

# Feasibility study: Powering electric vehicles on England's major roads



## Foreword



An efficient and effective transport system is vital to the UK's economic growth and driving remains the dominant transport mode in the UK. Vehicle technologies are advancing at an ever increasing rate, driven by international regulations and consumer demand for more efficient vehicles.

As technology develops, ultra low emission vehicles, including pure electric vehicles, plug in hybrids and fuel cell electric vehicles, will play an increasing role in the way we travel for leisure, to work and for businesses to get their goods to market. These vehicles are already on the market in significant numbers, and in the coming years will become a common sight in our towns and cities and on the strategic road network.

A rapid uptake in ultra low emission vehicles provide a number of significant opportunities for the UK such as attracting a new generation of investment into the UK's car industry and supply chains and helping economic growth, which we are committed to support.

We are investigating how we can grow the electric vehicle charging infrastructure. Plug in charging points are already available at motorway service areas in England, and we have committed to extend this service by installing plug in charging points every twenty miles on the motorway network. The concept of wireless power transfer equipment installed under the road surface is seen as a potential opportunity to extend the charging infrastructure for our customers.

This feasibility report aims to inform us about the viability of implementing dynamic wireless power transfer systems on the strategic road network that will provide a safe road environment for the projected growth in electric and hybrid vehicles using the network.

A handwritten signature in black ink that reads "Mike Wilson". The signature is written in a cursive style with a large, sweeping flourish at the end.

Mike Wilson, Chief Highways Engineer

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# Contents

Contents	3
1 Glossary	7
2 Executive Summary	12
3 Introduction	22
3.1 The project	22
3.2 Methodology and Approach	22
3.3 Project team and partners	23
3.4 Structure of this document	25
4 Stakeholder Engagement	27
4.1 Introduction to stakeholder engagement	27
4.1.1 Passenger car consumer survey methodology	27
4.1.2 Freight and coach operator survey methodology	28
4.1.3 Informed stakeholders	28
4.2 Results	29
4.3 Results of follow up interviews with selected freight operators	34
4.3.1 Likelihood of future uptake	34
4.3.2 Required infrastructure and vehicles	34
4.3.3 Perceived benefits	35
4.3.4 Other fuel technologies	35
4.3.5 Potential participation in funded trials	35
5 Functional Requirements	36
5.1 Introduction to DWPT technologies	36
5.2 Qualitative considerations on the DWPT deployment	37
5.3 Review of DWPT systems	38
5.4 Identification and characterisation of other services	41
5.4.1 Other services provided using DWPT technology	41
5.4.2 Other services provided through utilisation of DWPT installation process	44
5.5 Impacts of DWPT on other electrical services in close proximity	45
5.6 Sources of electrical disturbances	46
5.6.1 Conductive disturbances	46
5.6.2 Radiated disturbances	47
5.7 Experience of existing installations	48

	5.7.1	Milton Keynes	48
	5.7.2	ZeEUS	50
	5.8	Summary of relevant standards	50
6		System Performance Requirements	53
	6.1	Guidance for installation of DWPT equipment into vehicles	53
	6.1.1	Assessment of information on key components	54
	6.2	Results of trials of key components/ systems	57
	6.2.1	Identification of fitting options	59
	6.2.2	Safety	65
	6.3	Battery specifications and requirements	68
	6.3.1	Outline of the methodology	68
	6.3.2	Battery specification	68
	6.3.3	Recommendations for possible improvements to batteries to cope with DWPT	77
	6.4	Specification and costs for installation of systems under the motorway (types of installations to be investigated)	77
	6.4.1	Power supply system construction approach	77
	6.4.2	Existing construction methods and tools	77
	6.4.3	Costs	82
	6.4.4	Key requirements for a road installation tool	86
	6.5	Specification for a tool	87
7		Process requirements	89
	7.1	Power demand requirements for each vehicle	89
	7.1.1	Car and HGV requirements	89
	7.1.2	Power transfer rate from DWPT	91
	7.1.3	Method used for analysis of traffic flow data	94
	7.1.4	Assessment of power requirements	95
	7.1.5	Investigation of variations in vehicle flows	105
	7.1.6	Conclusions on power demand	105
	7.2	Commercial drivers and detracting factors	107
	7.2.1	Logistics provider revenue	107
	7.2.2	Energy prices/tariffs	108
	7.2.3	Detracting factors	121
	7.2.4	Charging unit identity	124
	7.3	Infrastructure Management System (IMS)	128
	7.3.1	Operational considerations	128
	7.3.2	IMS requirements	133
	7.3.3	System costs	141

7.3.4	Commercial drivers and detracting factors summary	142
7.4	DWPT network impact assessment	143
7.4.1	Working assumptions	144
7.4.2	Defining the supply voltage	146
7.4.3	Network modelling	150
7.4.4	Stakeholder cooperation	153
7.4.5	Outputs	154
7.5	Qualified inputs for a discounted cash flow model	154
7.5.1	High level input variable identification and qualification	154
7.5.2	Cost estimates	162
8	Preparing for off-road trials	167
8.1	Laboratory trials	167
8.2	Track trials	168
8.2.1	Overview of the track trials	168
8.2.2	Safety	169
8.3	Test-track trial Methodology	171
8.3.1	Installation	171
8.3.2	Road degradation	171
8.3.3	Measurement of power transfer efficiency	172
8.3.4	Emissions	172
8.3.5	Effect on the grid	172
8.3.6	Communications	173
8.4	Test scenarios	173
8.5	Trials design	174
8.6	Measurements	175
8.6.1	Vehicle parameters	175
8.6.2	Power transfer parameters	175
8.6.3	Grid parameters	175
8.6.4	Emissions and other safety parameters	176
8.6.5	Power transfer system parameters	177
8.7	Selection of track	177
9	Costs and Impacts	179
9.1	Identification of potential impacts (costs and benefits)	179
9.1.1	Economy (impacts on businesses)	180
9.1.2	Environmental	182
9.1.3	Social	184
9.1.4	Public accounts	185
9.2	Modelling costs and environmental impacts	187

9.2.1	Overview of modelling approach	187
9.2.2	Technology and power requirement	187
9.2.3	Scenarios modelled	188
9.2.4	Growth of vehicle numbers and power consumption with time in Scenarios	190
9.2.5	Overall summary of costs	190
9.2.6	Impacts on indirect taxation	191
9.2.7	Monetisation of Environmental Impacts	191
9.3	Conclusions and discussion	193
10	Summary of Conclusions	196
10.1	Stakeholder engagement	196
10.2	Functional requirements	198
10.3	System performance requirements	199
10.4	Process requirements	200
10.5	Preparation for off-road trials	204
10.6	Impact assessment	205
11	Bibliography	207
Appendix A	Battery requirements	212
Appendix B	Review of vehicles and driving patterns	216
Appendix C	Model development for each vehicle type	220
Appendix D	Description of Dynamic Wireless Power Transfer systems	223
Appendix E	Commercial Aggregation Service Providers (CASPs)	227
Appendix F	DWPT automatic vehicle identification	228
Appendix G	Network model data	230
Appendix H	Stakeholder cooperation	233
Appendix I	Gordon Growth Model	243
Appendix J	Applicable standards	244

# 1 Glossary

## Glossary of terms

Air gap	Distance between inductive charging plates.
Conductive disturbances	Disturbances that can affect equipment connected to the same installation or to neighbouring installations.
Dynamic Power Transfer	Power transfer which can be achieved while the vehicle is moving (can be either wireless or conductive).
Electrostatic power transfer (or Capacitive power transfer)	Power transfer through electrostatic induction. Two plates placed close together transfer energy through an electric field between the plates.
Fuel cell vehicle	A vehicle which uses hydrogen as a fuel for an on-board fuel cell, which converts it into electricity.
Hybrid powertrain	Can use either energy from the fossil fuel or electrical energy from the grid / regenerative braking.
Magnetic inductive power transfer	An inductive power transfer system that is analogous to an air-core transformer.
Oxides of Nitrogen/NO <sub>x</sub>	NO <sub>x</sub> is a generic term for the mono-nitrogen oxides NO and NO <sub>2</sub> .
Parallel hybrid	Plug-in hybrid vehicle which can use power from either electric power or power from the internal combustion engine.
Particulate Matter/PM	Microscopic solid or liquid suspended in the atmosphere. A key health risk.
Radiated disturbances	These occur where electromagnetic fields generated by a WPT device when current passes through a wire interacting with nearby electrical devices.
Rechargeable energy storage system/RESS	Energy storage systems that can be recharged (e.g. batteries).
Regenerative braking	Energy recovery system enabling some braking energy to be recovered via a generator.
Series hybrid	Plug-in hybrid vehicle which always uses electric power.
Strategic Road Network	The motorway and key trunk road network in England, maintained by the Highways England.
Trafficking	The passing of vehicle traffic (or replication of passing vehicle traffic) over a road surface.
Triad	Charging system for industrial and commercial users of electricity in the UK, used to manage peak loads.
Wireless Power Transfer	Any method of transferring electrical power without wire or cables connected.

## Glossary of Abbreviations

AADF	Annual Average Daily Flow
ANPR	Automatic Number Plate Recognition
AST	Appraisal Summary Table
AVID(S)	Automatic Vehicle Identification (System)
BM	Balancing Mechanism
BMS	Battery Management System
BMU	Balancing Mechanism Unit
C&U	Construction and Use
CAN	Controller Area Network
CAPEX	Capital expenditure
CASP	Commercial Aggregation Service Provider
CC	Congestion Charge
CDCM	Common Distribution Charging Methodology
CPT	Capacitive Power Transfer
CPT	Confederation of Passenger Transport
CWD	Charging While Driving
DC	Direct Current
DCF	Discounted Cash Flow
DECC	UK Department of Energy and Climate Change
Defra	UK Department of the Environment, Food and Rural Affairs
DfT	UK Department for Transport
DFR	Dynamic Response Frequency
DN	Distribution Network
DNO	Distribution Network Operator
DSRS	Demand Side Responsive Services
DVLA	Driver and Vehicle Licensing Agency
DVSA	Driver and Vehicle Standards Agency
DWPT	Dynamic Wireless Power Transfer
EES	Electrical Energy Storage
EFT	Defra Emissions Forecasting Tool



EHV	Extra High Voltage
EM	Electromagnetic
EMC	Electromagnetic Compatibility
EMF	Electromagnetic Field
EMI	Electromagnetic Interference
ER(s)	Engineering Recommendation(s)
EV	Electric Vehicle
EVSE	Electric Vehicle Supply Equipment
FABRIC	Feasibility analysis and development of on-road charging solutions for future electric vehicles project
FAU	Fast Acting Unit
FCDM	Frequency Control by Demand Management
FFR	Fast Frequency Response
FFR	Firm Frequency Response
FR	Frequency Response
FTA	Freight Transport Association
GSP	Grid Supply Point
HGEV	Heavy Goods Electric Vehicle
HGV	Heavy Goods Vehicle
HH	Half Hourly
HV	High Voltage
ICE	Internal Combustion Engine
ICNIRP	International Commission on Non-Ionizing Radiation Protection
IEC	International Electrotechnical Commission
IMS	Infrastructure Management System
INTIS	Integrated Infrastructure Solutions
IPSA	Interactive Power System Analysis
IPT	Inductive Power Transfer
IRLT	In Road Loop and Transponder
IVA	Individual Vehicle Approval
KAIST	Korea Advanced Institute of Science and Technology

LAF	Line Adjustment Factor
LCNF	Low Carbon Networks Fund
LCVP	Low Carbon Vehicles Partnership
LV	Light-duty Vehicle
LV	Low Voltage
MFID	Microwave Frequency Identification
MFR	Mandatory Frequency Response
MGEV	Medium Goods Electric Vehicle
MIDAS	Motorway Incident Detection and Automatic Signalling
MIC	Maximum Import Capacity
MIT	Massachusetts Institute of Technology
MOP	Meter Operator
MPAN	Meter Point Administration Number
MRL	Manufacturing Readiness Level
MV	Medium Voltage
ND	Next Day (delivery)
NDB	Next Day Before (delivery)
NDFR	Non Dynamic Frequency Response
NG	National Grid
NGET	National Grid Electricity Transmission plc
NOC	Network Operating Centre
NO <sub>x</sub>	Oxides of Nitrogen (NO and NO <sub>2</sub> )
NPV	Net Present Value
OCPP	Open Charge Point Protocol
OEM	Original Equipment Manufacturers
OLEV	Online Electric Vehicle
OPEX	Expenditure on operating costs
ORNL	Oak Ridge National Laboratory
PCI-DSS	The Payment Card Industry Data Security Standard
PHEV	Plug in Hybrid Electric Vehicle
PM	Particulate Matter
POC	Point Of Connection

POLITO	Politecnico di Torino
PTF	Pavement Test Facility (TRL)
PV	Present Value
RESS	Rechargeable Energy Storage System
RMS	Root-Mean-Square: the most common mathematical method of defining the effective voltage or current of an AC wave
RPC	Reduced Pollution Certificate
RFID	Radio Frequency Identification
SAMI	Stress Absorbing Membrane Interlayer
SCADA	Supervisory Command And Data Acquisition
SO	System Operator
SOC	State Of Charge
SRN	Strategic Road Network
STOD	Seasonal Time Of Day (electricity tariff)
STOR	Short Term Operating Reserve
TAG	Transport Analysis Guidance (also referred to as WebTAG)
TD	Two Day (delivery)
ToU	Time of Use
TN	Transmission Network
TNUoS	Transmission Network Use of System
TRL	Transport Research Laboratory
TRL	Technology Readiness Level
TS	Transmission System (electricity)
UHF	Ultra High Frequency
VCA	Vehicle Certification Agency
VED	Vehicle Excise Duty
VIN	Vehicle Identification Number
WebTAG	Web Transport Analysis Guidance (also referred to as TAG)
WEVC	Wireless Electric Vehicle Charging
WPT	Wireless Power Transfer
ZeEUS	Zero emission Urban Bus Systems project

## 2 Executive Summary

This project aims to inform the Highways England of the feasibility of implementing Dynamic Wireless Power Transfer (DWPT) systems on the Strategic Road Network (SRN) that will provide a safe road environment for the projected growth in electric/hybrid vehicles using the SRN. The project is the first stage in a much larger programme of work aimed at demonstrating this technology on the Strategic Road Network. Below is a summary of main findings from the project.

### Recommendations

1. In order to support the roll-out of DWPT and encourage adoption of EVs, relevant DWPT infrastructure would have to be deployed first to stimulate the demand for compatible vehicles.
2. The focus on early adopters should be on commercial operators, with a particular emphasis on road haulage companies using vehicles between 12t and 32.5t which regularly use particular stretches of the SRN.
3. A set of controlled trials and follow-on public demonstrators would be required to generate evidence of the system functionality and share outputs with potential users and other key stakeholders.

### Stakeholder engagement

Stakeholder engagement undertaken during the project involved a survey of consumers, surveys and discussions with freight and coach operators and other interested parties, to identify their views on electric vehicles and DWPT in particular, and to identify factors expected to influence decisions to adopt this new technology. Responses were received from 80 consumers with experience of driving electric vehicles, 10 national freight operators including a mix of 'hire and reward' and 'own account' businesses, the Freight Transport Association (FTA), the Confederation of Passenger Transport (CPT) and participants in a workshop with around 25 members of the Low Carbon Vehicle Partnership (LowCVP), of whom 12 responded to a follow-up survey.

The surveys of both private and commercial road users highlight the

'chicken and egg' issue which arises with the adoption of new technologies: the results show that vehicle purchasing decisions by both industry and consumers will depend on the wide availability of DWPT, but the business case for investing in the technology is weak without demand from users.

The small survey of industry stakeholders associated with the project workshop indicated that there is some support for the view that Highways England should deploy and own the DWPT infrastructure on the SRN, but that the DWPT infrastructure should be operated by a third party.

Commercial operators require a return on investment within 18 months to three years. Thus any additional cost of leasing or purchasing vehicles would need to be balanced by savings on operating costs to offset these additional costs over this relatively short time period. Industry stakeholders indicated that important factors in investment decisions related to DWPT technology would be automation and user-friendliness of the DWPT system, practicality and simplicity of charging and the level of CO<sub>2</sub> reduction.

Industry stakeholders indicated that they were more likely to purchase an EV if it were possible to use DWPT on equipped sections of the SRN. Similarly, the responses from

consumers indicate that introducing DWPT on motorways would increase the likelihood of having an EV as their main car in the next five years, and that the likelihood would increase if DWPT systems were introduced on main roads as well as motorways. These responses may be tempered by the expectation that a DWPT-enabled vehicle would be more expensive than current EVs, which are already considered to be more expensive than current diesel cars (it should be noted that the cost of EV technologies is expected to reduce with increased market penetration and economies of scale).

Thus, while respondents did not report that DWPT was the breakthrough technology they were waiting for, there were indications that DWPT could encourage EV adoption among private motorists. It is possible that DWPT is seen as addressing barriers such as limited range, although there was some evidence of concern about how much consumers would be expected to pay to use DWPT. There are indications therefore, that DWPT availability could play an important role in influencing consumer decision-making and behaviour.

