time required to deliver 160km (100 miles) of range decreased from eight hours down to one hour. The recharge time at which 50% of participants would be willing to consider a BEV as a main car was under three hours, and as a second car was around five hours. The latter could readily be achieved using a 7.2kW home charger, while the former is not far short of the rate that can be achieved with the same charger. To appeal to over 90% of participants as either a main or a second car, 160km (100 miles) of range would need to be delivered in one hour of charging. This rate of charge is beyond the capability of present home chargers, but could be delivered by rapid chargers (43kW) at public locations. Whether it is practical to install a widespread network of public rapid chargers to meet this apparent need remains to be seen: again, it may relate to participants' perceptions about the utility of vehicles for longer journeys, in which a network of rapid chargers at motorway services and equivalent locations on major trunk roads might meet the need. This is discussed in the next section.

4.2.4 Effect of access to public and workplace charging on willingness-to-pay for a BEV or PHEV

The influence of access to public and workplace charging was explored in the choice experiment, which assessed willingness-to-pay for a BEV if such access were available. Access to workplace charging added £564 to what participants would be willing to pay for a BEV; access to public charging added £1,677, and access to both added £1,808. Willingness-to-pay for a PHEV was not influenced by access to either public or workplace charging, suggesting that the ability to run on its ICE made access to charging away from home less relevant when considering a PHEV.

Willingness-to-pay for a BEV increased if there was access to rapid charging on motorways and major A-roads every 20 miles: by £2,674 for Cost-conscious Greens, £2,421 for Pragmatists, but only £1,161 for Uninterested Rejectors. These figures did not increase substantially if the network was more widespread (e.g. on all A-roads), indicating that Mainstream Consumers see a need for rapid charging only on major routes.

4.3 Key conclusions and implications for analysis

It is recognised that the consumer marketplace for cars includes acquisitions of both new and used vehicles. Many of the CVEI analyses investigated willingness to consider a PHEV or BEV, and intentionally did not include price so that they could be applied to both new and used car acquisitions. High willingness to consider means that a car has sufficient utility to be admitted into a person's choice set. This applies whether the person is intending to acquire a new or a used car.

It is also recognised that a high proportion of UK new car sales are to fleets rather than consumers. The CVEI fleet case studies (Deliverable D6.1) indicated that for fleet cars, the majority of VKT are from vehicles based at their users' homes, and that whether those cars were chosen by the users or centrally by employers, consumer preferences were taken into account. The findings of the Consumer Uptake Trial are therefore also relevant to fleet car choices (although not the only influence).

The key conclusions from the Consumer Uptake Trial were:

- **In the early stages of PiV market development[46], PHEVs are likely to be adopted more quickly in the mass-market than BEVs.** 23% of participants reported being very likely to choose a PHEV as a main car in the next five years, versus only 8% for a BEV. However, the AER of PHEVs needs to increase to around 80km for the majority of mass-market consumers to consider one.
- **BEVs will be adopted more slowly in the early stages, especially as main cars.** As AERs increase, so will the appeal and market share of BEVs. AERs of 200 miles would enable them to appeal to 50% of Mainstream Consumers; AERs of 300 miles would enable them to appeal to over 90%. BEVs with these ranges will be needed if the UK government's Road to Zero ambitions are to be achieved.
- **BEVs have higher appeal as second cars in households than as main cars.** BEV models with ranges that would appeal to 50% of Mainstream Consumers as second cars in households (i.e. around 150 miles) are already available and will likely be present in the market in increasing numbers and at lower cost in the near future.
- **The appeal of PiVs in this study appears greater than in previous studies.** Reduction of psychological distance in the trial is likely to have contributed to this. Participants were more familiar with BEVs and PHEVs than most Mainstream Consumers today; though it is reasonable to assume that familiarity with these vehicle types will increase as the market develops. Other contributing factors might include differences in the specific question(s) asked between studies, differences in sampling (for instance, the use of a stratified sample in the Consumer Uptake Trial), greater awareness of PiVs in the population now, and more and better models of PiVs appearing on the market.
- **3.6kW charging rates are perceived as insufficient for mass-market uptake of BEVs as main cars**. 7.2kW chargers would offer sufficient charging rates for 50% of Mainstream Consumers to be likely to choose a PHEV, or a BEV as a second car. For BEVs to appeal to over 90% of participants as either a main or a second car, charge rates which can deliver 100km of range in one hour are required. This rate of charge is beyond the capability of present home chargers; it can be delivered by rapid chargers, though at present these can only be found at public locations.
- **Mainstream Consumers would be willing to pay extra for BEVs if they knew that they would be able to have access to workplace charging or public charging networks**. Since participants were likely aware that PiVs at present have a price premium relative to ICEVs, this might be interpreted as indicating that such premiums are more likely to be accepted if access to workplace and public charging networks was perceived to be sufficient. However, they would not be willing to pay extra for PHEVs in the same circumstances.
- **Mainstream Consumers are also willing to pay more for BEVs if they know that they will be able to have access to rapid chargers every 20 miles on motorways and major A-roads.** However, a wider network of rapid chargers appears unnecessary (in

[46] Early stages of the PiV market are considered in the absence of the kinds of changes to the wider landscape that are considered in the Narratives other than Business as Usual.

that participants' willingness to pay a premium for a PiV was not affected by greater network density).

- **Mainstream Consumers can be segmented by attitudinal and behavioural variables.** The "Cost-conscious Greens" segment (26% of the trial sample) was more interested than average in adopting PiVs while the "Uninterested Rejectors" segment (19% of the sample) was substantially less interested. Overall the segments' attitudes towards PiVs were broadly similar, suggesting common factors that were important to all of them. The differences between the segments suggest that the benefits of PiVs might usefully be expressed in different ways to the different segments.

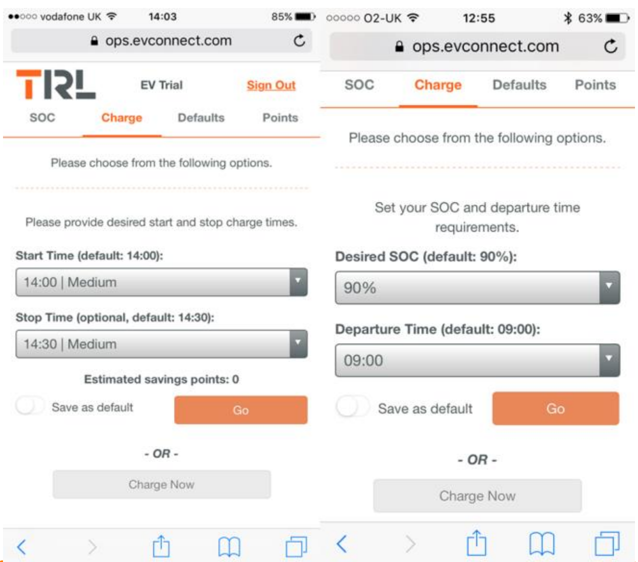
5 The Consumer Charging Trials

This section presents a summary of the Consumer Charging Trials; readers interested in the full details are referred to the Deliverable D5.3 report listed in the Bibliography.

The Consumer Charging Trials were designed to: (1) provide data on the charging behaviours of Mainstream Consumers using PHEVs or BEVs; (2) provide data on how far those charging behaviours were altered by participation in Managed Charging schemes; (3) identify how readily Mainstream Consumers would engage with Managed Charging schemes, and what factors would influence that engagement.

Two alternative Managed Charging concepts were tested:

- **User-Managed Charging**: The supplier provides price signals in the form of a banded multi-level tariff, with high rates at periods when electricity demand is usually high (e.g. early evening), and lower rates when demand is usually low (e.g. overnight)[47]. Users manage the timing of their PiV charging themselves, in response to these price signals.



Smartphone apps were developed to enable participants to engage with one of two Managed Charging schemes.

- **Supplier-Managed Charging**: Users specify the SOC they require and the time by which that SOC is needed. The supplier controls the timing of charging based on the variable cost of electricity during the period when the vehicle is plugged in and available to be charged, passing on a share of the cost savings achieved to the user. Users are encouraged to plug the vehicle in for as long as possible, to maximise the chance that low-cost electricity can be used.

[47] Different tariff structures were applied in winter and summer: for example, the timings of the winter bands were, in ascending order: Low (19:00-04:59), Standard (05:00-09:59), Medium (10:00-14:59), and High (15:00-18:59).

5.1 Key methodological features

Two parallel Consumer Charging Trials were carried out: in the first, 127 participants were provided with a Volkswagen Golf BEV for eight weeks, while in the second 121 participants were provided with a Volkswagen Golf PHEV for eight weeks. Participants in the BEV trial were recruited subject to a constraint that their typical vehicle usage patterns could be met by a BEV. Since the sampling criteria were different between the two trials, direct statistical comparisons between them were not possible, and the data were analysed separately for each.

Within each trial, participants were randomly allocated to one of three charging groups:

1. User-Managed Charging (UMC) group
2. Supplier-Managed Charging (SMC) group
3. Control group: Participants did not experience a Managed Charging scheme and were not incentivised to charge in any particular way

The Consumer Charging Trials had a number of methodological features:

- Mainstream Consumers (i.e. current ICEV owners) were recruited rather than the PiV Innovators who have participated in UK PiV charging trials to date.
- Participants were provided with either a PHEV or a BEV for the duration of the trial. Each participant had their vehicle for a minimum of eight weeks. To control for seasonal effects, participation was spread over a ten month period.
- Participants interfaced with their MC scheme via a smartphone app (in the case of the Control group, a simplified app enabled them to check their vehicle's SOC).

14,000 charge events, 60,000 journeys and 500,000 miles of travel were recorded in the Consumer Charging Trials

- To charge their PiV, participants were provided with a dedicated network-enabled 3.6kW charging unit at their home and with access to the Polar+ network of public chargepoints. (The UMC and SMC schemes were only applied to home charging.)
- Data on home charging events were collected via the charging unit. Telematics data from the vehicle recorded vehicle usage, including away-from-home charging data.
- The key dependent variables in the Consumer Charging Trials were a series of measures of home-charging behaviour such as the frequency of home charging, and the distributions of plug-in time and charge-start time. Aspects of charging away from home were also measured. It was anticipated that charging behaviours might differ at weekends because of potentially greater behavioural flexibility, so these measures were analysed separately for weekdays and weekend days. Self-reported attitudes and willingness to adopt MC schemes were also collected, before and after the trial experience.
- Participants completed a choice experiment following their experience of using and charging the vehicles, in order to characterise preferences for MC schemes and the relative importance of MC scheme attributes.