The view from consumers that businesses may be more likely to benefit from DWPT than private drivers indicates that separate use cases for drivers with high and low levels of business mileage would be worth considering.

It appears that if future trials focus on industry groups which may be expected to be early adopters of the DWPT technology, then it is recommended that the focus should be on operators with lighter weight goods vehicles (less than 32t). Among the goods vehicle operators, there appear to be four separate use cases: classifying them by vehicle weight (around 12 – 32.5t and less than 12t) and operating practice ('hire and reward' and 'own account' operations). Operators providing scheduled coach services should also be considered.

The large proportion of neutral responses to many of the questions addressed to consumers and their apparent continuing concern about range anxiety, also demonstrate that there is a need for more detailed information to be assembled, for those taking part in later stages of the project or eventual implementation, about technical and operational aspects. Trials of DWPT systems could facilitate gathering and sharing of such information.

### **Identification of requirements**

The project investigated a number of possible WPT technologies focusing on those able to function as DWPT systems. In total seventeen WPT systems were investigated, eight of which had a dynamic capability. Each system capable of dynamic functionality was evaluated by the project team against a number of metrics covering: power transfer level, operational speed, suitability for different vehicle types and availability for trials. An assessment of technology readiness and manufacturing readiness was carried out. Most DWPT technologies were found to be between Technology Readiness Level (TRL) 4 and 8, while Manufacturing Readiness Level (MRL) was found to be lower, between 3 and 7.

Other services that could be provided by DWPT systems were also investigated. These included installation of MIDAS road loops as part of DWPT sections of motorway, which could result in savings of up to £4,900 per km for Highways England. Using DWPT technology to support autonomous vehicle functionality on the SRN was also found to be possible and could help to improve safety.

Other services, such as provision of wireless communication and integration with Smart Motorways, were found to be unlikely to generate any direct benefit to Highways England.

It was found that there is a variety of load sensors that could be beneficial to install in the road at the same time as installing DWPT systems. These sensors could provide a wealth of information on condition and behaviour of the pavement. Such information can be utilised to improve asset management and scheduling of maintenance works as well as help to identify potential failures before they occur. However, as this information is not currently available or used widely, it is not possible to determine the value it could deliver. It is recommended that potential for installing such sensors along with DWPT systems is investigated further as part of off-road trials in order to derive an estimate of the possible value of such information and what impact it could have on road maintenance.

An investigation of how DWPT could affect other electrical services on the SRN revealed that there are two key areas where DWPT systems may have an impact. These are conductive disturbances and radiated disturbances.

The two main conductive disturbances likely to be caused by DWPT equipment are (1) current and voltage fluctuations caused by frequent switching on and off of the WPT equipment as vehicles pass over the primary coils, and (2) harmonics generated by the power electronics of the DWPT systems. Experience from trials of static WPT systems indicates that these problems are not insurmountable. Addressing the first of these will likely involve dedicated connections from the DNO specifically for the DWPT installation (possibly at high voltage), to provide a degree of separation from other customers. In the case of the second, harmonic filters can deal with any excess harmonics.

The second conclusion relates to radiated disturbances caused by the electromagnetic fields (EMFs) generated by the DWPT equipment which, unlike existing static installations, may extend beyond the perimeter of the vehicles. This does not prevent connection to the public electricity system as it is outside the scope of the DNO connection requirements. However, it does potentially impact on safety and electromagnetic compatibility with other equipment (such as other roadside equipment or vehicles). It is therefore important that the manufacturer of the DWPT equipment demonstrates compliance with the EMC standards to ensure safe operation.

Specifications for the installation of DWPT equipment into vehicles were considered as part of the study. It was found that there are no production DWPT systems currently available on the open market; however, several are in advanced trials and demonstration systems exist in a number of countries. Projects such as FABRIC are working on the development of technologies and developing demonstrator systems.

## Recommendations

4. For long term success of DWPT it will be essential to gain support of vehicle manufacturers for installing vehicle DWPT components. Non vehicle-manufacturer supported retrofits should not be attempted.
5. All three identified construction methods should be trialled in the PTF to gather evidence on complexity and cost of construction as well as long term impact on degradation of the interfaces and the road structure.
6. Once a preferred construction method is identified, a further investigation should be carried out to develop a concept for required machinery to optimise the construction method and minimise construction time.

Various options for fitting of DWPT equipment into vehicles were considered, including factory fit, manufacturer aftermarket fit and third party aftermarket fit, with and without manufacturer support. Third party fitment without manufacturer support is not considered viable, and is not recommended. Several case studies are presented showing different fitting options.

The implications for safety were considered. For factory fitted systems, safety is not considered an issue as all vehicles are required to meet stringent safety requirements before they are allowed to be sold in Europe. The safety of aftermarket fitted systems is more of an issue. It was clear that DWPT system could not be safely retrofitted to vehicles without vehicle manufacturer support. For vehicle manufacturers to approve use of a DWPT system with their vehicles, the systems would need to be extensively tested and validated. A

DWPT system fitted to a trailer may reduce some of the risk for vehicle manufacturers but would still require their support to define the necessary interfaces to the vehicle and its systems.

The requirements for EV batteries were found to be dependent on vehicle dynamics, duty cycles and vehicle powertrain technology. Requirements for cars, medium duty vans and HGVs were considered. Both cars and vans could viably be used in fully electric mode, with, DWPT increasing range and/or reducing required battery capacity. The increased distances driven by HGVs, together with their much greater energy requirements, means that fully battery electric HGVs, are generally not feasible. However, benefits can be expected from hybridisation, and these benefits are increased by DWPT. If sufficient SRN coverage can be achieved with high power DWPT systems (>140 kW), fully electric HGVs would become viable.

Three types of road construction were considered for DWPT, these being trench-based constructions (where a trench is excavated in the roadway for installation of the DWPT primary coils), full lane reconstruction (where the full depth of bound layers are removed, the primary coils installed and the whole lane resurfaced), and full lane prefabricated construction (where the full depth of bound layers are removed and replaced by pre-fabricated full lane width sections containing the complete in-road system).

The first two methods were both found to be viable. Identification of the most appropriate method would require trials. The full lane pre-fabricated method is likely to be prohibitively expensive, although further investigation is required as this is a relatively new construction technique.

The types of machinery which would be required were also considered, and key requirements for some specific road installations tools identified. However, given that an exact method of installation for DWPT systems does not yet exist and requires to be developed, tested and validated, a definitive set of tools and respective specifications cannot be identified at this stage.

Analysis of power requirements at two different DWPT penetration levels was performed. It was found that DWPT systems would likely impose high peaks and variations in power demand which will be dependent on traffic conditions at the time. Furthermore, the exact layout of the DWPT system and its maximum power supply capability will also have a substantial impact.

Two different example layouts for DWPT systems were considered:

### Recommendations

7. Systems with shorter coil lengths (up to 10m maximum) are likely to be safer and cope with higher utilisation. This will become of particular relevance in the case of high take up. However, for the purpose of trials, different coil lengths should be investigated to understand the variability and implications on safety in detail.
8. A back office system should be replicated during trials in order to test its functionality and necessary data exchange without making actual financial transactions.
9. A number of options should be considered by Highways England for ownership of a private distribution network. For low volumes of installations minimising asset ownership is recommended, resulting in higher initial connection costs. This could be used for trials and early demonstrators. For a more comprehensive DWPT system roll out, a private network, similar to Network Rail's, should be considered.

- Example layout 1: This consists of individual power transfer segments of up to 8m long which are combined into power transfer sections of up to 50m long (consisting of 4 segments with gaps between each segment). Up to 2 segments can be energised in any given 50m section. The power transfer is limited to 40kW for light vehicles and to 100kW for HGVs or coaches. Each 50m segment can supply two vehicles with power.

- Example layout 2: This consists of individual power transfer segments of up to 40m long. A gap exists between adjacent segments. The length of this gap is in the region of 5m. Each 40m segment can supply power to one vehicle. Power transfer is limited to 40kW for light vehicles and to 140kW for HGVs or coaches.

The analysis showed that under different traffic conditions and an assumed scenario for vehicle and technology penetration, average demand from DWPT systems can be as high as 500kVA (0.5MVA) per mile. Under these conditions, when utilisation of the system does not approach the maximum value, the expected demand is similar across both layouts. The number and length of segments under these conditions does not have an impact on total power

demand as the number of power transfer segments that can be occupied is limited by the number of vehicles on the road. Demand from example layout 2 is slightly higher than from 1 due to the higher power transfer capability for heavy duty vehicles.



Maximum power requirements per mile can vary between approximately 4MVA and 4.5MVA throughout the day, with the highest values occurring during the morning and evening traffic peaks.

Possible opportunities for EV fleet owners to benefit from EV charging at their depots were investigated. This showed that there are a number of mechanisms to deliver additional financial benefits including:

- Triad avoidance
- Demand side response services
- Common distribution charging methodology
- Short term operating reserve
- Frequency response
- Frequency control by demand management.

Actual benefits that could be derived from the above services will depend on the specific type and number of vehicles, the times of day when they would be connected to a charger at the depot and the flexibility of the charging regime based on the vehicle duty cycle. As such information is not available at present, possible magnitudes of the benefits for each mechanism were described.

The evaluation also considered the potential effects of:

- Energy prices and tariffs, and the likely effects and impacts of pricing models
- Opportunities presented by the Triad system
- Demand side response through dynamic load management
- Various ancillary services.

Various detracting factors were also considered; for example, the current vehicle licensing arrangements, the cost of fleet ownership, and other impacts of fleet electrification (e.g. exemption from paying the congestion charge).

It was found that large fleet operators could benefit from having EVs in their fleet by making use of revenue services described above. In particular, making use of seasonal time of day bands, Demand Side Response Services (DSRS) and Triad avoidance could help reduce the costs of electricity for the operator by minimising charges from electricity suppliers. While, making the vehicles available for Firm Frequency Response (FFR) and Frequency Control by Demand Management (FCDM) services during charging could help generate additional revenue by making the vehicle batteries available for those services. Although, this could result in additional revenue for fleet operators of up to £50 to £60 per kW per year (in the case of FFR) or £26 to £30 per kW per year for FCDM, it requires a commitment to make those vehicles available to the service during agreed periods.

Options for billing were considered, including the requirement to securely and robustly identify the bill payer (be it the driver or vehicle owner), as well as back office and operational requirements. It was found that a DWPT back office system could be created based on existing EV charging back office solutions and existing vehicle identification and communication technology. Although no such complete system exists at present, it is

believed that it could be developed with largely off-the shelf components. A set of requirements for such a back office system were described.

A specific example of a stretch of the M6 motorway was used in order to collect appropriate DNO data provided by WPD, and feed into a free cash flow calculation model. This was used to determine a possible process for recharging users for electricity from the DWPT system. Apart from purely technical considerations, this also looked at “softer” implications, considering planning laws and the relationship to the National Infrastructure Plan and other statutory instruments. A specific recommendation is made to include cooperation with the rail industry as there are distinct parallels with respect to network implications between rail electrification and DWPT.

Costs for setting up connections from the electricity grid to DWPT systems were analysed for the M6 example. It was found that the cost for a 1 km stretch of DWPT could vary between £350,000 to £425,000, depending on the exact layout of the DWPT infrastructure and the asset ownership model used.

### Preparation for off-road trials

#### Recommendations

10. A comprehensive set of PTF trials should be carried out to test different DWPT road construction methods with different DWPT system manufacturers and to understand in detail potential long term impacts on road degradation.
11. A comprehensive set of test track trials should be carried out to validate manufacturer claims and verify DWPT system safety and functionality, as well as to test road installation and grid connection.
12. Stakeholder engagement should be undertaken during the trials by holding a set of workshops, demonstrators and open days to show the technology in operation. This would also be an opportunity to interact with other trials and testing activities around the world, to share knowledge and potentially share testing facilities and trial vehicles, maximising lessons learned about other systems being developed.

Investigation of road construction methods showed that the in-situ full width lane reconstruction was the preferred option for the off-road trial and suitable on in-service Highway England roads. Other methods of installation such as, trench-based construction, should also be investigated during the trials in order to fully understand possible strengths and weaknesses of the different approaches. In order to achieve this, it was proposed that a set of laboratory trials should be undertaken using a pavement test facility and which should include the following:

- Trafficking - the passing of vehicle traffic (or replication of passing vehicle traffic) over a road surface, along the joint between the concrete and asphalt interface which would represent the interface between lanes 1 and 2
- Trafficking the adjacent construction which represents the wheel path (outside the width of the system)
- Trafficking directly above the top of the system to observe how the material surrounding the system behaves (i.e. structural integrity of the

slab with coil system).

The use of instrumentation in the test sections with strain gauges and thermocouples is also recommended. This would enable gathering more information as to the expected strains that these construction types would typically experience under standard wheel loads. Such information could potentially reduce the design thickness of the pavement or the concrete section surrounding the unit itself.

Requirements for test track length, DWPT segment length, power provision requirement and need for additional facilities, such as vehicle storage hangars, were evaluated and described. A track length of approximately 1km was identified as being necessary in order to support tests of up to 100km/h for trial vehicles with at least 2 lanes, each of 3.5m wide. Power supply of up to 800kVA was deemed to be necessary, both to support testing of up to three systems simultaneously, and to gain an understanding of the complexities of connecting the systems to the grid.

Track trials were shown to be an important precursor to eventual on-road trials, significantly de-risking them and providing valuable learning, so it is recommended that they be implemented. One of the key outputs of the trials would be to understand in detail possible safety risks of an on-road deployment.

## Costs and Impacts

### Recommendations

13. PTF and Test track trials should be carried out to validate and if necessary amend cost estimates for road construction and grid connection of DWPT systems.

14. A detailed investigation into specific locations and user groups should be carried out (a market study) that seeks to identify a potential public/private partnership for a demonstrator of DWPT implementation that would be operated on a commercially sustainable basis for vehicle operators. This should be considered as a possible next step if on-road trials prove to be successful.

15. The DfT should be informed of the issues around the appraisal mechanism used for appraising schemes that reduce conventional fuel use and encourage a switch to more environmentally friendly and less polluting vehicle fuels.

Following a review of the impacts that would need to be taken into account in a cost-benefit analysis of DWPT, it was concluded that a full appraisal would need to consider the following:

- Costs to the 'broader transport budget' (Highways England):
  - The DWPT equipment costs and installation
  - A connection to the distribution grid
  - Maintenance
  - User administration and 'back office costs'
  - Electricity charges from the grid
- Indirect taxation impacts on central government finances:
  - Loss of fuel duty
  - Loss of VAT on fuel saved by private users
- Business impacts:
  - The cost of DWPT vehicles in comparison with conventional ones
  - Fuel cost savings (after electricity costs are included)
- Social impacts (impacts on private users):
  - The cost of DWPT vehicles in comparison with conventional ones

- Fuel cost savings
- Environmental impacts:
  - The 'non traded' carbon price of CO<sub>2</sub> savings (taking account of CO<sub>2</sub> emissions from electricity production)
  - The monetised benefits of reduced NO<sub>x</sub> and PM emissions (which vary according to the exposed population and background air quality)

For the purpose of this report costs to business and users were not calculated. Such a calculation would also require information on the likely cost of DWPT vehicles, for which there is currently very little robust information. This report therefore focuses on assessing what the costs of providing a DWPT system might be under a chosen scenario, to both transport budgets and central government finances, and the monetised environmental benefits from reduced emissions.

A scenario was developed in which the proportion of DWPT vehicles using a representative section of motorway equipped with a single DWPT lane was increased steadily over 20 years. In the scenario, the proportion of light DWPT vehicles increased from 10% to 30%, constrained by having only one DWPT lane, while the proportion of heavy DWPT vehicles from 5% to 75%. A spreadsheet model was used to quantify some of the costs and impacts that arise from this scenario, giving the following conclusions:

- The Net Present Value of construction and operating costs, per km, would be £17M, of which infrastructure costs (including a 60% 'optimism bias') account for 30% and electricity 70%.
- In this scenario, the NPV of monetised CO<sub>2</sub> savings would be nearly £2M per km, equivalent to half the capital cost. This corresponds to approximately 45% reduction in emissions compared with the 'without DWPT' case.
- Local emissions of NO<sub>x</sub> and PM would be reduced, in this scenario, by approximately 35% and 40% respectively. The NPV monetised value of these reductions would be less than £100k, except in areas where populations are exposed to poor air quality. Where the NO<sub>2</sub> limit is exceeded, the value of NO<sub>x</sub> reductions would rise to over a million pounds per km over the appraisal period, although this would not be expected to apply to more than a few locations on the SRN.
- There would be a reduction of around £14M in central government revenue, because of the 'loss' of fuel duty and VAT from reduced fuel consumption. This is significantly greater than the capital costs of the fixed infrastructure.

A number of other potential impacts were identified qualitatively, but were not considered further because of a lack of information. However, some would require further investigation as part of any assessment of a proposed scheme, in particular any relating to the maintenance implications of the road, and potential changes in road user behaviour, or demand for transport that might occur.

There are other drivers that could support a business case, in particular the growing need for low and zero emission vehicles in urban areas. If a broader environmental case such as this is being made for buying an EV or plug in hybrid, then the availability of DWPT on motorways will support that case, as the running costs per km will be lower than for a conventional vehicle even at the higher mark-ups on electricity charges considered in this study.



## 3 Introduction

### 3.1 The project

In order to avoid the most severe climate change, it is widely accepted that world-wide emission of greenhouse gases must be halved by 2050, and the UK government has committed itself to reducing CO<sub>2</sub> emissions by 80% by 2050. In 2013, 25% of UK CO<sub>2</sub> emissions were from transport. There is a clear move towards accelerated introduction of Low Carbon Vehicles. Although the UK and European governments' policies are technology agnostic and focus on supporting any technologies that are able to meet government objectives, particular attention has recently been placed on electrified vehicles, as evidenced by the DfT's policies, such as Plugged-in-Places and Plugged-in-Car/Van grants in the UK and the European Commission Directive which specifies what alternative fuels infrastructure should be deployed by the Member States, with particularly high targets for EV charging infrastructure in the latter. At the same time, many of the world's leading automotive manufacturers are making significant long-term investments into electro-mobility, which are indicative of a growing and maturing market.

In 2012, major roads in England (Motorways and A-roads) carried two thirds of the traffic (65.5%), with motorways seeing continued growth since 2010. Therefore, Highways England (previously known as the Highways Agency), as operator of the Strategic Road Network (SRN), is in a prime position to facilitate and support the transition to Electric Vehicles. At the same time, the implementation of Dynamic Wireless Power Transfer (DWPT) may open up opportunities for providing additional services to the users of the SRN and, in the process, create an additional revenue stream for Highways England that can support wider implementation of this programme and therefore, higher benefits.

DWPT is being considered first (ahead of other technologies such as rapid battery charging and overhead conductive charging) for a number of reasons. It could potentially be implemented on all vehicle classes and types (unlike some conductive charging options, such as, catenary-based systems). It overcomes issues (whether real or perceived) with battery performance by receiving power on the move. Because DWPT systems can be installed under the road without any additional visible infrastructure, they do not introduce additional safety risks (collision or electrical safety) and potentially minimise the need for maintenance.

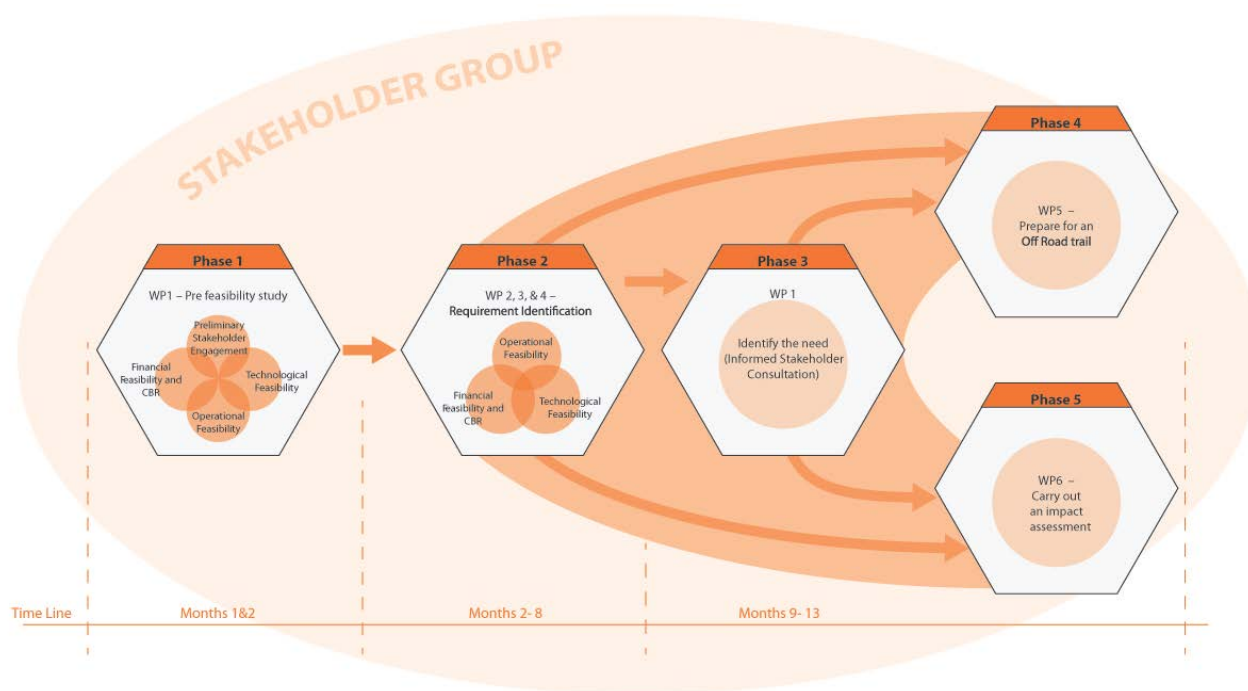
This project aims to inform Highways England of this potentially environmentally friendly solution that will provide a safe road environment for the projected growth in electric/hybrid vehicles using the Strategic Road Network. The project is the first stage in a much larger programme of work aimed at demonstrating this technology on the SRN.

### 3.2 Methodology and Approach

This feasibility study is expected to be Stage 1 in a larger research programme put forward by Highways England. The description of the full programme can be found here:

<http://www.highways.gov.uk/knowledge/projects/preparing-the-strategic-road-network-for-electric-vehicles/>

The methodology for this feasibility study consisted of five phases as shown in Figure 1. Although it was originally planned to be delivered in 13 months, delivery of the study was accelerated at the request of Highways England and completed within 7 months.



**Figure 1: Methodology overview**

Phase 1 of the project focused on undertaking a comprehensive stakeholder engagement programme with potential private and commercial vehicle and system users. During this phase the scope of the feasibility study was also finalised.

Phase 2 focused on requirements identification for the DWPT system as a whole and also on its integration into the road, different vehicle types and connection to the electric grid.

Phase 3 built on stakeholder engagement from Phase 1 and combined it with preliminary project outputs that could be shared with stakeholders to seek further, more informed feedback on attitudes towards DWPT.

Phase 4 focused on preparing for off-road trials of DWPT technology in the UK that were expected to follow the feasibility study in future stages of the research programme.

Phase 5 was dedicated to carrying out a comprehensive impacts assessment of introducing DWPT on the SRN in England. It covered environmental, economic and financial aspects for introduction of DWPT in different use cases.

### 3.3 Project team and partners

The novelty and complexity of the project required a multidisciplinary team of experts to fully address all of the elements of the feasibility study. TRL selected and led a team of experts from around the world to support TRL in the delivery of the aims and objectives of this study.

The following organisations were either partners in the delivery of the project or provided valuable information and support during the project:





The project team would also like to thank **Jaguar Land Rover** for their views, opinions and contributions to the study.

### 3.4 Structure of this document

The following sections provide an overview of project findings based on tasks undertaken during the project:

Section 4: Stakeholder Engagement – this section covers the initial stakeholder engagement (with private EV drivers and commercial operators) and follow on engagement with selected organisations based on preliminary project results.

Section 5: Functional requirements – this section covers a review of existing technologies, characterisation of other services that could be provided by Dynamic Wireless Power Transfer (DWPT) installations and the impact of DWPT on other electrical services

Section 6: System performance requirements – this section develops guidance specifications for the installation of DWPT systems in vehicles and road infrastructure, as well as identifying requirements for battery systems

Section 7: Process requirements – this section identifies power requirements for DWPT systems, reviewed commercial opportunities for EV fleet operators, identified requirements for a back office system and identified requirements and costs for connection of DWPT system to the electric grid

Section 8: Preparing for off-road trials – this section develops recommendations for how to proceed to off-road trials as part of the next phase of the programme, covering test track trials and pavement test facility trials

Section 9: Costs and Impacts – this section performs impact assessment for the introduction of DWPT for the infrastructure operator, and for a national level transport scheme appraisal.

An overall summary is provided in Section 10.

## 4 Stakeholder Engagement

### 4.1 Introduction to stakeholder engagement

There are two main areas of the market when considering EV and PHEV uptake: fleet and private consumers. Car purchase behaviour falls somewhere between economic models that inform both fleet and private decision makers and understanding the attitudes of the fleet manager and the private consumer. Studies have demonstrated that fleet managers are more reliant on economic models of decision making, although companies may be willing to pay more to present a particular image that they feel an EV or PHEV provides (Hutchins & Delmonte, 2012). Private consumers are less reliant on economic models; instead it is necessary to understand their attitudes, which have been shown to be a key determinant in understanding future uptake of EVs and PHEVs (ETI, 2013). Attitudes refer to a variety of personal attributes such as concern, awareness, understanding, opinion, and beliefs. Attitudes that influence consumer decision making can be further defined as instrumental, symbolic and affective:

- Instrumental attitudes are factors relating to general practical or functional attributes of driving
- Symbolic attitudes relate to what the car says about its owner in terms of social status, social conscience and personal values
- Affective attitudes refer to the feelings evoked by owning and using a car.

These attitudes are not mutually exclusive as, for example, the symbolic status a car gives may influence the way a car makes you feel.

#### 4.1.1 *Passenger car consumer survey methodology*

An online questionnaire survey was designed and administered to 200 participants from the TRL participant database who had previously had experience of driving an EV or PHEV. For previous trials these participants had been identified as being representative of new, or nearly-new, car buyers in Great Britain. This sample was selected to ensure that participants had at least some background understanding of using and driving an electric powered vehicle, and were typical of those who purchased new or nearly new cars. Prior to starting the questionnaire, participants were provided with information about DWPT technology.

A total of 80 respondents completed the online survey. There was an even split of male (51%) and female (49%) respondents.

The questionnaire itself was designed to collect the following data:

- General demographics
- Household characteristics (e.g. Number of vehicles, postcode, employment status, income, relationship status)
- Travel patterns (e.g. annual mileage, journey purpose)
- General attitudes to driving
- Knowledge of and attitudes to EVs and DWPT (including instrumental, symbolic and affective attitudes)

- Likelihood of owning an electric vehicle in the future (with and without access to DWPT)
- Expected cost of DWPT enabled vehicles compared to current internal combustion engine (ICE) vehicles and EVs.

#### **4.1.2 Freight and coach operator survey methodology**

Due to the technical and 'future' focus of the subject matter, the companies which were approached for this survey were national operators in the road haulage and third party logistics sectors, and the coach sector. These were considered to be in a position to provide a strategic perspective on a technology that many smaller operators would not necessarily consider as an option for their business at this stage of vehicle and infrastructure development.

Separate questionnaires were prepared for the road haulage and coach sectors, each of which described the technology as it applies their industry. The questionnaires asked 18 questions that included their current electric vehicle usage, cost and investment indicators, and environmental views. Agreement in principle was sought for participating in any trial to be conducted (at no cost or risk to the operator). The background information provided was the same as for consumers.

Contact was made with the following:

- 10 National operators with a strong regional presence, a combination of:
  - Hire and reward
  - Own account operators
- National bus/coach operators with a strong regional presence including:
  - Scheduled coach operations
  - Non-scheduled coach operations.

Interviews were also conducted with representatives from the Freight Transport Association (FTA) and the Confederation of Passenger Transport (CPT).

Some of the industry contacts asked to complete the questionnaires as telephone interviews, whilst others did so in their own time and returned the questionnaire. The response rate for road haulage was 90% whilst the coach sector response was nil.

Whilst knowledge and experience of electric vehicles and other alternative fuels is relatively high in the bus industry, there is a knowledge and technology gap within the coach industry that was evident from the interviews conducted during the project. According to the CPT, very few of its members from the coach industry were familiar with EV technologies. Discussions within the industry and confirmed by CPT have established that there are not yet any electric variants of coaches in operation in the UK, either scheduled or non-scheduled. Until such time as an electric powered vehicle is visible to the coach industry, DWPT technology will remain unsighted as a viable alternative fuel technology.

#### **4.1.3 Informed stakeholders**

A further set of interviews were carried out towards the end of the project with those stakeholders showing the most interest in the technology. The purpose of the interviews

was to understand stakeholder perceptions of the technology, based on the most up to date information available as a result of this project.

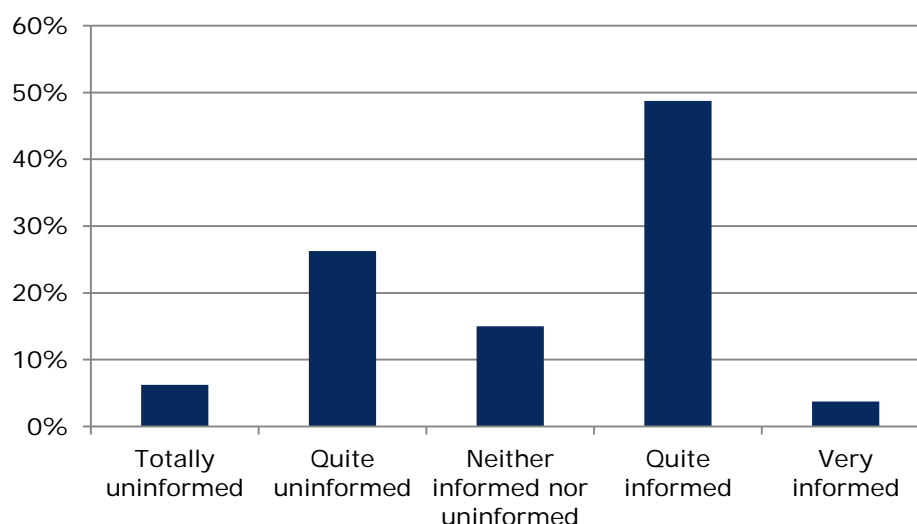
Of the original ten vehicle operators interviewed at the beginning of the project, four were in a position to answer further questions (the remaining four felt the technology was inappropriate to them). Interviewees were presented with the cost-benefit analysis information sheet that outlined possible costs, benefits and payback timescales for the DWPT technology as calculated during the project. Two interviews were carried out; the other two of the respondents were unavailable at the time of writing.

Interviews were carried out over the phone. They were recorded with the respondents' permission, and notes were taken during the conversations. The questions asked about:

- Likelihood of DWPT-enabled vehicles becoming a part of their fleet
- Perceived requirements for how much infrastructure should exist before considering committing to adopting these vehicles
- Concerns related to DWPT-enabled vehicles and the associated infrastructure
- Benefits for their organisation of incorporating DWPT-enabled vehicles into the fleet.

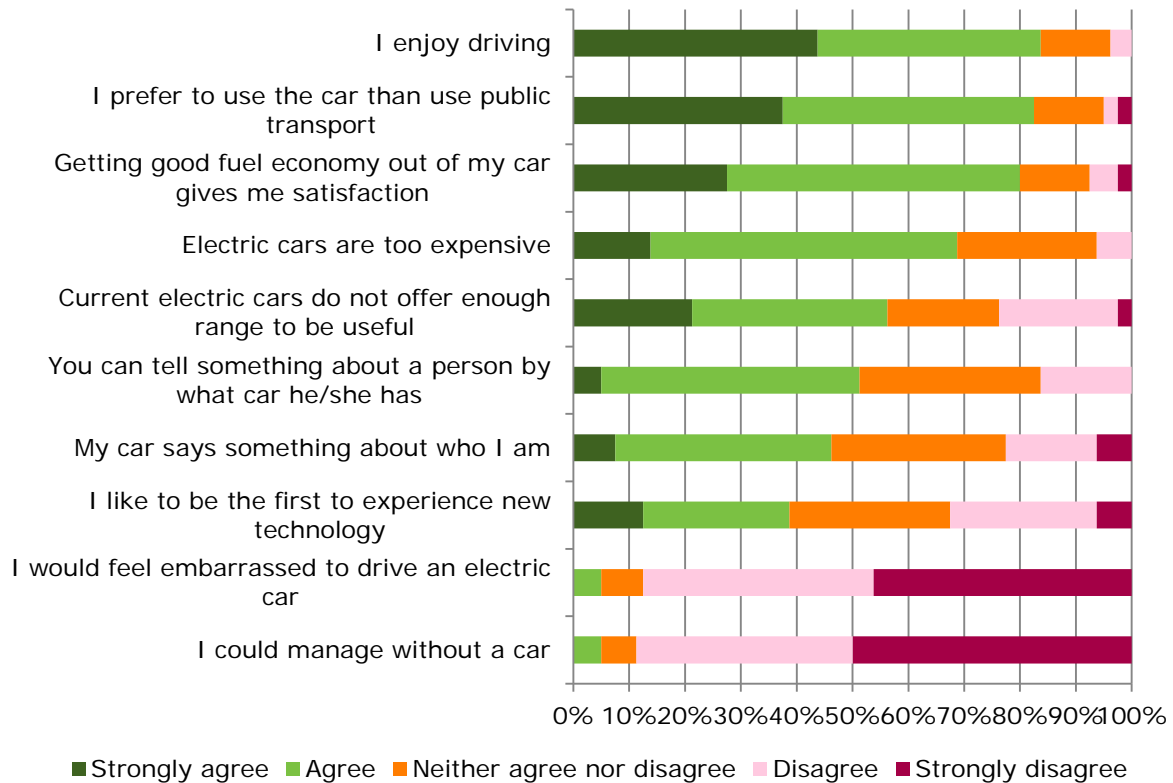
## 4.2 Results

Despite having previous experience with EVs, a third of car drivers stated that they felt uninformed about them. This is possibly symptomatic of the current lack of market penetration of electric powered vehicles, see Figure 2.