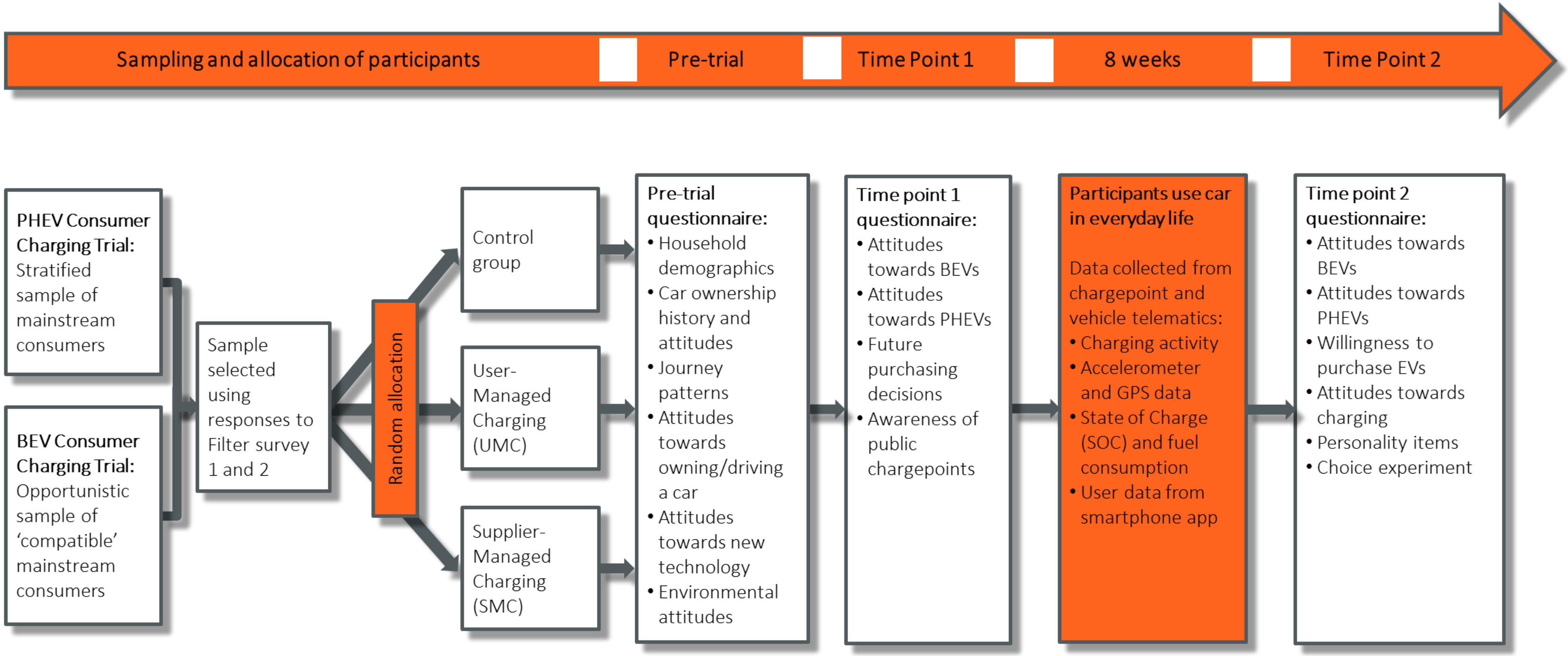


Figure 14: Overview of the Consumer Charging Trials method

5.2 Key findings

The majority of charging events during the Consumer Charging Trials took place at home. Although data on away-from-home charging events were collected, these are not discussed here; readers are referred to the detailed reports on the Consumer Charging Trials that are listed in the Bibliography.

5.2.1 Charging behaviour without Managed Charging

Control Group participants, who were not involved in a Managed Charging scheme, usually started charging at home in the late afternoon/early evening (15:00 to 20:00), with a peak in weekday charge starts between 17:00 and 18:00 for PHEV participants, and between 18:00 and 19:00 for BEV participants, as shown in Figure 15.

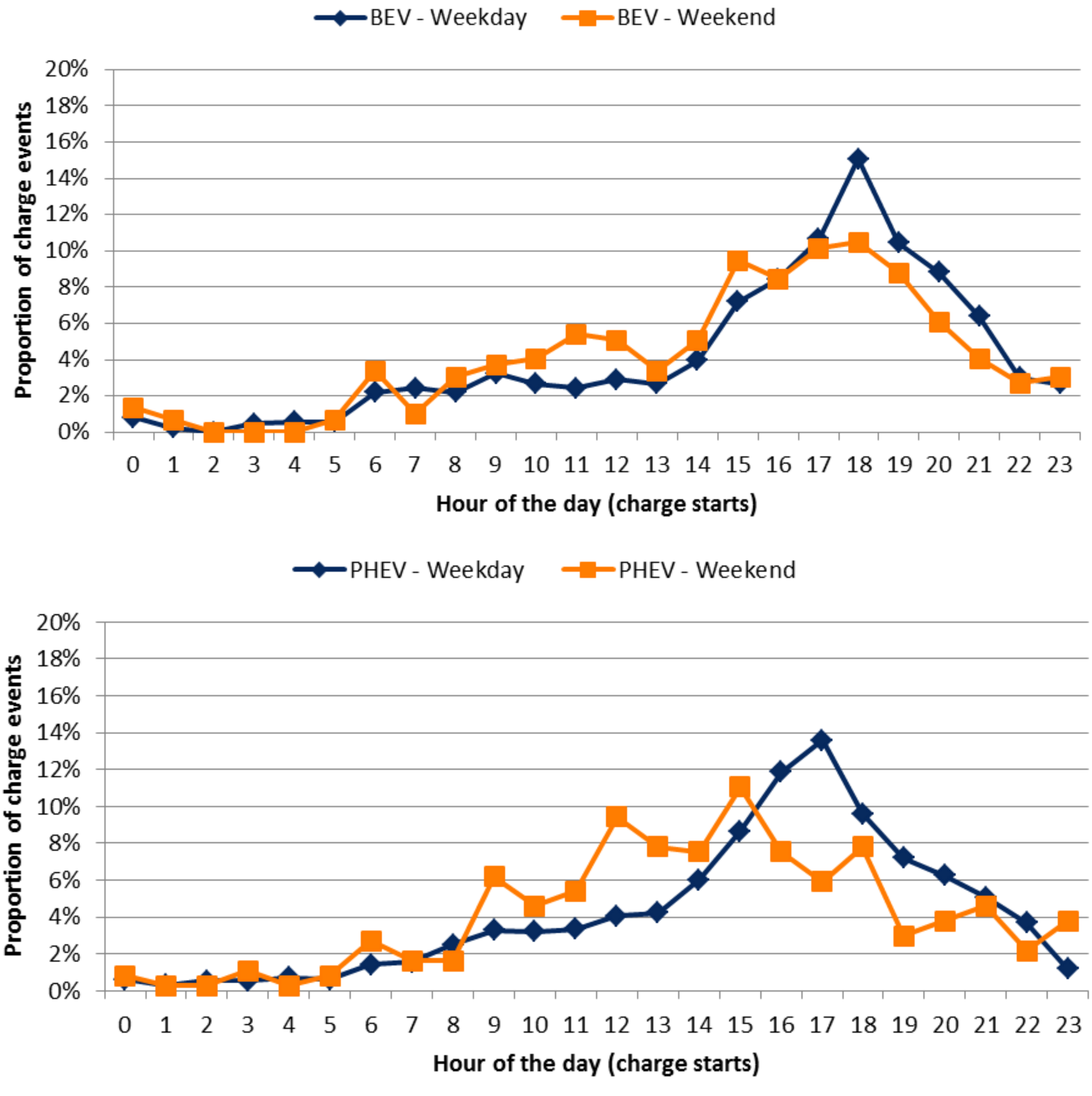


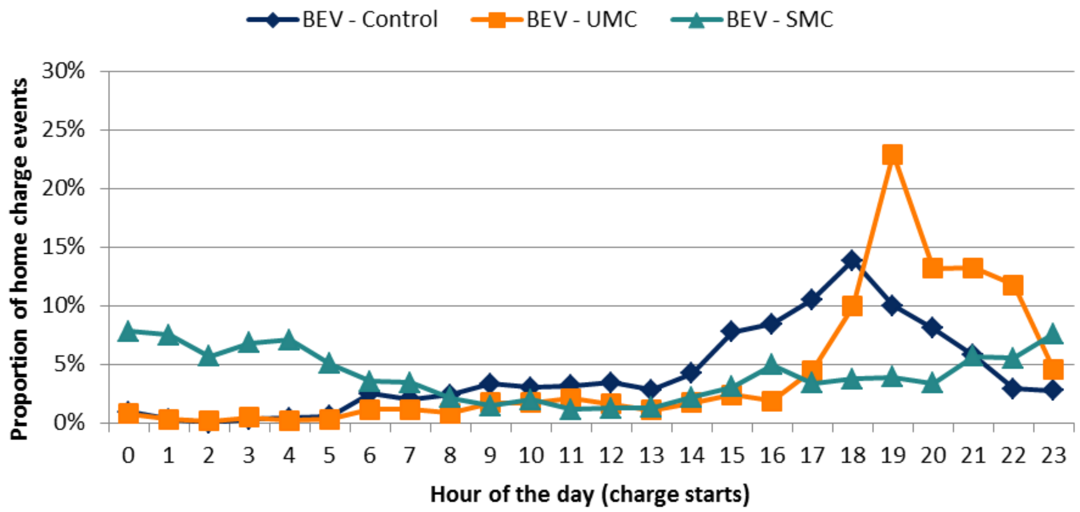
Figure 15: Percentage of control group home charge weekday and weekend charging events starting in each hour of the day (BEV – top, PHEV – bottom)

At weekends the peak in charge starts was less pronounced, with a greater share of charge events starting earlier in the day. Median control group charging durations were approximately 3.7 hours for BEV users and 1.8 hours for PHEV users. Thus without MC, on average, peak demand from BEVs extended to around 21:00, and from PHEVs to around 19:00.

These results confirm that when charging is not managed, Mainstream Consumers are likely to start charging their vehicles in the early evening when other electricity demands are high.

5.2.2 *Effects of UMC and SMC on charging behaviour*

Figure 16 shows that both UMC and SMC were effective at shifting the time at which PiV charging started to later in the evening (UMC) or overnight (SMC) when other electricity demands are lower. This effect, which was observed for both BEV and PHEV participants, is shown aggregated over both weekdays and weekend days; the differences between weekday and weekend day profiles are available in D5.2.



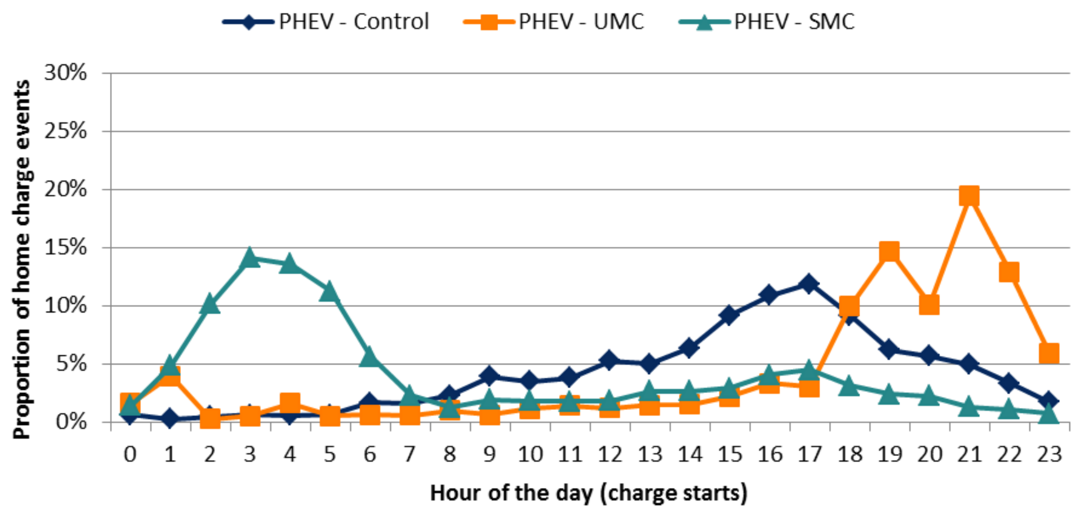


Figure 16: Percentage of home charge events starting in each hour of the day for Control, UMC and SMC participants (Top – BEV, Bottom – PHEV)

The effect of SMC on charge start time was to some extent an artefact of the way SMC was simulated in the trial. The trial used a simplified charging algorithm in which charging was started at the latest time by which the required state of charge could be delivered an hour before the participant’s required finish time. It is useful, therefore, to consider when participants plugged their vehicles in, since the plug-in time represents the start of the time window when the vehicles were available for the supplier to manage charging. This is shown for BEV users in Figure 17 (the profiles were similar for PHEV users).