**Figure 2: Car consumers: How informed do you currently feel about electric cars in general?**

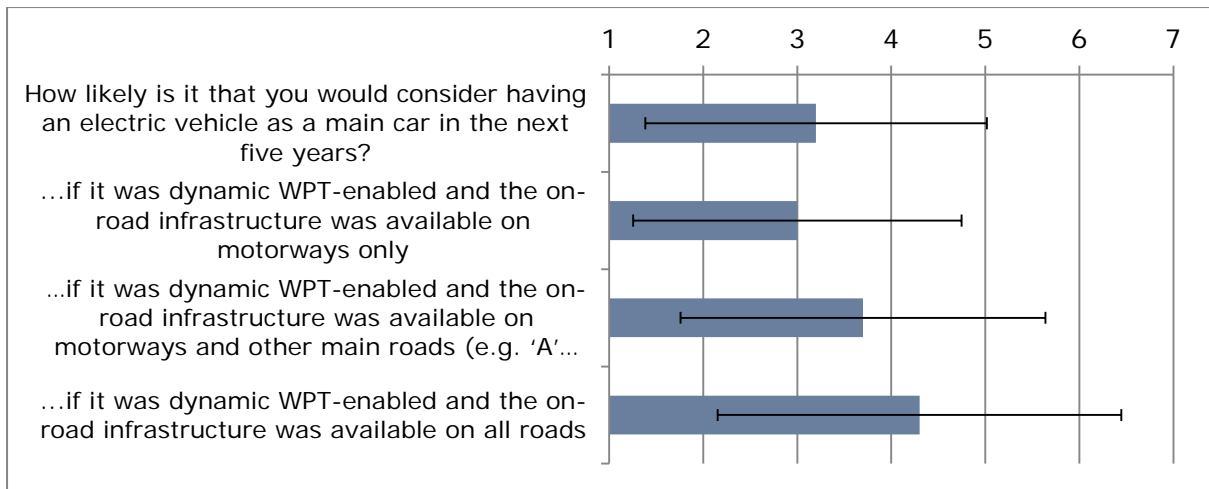
Car drivers' general attitudes to driving suggested that they enjoy driving, and that the car is a necessary and preferred mode of transport. Symbolic attitudes towards EVs were positive although responses to instrumental items suggests that for the majority of those surveyed, EVs are too expensive and do not offer enough range to be useful, see Figure 3.



**Figure 3: Car consumers: Level of agreement with electric car statements**

Awareness of DWPT prior to the survey was low. This was reflected in the responses to a number of items which suggest that many had not acquired enough information, or had not had enough time to process the information, in order to develop positive or negative attitudes.

The surveys of both private and commercial road users highlight the ‘chicken and egg’ issue which arises with the adoption of new technologies: the results show that vehicle purchasing decisions by both industry and consumers will depend on the wide availability of DWPT, but the business case for investing in the technology is weak without demand from users, see Figure 4 showing responses from private car users.



**Figure 4: Car consumers: Expected likelihood of EV purchase - mean response and range (1=not at all likely, 7=very likely)**

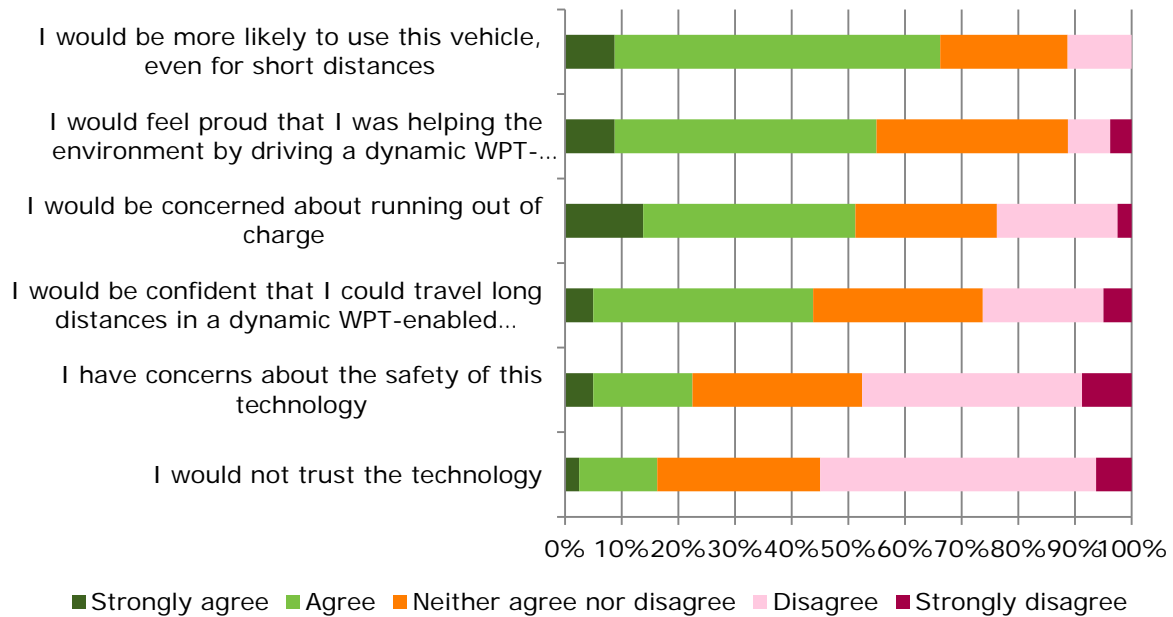
The small survey of industry stakeholders associated with the project workshop indicated that there is some support for the view that the Highways England should deploy and own the DWPT infrastructure on the Strategic Road Network, but that the system should be operated by a third party (50% of respondents had this view).

The improved performance of new Euro VI light and heavy duty engines is seen by some operators as meeting the requirement to reduce emissions without increasing risk to businesses, while competing alternative fuel technologies create an investment risk. Residual value of DWPT enabled vehicles was also found to be a dissuading factor in decisions on replacing commercial vehicles, as DWPT-enabled vehicles were expected to cost more than standard diesel vehicles and have a lower residual value in the early stages of adoption.

Commercial operators require a return on investment within 18 months to three years. Thus any additional cost of leasing or purchasing vehicles would need to be balanced by savings on operating costs to offset these additional costs over this relatively short time period. Industry stakeholders indicated that important factors in investment decisions related to DWPT technology would be automation and user-friendliness of the DWPT system, practicality and simplicity of charging and the level of CO<sub>2</sub> reduction.

The survey of consumers who had some previous experience of using an electric vehicle indicates that although participants were mainly positive about EVs, they were unlikely to have an EV as a main car in the next five years; for the majority, EVs were seen as too expensive and not offering enough range to be useful.

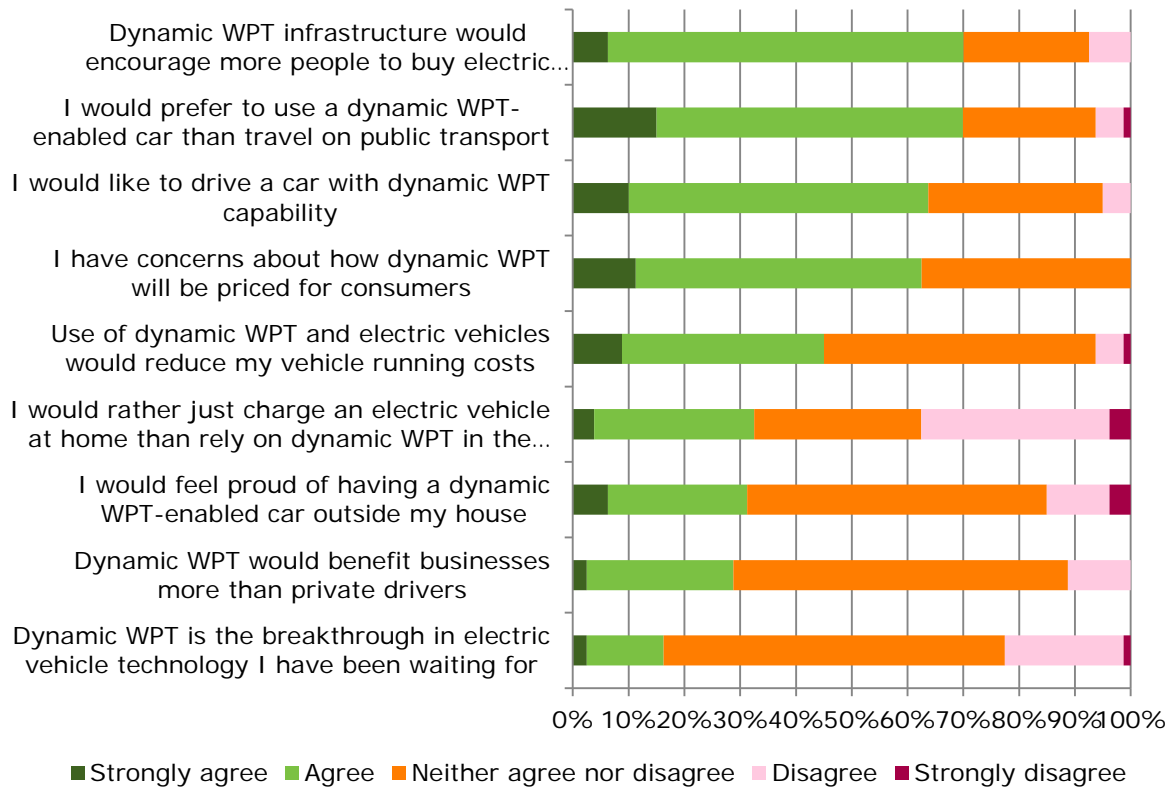
Consumer respondents appeared to trust the DWPT technology and only a minority had concerns about safety, but a large proportion said they would still be worried about running out of charge; this suggests that range anxiety continues to be a barrier to be addressed through marketing, information, technological advances and/or further experience, see Figure 5.



**Figure 5: Car consumers: Level of agreement with further WPT statements**

The results suggest that the majority of respondents believe that this technology could at least in part address barriers to the adoption of EVs, barriers that are likely to be related to range limitations, see Figure 6. Nevertheless, a majority of car drivers also expressed concerns with regard to how the technology would be priced. A large number of respondents also neither agreed nor disagreed with the statement about the pricing of DWPT; a pattern that is apparent in several other statements. It is likely that drivers have not yet had enough exposure to this issue, or the necessary time to form positive or negative attitudes towards it.





**Figure 6: Car consumers: Level of agreement with WPT statements**

Industry stakeholders indicated that they were more likely to purchase an EV if it were possible to use DWPT on equipped sections of the Strategic Road Network. Similarly, the responses from consumers indicate that introducing DWPT on motorways would increase the likelihood of having an EV as their main car in the next five years, and that the likelihood would increase if DWPT were introduced on main roads as well as motorways. These responses may be tempered by the expectation that a DWPT-enabled vehicle would be more expensive than current EVs, which are already considered to be more expensive than a current diesel car (it should be noted that the cost of EV technologies is expected to reduce with increased market penetration and economies of scale).

Thus while car consumers did not report that DWPT was the breakthrough technology they were waiting for, there were indications that DWPT could encourage EV adoption among private motorists. It is possible that DWPT is seen as addressing barriers such as limited range, although there was some evidence of concern about how much consumers would be expected to pay to charge their vehicles using DWPT. There are indications therefore, that DWPT availability could play an important role in influencing consumer decision-making and behaviour.

The third of car consumers who thought that DWPT would benefit businesses more than private drivers provides an indication that people who drive regularly for business may be more likely to be early adopters of DWPT-enabled vehicles than those who drive predominantly for private purposes.

Even this group of consumers with previous experience of using an EV included a substantial minority who felt uninformed about EVs. Having been provided with background information about DWPT, the responses indicate that respondents had not yet developed positive or negative attitudes, with many neutral responses to some

questions. There is clearly more to be done to extend public knowledge and experience of EVs in general, and DWPT in particular, in order to overcome some of the perceived barriers to EV adoption.

### **4.3 Results of follow up interviews with selected freight operators**

#### **4.3.1 Likelihood of future uptake**

Organisation 1 felt that the future uptake of DWPT-enabled vehicles in their fleet was highly likely, but infrastructure would need to “fall into place” before they made any adaptations to their fleet. They had previously been involved with Volvo and Scania trials and so tend to be early adopters of the newest technologies before most other organisations. If full scale trials of DWPT-enabled vehicles came about, they would certainly be open to discussions, but a full-scale change to the technology would depend on where the routes were planned to be. They would also need to consider the length of time they would need to spend off the grid.

Organisation 2 tends to be interested in projects which allow them to be at the forefront and try out pioneering technologies. They have had involvement with new technologies such as telematics, and being early adopters is part of their company philosophy. They would be likely to use the DWPT network for night time driving (which uses the motorway network) rather than for their larger retail delivery fleet (which uses local roads).

Organisation 3 was very interested in taking up DWPT technology. This organisation only operates vehicles over 7.5 tonnes and is currently operating an electric vehicle in London. The interest in DWPT technology is driven by their perceived customer expectation for freight operators to be proactively seeking ways to reduce emissions and pollution from their vehicles. Timescales for take up will be influenced by availability of infrastructure and vehicle reliability.

#### **4.3.2 Required infrastructure and vehicles**

Organisation 1 stated that they tend to have dedicated routes, with starting and end points not tending to change for their major clients. Therefore installation of WPT on any of their standard trunking routes would be suitable for a future trial. There were concerns over whether a WPT-enabled vehicle would require a reduction in the vehicle load capacity, and also any reduction in the range of the vehicle.

Organisation 2 does a great deal of motorway driving (for their night-time fleet) but felt that the vehicles were more of a concern than the routes at this stage. There were concerns over range limitations of the vehicles, as they have experience of hybrid vehicles not being big enough for their needs. They stated that any trials would need to involve at least two vehicles to establish whether the technology would be suitable.

Organisation 3 is expecting to dedicate potential DWPT vehicles to a specific route. Ideally, they would like to see part of the M25, on the north section, equipped with such systems in order to support their operations into London. The requirement for vehicles is for them to be reliable. Capital and whole life costs of the vehicles must be competitive.

#### **4.3.3 Perceived benefits**

The main concern for Organisation 1 was that the technology would not be cost effective. They would not be able to move to the technology for purely environmental reasons. Whilst clients are pushing for fuel efficiency, they also require organisations to re-tender for the work every five or ten years. Organisation 1 would need to maintain their competitiveness in the marketplace, and the move to a new technology would involve many costs and, therefore, become a stumbling block with a negative knock on effect on the business. Organisation 1 suggested that the best way forward for a trial may involve a partnership approach between them and a major client, with shared costs.

Organisation 2 stated that they try to be as environmentally positive as possible, and any technology that reduced fuel consumption is good for the business, both financially and environmentally.

For Organisation 3, the main perceived benefits are around use of more sustainable vehicles which will help them to meet requirements imposed by customers, particularly for operations into and out of London. Reduced running costs would also be expected.

#### **4.3.4 Other fuel technologies**

These organisations have considered alternative fuels, with Organisations 2 and 3 having undertaken trials of electric and hybrid vehicles or continuing to operate at least one EV. However no organisations had found an alternative fuel that worked for their business. In particular, gas vehicles were highlighted by these organisations as having poor reliability that deterred some operators from using them (although there are some large HGV fleets with gas-fuelled vehicles at present).

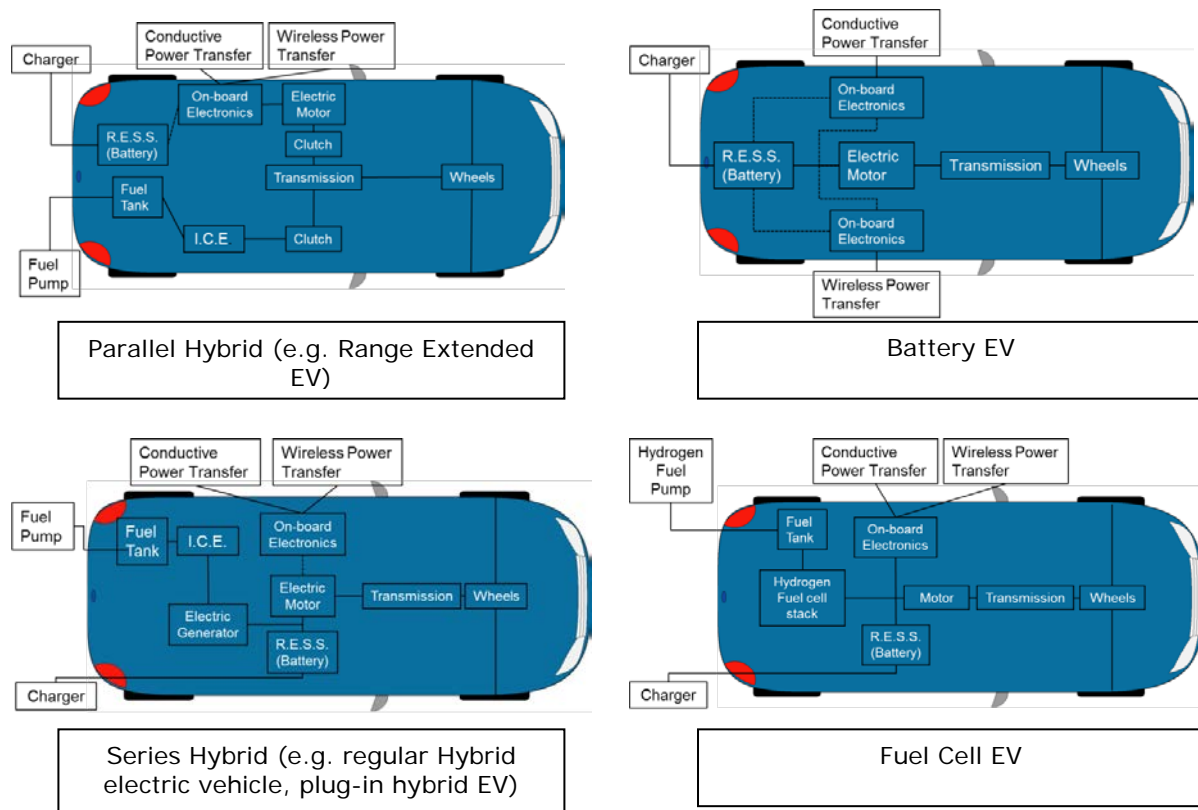
#### **4.3.5 Potential participation in funded trials**

The representatives of all three organisations stated that they would be willing in principle to trial DWPT-enabled vehicles as part of funded trials. At least one organisation also expressed the need (if the trials prove successful) to follow up the trials (off-road and on-road) with a longer term "implantation" of a small number of vehicles in their fleet. This would make it possible to test them over the expected lifetime in typical operational use before the organisation could commit to purchasing the vehicles.

## 5 Functional Requirements

### 5.1 Introduction to DWPT technologies

The main focus of this section is to identify possible DWPT technologies that would be suitable for taking forward to an off-road trial in the UK and their key characteristics / performance parameters; identify and characterise potential other services; and analyse the impacts of dynamic DWPT on other electrical services. A brief overview of vehicle technologies and DWPT principles is presented in Figure 7 and Appendix D.



**Figure 7: Examples of powertrains that can be used with dynamic power transfer**

For all electrified vehicle powertrain options, including hybrid powertrains, a vehicle can make use of a power transfer system to charge the on-board Rechargeable Energy Storage System (RESS – the battery) or to provide power to the electric motor. Typically, such power transfer systems are plug-in electric chargers (as shown in Figure 8a) that charge the vehicle batteries at varying levels of power (usually between 3kW and 50kW, although some, like the Tesla supercharger can go up to 120kW) while the vehicle is stationary and switched off. However, it is also possible to use wireless power transfer to charge the batteries while stationary, using charging “pads” as shown in Figure 8b. Both of these solutions are adequate for charging at home or in car parks but still require the vehicle to stop in an appropriate location to charge the battery. Dynamic power transfer is another option for supplying power to electric vehicles and, as it can be used while the vehicle is moving, it can help to reduce or eliminate issues with restricted range. Dynamic power transfer can be either conductive (as shown in Figure 8c) or wireless (as shown in Figure 8d). It can be used to supply the electric motor with power directly or to charge the on-board RESS, or both, as shown in Figure 7.

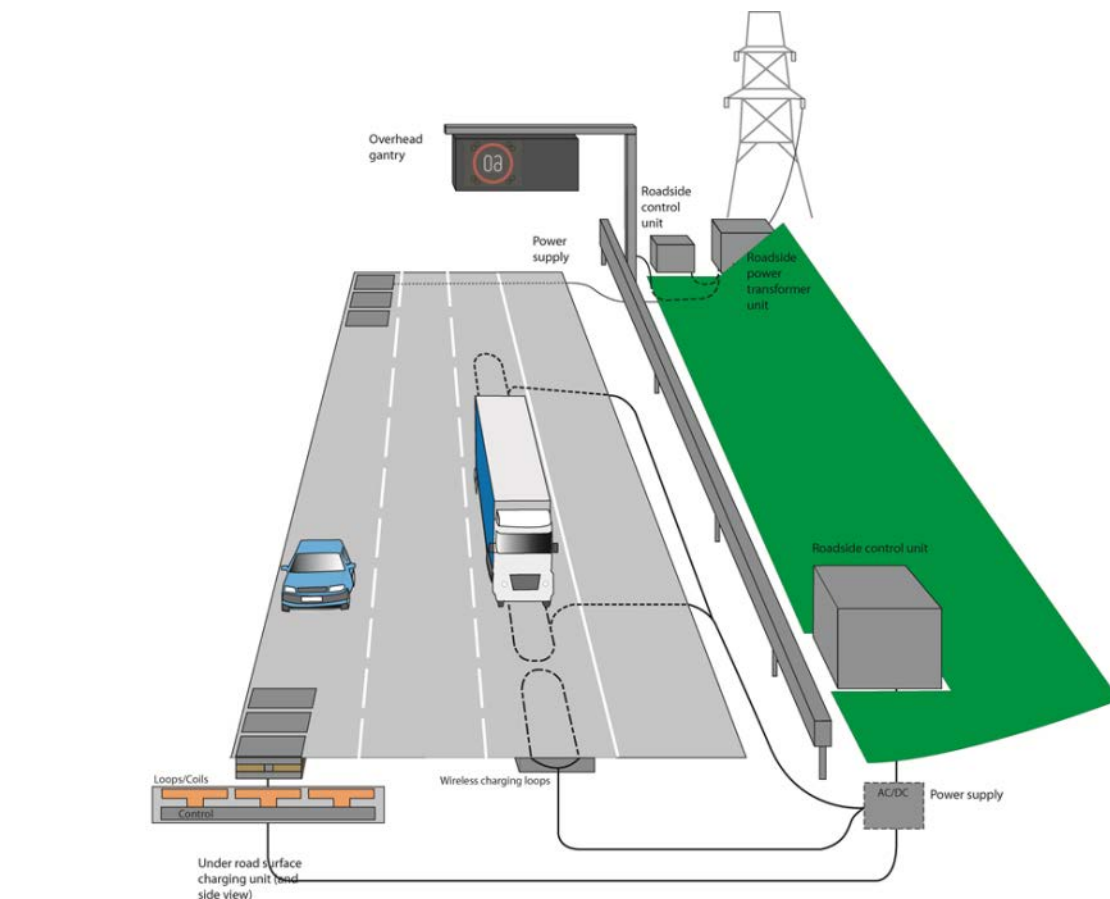
Conductive dynamic power transfer is only practical for vehicles of a certain size (in the case of pantograph solutions) and requires a considerable amount of over ground infrastructure and cables, which could present a considerable maintenance challenge and a potential safety hazard. In the case of in-road conductive rail systems, there are some substantial issues associated with electrical safety and operational durability of such systems if deployed in the motorway environment. Therefore, for the purpose of this project, the feasibility of WPT systems is considered.



**Figure 8: Types of power transfer solutions**

## 5.2 Qualitative considerations on the DWPT deployment

A road equipped with a DWPT system can be represented as in Figure 9: at the roadside, substations receive electric current from the grid and they adapt it in order to feed the primary circuits embedded in the road.



**Figure 9: Dynamic wireless charging topology**

A more detailed assessment of power and energy requirements is described in Section 7 of this report but for the purposes of assessing existing solutions, it is assumed that the required power transfer level from a DWPT system on a motorway is around 20kW to 40kW per vehicle for cars and light vans, and between 100kW and 180kW for trucks and coaches, based on the power required to maintain constant motorway speed.

### 5.3 Review of DWPT systems

The project has investigated a number of possible WPT technologies focusing on those able to function as DWPT systems. In total, 17 WPT systems were reviewed, 8 of which were found to have DWPT capability of some capacity. Table 1 below provides a high level overview of the reviewed systems.

**Table 1: Overview of WPT systems reviewed**

Supplier	Description
<b>Energy Dynamics Lab</b>	<p>Part of Utah State University.</p> <p>Still doing research but technology developed was spun out to Wave Inc. (see below)</p>
<b>Evatran</b>	<p>Marketed as 'Plugless Power'.</p> <p>After market system for replacing current plug-in chargers with wireless system for residential charging only.</p> <p>Evatran have partnered with Yazaki to commercialise the system.</p>
<b>Fraunhofer Institute</b>	<p>A large German research organisation involved in a wide range of activities.</p> <p>Technology demonstrator only using inductive pads mounted on the front of the vehicle for residential charging. Uses smaller coils due to closer coupling and easier positioning. Not suitable for dynamic charging.</p>
<b>InovaLab</b>	<p>InovaLab was a spin off from the University of Padua which is now owned by SAET Group. InovaLab are participating in an EU funded programme called FABRIC (Feasibility analysis and development of on-road charging solutions for future electric vehicles).</p> <p>InovaLab are developing the primary infrastructure as part of FABRIC and aim to develop their own vehicle based components in order to be able to supply a complete DWPT system.</p>
<b>INTIS</b>	<p>INTIS (Integrated Infrastructure Solutions), subsidiary of the IABG group, developed an inductive energy transfer system for cars and buses. The system has been developed to operate as static or DWPT system. The project has been carried out in collaboration with Fraunhofer (Electromobility) plus a number of other companies and associated partners and it has been funded by the German Federal Ministry of Transport and Digital Infrastructure.</p>
<b>IPT Technology (sub-division of Conductix Wampfler)</b>	<p>Joint venture between Conductix Wampfler and PROOV B.V to develop applications in electric mobility.</p> <p>Long experience in the field due to parent company involvement. Concentrates on autonomous industrial system and bus applications for static charging, including eight buses on a route in Milton Keynes.</p>
<b>KAIST (Korea Advanced Institute of Science and Technology)</b>	<p>Korea Advanced Institute of Science and Technology.</p> <p>Magnetic resonance system which can operate over longer range than standard inductive charging systems.</p> <p>Currently fitted to demonstrator cars and buses. Technology licensed to OLEV Technologies (see below)</p>
<b>OLEV Technologies</b>	<p>Licenses technology from KAIST.</p>

Supplier	Description
	Target markets are buses, port transportation, trucks.
<b>ORNL (Oak Ridge National Laboratory)</b>	American research institute which has laboratory based technology demonstrators for dynamic charging.
<b>POLITO</b>	Politecnico di Torino (POLITO) together with Centro Ricerche Fiat is working on the Charge While Driving (CWD) solution. The solution is being developed as part of a European Commission co-funded project FABRIC.
<b>Primove</b>	<p>Primove is the e-mobility unit of Bombardier transportation who are a large supplier to the rail industry.</p> <p>Inductive charging system aimed at light rail, bus and automotive fleet operations.</p> <p>Concentrates on static charging, though claims dynamic charging capability as well.</p>
<b>Qualcomm Halo</b>	Founded as Halo IPT by Arup using magnetic resonance technology originally developed by Auckland University. Halo IPT was purchased by Qualcomm in 2011 to found Qualcomm Halo. Currently working on a static charging system with ongoing research into dynamic charging. Also, part of the FABRIC project.
<b>SEW Eurodrive</b>	Offer industrial systems and electric bike systems only.
<b>Siemens</b>	Offer the Sivetec inductive charging system for static charging.
<b>TDK</b>	TDK Corporation made an intellectual property license agreement for the wireless power transfer technology developed by the MIT spin-off company WiTricity (see below). They aim to commercialise the static charging system, and to demonstrate a DWPT application.
<b>Wave Inc.</b>	This is a spin off from Utah State University (Energy Dynamics Lab) to market the technology. It concentrates on bus applications. They provide purely static charging systems situated at bus stops along the routes.
<b>Witricity</b>	Witricity have developed wireless charging systems based on magnetic resonance for static charging. The technology was originally developed at MIT.

Each system that is capable of dynamic functionality was evaluated by the project team and assigned a Technology Readiness Level (TRL) and Manufacturing Readiness Level (MRL). Table 2 below summarises the findings.



**Table 2: TRL and MRL of DWPT systems**

DWPT System Developer/Supplier	TRL	MRL	Comments
<b>OLEV - KAIST</b>	8	7	The most market ready solution – demonstrated at test tracks and in an operational environment
<b>Primove – Bombardier</b>	7	5	Demonstrated but no fully integrated dynamic system has been demonstrated in operational environment for road vehicles
<b>INTIS</b>	6	4	A working prototype demonstrated in laboratory conditions with multiple vehicles
<b>ORNL</b>	6	4	A working prototype demonstrated in laboratory conditions
<b>WiTricity / TDK</b>	5	3	A small scale laboratory prototype has been demonstrated
<b>Polito</b>	5	3	A small scale laboratory prototype has been demonstrated
<b>Qualcomm Halo</b>	4	3	A small scale laboratory prototype has been demonstrated
<b>Saet</b>	4	3	A small scale laboratory prototype has been demonstrated

## 5.4 Identification and characterisation of other services

It is possible that installation of DWPT technology in the highway could provide added benefits to Highways England and its customers as well as other stakeholders.

Two types of possible ways of providing other services are considered:

1. Other services that could be provided using existing technology and capability of dynamic WPT systems
2. Other services that could be provided by utilising the installation process and civil works that will be undertaken during installation of DWPT systems

These options are described below and, where possible, the benefits are defined and quantified. However, at this stage of the project all work is based on desk-based studies with little hands-on experience of the equipment and its capabilities. There is also very limited evaluation of such possible additional services from the technology suppliers themselves due to relatively low maturity of the technology. For these reasons, quantification of benefits can be difficult. Where such information is not available, possible benefits are outlined.

### 5.4.1 Other services provided using DWPT technology

A typical DWPT system consists of a number of primary coils embedded in the road, connected to roadside units deployed on the verge behind crash barriers, which are then connected to a Distribution Network Operator (DNO) supply. In addition to these basic

components, a typical DWPT system also includes a communication system that allows communication between the vehicle (secondary coil and relevant on-board electronics) and the road side unit, and a sensor that detects when a vehicle is approaching the primary coil or is positioned over the coil. A number of components within this system which could provide additional functionality are listed below.

#### *5.4.1.1 Network management and Smart Motorways*

This service is perhaps the hardest to quantify as it is heavily dependent on the penetration rates of vehicles able to use the system and the length of system deployed across the SRN. However, theoretically, DWPT systems could be integrated with Smart Motorways. In particular, there are two possible ways of doing this:

1. The system can be remotely configured to function only for vehicles moving at certain speeds. This remote configuration could be automated and be linked to messages sent to variable speed limit displays. Vehicles wishing to use the DWPT system and benefit from the ability to receive power on the move would need to maintain the recommended speed, helping to achieve a smoother flow on that section of the network. Furthermore, as each coil can only be occupied by a single vehicle for the system to function effectively, this requires a certain vehicle headway to be maintained. This could encourage drivers to keep a safe distance from the vehicle in front and thereby reduce the number of incidents related to insufficient distance between vehicles.
2. The second way could be utilising the existing sensors in the DWPT in-road equipment to assist with measuring traffic flows and collecting flow data. Alternatively, traffic loops could be installed in the ground as part of the DWPT installation process, thereby minimising the additional cost of installation (see Section 5.4.2.1).

#### *5.4.1.2 Provision of communication and connectivity*

With increased interest from Highways England in possible provision of infrastructure that could support cooperative services and communication along the SRN, it is relevant to explore what communication and connectivity could be provided by the DWPT systems. Since there is no physical connection between the secondary coils on the vehicle and the supply equipment on the ground, DWPT systems rely on the use of wireless communications to ensure that the system functions as intended.

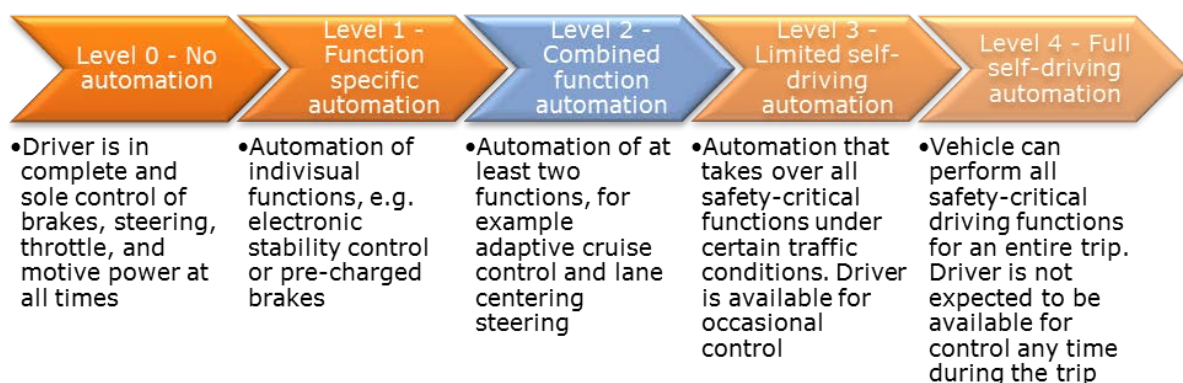
Systems reviewed during the project tend to use closed communication systems between the vehicle and the ground supply equipment. These can be RFID, Wi-Fi or Bluetooth based systems. There will be no way for other road users to access these communications in order to gain internet connectivity. Therefore, these short range communication systems are unlikely to provide any additional benefit to other road users.