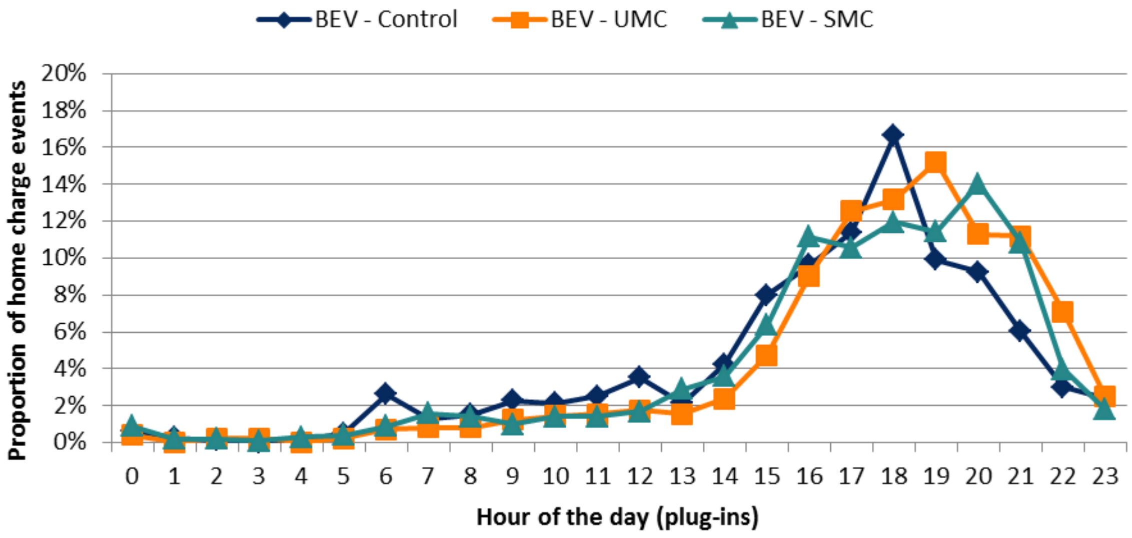


Figure 17: Proportion of home charge events by plug-in hour for BEV users in Control, UMC and SMC groups

There was some evidence of SMC participants plugging in a little later in the evening than Control group participants, but importantly the majority of vehicles were available for charging throughout the later evening and overnight when demand (and therefore prices) is generally lower. The average home charge duration for SMC BEV users was about 4 hours, whilst they plugged in for an average of 13 hours. These results suggest that, on average, BEV SMC users were providing suppliers with substantial flexibility over the timing of charging. For PHEV users in the SMC group, there was even greater flexibility, since average plugged-in time windows were similar (at 14.5 hours) but average charge times were lower at about 1.6 hours.

5.2.3 Impact of charging behaviour on energy demand profiles

Figure 18 and Figure 19 show the impact of MC on the average hourly energy demand per participant from BEV and PHEV charging, respectively, on weekdays. Participation in UMC or SMC had a substantial effect on the hourly energy demand profiles compared to when participants were not in such schemes (Control group). The peaks in the energy demand profiles for both BEV charging and PHEV charging were shifted to later times with both UMC and SMC schemes. Such shifts have the potential to alleviate grid-level issues of supply-demand balancing, and issues of operation within local network capacity constraints. With UMC however, consideration should be given to the risk of creating a new peak in demand, if the majority of consumers shift their demand to the first or early hours of the off-peak period. This could cause problems in itself, especially if large clusters of PiV drivers in a local area follow the same UMC tariff band structure.

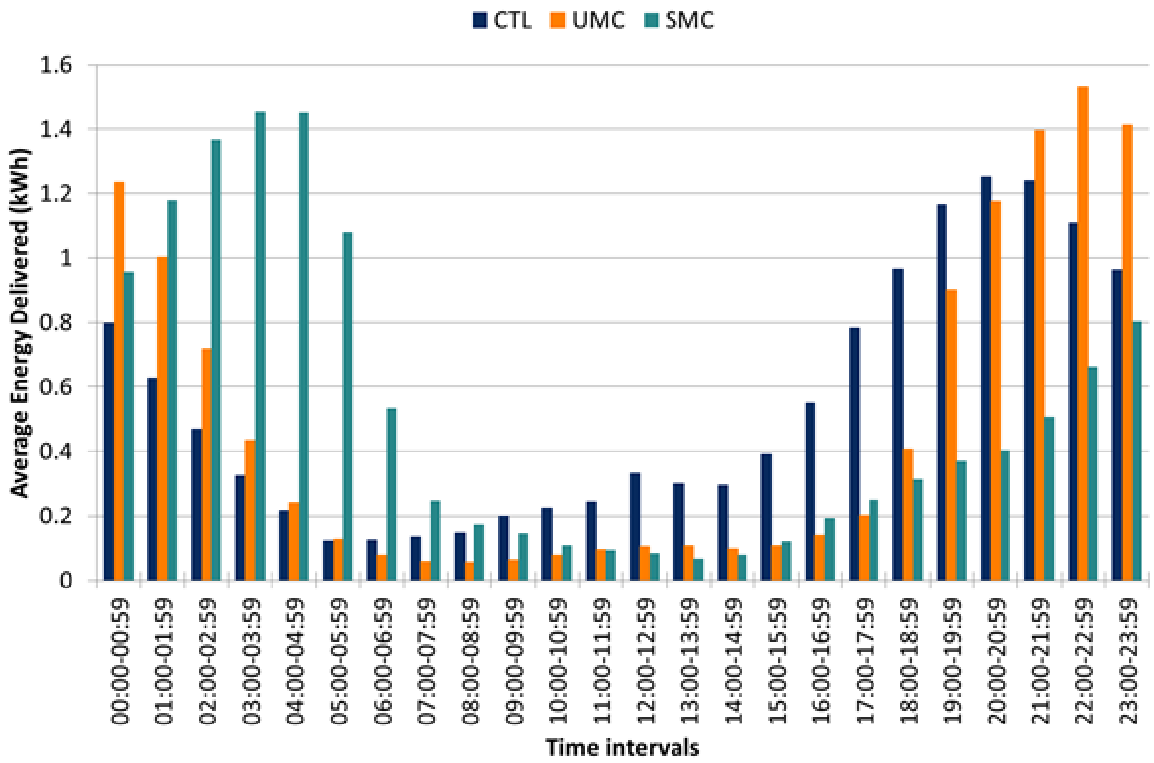


Figure 18: Average energy delivered per participant per hour of the day for BEV charging, weekdays, for Control, UMC, and SMC groups

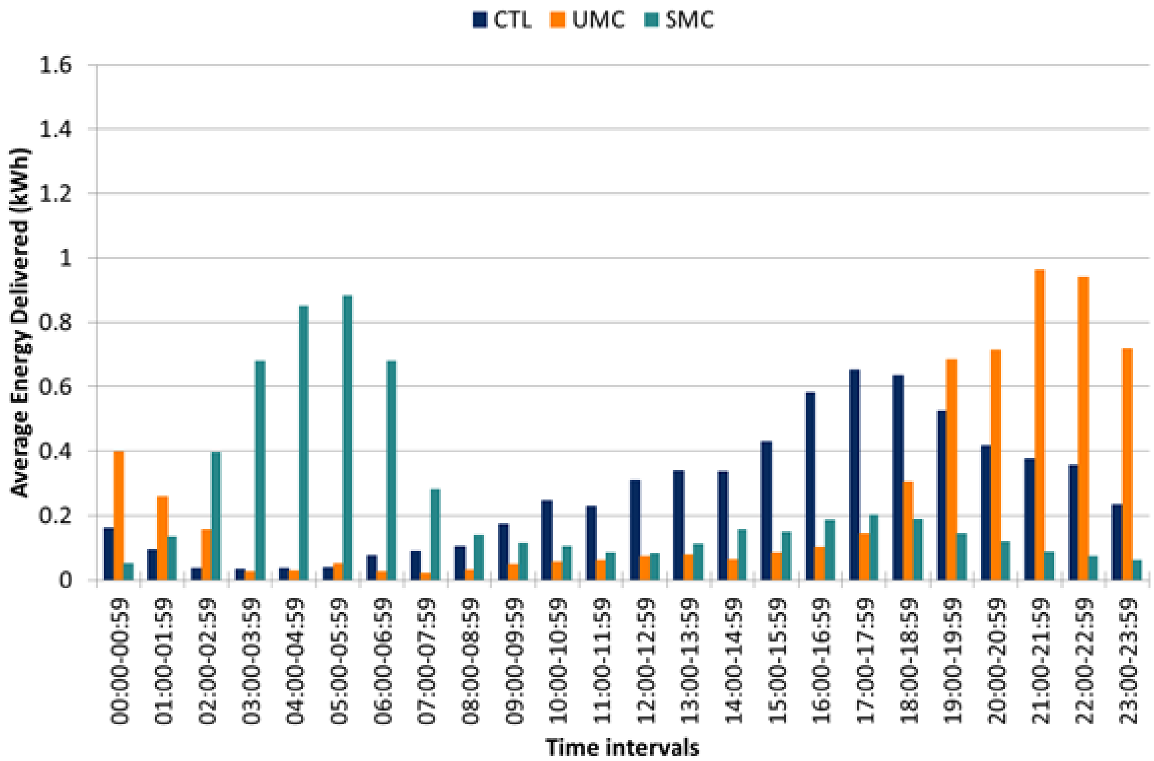


Figure 19: Average energy delivered per participant per hour of the day for PHEV charging, weekdays, for Control, UMC, and SMC groups

5.2.4 Evaluations of and attitudes towards UMC and SMC

The majority of participants in the UMC and SMC groups were either satisfied or very satisfied with the MC scheme they had experienced in the trial.

Participants' willingness to choose UMC or SMC after their trial experience was found to be high. Averaged across groups, just under 90% of participants would choose either UMC or SMC over unmanaged charging, whether they had a PHEV or a BEV.

Even participants from the Control groups, who had not experienced MC during the trial, expressed a preference for both forms of MC over unmanaged charging: this suggests that the basic concept of MC has appeal to PiV users even when they have not experienced it for themselves. Control group participants were substantially more likely to choose UMC over SMC, resulting in UMC being preferred to SMC by a majority of the participants taken as a whole. However, BEV users who had direct experience of SMC were more likely to prefer an SMC scheme. This suggests that experience with SMC is important for adoption of that type of MC scheme.

Choice experiment results showed that the value BEV participants attached to MC tended to be higher if there was nearby public charging, and with that value increasing the nearer the public charging was to their homes. It may be that nearby public charging was perceived as a back-up in case the vehicle was needed sooner than planned and had not yet charged to the level required. The effect was not observed for PHEV drivers, possibly since they could fall back on the ICE in the event of insufficient charge.

Participants attached more value to MC the greater the expected annual cost savings, and the lower the peak cost of charging within a scheme. An override feature enabling users to charge at once was a desirable feature. Participants did not attach much value to the accuracy of estimates of cost saving, or to anticipatory charging in SMC (where the system charges the vehicle more than the user has specified if electricity is cheaper than anticipated in the immediate few days).

5.3 Key conclusions and implications for analysis

Charging profile data (as discussed in Sections 5.2.1 and 5.2.2) was incorporated directly into the Whole-System Analysis to enhance the accuracy of modelling of PiV charging demand and to enable exploration of the systemic impacts of UMC and SMC. The key conclusions from the trials are summarised below. An account of the wider conclusions from the trials is given in the detailed reports listed in the Bibliography.

- **Control group participants (not participating in formal Managed Charging schemes) usually started charging at home in the late afternoon/early evening (15:00 to 20:00)**. At home, weekday charge start times peaked between 17:00 and 18:00 for PHEV participants, and between 18:00 and 19:00 for BEV participants. At weekends the peak in charge start times was less pronounced, with a greater share of charge events starting earlier in the day.
- **Compared with unmanaged charging, the proportion of home charge events starting between 16:00 and 19:00 was more than halved in the UMC and SMC groups.** The greatest reduction was observed in the SMC group. The majority of charging was shifted to later in the evening (UMC) or overnight (SMC). This effect was observed for both weekday and weekend charging.

- **Managed Charging was found to be more appealing than unmanaged charging** to the majority of participants, even when they have not themselves had any direct experience of Managed Charging.
- **In general, after receiving information about both MC schemes at the end of the trial, participants indicated that UMC schemes have higher appeal than SMC. However, BEV drivers who have had direct experience of SMC are more likely to prefer an SMC scheme.** This suggests that experience with SMC is important for adoption of that type of MC scheme, which has important implications for policy. The close proximity of public charging infrastructure to home may shift preference towards SMC.
- **The key attributes that contribute to an attractive MC scheme for consumers include high annual cost savings, low peak electricity costs, and nearby public charging.** The findings overall suggest that the quality and reliability of service and who bears the financial risks and is in control of when the vehicle is charged are important factors. Specific features which make SMC more attractive include an override function (even where the user bears all the financial penalty of changing settings), and availability of a rapid charge point within five minutes of participants' homes.

6 Analysis: comparison of Narratives

This brief summary of the analysis focusses on comparing the Narratives; readers interested in the sensitivity analyses are referred to Deliverable D7.4 listed in the Bibliography.

6.1 Quantitative metrics

Table 4 shows the key quantitative metrics for each of the Narratives (the metrics are defined in Table 2). The solid green colour coding indicates that the Narrative scored favourably on the metric compared to the other Narratives, whereas the solid red at the other end of the spectrum indicates that it scored lower than other Narratives. The table shows the gap between government tax income from road transport and expenditure on it. In addition it shows the cost of introducing a technology-neutral mechanism to fill this gap (expressed as both a fixed cost per vehicle and as a cost per km driven).

The analysis shows that no Narrative scored highly on all metrics, for example:

Transport on Demand Narrative	Scored relatively well on metrics relating to the Customer Proposition and Physical Supply Chain, but relatively poorly on metrics relating to the government aspects of the Market and Policy Framework (MPF).
Business as Usual Narrative	Scored relatively well on metrics relating to the MPF and Commercial Value Chain, but relatively badly on metrics relating to the Consumer Proposition and Physical Supply Chain.
Composite Narrative	Intended to combine aspects of what 'good' looks like from the original Narratives. It was successful in driving a higher level of low carbon vkm compared to the non-Road to Zero narratives (ca. 90% versus ca. 80%) with a relatively limited increase in absolute government support, due to its better targeting of policy measures. However, significant incremental effort is still required to move to closer to the Road to Zero requirements.

Since none of the Narratives led straightforwardly to positive outcomes on all metrics, a degree of trading-off between metrics is required, and policymakers and other actors will need to prioritise between dimensions. For government, the focus is likely to be on metrics which highlight the extent of light-vehicle decarbonisation achieved (e.g. low carbon VKT, residual cost of the carbon) versus the implications for transport-related finances to achieve high levels of decarbonisation. Commercial actors are focused on generating sufficient returns from vehicle sales and in infrastructure; the primary focus would be on the metrics of consumer transport costs and low carbon VKT (i.e. giving an indication of the attractiveness of potential ULEV vehicle sales) and the scale subsidy required for new infrastructure. The analysis indicates that the Composite pathway appears the most favourable through to the 2030s and early 2040s, achieving very high levels of transport decarbonisation at moderate costs compared to the other pathways. However, policy makers are still faced with the challenge of how to decarbonise the remaining ca. 10% of vkm given the likely costs of trying to achieve this via incentive policy compared to the more politically challenging route of removing consumers' ability to purchase conventional vehicles.

Table 4: Quantitative metrics for each Narrative

Narrative scores poorly relative to other Narratives → Narrative scores favourably relative to other Narratives

Key quantitative metrics			BaU	OEM	City	ULEV	H2P	ToD	Comp	Context
Customer	Low carbon vkm 2050	%	75%	82%	81%	99%	97%	99%	91%	The corresponding transport emissions across the Narratives are 1-20 MtCO2/year in 2050, compared to 90 MtCO2/year in 2018. In 2050, the share of emissions from transport is around 1-19% of the total 105MtCO2/year limit across the Narratives, compared to 20% in 2018. In 2018, the average cost of transport is 31 p/km.
	Car transport costs 2050	p/km	23.0	22.3	22.0	20.7	18.8	20.0	22.2	
Physical	PV residual carbon cost over pathway (at SDR)	£bn	95.3	78.6	74.1	38.3	53.4	20.1	66.7	The PV of the residual carbon cost if emissions continue at 2018 levels ranges from £148-220bn across the Narratives.
	Undiscounted residual carbon cost in 2050	£bn/yr	11.0	6.7	8.2	0.4	1.0	0.3	3.0	The residual carbon cost in 2050 if emissions continue at 2018 levels ranges from £33-50bn across the Narratives.
Commercial	PV potential subsidy over pathway for selected entities (at WACC/margin)	£bn	0.3	0.4	0.3	4.9	6.7	1.3	0.5	The subsidy for charging and H_2 infrastructure represents up to 1-2% of their CapEx over the pathway and up to 7-8% with H_2 pipelines.
	manufacturer penalty	*£bn*	-	-	-	-	-	-	-	There are no expected penalties given that the level of ULEV uptake is sufficiently high to be below the emissions threshold.
Government	PV of net tax and spend gap over pathway (@SDR)	£bn	208	245	223	347	411	440	232	The gap is between 28-73% of the taxes received from transport due to spending on grants and subsidies. Net revenues from transport represent around 2.5% of Gross Domestic Product (GDP) in 2018, reducing to below 0.9% for all the Narratives by 2050 and negative for H2P due to high subsidies on FCVs.
	of which direct subsidy	*£bn/yr*	*0.6*	*15*	*14*	*67*	*155*	*103*	*5*	
	Undiscounted net tax and spend gap in 2050	£bn/yr	43	48	36	55	81	53	48	
To fill PV of MPF gap (@SDR)	*Average vehicle tax*	*£/veh/yr*	145	170	165	243	286	345	161	Currently VED which, from 2017, is a fixed £/veh cost independent of the vehicle type is £140/year.
	Average road usage charges	*p/vkm*	0.8	0.9	0.9	1.4	1.6	1.6	0.9	On average this represents 3-8% of the actual cost of transport across the pathway to 2050 in the Consumer metric.

Innovation; City: City Led; ULEV: ULEV Enabled; H2P: Hydrogen Push; ToD: Transport on Demand; Comp: Composite)

6.2 Evolution of light duty vehicle parc powertrain numbers

Figure 20 shows the assumed evolution of the total car and van vehicle parc over time within the Narratives. It also highlights the impact on the car stock from different assumed levels of car sharing within the City and Transport on Demand Narratives.

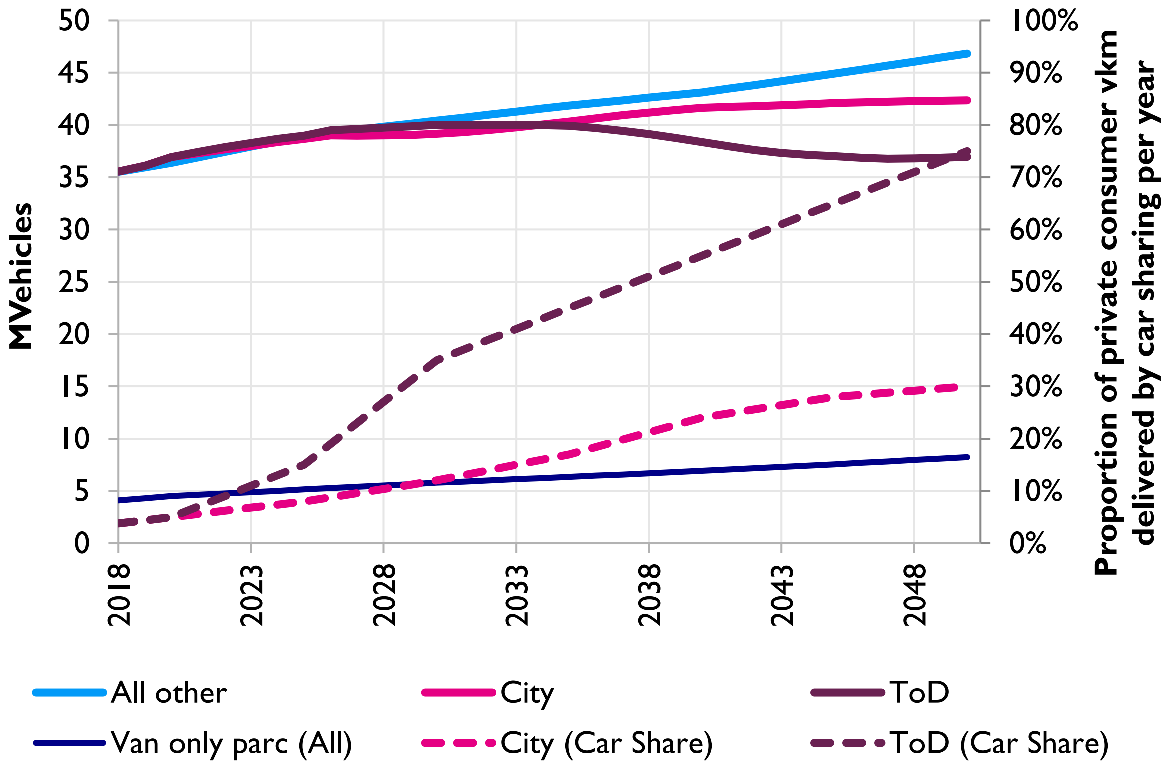


Figure 20: Total vehicle parc over time given proportion of car sharing

Figure 21 shows the evolution of the number of each of the major light duty powertrain types (ICEV, BEV, PHEV and FCV) in the UK light duty vehicle parc over the interval to 2050 in each of the Narratives. The number of ICEVs is predicted to fall from its present level in all Narratives, but there are substantial differences in how far: to virtually zero in the Transport on Demand and ULEV Enabled Narratives, but only to 13m in the Business as Usual Narrative.

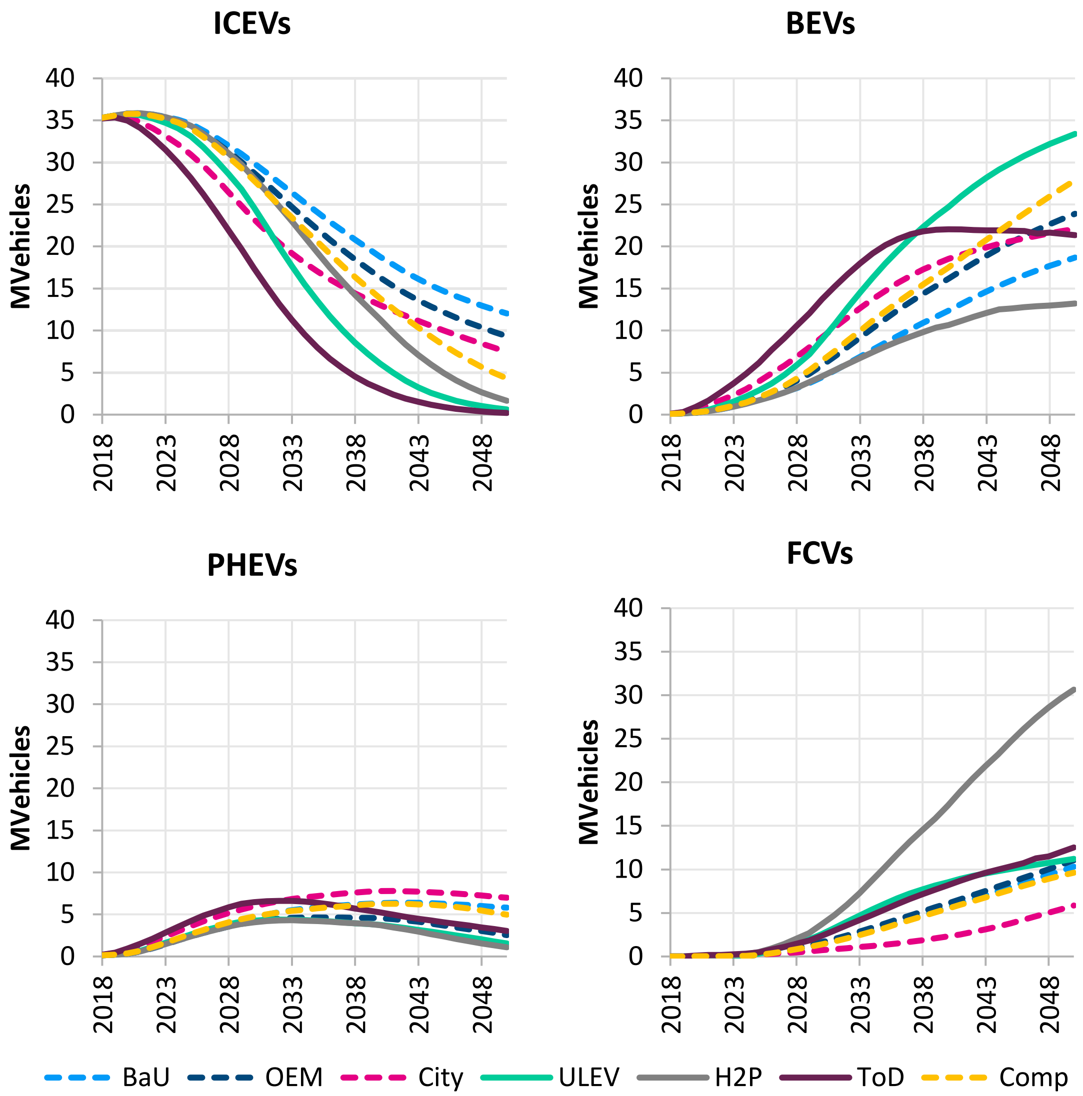


Figure 21: Numbers of major powertrain types in the UK light duty vehicle parc over the interval to 2050 under each Narrative (M Vehicles = Million vehicles)

The analysis indicates that under the BaU Narrative, there would be more PHEVs (approximately 5 million) than BEVs (approximately 3.5 million) by 2027, consistent with the Consumer Uptake Trial findings that Mainstream Consumers at present are generally more likely to consider a PHEV over a BEV.