DWPT systems also rely on long range communications for remote monitoring and diagnostics of the ground supply equipment. This is typically some sort of a mobile GPRS-based communication capability (typically 3G or 4G). In theory, it would be possible to open up this communication channel to nearby road users, perhaps by creating a series of local Wi-Fi hotspots that a user could connect to. A certain amount of the available bandwidth would need to be reserved for the DWPT system itself in order

to ensure that it can have a communication link with the remote back office / monitoring centre, regardless of demand from other road users. However, a closer examination of this particular use case suggests that this would not be feasible. The main reason for this is that if the primary supply equipment is able to gain a mobile data signal then this signal should also be available to users on a nearby section of motorway. Unless the DWPT Wi-Fi hotspot was provided free of charge for users who could then use it instead of the mobile data signal, it would not make sense for road users to use this service. They could use the available 3G or 4G signal directly themselves. Furthermore, if the Wi-Fi hotspot was provided as a free service, it would then result in additional costs to the DWPT operator arising as result of increased data use by road users. Therefore, it is not foreseen that provision of connectivity to road users could be a viable additional service provided through DWPT systems.

#### 5.4.1.3 Supporting vehicle automation

Vehicle automation is a topic that has seen much attention in recent years. There are various degrees of automation, which are typically described in Levels from 1 to 4. Level 1 represents basic components of autonomous functionality working in isolation and Level 4 represents full autonomous functionality with no driver input required, as described in Figure 10.



**Figure 10: Levels of vehicle automation**

Most vehicle manufacturers have already implemented Level 2 systems in their vehicles and most current research and pilot studies are focusing on developing and evaluating the performance of Level 3 systems. However, in order to achieve limited self-driving, a vehicle must be aware of its surroundings: both static surroundings such as road infrastructure and dynamic surroundings such as other road users. In order to “see” the sensors use reflecting electromagnetic waves of different lengths from surrounding objects and then process the detected reflected signals in real-time to develop a picture of the surrounding environment. Such sensors could include cameras, lasers and radar systems, and LIDAR systems. However, in a motorway environment where there is a relative lack of 3D objects distinguishing one lane from another or, defining geometry of the road itself, it can be difficult for an autonomous vehicle to accurately determine its relative position on the motorway and maintain its position in the lane. Camera-based systems with sophisticated image processing algorithms can help with this task, such as those used for lane centring, by detecting vehicle position in between the white lanes of

a lane. However, camera-based systems are dependent on having a clear and undistorted view of the surroundings. Adverse weather conditions such as thick fog, heavy rain, snow or even glare from bright light sources, can sometimes stop such systems from working effectively thus preventing autonomous vehicle functionality.

Buried coils under the road surface can provide an alternative method for a vehicle to accurately detect its position within the lane and maintain its position regardless of weather or road conditions. The strength of the magnetic field generated by the DWPT loops buried under the road can be continually measured by the secondary coils on board the vehicle. Deviation of the vehicle from the primary coils can be detected instantly. This information can then be fed into the autonomous vehicle controls.

Some stationary WPT systems already use this functionality in order to inform the driver of how well aligned the vehicle is to the primary coil. Furthermore, as far back as 1975, TRRL (at the time known as TRRL) showed that similar systems can be used to achieve fully automated driving by demonstrating a fully automated car and bus on its test track while maintaining speed (up to motorway speeds) and steering (Stoneman, 1975). Systems developed at the time used a buried cable, 15cm below the road surface, emitting a magnetic field of around 5kHz and detector coils on the vehicle. If DWPT systems were installed on the motorway, it is feasible that they could also be used by equipped vehicles to maintain lane position under any weather conditions.

It is not possible at this stage to quantify the value of this service. However, it does appear to offer to an attractive method for facilitating autonomous functionality on the motorway and could help to reduce accidents.

#### **5.4.2 Other services provided through utilisation of DWPT installation process**

The extensive road works required for installation of DWPT systems are expected to be costly and time consuming. However, it is also possible that the installation process may present an opportunity to install other devices in the road, the installation of which would typically be considered to be too disruptive or expensive. An investigation was carried out into possible sensors that could be deployed in the road surface as part of the DWPT installation process. It was found that there are two primary types of sensors that would be beneficial to install at the same time as installing DWPT systems: Traffic count sensors and Load response sensors.

##### *5.4.2.1 Traffic loop installation*

Most DWPT systems include a gap of a few metres (up to 5m typically) between adjacent power transfer segments. Road loops could be placed within this space during construction of DWPT sections of motorway. Currently, MIDAS road loops are placed approximately every 500m on equipped sections of the motorway. Such distances can be maintained in DWPT sections also. It should be noted that road loops cannot be placed directly over power transfer coils or within a certain distance of the coils because they would interact with the magnetic field. This typically means that a road loop cannot be closer than 30cm to the power transfer coil, although the exact distance will depend on manufacturer specifications and could be longer.

There are approximately 7,500 loop locations across all motorways in England. Highways England figures suggest that the cost of replacing a loop is approximately £3,500 (Highways Agency, 2014). If the vast majority of the replacement cost (assumed to be

at least 70%) can be assumed to be non-capital and reducible by combining with other related road works, then the maximum possible cost saving that could be achieved by combining installation of the loops with installation of DWPT sections is £3,500 x 0.7 x 7500 locations = £18.4 million for the whole motorway network. In reality, it is unlikely that all traffic loops will be replaced via this method; therefore, assuming there are two traffic loop sites per 1km of equipped motorway in order to maintain the 500m gap, £4,900 per km could be saved on installation of traffic loops on DWPT sections.

#### *5.4.2.2 Load sensor installations*

In mechanistic pavement design, it is well known that there are two primary critical locations which govern expected pavement performance and these are at the bottom of the bound layer and at the top of the unbound layer (Timm & Newcomb, 2003). Measurement of in-service strain make it possible to monitor the performance of a pavement and to plan future maintenance works more effectively. Horizontal tensile strains experienced at the base of the bound layer are highly correlated to fatigue cracking potential (particularly evident in newly built pavements) and vertical compressive strain data is especially useful in monitoring permanent deformation potential in the subgrade. In addition, collection of in-service strain data can provide a pavement performance database for both 'good' and 'bad' pavements (based on associated condition). In doing so, all Highways England pavements surveyed will have estimated strain results compared with newly defined 'good' and 'bad' criteria.

There is a variety of load sensors that could be beneficial to install in the road at the same time as installing DWPT systems, such as linear variable differential transducers, full bridge, single gauge, inductive strain coils, fibre optic sensors, accelerometers, multi-depth deflectometers, pressure cells, weigh in motion sensors plus environmental related sensors.

These sensors could provide a wealth of information on the condition and behaviour of the pavement. Such information can be utilised to improve asset management and scheduling of maintenance and, help to identify potential failures before they occur. However, as this information is not currently available or used widely, it is not possible to determine the value such information could deliver. It is recommended that the potential for installing such sensors along with DWPT systems is investigated further as part of off-road trials, in order to try and estimate possible value of such information.

## **5.5 Impacts of DWPT on other electrical services in close proximity**

There are already a large number of electrical devices present on, in or alongside, the SRN infrastructure. These vary from simple inductive road loops, to radar and communication modems as well as cabling and utilities. Most of these devices and services have dedicated standards that include EMC. Innovative devices such as WPT equipment have the capability of introducing new disturbances into nearby electrical equipment both through the physical connections and through transmitted electromagnetic fields. Indeed, the creation of a powerful EMF is the essential feature of WPT. How the WPT provider designs the equipment to control and manage these EMFs will be a key consideration in the choice of supplier.

## 5.6 Sources of electrical disturbances

### 5.6.1 Conductive disturbances

Non-linear loads on the electricity system create disturbances that can affect equipment connected to the same installation or to neighbouring installations. Where these disturbances could be detected on neighbouring installations, the network operator may refuse to connect the equipment to the network. It is therefore important to understand the likely sources of disturbance and the limits applicable to them.

A key source of disturbance from a non-linear load is the solid state inverter which is often used for controlling variable speed drives or variable frequency loads. Such devices produce harmonics which can result in high neutral currents on the distribution network and cause overheating in other electrical components, resulting in power quality problems.

One of the main components of WPT is a high power inverter and these are spaced at regular intervals along the roadside. The harmonics from these inverters will need to be managed to ensure that they are within the prescribed limits.

Loads that have sharp variations in demand can cause voltage fluctuations which result in perceivable “flicker” on lighting systems and other sensitive equipment. Large motors and welding equipment are examples of devices that need careful consideration when designing the network. For the WPT application, power will be switched on and off at regular intervals as vehicles pass over successive primary coils.

As an example, with a primary coil of 20m length, a vehicle passing at 80km/h will pass over a primary coil in 0.9 seconds then move on to the next one. This 0.9 second interval will be characterised by three phases: pick up, steady state and drop off. The power input to the primary coil, and hence the power demand from the distribution system, depends on the overall efficiency, assumed to be in the range 60-75% from current literature and experience of WPT installations. A 120kW secondary coil could therefore need 170kW at 70% efficiency. This is around 250 Amps per phase from a three phase supply.

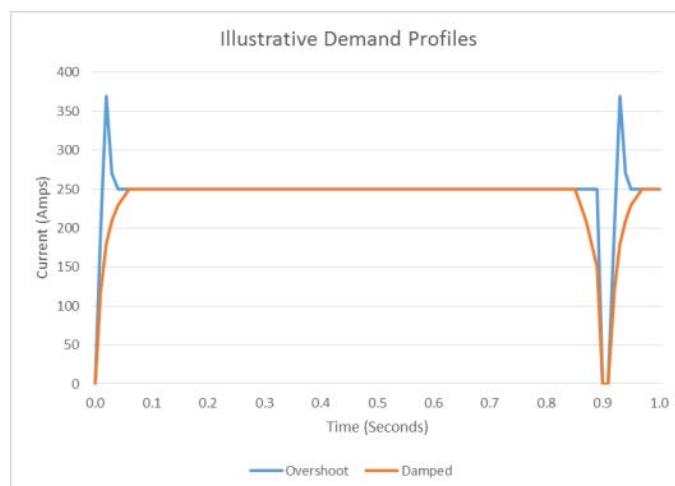
Pick up is where power is switched on and is a very important phase in terms of the system design. Some electrical equipment such as motors, transformers and power electronics have a very low impedance at switch-on and the impedance starts to rise as current flows in the equipment. This low initial impedance leads to an “inrush” of current that can be many times the steady state level. The supplier of the WPT equipment will need to explain whether there is an inrush current during start-up, and if so, its magnitude and how it is controlled. For example, if the pick-up overshoot is 50% then the supply will have to cater for nearly 350Amps per phase. A more damped start-up phase would mean that only the steady state power would need to be catered for.

Steady state is where the vehicle is receiving maximum power from the primary coil. This phase extends over the period for which the vehicle is picking up power from the WPT equipment, and may vary from the calculated steady state figure due to misalignment of the vehicle and variations in the air gap. The WPT supplier will need to describe how the power input varies with alignment and air gap variations.

If the variations from the steady state figure cannot be adequately quantified by the supplier, than a pessimistic view of supply characteristics should be used for network design purposes, affecting the cost of the required electrical infrastructure.

Drop off occurs where the vehicle moves off one primary coil and moves on to the next one. It is assumed that the demand drops to zero at that point. The rate of drop-off will again depend on the design of the WPT equipment but is not as critical as the start-up phase.

Illustrative demand profiles for such overshoot and damped variations with the above parameters are shown in **Figure 11** below.



**Figure 11: Illustrative demand profile of a DWPT coil based on one vehicle moving at constant velocity**

In this illustration, the fluctuations occur at 0.9 second intervals for this combination of primary length and vehicle speed. In general, the frequency of disturbance will depend on the vehicle speed and the length of the primary coil sections.

For example, with a 5m primary and a speed of 90kph, the frequency of fluctuation would be 0.2 seconds, or 5Hz. This is a sub harmonic of the system frequency of 50Hz and would be subject to the harmonic limits of Engineering Recommendation (ER) G5/4.

### **5.6.2 Radiated disturbances**

Radiated disturbances occur where electromagnetic fields are generated by the device. When current passes through a wire, magnetic fields are generated and there are already many examples of magnetic fields in transportation. The most obvious perhaps is electric railways, where overhead wires are in relatively close proximity to electrical equipment and indeed the passengers within the train. With many devices such as mobile phones and near field communication systems in widespread use, there are various standards on electromagnetic compatibility (“EMC”) that are relevant in the design of any equipment that may generate EMFs. This is to ensure firstly that the EMFs do not create electrical interference with other electrical equipment and, secondly, to ensure the safety of people in the vicinity of the EMFs. Any electrical interference could cause malfunctioning of other sensitive electronic equipment on the SRN, such as signalling systems. Strong EMFs can also pose a health hazard and standards exist to limit the exposure to EMFs. For example, Table B4 of EU Directive 2013/55/EU defines the Action Level (AL) for magnetic fields so as to avoid interference with implanted pacemakers and for the “attraction projectile” risk in the vicinity of magnetic fields; see Figure 12.

### ALs for magnetic flux density of static magnetic fields

Hazards	ALs(B <sub>0</sub> )
Interference with active implanted devices, e.g. cardiac pacemakers	0,5 mT
Attraction and projectile risk in the fringe field of high field strength sources (> 100 mT)	3 mT

**Figure 12: Action Level (AL) for magnetic fields**

ICNIRP has also published guidelines for limiting exposure to electric and magnetic fields, and Table A4 of their report is shown below in **Figure 13**.

Frequency range	Electric field strength, $E$ (V m <sup>-1</sup> )	Magnetic field strength, $H$ (A m <sup>-1</sup> )	Magnetic flux density, $B$ (μT)	Equivalent plane wave power density, $S_{eq}$ (W m <sup>-2</sup> )
Up to 1 Hz	-	32 000	40 000	-
1 Hz – 8 Hz	10 000	32 000/ $f^2$	40 000/ $f^2$	-
8 Hz – 25 Hz	10 000	4 000/ $f$	5 000/ $f$	-
0.025 kHz – 0.8 kHz	250/ $f$	4/ $f$	5/ $f$	-
0.8 kHz – 3 kHz	250/ $f$	5	6.25	-
3 kHz – 150 kHz	87	5	6.25	-
0.15 MHz – 1 MHz	87	0.73/ $f$	0.92/ $f$	-
1 MHz – 10 MHz	87/ $f^{1/2}$	0.73/ $f$	0.92/ $f$	-
10 MHz – 400 MHz	28	0.073	0.092	2
400 MHz – 2000 MHz	1.375/ $f^{1/2}$	0.0037/ $f^{1/2}$	0.0046/ $f^{1/2}$	$f/200$
2 GHz – 300 GHz	61	0.16	0.20	10

**Figure 13: Table A4 from ICNIRP guidelines for limiting exposure to electric and magnetic fields**

The main purpose of a WPT device is to generate a strong EMF to enable power to be transferred to a moving vehicle. There are also secondary wireless systems for communication between the roadside systems and the vehicles to authorise power transfer and to synchronise the switching between successive primary coils in the roadway. It is therefore important that the EMFs generated by the WPT system do not interfere with other electronic equipment or pose a health hazard.

## 5.7 Experience of existing installations

There are two installations of WPT in the UK which this project team's partners have been involved in: the Milton Keynes Bus Project and the EU funded Zero Emission Urban Bus Systems project (ZeEUS) which has installations in Glasgow and London as well as several other European cities.

Both these installations are of static rather than dynamic WPT and the key considerations have been on power requirements and power quality.

### 5.7.1 Milton Keynes

The Milton Keynes project is a fully commercial full electric bus project involving a fleet of buses on a fixed route in Milton Keynes. Buses are recharged at each end of the route in the dead time allowed by the timetable and can thus run continually on electric power. Each of the WPT charging stations employs two 60kW nominal rating IPT units



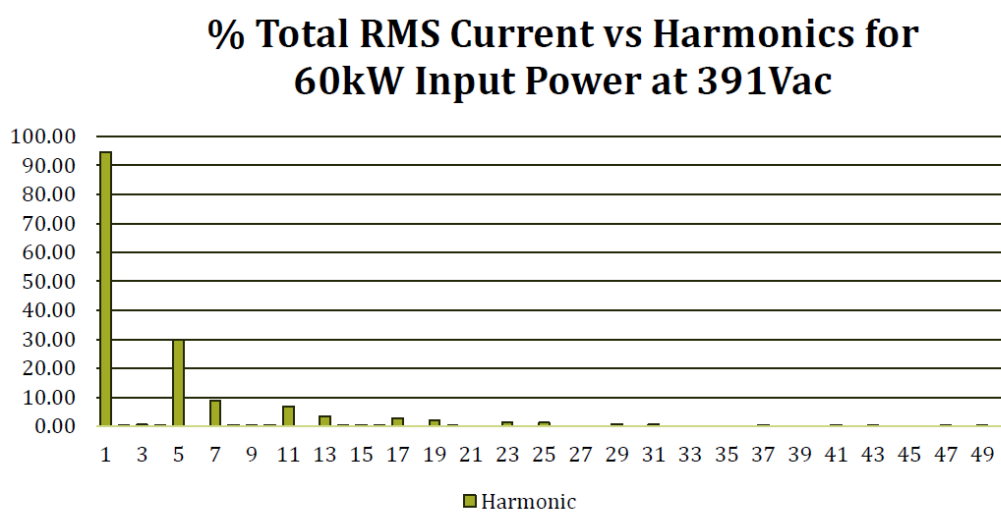
embedded in the road to provide 120kW power transfer capability to the vehicles -see Figure 14.