BEV numbers increase in all Narratives, but with very large differences in how far: to 34.1m in the ULEV Enabled Narrative, but to only 13.4m in the Hydrogen Push Narrative (where instead the FCVs dominate). In the Transport on Demand Narrative BEV numbers peak at 22.4 million in 2040 but then fall, as increasing dominance of the MaaS model requires fewer vehicles on the road.

In all Narratives PHEVs play a transitional role, providing some fuel flexibility and system resilience in the short to medium-term. PHEV numbers initially increase in all Narratives as their costs reduce and their AER improves. After 2040 their numbers level off or decrease, depending on the Narrative concerned. They become less attractive than BEVs or FCVs, both of which are expected to improve substantially by this date.

FCV numbers increase to around 11m vehicles in most Narratives, but are much higher (31.7m) in the Hydrogen Push Narrative, where they come to dominate the market. In the core narratives a smaller backbone hydrogen infrastructure is developed organically over time, from the late 2020s onwards, focused around serving smaller numbers of longer-distance van and company car drivers.

6.3 Road transport CO_2 emissions

Figure 22 shows the share of total low-carbon[48] light duty VKT per annum in the UK over the interval to 2050 in each Narrative (the *underlying customer demand* for VKT is the same in each Narrative however the total VKT is higher due to 'dead miles' repositioning the vehicles which are not associated with meeting the underlying demand).

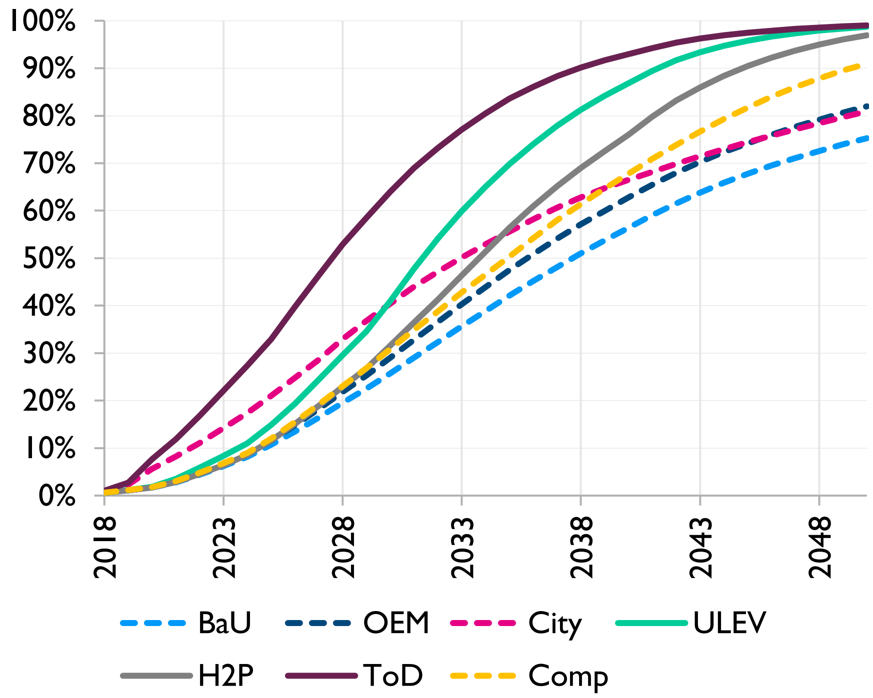


Figure 22: Evolution of the share of total light duty VKT that is low-carbon, over the interval to 2050, in each Narrative

The share of low-carbon VKT is a critical metric that depends on uptake of low-carbon vehicle types, and, in the case of PHEVs, their utility factor (the fraction of their VKT driven under electric rather than ICE power)[49], and, for both types of PiV, on decarbonisation of power generation. It increases in all Narratives, reaching 73% by 2050 in the Business as Usual Narrative. In other Narratives it is much higher: in Hydrogen Push, 95.9%; in ULEV Enabled, 98.5%, and in Transport on Demand, 99.4%.

[48] This is defined as zero emissions at tail-pipe (i.e. from electric and hydrogen delivered vkm). The Whole-System Analysis approach means that the production of electricity and hydrogen is consistent with a UK energy system achieving an 80% reduction in greenhouse gas emissions by 2050 compared to 1990 levels.

[49] Share of electric vkm driven for a PHEV are modelled as a concave function of battery range. As an example, at a battery range of c. 25km around 50% of all vkm are assumed to be driven under electric power, whilst at 50km this rises to c. 75%.

As a consequence, road transport CO_2 emissions fall substantially in all Narratives, as shown in Figure 23. Even in the Business as Usual Narrative they fall from around 90MtCO_2 to 20 MtCO_2; under the Transport on Demand, ULEV Enabled, and Hydrogen Push Narratives they fall to close to zero.

Importantly, share of low-carbon VKT is greater, and CO_2 emissions are lower, much earlier in the pathway under the Transport on Demand Narrative than in any of the others. Since climate change is driven by the cumulative amount of greenhouse gases in the atmosphere, (e.g. Allen, Frame, Huntingford, Jones, Lowe, Meinshausen & Meinshausen, 2009; Energy Technologies Institute, 2013; Skippon, Veeraraghavan, Ma, Gadd & Tait, 2012) measures that reduce CO_2 emissions earlier have a greater positive effect in containing climate change than those that take longer to materialise. In terms of the contribution to limiting climate change, the Transport on Demand Narrative is the most effective.

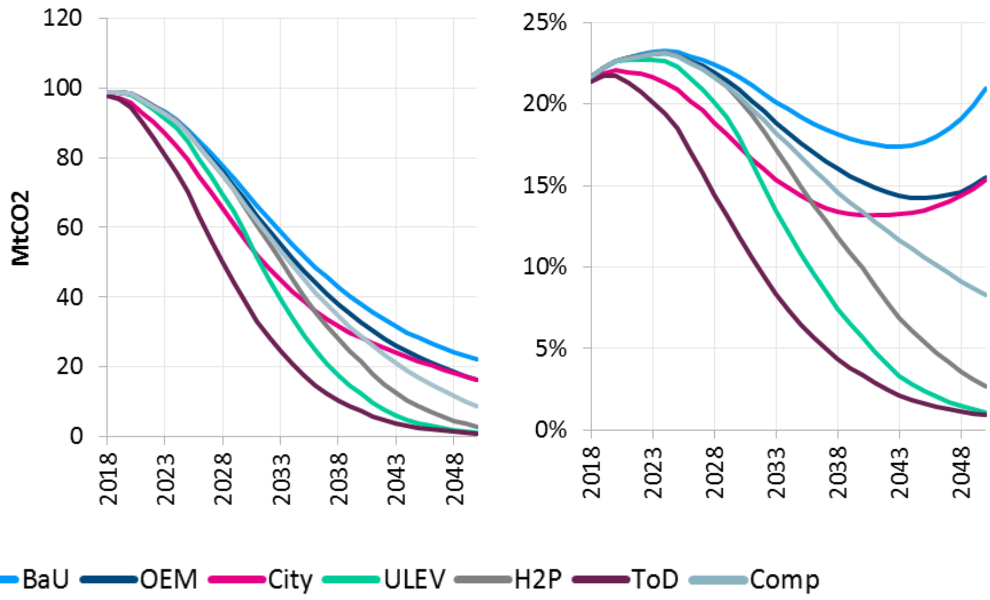


Figure 23: Road transport tailpipe CO_2 emissions (left), and percentage share of total annual CO_2 attributed to cars and vans (right) over the interval to 2050 in each Narrative

The primary production of electricity and hydrogen is calculated as part of the Whole-System Analysis and framed within the UK's target of an 80% reduction in greenhouse gas emissions by 2050 and intermediate carbon budgets. As a result, their long-term carbon intensity of production is very low. By 2050 around half of the hydrogen is produced via biomass with Carbon Capture and Storage (CCS) routes, with the remainder from fossil plus CCS routes. For electricity, by 2050, less than 0.5% of all generation is from unabated fossil routes with the remainder from a mix of renewables, nuclear and fossil plus CCS.

6.4 Qualitative metrics

Table 5 compares the Narratives using the two qualitative metrics, Transport utility and Impact on wider UK economy. Each Narrative is compared to Business as Usual (BaU), and is given a subjective rating relative to BaU at the start of the entry for each metric, at the head of the column.

Table 5: Comparison of Narratives: qualitative metrics (continued on next page)

Narrative scores poorly relative to BaU — Narrative scores favourably relative to BaU

Metric	Guided OEMs	City Led	ULEV Enabled	Hydrogen Push	Transport on Demand	Composite
Transport utility	Customers still retain ownership of the vehicles as an asset Modest effort is expended (e.g. with respect to charging infrastructure) to try to ensure that any adverse implications for transport utility (e.g. refuelling/charging and the implications this may have for travel patterns) associated with people and goods are minimised. However, this is still likely to result in some loss of utility compared to the BaU Narrative.	Vehicle sharing, particularly at lower levels of penetration, may lead to some loss of flexibility in transport utility (e.g. booking ahead and fixing patterns to secure availability of a vehicle). This may not be acceptable to consumers who may prefer to retain utility but at increased cost. Car sharing only focused in urban areas may impose some additional restrictions on flexibility for longer distance journeys (e.g. increasing reliance on public transport). Consumers may face less choice of vehicle sizes/styles for shared cars versus privately owned cars. In addition, widespread application of congestion charging may also impact adversely on desired travel patterns, but with different distributional impacts for different types of vehicle users (i.e. ULEV users may benefit from near term exemptions).	Customers still retain ownership of the vehicles as an asset. Significant effort is expended (e.g. with respect to charging infrastructure) to try to ensure that any adverse implications for transport utility (e.g. refuelling/charging and the implications this may have for travel patterns) are minimised. However, at best this is still likely to result in a level of transport utility comparable to BaU Narrative.	As per ULEV Enabled	Vehicle sharing may lead to some loss of flexibility in transport utility (e.g. booking ahead and fixing patterns to secure availability of a vehicle). This may not be acceptable to consumers who may prefer to retain utility but at increased cost. With extended car sharing there may be wider choice in vehicle sizes/styles versus urban car sharing and consumers may be able to tailor their vehicle choice to their type of trip. The car sharing operators may handle the majority of refuelling/charging needs, as well as covering the maintenance and insurance. Further, the potential for dedicated parking along key routes/in dedicated hubs may increase the convenience for consumers.	As per Guided OEMs

Narrative scores poorly relative to BaU — Narrative scores favourably relative to BaU