**Figure 14: Example of IPT Technology WPT chargers installed in Milton Keynes**

The equipment is powered at 400 Volts 3 phase AC on separate supplies either from an existing substation or a new substation specifically for the WPT system. Although the WPT equipment is rated at 120kW, the power drawn from the DNO system is higher than expected at 165 kVA peak. The DNO installation was designed with some spare capacity so this does not pose any problems. This input/output ratio gives an overall efficiency of 72% which is lower than might have been expected from the manufacturer's specifications. Since this static installation has a small air gap and precise alignment of primary and secondary coils, it would be expected that DWPT installations would have a lower efficiency due to the higher air gap and likely deviations from the ideal positioning of the vehicles as they drive along the road.

The WPT equipment employs a 6 pulse AC/DC converter to generate the high frequency power transfer field and this generates strong 5<sup>th</sup> and 7<sup>th</sup> harmonics as shown in Figure 15 below.



**Figure 15: Expected harmonics from WPT equipment**

Although the current harmonics are higher than expected, the voltage harmonics were within the recommended levels of G5/4 due to the high fault level.

### 5.7.2 ZeEUS

The ZeEUS project (Zero Emission Urban Bus Systems) involves installations in several European cities with different technologies for power transfer, including static wireless technologies in two cities in the UK: Glasgow and London.

The first WPT installation has been completed in Glasgow at a test and research centre for DNO systems - see Figure 16. It is of identical construction to the Milton Keynes unit, but only one is deployed in the installation as the bus used for this demonstration is an extended range hybrid.



The performance and characteristics are therefore very similar to the Milton Keynes example. Further installations are planned in Glasgow Bus Stations for full operational demonstration, and in London as part of the ZeEUS project.

However, unlike the Milton Keynes example, the DNO has recommended that harmonic filters are fitted to avoid disturbances to other customers when the operational units are installed.

**Figure 16: IPT Technology chargers trialled in Glasgow**

## 5.8 Summary of relevant standards

There is a wide range of standards and requirements, ranging from the high level electromagnetic compatibility requirements for electrical plant emanating from the EMC Directive 2004/108/EC and the Low Voltage Directive 2006/95/EC down to the detailed specifications for installation. Directive 2013/35/EU specifically applies to the minimum health and safety requirements regarding the exposure of workers to the risks arising from electromagnetic fields. Although this latter directive has not yet been transposed into National legislation, the limits set out in this Directive will be relevant.

The key standards of relevance to WPT equipment have been reviewed (see Appendix J) and the requirements have been compared with the EMF emissions from the charging solutions to identify any possible conflicts. A summary of the relevant standards is shown in Table 3.

**Table 3: Summary of standards**

<b>Standard</b>	<b>Topic</b>	<b>Comments</b>
<b>BS 7671</b>	Requirements for electrical installations	Relevant for Electrical contractors carrying out installation of WPT equipment
<b>IEC50160</b>	Characteristics of electricity systems	Implemented through BS EN 50160:2010 Relevant for manufacturers of equipment such as WPT to ensure it is compatible with the UK electricity system
<b>Engineering Recommendation G5/4</b>	Harmonics	Harmonic limits for design of UK public electricity supply system. Relevant for manufacturers of WPT equipment to ensure harmonic levels are within limits. See also IEC 61000
<b>Engineering Recommendation P28</b>	Voltage fluctuations ("flicker")	Limits for voltage fluctuations or "flicker". Suppliers of WPT should specify frequency and scale of demand fluctuations so that the connection can be adequately designed.
<b>IEC 61000</b>	Electromagnetic Compatibility (EMC)	Implemented through a range of British Standards to ensure that emissions from WPT equipment are at an acceptable level and do not interfere with other equipment.
<b>ETSI EN 300220</b>	EMC 25 to 1,000MHz devices	Relevant for any ancillary communications equipment operating in the stated frequency range
<b>ETSI EN 302288</b>	EMC 24GHz Short range Radar	Relevant for any ancillary communications equipment operating in the stated frequency range
<b>ETSI EN 300330</b>	EMC inductive loop systems 9kHz to 30MHz	Relevant for the main WPT system
<b>BS EN 50293</b>	Road traffic signal systems. Electromagnetic compatibility	Relevant to the operation of other electrical devices on the SRN
<b>TR2130</b>	Environmental Tests for motorway communications equipment	Possible application to WPT

Standard	Topic	Comments
<b>BS EN 50556</b> <b>(Supersedes BS7987)</b>	Road Traffic Signal Systems	Relevant to the operation of other electrical devices on the SRN
<b>MCH 1540</b>	Specification for installation of detector loops	Application to elements of WPT required for detecting the presence of vehicles and for communication

## 6 System Performance Requirements

The main focus of this section is on assessing the technical requirements of integrating DWPT systems with the vehicle, vehicle on-board storage and the road infrastructure.

First the specifications for the installation of WPT equipment into vehicles were considered. The key components were identified and their technology readiness level assessed.

Various options for fitting of WPT equipment into vehicles were considered, including factory fit, manufacturer after-market fit and third party aftermarket fit, with and without manufacturer support. Third party fitment without manufacturer support is not considered viable, and is not recommended. Several case studies are presented showing different fitting options.

The implications for safety were considered. For factory fitted systems, safety is not considered an issue as all vehicles are required to meet stringent safety requirements before they are allowed to be sold in Europe. The safety of after-market fitted systems is more of an issue.

Specifically for use in trials which are expected to use after-market fitted systems, the options for using and, where required, registering vehicles in the UK were investigated. Proposals for ensuring that vehicles used during the DWPT trials are safe and legal are presented.

A number of relevant international standards have been identified and listed. Various standards bodies are in the process of developing standards for the use of wireless power transfer systems, both static and dynamic.

Following this, the requirements for batteries for DWPT-equipped vehicles were examined. The requirements for batteries are dependent on vehicle dynamics, usage duty cycles and power train technology. The requirements for cars, medium duty vans and HGVs were considered.

Then the specifications and costs for the installation of systems into the motorway were assessed.

Three types of construction were considered:

- Trench-based construction, where a trench is excavated in the roadway for installation of the DWPT primary coils
- Full lane reconstruction, where the full depth of bound layers are removed, the primary coils installed and the whole lane resurfaced
- Full lane prefabricated construction, where the full depth of bound layers are removed and replaced by pre-fabricated full lane width sections containing the complete in-road system.

The types of machinery which would be required were also considered, and key requirements for some specific road installations tools were identified.

### 6.1 Guidance for installation of DWPT equipment into vehicles

This section of the report addresses the installation of WPT equipment on to vehicles. It identifies requirements for adaptation of equipment and the key components needed.

### **6.1.1 Assessment of information on key components**

There are three basic ways of implementing wireless power transfer infrastructure:

- 1) Charging at base; Home, work, depot (vehicle stationary)
- 2) On road static charging (vehicle stationary)
- 3) On road dynamic power transfer (vehicle moving).

From the vehicle perspective, the key components should be the same for all wireless power transfer methods. The variations in key component parameters are associated with the type of wireless power transfer implemented, as described above, the amount of power transferred and the voltage rating of the on-board battery. Control of battery charging takes place by means of an on-board battery management system (BMS). There should be a communication link between the BMS, the on-board pick up coil and the roadside supply equipment.

For dynamic power transfer, the vehicle control strategy is different from charging at base or static charging. The control system needs to decide when to use WPT technology for charging the battery and/or driving the electric motor, and whether regenerative energy from vehicle braking should be prioritised over WPT for charging the battery. This section of the report focuses specifically on the on-board components of a DWPT system. The key system components that need to be fitted to the vehicle are:

1. Secondary pick up coil(s)
2. Control electronics
3. Power electronics (e.g. rectifier, inverter) to charge the battery or power the electric traction motor.

It is likely that some of these components will be integrated into a single assembly. In addition to DWPT hardware, the control strategy within the vehicle control unit will require modification. Accurate alignment of the primary and secondary coils optimises the power transfer efficiency. Some vehicles may also include a means of assisting the driver to accurately position the on-board secondary coil to align with the in-road primary coils, although this is not considered to be an essential part of a DWPT system.

The sections below describe requirements for each of the main components identified in more detail.

Other components which are not specifically discussed as they are not a strictly necessary part of a DWPT system, but which would be used in a fully functioning market ready solution, include:

- Communication modules – most EVs and modern vehicle have built-in communication capability so this is not considered to be a major additional component
- Billing systems / back office – there are a number of billing and back office systems already in use for applications such as congestion charging, road tolling or road pricing and mobile phone billing
- Additional safety systems to monitor use of infrastructure – these may not be necessary and will depend on each manufacturer's approach to ensuring safety

- Shielding from EMF – this is likely to be a necessary component but its exact specification will depend on the specific requirements of the vehicle and the DWPT system implemented
- Energy storage systems – most EVs and Hybrid vehicles already use such systems so they are not considered as components required specifically for DWPT.

#### *6.1.1.1 Secondary (pick up) coil*

The size of the secondary coil is dependent on three main factors:

- Type of system and operating frequency. Systems based on magnetic resonance are more efficient than standard inductive charging and, as such, are likely to have smaller coils for a given power transfer rate. They are also not as dependent as the standard inductive charging system on accurate alignment of the primary and secondary coils, and can typically accommodate misalignment in the x and y axis of up to 15cm.
- Level of power transfer. Coils for aftermarket residential systems with relatively low levels of power transfer (single figure kilowatts) will be much smaller than those aimed at static and dynamic bus systems (hundreds of kilowatts). Rather than one large pad, some systems use a number of smaller pads connected in parallel.
- Air gap between the coils. The gap between the primary and secondary coils will affect the size of the secondary coil. To maintain a given power level and efficiency, as the air gap increases, the size of the secondary coil will also increase.

Based on a number of systems investigated during the project, secondary coil sizes were found to differ considerably, with the pads (housing containing the coil wires, necessary connections and any ferrite material) ranging in size from approximately 40cm x 40cm to 220cm x 90 cm. Most secondary coil assemblies were between 8 and 12 cm in thickness.

Some manufacturers use multi-secondary coil arrangements on the vehicle in order to achieve higher levels of power pick up, using anywhere between 1 and 5 coils to achieve total power transfer of up to 140kW for DWPT.

In comparison, low power (up to 7kW) static WPT secondary coils designed for cars are much smaller, between 25cm x 25cm and 40cm x 40cm.

#### *6.1.1.2 Control electronics*

The control electronics consist of a low power control module based on a microcontroller. This would be a relatively small unit and would need to be powered from the vehicle 12V system when the vehicle battery is being charged. The control electronics module is likely to be based on the CAN (Controller Area Network) interface.

#### *6.1.1.3 Power electronics*

Three main factors determine the specification of the power electronics:

- Vehicle battery voltage

- Maximum charge current which is dependent on the ability of the vehicle battery to accept charge without overheating
- The level of power that is transmitted by the WPT system.

For high levels of power transfer, active cooling of the power electronics is likely. For most DWPT systems, power electronics will consist of a rectifier and a regulator. In addition, it may be necessary to include a transformer if the power from the secondary coil is used to power the traction motor directly.

Rectifiers can vary in size depending on the power level they are designed for and whether they have built-in cooling systems. They can currently comprise a single unit of approximately 80cm x 80cm x 15cm (width x depth x height) and weight of approximately 55kg, with the potential to be significantly reduced in size in future.

A DC-DC converter for low voltage power supply (and to even out the voltage and current supply) is also required.

#### *6.1.1.4 Vehicle control strategy and battery management system (BMS)*

Accurate control of the battery State Of Charge (SOC) is essential on both hybrid and full electric vehicles in order to maximise the battery life and accurately calculate vehicle range.

Calculation of SOC is done within the battery pack by the battery management system and for this calculation it needs information regarding the energy put into the battery and taken out of the battery. For electric vehicles with a wired charging system, this is straightforward as there is only one source of energy output (to the high voltage supply network) and two mutually exclusive sources of energy input:

- Energy from the electrical machine during regenerative braking
- Energy from the battery charger.

Regenerative braking can only occur when the vehicle is moving which is mutually exclusive with the battery charger being connected (or static charging from a wireless charging system), which can only happen when the vehicle is stationary.

With DWPT this is not the case as it is possible that regenerative braking and DWPT could occur at the same time. This is not desirable and must be managed. This situation is analogous to hybrid vehicles where energy can be supplied from regenerative braking and the combustion engine simultaneously. Under this condition the control strategy within the vehicle control unit decides on which source of energy is best used to charge the battery or power the motors. For battery electric vehicles this function is not present and would need to be added if the vehicle is to support DWPT.

Furthermore, currently, charging protocols used by all EVs for the on-board charger that is connected to external power supply dictate that the vehicle must be stationary when the vehicle is receiving power from an external source. This is a fail-safe measure designed to prevent vehicles from driving off while they are being charged. For DWPT, a new interface would need to exist, in addition to the plug-in charging interface, to allow power to be transmitted to the vehicle while it is moving.



## 6.2 Results of trials of key components/ systems

A number of trials of the DWPT technology have been carried out in recent years. Table 4 summarises trials of DWPT that were identified by the project team. The table covers trials that have already been completed or are still ongoing and, those understood to be planned for the near future.

**Table 4: DWPT trial**

Company	Description of DWPT trials	Comments
<b>Qualcomm Halo</b>	Trials are being prepared as part of the FABRIC European project. The technology being developed is aimed at cars and small vans with power transfer of 20kW and urban speeds. The technology is anticipated to be tested on Renault vehicles at a Vedecom test site in France.	Trials are planned to start in mid- 2016.
<b>SAET / POLITO</b>	Trials are being prepared as part of the FABRIC European project. The technology being developed is aimed at vans, with power transfer of up to 20kW (POLITO) and 40kW (SAET) at urban speeds. The technology is anticipated to be tested on FIAT vehicles at a test site in Italy.	Trials are planned to start in mid-2016.
<b>KAIST / DW OLEV</b>	<p>KAIST-developed OLEV technology has been trialled in various locations since 2010.</p> <p>In 2011 public service of OLEV vehicles in Seoul Grand Park started (route length: 2.2km, length of DWPT: 373m, number of DWPT sections: 3, number of vehicles used: 3).</p> <p>Trial during Yeosu Expo 2012, operation of a commercial, public service (route length: 3.5km, length of DWPT: 36m, number of DWPT sections: 1, number of vehicles used: 3).</p> <p>Commercial operation of the KAIST shuttle bus from 2012 to present (route length: 3.76km, length of DWPT: 65m, number of DWPT sections: 1, number of vehicles used: 2)</p> <p>Commercially operated public bus service in Gumi City, from 2013 to present (Route length: 35km, length of DWPT: 144m, Number of DWPT sections: 4, number of vehicles used:</p>	Results of the trials have shown real-world performance of the OLEV system to be around 75% efficiency for dynamic application and that EMF emissions are within international guidelines for static use. Dynamic use requires testing for each individual case. The trials provided valuable information regarding road construction for DWPT systems and grid connection and led to the development of a specially designed ferrite structure and primary coil-prefabricated concrete modules. However, as most of the trials were carried out to Korean standards, they would need to be verified in the UK.