Metric	Guided OEMs	City Led	ULEV Enabled	Hydrogen Push	Transport on Demand	Composite
Wider impact on UK economy	OEM's focus on additional services (e.g. maximising convenience or information services for the consumer) and/or better integration of current services (e.g. maintenance) is likely to lead to some additional innovation and economic benefit compared to the BaU Narrative. However, the expectation is that this is modest compared to the core developments related to power trains and direct infrastructure.	Vehicle sharing, particularly at higher levels of penetration, leads to a higher stock turnover (on the assumption that vehicles are typically retired at three times the rate of Private Consumer vehicles, not accounting for whether it is economic to design them for longer lives). As car sharing is concentrated in urban areas, those in rural areas may face a higher cost of transport which, if prohibitively high, could limit travel from these areas creating local silos and potentially negative social and economic consequences as a result. Higher stock turnover could provide a potential boost for manufacturers and other related entities on the supply chain as returns from new innovation may be realised more quickly (in a regional/ global context).	A combined government and OEM focus on different aspects of additional services (e.g. maximising convenience or information services for the consumer) and/or better integration of current services (e.g. maintenance) is likely to lead to some additional innovation and economic benefit compared to the BaU Narrative. However, the expectation is that this is modest compared to the core developments related to power trains and direct infrastructure.	A significant and focused pull towards hydrogen as the only core ULEV energy vector could result in a greater rate of innovation in FCVs and associated technologies (assuming the UK becomes a leader in related areas). In addition, this could be accelerated further for other parts of the hydrogen value chain when considering hydrogen production and transmission for ULEVs in conjunction with the use of hydrogen in the wider energy system (in particular for power and industry and aviation).	Generally, as per City Led, higher levels of penetration and a substantially smaller vehicle parc (assumed to be the case provided there is no modal shifting) may lead to other benefits such as a freeing up of land used for parking.	Similar to the BaU Narrative, noting that whilst this Narrative included charging behaviour that is similar to OEM and a carbon tax, as per ULEV, the Narrative is otherwise heavily based on BaU.

7 Roadmap and recommendations

The analysis was used to identify potential elements of a solution for transitioning to a secure and sustainable low-carbon UK parc of light duty vehicles, and to set these out on a roadmap, as shown in Figure 24. The roadmap gives broad timing guidelines both for when government intervention is required and when key industry participants should act in order to achieve efficient ULEV deployment and use[50].

The elements of a solution are summarised in Table 6. They are prioritised as follows:

Essential	Actions clearly identified as having a clear positive ('good') impact, and which were found to be robust to different circumstances explored through the sensitivity analyses. They are considered to be high priority actions. However, this does not imply that all of these actions need to be implemented immediately as outlined in Figure 24[51].
Desirable	Actions for which a strong case exists and which are likely to have a positive impact under most circumstances. However, a failure to employ these actions is unlikely, by itself, to lead to a failure to achieve mass uptake and use of ULEVs. Additional evidence or reduced uncertainty may also be desired by individual actors before a decision is made to implement them.
Provisional	Actions for which a positive case may exist, but for which the extent or timing of deployment is likely to depend on reduction of uncertainty in the basis of analysis. This may occur through the passing of time and, for example, realisation of total (out-turn) costs. Alternatively, it may occur through obtainment of additional or expanded evidence from trials or initial pilot scale deployment.

An extended version of Table 6, giving further details of each element, can be found in the Deliverable D7.4 Market Design and System Integration report, listed in the Bibliography.

[50] Several additional analyses were also carried out. These included the sensitivity analyses and thematic analyses around the UK government's RtZ ambitions, the role of Demand Management and the potential shift towards Mobility as a Service. Details of these analyses can be found in the Deliverable D7.4 report, listed in the Bibliography.

[51] For example, the need to fill a long-term gap in transport related revenues, by a mechanism such as road pricing, occurs under all Narratives and sensitivities explored. However, this does not become material until the latter half of the pathway.

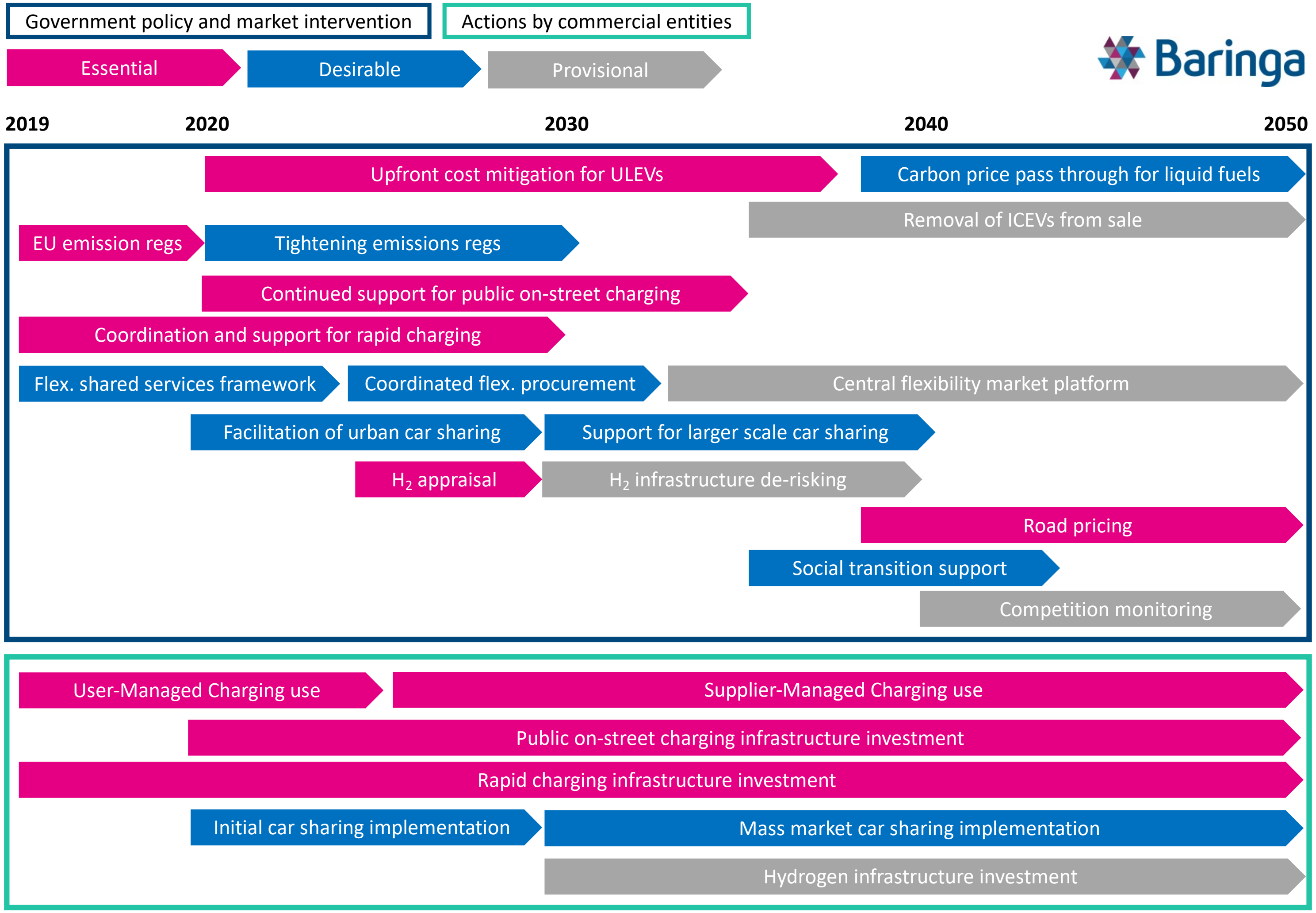


Figure 24: Roadmap for efficient ULEV deployment and use

Table 6: The key requirements of government policy and market intervention

(actions grouped into Essential, Desirable, and Provisional categories as in Figure 24)

Element	Commentary
Essential	
Upfront cost mitigation for ULEVs	▸ **Reducing upfront ULEV costs is crucial to driving enhanced ULEV uptake, however, the proportion of low carbon vehicle km can be significantly increased by 2050 versus today through use of modest subsidies for a limited period only.** The results from this analysis show that a Narrative with no further subsidies after the current Plug-in Grant schemes end in 2020 resulted in the proportion of vkm that are low carbon being 42% by 2035 (compared to around 1-2% currently), whereas in a Narrative with limited subsidies for an interim period[52], the low carbon vkm accounted for 48% by 2035[53]. ▸ **Stronger incentives will be needed to reach RtZ ambitions.** ▸ The results from this analysis suggest that getting the remaining few vehicle users to switch to zero-emission vehicles (i.e. in the post-2040 period) will be difficult, even with a continuation of ULEV grants. Thus, the removal of conventional vehicles from sale may also be necessary in line with the government's current commitment in its RtZ strategy.
EU emissions regulations	▸ **Current 2020 EU targets for average CO_2 emissions for new car and van sales must be kept in place to encourage innovation and learning in the near-term that consequently reduces the cost of ULEVs.** The Narrative results show carbon emissions of 62 to 92 gCO_2/km as the new car average by 2020, below the target of 100 gCO_2/km, and 142 to 144 gCO_2/km as the new van average, below the target of 147 gCO_2/km. As a result, there is a case for tightening these further over the medium term (see later entry in this table).
Hydrogen appraisal	▸ **Major decisions on government support for FCVs and the associated infrastructure can be postponed until the mid-to-late 2020s to allow time for uncertainty over long-run costs**

[52] £500 per ULEV car and £1000 per ULEV van from 2025 to 2035 versus current Plug-in Car and Van grants offering up to £3,500 and £8,000 reduction on eligible cars and vans, respectively.

[53] It may be possible to reach similar levels of ULEV uptake in the medium-term with a shorter period of subsidies by conducting further analysis on different subsidy levels and timings.

	to reduce. ▸ FCVs appear to be important in the longer-term to reach the RtZ ambitions, particularly for the van sector, which is less suited to PiVs due to the duty cycle restrictions and current expectations about BEV range[54]. However, uptake of FCVs is expected to be relatively slow until the purchase price decreases substantially, around 2030[55], and in the long-term it depends on the level of access to on-street charging for competing BEV alternatives.
New tax on ICEVs and ULEVs (road pricing)	▸ **A new tax that applies to both ICEVs and ULEVs is likely to be required because it appears that simply extending the taxes that apply today, e.g. Vehicle Excise Duty (VED) and fuel duty, will lead to a gap in public finances between the net revenues from light duty transport sector and an assumed target.** The analysis evaluated the impact of different subsidies and taxes on public finances versus an assumed target net position for road transport[56], finding that measures that differentiate ULEVs from ICEVs can only go so far in driving ULEV uptake without causing long-term revenue cannibalisation[57], thus a technology neutral tax is necessary. This could be applied equally to equivalent ICEVs and ULEVs but still differentiated between vehicle segments and it does not need to be completely neutral; it could incorporate a low carbon discount. In the Narratives, the price for road usage ranges from 0.8 to 1.6 p/km on average across the pathway to 2050, assuming the gap in public finances is applied equally to all light vehicles. This represents between 3% and 8% of the actual cost of transport[58]. An alternative would be a per-vehicle annual tax, which ranges between around £145 to £345 in the

[54] The result is that by 2050, around 25% to 95% of vans in the parc are FCVs depending on the Narrative.

[55] On a TCO[55] basis, consumer car segment B FCVs reach parity with petrol ICEVs in 2029 and petrol PHEVs in 2030 at the earliest (across the Narratives), including subsidies. The assumption about FCV cost reduction is dependent on continued investment by the automotive sector in the technology and its production.

[56] This project has explored options to meet the target revenue for road transport from within the road transport sector although the government could use other routes to bring down spending or obtain tax receipts from elsewhere in the economy.

[57] E.g. a higher tax on ICEVs may result in less use of ICEVs and less tax collected.

[58] The overarching cost of delivering the underlying transport service for car users, i.e. the total fixed and variable costs of the vehicles and fuel per year spread across the vkm travelled.

Narratives and would be a substantial increase on the current VED tax[59].

It is noted that, assuming no change to current taxation, long-term revenue cannibalisation may happen without PiVs if the efficiency of ICEVs improves or if UK mileage growth declines as fewer people learn to drive or own cars. However, this analysis assumes that no OEMs transition to developing electrified powertrains and there are no further ICEV efficiency measures deployed beyond 2020.

Support for public on-street charging

- **The majority of charging occurs overnight at home for consumers and home-based fleet drivers during the horizon to 2050, assuming current expectations about charging behaviour and technologies. Thus deployment of on-street residential charging points is necessary to unlock ULEV uptake for those without access to off-street parking and to support the high levels of uptake set out in the RtZ.**

The analysis tested implementation of on-street residential charge points, finding that the proportion of low carbon vkm in 2050 rises from around 86% when on-street residential charge points are not available to 91% when they are available. This suggests that to reach levels consistent with RtZ ambitions, on-street charging will probably be needed. However, the impact is lower than expected given that around 20% of new car buyers and 50% of new van buyers, who keep their vehicles at home, do not have access to off-street parking but this is because some PiV drivers switch to FCVs instead in the absence of on-street charging. However, providing overnight access to those without off-street parking in the near term is important for social solidarity and also because ULEV uptake is initially likely to be higher in cities where the availability of off-street parking is lower, although these consumers may have lower than average mileage and could potentially be better served by integrated transport services.

The analysis showed that direct support for on-street residential charging providers may be necessary, for example, if investment ahead of need is required[60], or if drivers' perception of access to charging is likely to lag behind the actual infrastructure available.

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[59] Current VED rates are applied uniformly across all non-zero emission vehicles from the second year at £140/year.

[60] Tested in the analysis via faster deployment of charging points based on the total ULEV uptake than the demand at those charging points.

Coordination and support for rapid charging	▸ **To give certainty of access to charging outside of the home, a widespread network of rapid charging points is essential in the near to medium-term[61] and this may require some de-risking and direct support[62] to encourage investment[63].** As the battery size of BEVs increases, overnight charging with some top-up from rapid charging is likely to be able to meet the vast majority of charging demand requirements. The analysis indicated that a modest amount of direct government support may be needed whilst charging point businesses are still in their initial loss-making periods[64], especially as investment is particularly important in the near-to-medium term in order to reduce the range anxiety associated with access to charging, which remains a key barrier to uptake. By comparison, there is a more limited long-term role for standard public destination and workplace charging (except where the former is needed to facilitate car sharing); demand at these locations declines after 2025 and around 2030 respectively[65].
Desirable	
Carbon price pass through for liquid fuels	▸ **In the longer-term a well-designed support scheme would then switch the emphasis of policy intervention from incentivising ULEVs towards dis-incentivising ICEVs, for example through a long-term carbon tax[66].** After a competitive position for ULEVs has been established economically and in terms of their convenience, which is expected to be in the mid to late 2020s for segment B cars, it appears to be worth implementing a carbon tax on liquid fuels

[61] i.e. 50kW and greater.

[62] For example, from the £400mn Charging Infrastructure Investment Fund that the government is currently in the process of constructing to support non-home infrastructure development.

[63] Further sensitivity testing would be needed to establish the relative importance of rapid versus on-street residential charge points.

[64] For context, the Commercial Value Chain subsidy required for rapid CPOs is around £10mn to £100mn, which is small when compared to total capital expenditure over the pathway.

[65] The share of workplace charging decreases over time as PiV ranges increases and consumers focus can meet the majority of their needs through a combination of home or on-street residential charge points and rapid charging.

[66] The system-wide CO_2 price refers to the marginal cost to the system to decarbonise the system by 1 ton CO_2. In some Narratives this marginal cost has been passed through to the petrol and diesel retail prices as a tax at different levels depending on the Narrative (i.e. 100% pass through level transfers the full carbon cost).

as an effective way of dis-incentivising conventional vehicles whilst increasing the net position of public finances (i.e. as opposed to trying to drive ULEV uptake through further subsidies). However, policymakers should carefully consider any dis-incentives applied on ICEVs in the longer-term to avoid targeting people on lower incomes who are likely to be disproportionately the owners of these vehicles.

- **The push for decarbonisation from ULEVs needs to be considered together with decarbonisation of other sectors such as industry, building heat and power generation in order to reduce emissions as efficiently as possible.**

In the nearer-term the higher costs of ULEVs versus conventional vehicles may result in a relatively high cost of decarbonisation of road transport; however, it may be easier to generate momentum with ULEVs than with other forms of abatement (e.g. heating or efficiency measures) depending on the relative barriers to adoption. On the other hand, while progress with ULEVs is essential, it may prove harder to deliver decarbonisation than the Narratives imply and action on other sectors should not be neglected. In particular, decarbonisation of PiVs is closely linked to decarbonisation of power and it will be problematic if the large added load for charging is met from high carbon sources.

Further tightening of vehicle emissions regulations

- **It appears desirable to further tighten national CO_2 limits on new cars and vans beyond the values already set by the EU for 2020/21, as both a backstop measure to enforce decarbonisation and as stimulus for manufacturer innovation.**

Across the Narratives, average emissions are between 7 and 41 gCO_2/km for new cars and between 17 and 75 gCO_2/km for new vans, both much lower than targets agreed by the European Parliament in December 2018 of a 37.5% reduction for cars and 31% for vans by 2030 versus 2021[67]. In order to encourage innovation and support ULEV uptake post 2020/21, vehicle emissions targets that are much more stringent than those already agreed could be implemented without subjecting vehicle manufacturers to large penalties[68].

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[67] Current targets are 95 gCO_2/km by 2021 for new cars and 147 gCO_2/km by 2020 for new vans, based on the New European Driving Cycle test procedure, which is in the final stages of being replaced with the Worldwide Harmonized Light Vehicle Testing Procedure. The reduction percentages should be equivalent to 59 gCO_2/km by 2030 for cars and 101 gCO_2/km for vans versus modelled targets of 65 gCO_2/km by 2030 for cars and 100 gCO_2/km for vans.

[68] If the current targets were to be reduced substantially to 25 gCO_2/km by 2030 for cars and 75 gCO_2/km by 2030 for vans then manufacturers would likely end up paying penalties (although these only appear in 2030-

Possible alternative mechanisms to encourage innovation and emissions reduction could be taken forward for further consideration, such as the effectiveness of incentives as opposed to penalties.

Support for the provision of flexibility (flex. shared services framework & coordinated flex.procurement)

- **Wider market arrangements need to evolve to ensure that there are clear routes-to-market that enable the use of flexibility provided by Managed Charging (MC).**

  This could include, for example, a Flexibility shared services framework, which would aim to establish coordination between the entities that have an active interest in flexibility, setting out how this resource could be shared between Distribution Network Operators (DNOs) and the Electricity System Operator (ESO). This could be followed by co-ordinated flexibility procurement (e.g. with an entity such as the ESO responsible for contracting services and then selling them on to other entities when they need them), which would represent a more substantial change to the market framework requiring, for example, reconsideration of price control frameworks. Further down the line, a central flexibility market platform could be developed, operated and regulated, allowing demand and/or generation to be optimised across all sellers and buyers of flexibility services for all purposes, including those with specific locational needs.

- **MC propositions result in substantial cost reductions for the ESO and the DNOs.**

  The two schemes modelled in this analysis (using data on charging behaviour from trials with around 240 participants, conducted as part of this project) are User-Managed Charging (UMC)[69] and Supplier-Managed (SMC)[70]. The benefits of MC are substantial, accounting for £1.1bn to £4.4bn in Present Value (PV) terms across the pathway to 2050 for the ESO[71], and £1.6bn to £2.1bn in avoided network reinforcement costs for the DNO[72]. These would account for £7 to £22 per PiV per year

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2031 and 2039 for cars and 2024-2025 for vans, of around £1bn in total). In the analysis the new car average reduces from 31 gCO_2/km to 27 gCO_2/km in 2030 and the share of low-emission car sales increases from 66% to 71%.

[69] I.e. consumer shifting of charging load to cheaper periods in response to static Time of Use tariffs.

[70] I.e. more complete load shifting in which a third-party such as an aggregator optimises the charging profile against prices across the available plug-in window provided by the driver.

[71] These are the long-run avoided costs of (more expensive) energy balancing and peaking plant, covering part of the balancing market, short term operating reserve and additional peaking plant.

[72] Note that savings for the TNO appeared to be negligible.

for the ESO and £39 to £56 per PiV per year for the DNO (both on average from 2020 to 2050). Incremental savings from SMC are greater towards the middle-to-end of the pathway.

A more in-depth analysis of Demand Management (DM) aggregator[73] cash flows in the nearer term was also carried out as part of the CVEI project, using data from the trials[74]. This indicated that the value of flexibility (without Vehicle-to-Grid, V2G, technologies) that the aggregator could monetise would be in the order of 5% of the annual electricity cost for charging a PiV in 2030, but noting that the current market arrangements do not always sufficiently reflect the underlying system value of flexibility, in particular with respect to the avoided cost of reinforcement on the distribution network.

Support for car sharing (facilitation of urban car sharing)

- **The economics of car sharing appear positive and policymakers should support a role for shared cars that leads to efficient use of vehicles (i.e. does not increase total mileage through shifting demand away from public transport). For example, policymakers could avoid support for vehicle purchase where access to integrated transport services would be better for consumers[75].**

Car sharing reduces the overall cost of transport by around 20% to 30% versus the cost of using a privately-owned consumer car[76], depending on how widespread the car sharing is[77]. With no 'dead miles', widespread car sharing reduces the cost of transport to 11-17 p/vkm for shared cars from 11-24 p/vkm for privately owned consumer cars taking into account the costs across the pathway to 2050. Shared cars may result in shifting of vehicle demand away from public transport; however, if this reduces cost to consumers overall it could be left to the market to decide how this could evolve.

[73] A Demand Management Aggregator is a third party company specialised in demand management. It aggregates demand from its customers (industrial, commercial, PiVs etc.) and provides flexibility as a service to the system.

[74] The results of which can be found in the Deliverable *D7.3 DM Aggregator Framework.*

[75] E.g. With a transport package offering a monthly fee or pay as you go charge to access multi-modal transport.

[76] Comparing the average cost across 2019 to 2050.

[77] This analysis tested 'urban' car sharing, in which shared cars account for around 30% of total mileage in 2050 and extended car sharing when shared cars account for 75%. Note that this does not account for any modal shifting which was out of scope for this project; although reaching 75% of mileage in shared cars may require CAVs to capture the proportion of drivers that will not walk to pick up a shared car.

Social transition support

- **From a social policy perspective support could be targeted towards lower priced models and/or the second-hand market to help tackle transport poverty issues as part of a widespread transition to ULEVs.**
  - The exact policy options would need to be carefully considered as, for example, providing grants to the second-hand market may not be effective if this is then indirectly priced into new car sales. An alternative could be to drive fleet decarbonisation harder to increase the supply of PiVs, on the basis that greater supply could reduce the costs of used vehicles.

Provisional

Removal of ICEVs from sale

- **Meeting the 2050 RtZ ambition of 100% of new vehicle sales being zero-emission vehicles may require policy mechanisms that are more interventionist than financial incentives, such as preventing the sale of carbon emitting vehicles.**

  Several of the Narratives aimed to reach the 2050 RtZ ambition and demonstrated the difficulty in getting the residual proportion of vehicle users to switch to zero-emission vehicles without very high subsidies. This suggests that the removal of conventional vehicles from sale may also be necessary, although the analysis showed that this type of action might only be needed when sales of ICEVs or PHEVs have already fallen to very low levels[78].

Competition monitoring

- **Market supervision and regulation may become necessary to ensure fair treatment of consumers and avoid formation of natural monopolies as this nascent market evolves, for example, with respect to ownership of non-home charging infrastructure.**

[78] In Narratives in which the Road to Zero ambitions are implemented, it is assumed that manufactures will remove conventional petrol and diesel powertrains from sale once their market shares, within their segment, fall below 5%. This does not necessarily assume a government ban and could instead be the response of manufacturers to falling profit margins as production volumes fall and their unwillingness to invest in the continued development of these powertrains in anticipation of unfavourable policy conditions post-2040. However, ultimately a ban may still be needed to prevent the laggard consumers from buying an ICEV and policymakers should signal this far in advance.

8 Future research needs

The CVEI project has raised a number of issues that could benefit from further investigation, either using the Whole-System Analysis or as stand-alone studies (that might inform a future revision of the Whole-System Analysis). These include:

- Refinements to the direct vehicle grants used in the modelling, in terms of:
  - the optimum level of subsidy required to support a certain ULEV uptake or low-carbon VKT target;
  - the year in which subsidies should be introduced for maximum impact;
  - the variation in subsidy levels needed across different segments (i.e. via a subsidy mechanism as a proportion of the purchase price, for example, as opposed to a consistent value in monetary terms across all vehicle segments);
  - impact of using other mechanisms instead of grants (e.g. discounted VAT on the vehicle purchase price).
- Further analysis on reaching the UK government's Road to Zero ambitions, such as:
  - alternatives to the targets of all new cars and vans being 'effectively zero emission' by 2040 and almost every car and van being zero emission by 2050, taking into account public finances and the level of decarbonisation in the wider system, and particularly the difficulty in the transition from around 90% to 100% decarbonisation;
  - the optimal timing of a potential ban on ICEV sales;
  - investigation of other ways of incentivising the consumer 'laggards' to adopt.
- Further work on understanding the impact of shared cars in driving different levels of car use and / or travel patterns, including modal shifts
- Consumer research, equivalent to CVEI's consumer trials, to establish an equivalent knowledge base about consumer uptake and use of FCVs, ahead of the mid-2020s when decisions on investment in hydrogen infrastructure may be needed
- Further research related to PiV uptake, for example:
  - To what extent do PHEVs serve as a "gateway" or "transition" PiV, leading to later uptake of BEVs?
  - What measures are effective at encouraging Mainstream Consumer PHEV users to maximise the fraction of their VKT that they drive under electric power?
  - How do Mainstream Consumers construe 'range'?
  - How do multi-car and multi-user households use their vehicles, and how does this change with PiVs?
  - What forms of public charging provision would support uptake of PiVs by the (approx.) 40% of households who are presently unable to charge one at home because their cars must be parked on-street?
- Further research on PiV charging, for example:

  - What requirements do multi-car and multi-user households have for MC?
  - What are the most effective Customer Value Propositions (e.g. consumer reward schemes) for encouraging uptake of and engagement with MC schemes? How can these products and business models be designed to balance benefits for the consumer and the markets?
  - When and why do drivers operate PHEVs in ICE, electric, and blended modes? How can the electric utilisation factor be increased, and what would be the implications for charging demand?
- Consumer research to establish the conditions under which Mainstream Consumers would be willing to switch from private ownership/lease of cars to Mobility as a Service options like car sharing
- Further work on how the ULEV market and the wider energy system will be affected by development and market introduction of Connected and Autonomous Vehicles (CAVs).

9 Conclusions

The CVEI project has provided the first Whole-System Analysis of the transition towards a low-carbon future for light duty transport in the UK. This approach has generated unique insights into the elements needed for a successful transition to low-carbon light duty road transport in the UK.

The validity of the analysis has been underpinned by original, scientific research using rigorous experimental design to minimise findings being confounded by learning effects or uncontrolled external variables:

- The project undertook the first research on potential uptake of PiVs with Mainstream Consumer participants who have had direct experience of using both BEVs and PHEVs. The Mainstream Consumer sample means that findings are generaliseable to the whole driving population rather than restricted to PiV Innovators who have special motivations.
- The project also undertook the first research on the charging behaviour of Mainstream Consumers when using PHEVs and BEVs; and the first research with Mainstream Consumer participants investigating the effectiveness of both User-Managed Charging ("Time-of-Use" tariffs) and Supplier-Managed Charging as means of mitigating the impacts of PiV charging on the electricity supply system.
- Case studies with fleet operators that have provided new understandings of the factors that influence their potential uptake of PiVs.

Key conclusions from the project include:

- Empirical data from the Consumer Uptake Trial indicates that, over the next five years, PHEVs are likely to be adopted more quickly in the mass-market than BEVs.
- Ranges of 200 miles would enable BEVs to appeal to 50% of Mainstream Consumers as main cars; ranges of 300 miles would enable them to appeal to over 90%. BEVs with ranges of 150 miles would appeal to 50% of Mainstream Consumers as second cars in households. These findings indicate what needs to be achieved in terms of BEV development in order to achieve the UK government's Road to Zero ambitions.
- Mainstream Consumers who are not participating in formal Managed Charging schemes are likely to undertake most of their charging at home in the late afternoon/early evening (15:00 to 20:00), particularly on weekdays. These timings coincide with peak demands from other sources, confirming that additional energy demand from PiVs could lead to issues with supply-demand balancing and local network capacity, and an increase in higher-CO_2 electricity generation.
- Managed Charging schemes have the potential to shift the timing of charging to the late evening and overnight, substantially alleviating these issues for the energy system at grid and local network levels. Managed Charging schemes also have substantial appeal to Mainstream Consumers.
- UMC ("Time-of-Use" tariffs) have more a priori appeal to Mainstream Consumers, but SMC has similar appeal when those consumers are familiar with it.
- The Whole-System Analysis showed that 'Business as Usual' would result in a lower fraction of low-carbon VKT, a higher cost of car transport, higher residual carbon

costs, higher light duty road transport CO_2 emissions, and lower uptake of ULEVs than other Narratives considered. However, the gap between government transport-related tax and spend would be lower than in other Narratives.

- The greatest fraction of low-carbon VKT and reductions in light duty road transport CO_2 emissions by 2050 would be achieved under the 'ULEV Enabled' and 'Transport on Demand' Narratives. The cumulative reduction in CO_2 emissions would be substantially greater under the Transport on Demand Narrative, as reductions in annual emissions would be made substantially earlier in the pathway to 2050.
- The Whole-System Analysis indicates that PHEVs initially are adopted at slightly higher or similar rates to BEVs early in the pathway in all Narratives, but as the range of BEVs improves the uptake of PHEVs peaks and then stabilises or declines (the timing and magnitude of the peak depending on the conditions represented in each Narrative). The Consumer Uptake Trial findings suggest that this analysis may underestimate the adoption of PHEVs in the first five years, while confirming that BEV uptake will increase as the range of BEVs increases.
- Vehicle usage data indicates that PHEVs are not necessarily driven in a way that maximises their low-carbon VKT (i.e. kilometres driven under electric power). As well as increased electric range, greater public awareness of the CO_2 and cost saving benefits of efficient PHEV driving and motivation on the part of users will be needed for PHEVs to make the maximum contribution to decarbonisation of light duty road transport.
- Uptake of hydrogen FCVs increases steadily in all Narratives particularly in consumer/fleet segments driving longer distances for whom limited battery ranges are more prohibitive, but is substantially less than uptake of BEVs, except in the 'H_2 Push' Narrative where a concerted effort is made to drive a transition towards FCV deployment.
- Based on the experimental findings and the Whole-System Analysis, a number of policy choices are recommended that are likely to be robustly effective across a range of circumstances (as represented in the various Narratives plus the additional sensitivity analyses). The most important of these, that should be applied early in the pathway, are:
    - Upfront cost mitigation for ULEVs.
    - Maintenance of EU emissions regulations or equivalent UK-specific regulations to encourage innovation and learning that increases the CO_2 emissions reduction potential and decreases the cost of ULEVs. Further tightening of emissions regulations is also desirable.
    - Support for on-street charging to encourage uptake of PiVs by the large proportion of households that do not have off-street parking, and by fleets where vehicles are based at users' homes where those homes do not have off-street parking.
    - Early support for a network of rapid chargers to provide reassurance of opportunities to charge away from home until BEV ranges increase substantially beyond present (2019) levels.

- Managed Charging propositions offer substantial benefits to the Electricity System Operator and Distribution Network Operator and the regulatory and market environment should ensure that both User-Managed ("Time-of-Use" tariffs) and Supplier-Managed Charging can be made available to users.
- Policymakers should support an early transition towards MaaS as this has the potential to yield greater reductions in cumulative light duty transport CO_2 emissions early in the pathway.
    - For example, policymakers could avoid support for vehicle purchase where access to integrated transport services would be better for consumers[79]. Such a transition should encourage movement from private to shared cars (whilst discouraging movement away from Public Transport).

The introduction of a new fiscal mechanism to close the gap between the government's road transport-related tax and spending that will emerge as fuel tax revenues decline will also be essential, though the need for this will develop somewhat later as ULEV uptake increases. The mechanism should be neutral with respect to the powertrain technology of light duty vehicles (i.e. apply equally to ICEVs, PiVs, and FCVs).

Major decisions on government support for FCVs and the associated infrastructure could potentially be postponed until the mid-to-late 2020s to allow time for uncertainty to reduce over long-run costs of FCVs, particularly the fuel cell stack within them. At present, there is far less certainty over manufacturers' future commitments to developing and producing these in large volumes compared to PiVs. In addition, this support needs to consider the associated hydrogen supply and distribution needs.

The CVEI project was an ambitious study that blended multiple market and knowledge disciplines within the delivery Consortium, building on prior work including, among others, the ETI's previous Plug-In Vehicles project, and using high-quality scientific research to fill identified gaps in knowledge. The CVEI Whole-System Analysis has shown that there are no easy answers that lead to straightforward success across all metrics. It has, however, identified what a good solution that is robust in a range of transport futures could look like, and has provided a set of evidence-based, prioritised recommendations for policymakers and other stakeholders. If followed, these will substantially improve the chances of a transition to widespread adoption of ULEVs, integrated with the wider energy system through Managed Charging, and contributing to its efficient operation at lower cost than would be possible without that integration. The CVEI project's findings are relevant to stakeholders including the UK government, the transport sector including vehicle manufacturers, and the energy sector including the Energy System Operator, electricity retailers, and Distribution Network Operators.

[79] E.g. With a transport package offering a monthly fee or pay as you go charge to access multi-modal transport.

10 Bibliography

The following deliverables were produced for the CVEI project. These are available on the CVEI website (cveiproject.trl.co.uk):

Deliverable ID	Deliverable Title
D1.1	Summary of approach, conceptual design and key research questions
D1.3	Market Design and System Integration (full report)
D1.3	Market Design and System Integration (summary report)
D1.4	Stage 2 Trial Design, Methodology and Business Case
D2.1	Consumer attitudes and behaviours report
D3.1	Battery Cost and Performance and Battery Management System Capability Report and Battery Database (Excel model)
D3.1	Battery Cost and Performance and Battery Management System Capability Report and Battery Database
D3.2	Battery State of Health Model
D3.2	Battery State of Health Model (Excel model)
D4.1	Initial Analysis of Technology, Commercial and Market Building Blocks for Energy Infrastructure
D4.1	Initial Analysis of Technology, Commercial and Market Building Blocks for Energy Infrastructure (Excel model)
D4.2	Final Analysis of Technology, Commercial and Market Building Blocks for Energy Infrastructure (Excel model)
D4.2	Final Analysis of Technology, Commercial and Market Building Blocks for Energy Infrastructure
D5.1	Supplementary Details of Design, Materials and Management Arrangements for Consumer Trials
D5.2	Consumer Uptake Trial Report: Mainstream Consumers' Attitudes and Willingness to Adopt BEVs and PHEVs
D5.3	Consumer Charging Trials Report: Mainstream Consumers' Attitudes and Behaviours under Managed Charging Schemes for BEVs and PHEVs
D6.1	Fleet Study Report
D7.2	Analytical Framework (Updated)
D7.3	Demand Management Aggregator Framework
D7.4	Market Design and System Integration Report (Updated)
D7.5	Systematic Sensitivity Analysis
D7.6	Additional System Analysis

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Deliverable 8.1 - Final Project Summary Report

TRL
Crowthorne House, Nine Mile Ride,
Wokingham, Berkshire, RG40 3GA,
United Kingdom
T: +44 (0) 1344 773131
F: +44 (0) 1344 770356
E: enquiries@trl.co.uk
W: www.trl.co.uk

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