Company	Description of DWPT trials	Comments
	2).	
<b>Bombardier Primove</b>	<p>Primove technology has been trialled on a test track built on a public road. During a feasibility study in Lommel, Belgium between 2011 and 2013, a Van Hool 12m bus was retrofitted with the first generation of a 120kW Primove DWPT system. It should be noted that in order to simplify testing of energy transmission, the bus used its diesel hybrid propulsion to drive. The energy transferred to the vehicle was not used by the vehicle but rather used up in resistors on board the vehicle. A section of a public road was closed off during the trials where the Primove system was integrated into the road.</p> <p>Another test track-based trial of the Primove technology with a 200kW Primove DWPT was carried out as part of the Swedish Slide-in project between 2010 and 2013. These trials included retrofitting a Scania diesel truck with the Primove DWPT system and installation of the system in a test track.</p>	<p>Lommel trials: A detailed report is available from the trials (Flanders Drive, 2013). The report states that both concrete and asphalt in-situ installations were feasible and facilitated use of the DWPT infrastructure. It also stated that with the Primove generation used, a power level of up to 50kW could be transferred to the vehicle without exceeding EMF limits.</p> <p>Slide-in project trials: Road installation was not tested as part of the project as a flexible, temporary road installation was created for the trials. The trials focused on vehicle integration and showed that power transfer of up to 160kW can be achieved safely at speeds of up to 80km/h.</p>
<b>INTIS</b>	<p>An indoor test facility was created for trialling the INTIS DWPT system. The facility was created to test DWPT for all vehicle types, including cars, vans, buses and trucks.</p>	<p>Road integration of the INTIS DWPT was not attempted so it is not clear how well this system would function if integrated into the road structure. Power transfer at up to 60kW was demonstrated to be possible and safe. Full integration into electric vehicle architecture was achieved.</p>
<b>Utah State University</b>	<p>The university's Energy Dynamics Laboratory has recently completed the construction of its Electric Vehicle and Road way (EVR) test track which is designed specifically to trial DWPT technology (Charged Electric Vehicle Magazine, 2015).</p>	<p>No results are available at this stage.</p>

Company	Description of DWPT trials	Comments
<b>Oakridge National Laboratory (ORNL)</b>	ORNL has previously developed and trialled a low power (20kW) DWPT system at its indoor test facility in 2011.	The trial focused on proof of concept and did not include in-road integration. A six coil indoor track was built and power transfer of 10kW at 58% efficiency was achieved to power a small EV.
<b>Nissan</b>	In 2013 Nissan published results of their DWPT technology trials. A low-power (1kW) system was integrated with a small EV and trialled on a small section of road.	Results showed that 90% efficiency was achieved in transferring power of 1kW to a small EV at low speed. Road construction techniques were also trialled and resulted in a suitable methodology being developed that would ensure that coils are not damaged during installation. The road was not constructed to highway standards (Throngnumchai, Hanamura, Naruse, & Takeda, 2013).

### **6.2.1 Identification of fitting options**

Currently, no vehicle manufacturers offer factory fitted DWPT systems for their vehicles. It is unlikely that this will become viable until a substantial amount of infrastructure is in place and the demand for vehicles is created. Therefore, a number of possible options were considered for how DWPT devices can be fitted to different vehicle types.

Options investigated are:

1. Installation of a DWPT system by the vehicle manufacturer – i.e. factory fitted
2. After market installation of a DWPT system by the vehicle manufacturer
3. Addition of a DWPT system specifically developed with the vehicle manufacturer as an aftermarket fit – i.e. manufacturer approved retrofit
4. Addition of a DWPT system without the support of the vehicle manufacturer – i.e. non manufacturer approved retrofit, see discussion below.

Following discussions with vehicle and DWPT system manufacturers during the project, it was found that it would not be practical for a DWPT system to be properly developed and installed without the support of the vehicle manufacturer (Option 4). This is because installation of DWPT systems introduces a fundamental change to the way energy is handled on board the vehicle, particularly with regards to managing power flows between the regenerative braking system, the DWPT system, the traction motor and battery while the vehicle is moving.

The vehicle control strategy algorithm will need to decide which source would be most suitable for charging the battery under many different use-case scenarios. In order to achieve such integration, it is necessary to add new hardware on board the vehicle to ensure that the voltage and current coming out of the secondary coil is optimised for use by the battery or the traction motors. It is also necessary to rewrite the power control software. Making such drastic changes to a vehicle would be extremely time consuming and costly without manufacturer support. Furthermore, it would likely void the vehicle warranty and could result in the safety and reliability of the vehicle being compromised.

Fitting of DWPT systems would also introduce additional EM emissions on board the vehicle. It would therefore require extensive additional EMC testing for immunity of vehicle electronics.

Based on findings from the feasibility study, Option 4 (non-vehicle manufacturer supported retrofit) is not recommended and is not considered to be a viable option. Although retrofitting of static charging systems to vehicles is possible, for example, Evatran Plugless Power is an aftermarket fitter of static WPT system for cars in the US, they do not require such in-depth interfacing to existing vehicle systems as DWPT. Because the vehicle is stationary during power transfer, there are fewer safety concerns and the risk associated with possible malfunction is considerably lower.

Options 1, 2 and 3 are discussed in more detail below.

#### *6.2.1.1 Vehicle manufacturer supported system*

##### *Factory fit*

From a technical and safety standpoint, this is the best option for fitting a DWPT system to a vehicle. However, this may not be viable for vehicle manufacturers if production volumes are too low and it adversely affects the production line.

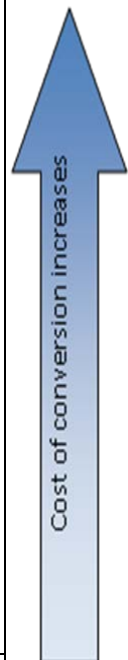
The DWPT system can be properly integrated with the vehicle electrical system and its performance optimised with regard to interfacing to the battery management system and vehicle control strategy. The vehicle could then undergo type approval with the DWPT system fitted, ensuring that it is fully homologised.

Among the vehicle manufacturers contacted during the project, there was clear consensus that this option would be the preferred option and would likely result in the best performance. Particularly, the ability to take a full system design approach and be able to make changes to both the vehicle and the DWPT system during the design stages is likely to result in better quality outputs.

Table 5 below summarises feedback from manufacturers on the most likely implementation of DWPT by vehicle and powertrain type.

**Table 5: Most likely DWPT vehicle installation options**

Complexity and cost of conversion vs scalability and safety		Factory fitted		
		Cars	Vans	HGVs/Buses
Type of vehicle powertrain before conversion	ICE (Petrol)	Not considered due to cost/complexity	Not considered due to cost/complexity	Not considered due to cost/complexity
	ICE (Diesel)	Not considered due to cost/complexity	Not considered due to cost/complexity	Not considered due to cost/complexity
	ICE (Gas)	Not considered due to cost/complexity	Not considered due to cost/complexity	Not considered due to cost/complexity
	ICE-Electric Hybrid	Possible but unlikely in the near term due to the required redesign of motor rating and other electrical components.	Possible but unlikely in the near term due to the required redesign of motor rating and other electrical components.	Possible but would require re-sizing of the traction motor to cope with longer operating times at peak power. For HGVs, only smaller electric powertrain platforms and mostly from niche manufacturers exist today that would be suitable but more prototypes are in development by big manufacturers. Heavy vehicles are a strong candidate for DWPT implementation due to their duty cycle.
	ICE-Electric PHEV/RE EV	Possible but unlikely due to the required redesign of motor rating and other electrical components.	Possible but unlikely due to the required redesign of motor rating and other electrical components.	Same as above.
	Battery Electric (BEV)	Possible but limited anticipated use until a large amount of infrastructure exists	Possible but limited anticipated use until a large amount of infrastructure exists	Possible. Buses are strong candidates for this adaptation.



At the time of writing, a factory fitted DWPT system can only be considered in theory as no vehicle manufacturers have implemented the necessary process.

#### *Manufacturer after-market fit*

It is also possible that a vehicle could be designed to accommodate DWPT as an option but the system would only be included in vehicles where the option was selected. As such, it may be possible that a compatible vehicle can be retrofitted with the system by an especially approved installer. In this case, there is little difference between this scenario and the Factory Fit option described above. It has the same advantages. The only difference is the location where the charging system is fitted.

It should also be noted that it is more likely that this approach could be adopted for light duty vehicles than for heavy duty vehicles. Heavy duty vehicles that do high annual mileage on the highway have an expected first user life-span of 2 to 3 years. Therefore, unless the vehicle is fitted with the system at the factory, it is unlikely that it will be perceived by the second user to be of sufficient value to add it retrospectively.

#### *6.2.1.2 Aftermarket system fit (vehicle manufacturer approved)*

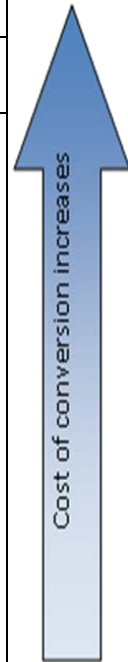
As stated in the introduction to this section, retrofitting of a system that has not been developed for the vehicle with the vehicle manufacturer's approval or support is unlikely to be practical for DWPT systems. However, it may be possible for a vehicle manufacturer to define mechanical and electrical interfaces to the vehicle and for third parties to provide approved DWPT systems that meet those specifications and requirements. This option is similar to the one discussed above in the previous section, but has a variety of possible DWPT suppliers and approved installers

Although possible, this option will be heavily reliant on a very precise specification of interfaces to the vehicle. This would require a vehicle manufacturer to undertake a comprehensive programme of development, testing and validation to define the necessary interfaces and ensure that third party DWPT suppliers and installers comply with the specifications.

There are several possible safety and performance related issues for aftermarket fitting of such devices. At present it is not clear how such systems would affect vehicle warranty. The high voltage battery is one of the most expensive components on the vehicle and the vehicle manufacturer will likely be concerned that fitting a badly engineered after-market DWPT system to the vehicle could have a detrimental effect on battery performance and/or life. As such, interfaces to the vehicle battery or powertrain would need to be carefully defined to ensure that power is provided in a way that is compatible with those components. Table 6 below provides an overview of fitting for option 2.

**Table 6: Overview of fitting options for aftermarket system fit**

Complexity and cost of conversion vs scalability and safety		Aftermarket system fit (vehicle manufacturer approved)		
		Cars	Vans	HGVs/Buses
Type of vehicle powertrain before conversion	ICE (Petrol)	Same as Table 5	Same as Table 5	Same as Table 5
	ICE (Diesel)	Same as Table 5	Same as Table 5	Same as Table 5
	ICE (Gas)	Same as Table 5	Same as Table 5	Same as Table 5
	ICE-Electric Hybrid	Same as Table 5. Plus, it may be possible to develop a trailer system that carries the necessary coils, batteries, and power electronics, which interfaces with the vehicle powertrain	Same as Table 5. Plus, it may be possible to develop a trailer system that carries the necessary coils, batteries, and power electronics, which interfaces with the vehicle powertrain	Same as Table 5. Plus, it may be possible to develop a trailer system that carries the necessary power electronics and batteries, which interfaces with the vehicle powertrain. Coils will likely need to remain under the main vehicle in order to ensure sufficient shielding is provided from EMF for other road users.
	ICE-Electric PHEV/RE EV	Same as above	Same as above	Same as above
	Battery Electric (BEV)	Same as above but the batteries will likely remain on-board the vehicle	Same as above but the batteries will likely remain on-board the vehicle	Same as above but the batteries will likely remain on-board the vehicle



Although the table above provides a high level overview for each vehicle and powertrain type based on manufacturer feedback, detailed examination of what is possible would need to be performed for each model of vehicle. Each model will have a set of unique electrical and mechanical considerations that would need to be investigated.

*Retrofit via a trailer system*

As well as adapting a vehicle to be compatible with a DWPT system, it may be possible to develop a separate add-on trailer unit that houses some or all of the necessary additional DWPT components. Attaching this trailer to a compatible vehicle would

essentially provide a DWPT capability for the vehicle. The advantage of such a system would be the flexibility it offers in terms of price and vehicle design. The vehicle design could remain largely unaffected, apart from the definition of electrical and communication interfaces to the vehicle power and energy management systems.

Such DWPT systems do not exist and, as far as the project team is aware, none are in development. However, a similar system has been developed by at least one manufacturer for providing an electric range extender to battery EVs. A company called EP Tender is the developer of one such solution, see Figure 17.



**Figure 17: EP Tender range extender trailer solution**

The EP Tender solution consists of external ICE generator mounted on a trailer. The trailer connects to the vehicle via a defined electrical and mechanical interface that forms an umbilical which is capable of delivering electrical power to the traction motor and the battery in the vehicle. The flexibility of the system means that owners of EVs can use the vehicle as it is without any modifications, but when they make a longer trip on the highway a range extender trailer can be rented and the user benefits from the functionality of a range extender for the duration of the trip. The drawback of this system is that it increases the emissions of an EV when used. However, as the range extender is expected to be used only occasionally, it should still be less polluting than driving a regular ICE. The trailer is equipped with a self-steering system when reversing, so that it does not “jack-knife”.

If appropriate electrical interfaces can be defined and standardised between a trailer and the vehicle, then a similar solution could be adapted for a DWPT system. In this instance the ICE generator would be replaced by the necessary power electronics and potentially, additional battery storage. For cars, small secondary coils could also be fitted to the trailer instead of the vehicle, simplifying considerably the installation and adaptation process. For larger vehicles requiring larger coils or more shielding the secondary coils may still be required to be placed on the vehicle. However, the trailer could house the necessary power electronics and battery storage, considerably reducing the requirements for fitting those components on the vehicle itself. The trailer will produce additional friction in the form of air resistance and friction with the road surface, and the additional weight of the trailer would also affect energy efficiency. Therefore, the total improvement in energy efficiency and running cost using such a system would need to be investigated in detail for different vehicle types.

Such a system may be particularly attractive to commercial operators as it removes some of the risk associated with large capital expenditure on a vehicle that has been



optimised for DWPT. Such trailers can be used to provide DWPT capability to vehicles as required and interchanged between vehicles. In principle, there is no reason why such a system could not be used for heavy vehicles such as coaches or HGVs, although technical viability would need to be evaluated and tested.

#### *6.2.1.3 Maintenance and spare parts*

Systems fitted directly to vehicles, either factory fitted or retrofitted, are unlikely to have requirements for any additional maintenance. Most electrical components do not require maintenance. It is possible that periodically a replacement may be required for some components but this should be in line with regular practice for EV maintenance, which is generally considered to be better than that of ICE vehicles, due to fewer moving parts and the greater reliability of electric motors.

If lowering mechanisms for secondary coils are used, then those may require periodic maintenance but this is not anticipated to be a significant change.

If a trailer system is used then the trailer may require periodic checking but these checks would be basic safety checks as the electrical components should require very little maintenance.

#### *6.2.1.4 Future proofing*

It is difficult to comment on this topic as the standards and regulations applicable to WPT systems are still in preparation. However, it is unlikely that standards will be finalised for at least the next 3 years. Once finalised, they can be expected to stay in force for approximately 10 years. However, it is possible that they could be updated during this period if technology advances require it.

It is also clear that static WPT systems being currently developed and implemented into vehicles are not designed to be interoperable with DWPT systems. This suggests that they will not be interoperable or compatible with DWPT infrastructure. However, developers of DWPT systems are ensuring that their systems can work either statically or dynamically.

### **6.2.2 Safety**

The following section considers the safety of the components being installed. It also considers the relevant regulations which need to be adhered to, for example in order to obtain vehicles for trials in the UK. There is also a consideration of what may happen in the event of an accident.

#### *6.2.2.1 Evaluating the impact on vehicle and occupant safety*

This section is only applicable to aftermarket systems. Any system designed by the vehicle manufacturer either, as original fit or aftermarket fit, would have undergone the relevant safety testing in order for the vehicle to receive type approval.

The addition of a wireless charging pad and high voltage (HV) equipment underneath the vehicle leads to the risk of these parts being exposed following an accident. It is also possible that manufacturer's original crash tests may no longer be valid due to the additional parts fitted after the tests were completed. This may lead to additional risks for emergency service responders who may not be aware of the retrofit HV parts.

If a vehicle retrofitted with a DWPT system is imported from a country outside the EU, it would be required to meet UK vehicle approval in order to be registered in the UK. A vehicle used on public roads in the UK must comply with national law.

#### *6.2.2.2 Safety regulations and vehicle homologation issues (regulations and standards)*

##### *Vehicle approval*

Evidence for vehicle approvals is required in order to register a vehicle in the UK; without registration a vehicle cannot be driven on the public road. Since all DWPT system manufacturers and the majority of vehicle manufacturers are not based in the UK, it is likely that DWPT vehicles will originate from outside the UK.

For M1 and N1 vehicles (cars and light vans) this evidence is achieved via mutual recognition (if the vehicle has a certificate of conformity or has been approved to those standards that are mutually recognised for approval purposes). It is assumed that vehicles originating from the EU would already have European approvals and Conformity of Construction certificates from the manufacturer. If so, the vehicles would have European number plates and be loaned for use in trials in the UK.

If a vehicle was in the UK for more than 6 months, approval evidence would need to be provided. It is suggested that the DVSA is notified of the intention to use the vehicles in the UK. If this is not acceptable, the vehicles would need to be registered in the UK. This is achieved via mutual recognition (if the vehicle has a certificate of conformity or has been approved to those standards that are mutually recognised for approval purposes).

If a vehicle does not have European type approval, then, in order to be registered, it would need Individual Vehicle Approval (IVA) which is a series of tests carried out by an approval authority (in this case DVSA). The vehicle would need to be taken to an approved test station to ensure that the level of safety and environmental protection are similar to that conferred by European type approval. The length of this approval process is unclear; according to VCA, it may require details of the national approvals to be sent in advance so that the testing required can be determined.

##### *Compliance with national law*

For a vehicle that is imported on a temporary basis, it appears that no approval is required (assuming the registration and approval have been carried out in the originating country and the vehicle has a set of number plates). However, a vehicle used on the public roads would need to comply with national law even if it were not registered in the UK. Safety of vehicles on the road in the UK is governed by the Construction and Use Regulations (C&U).

These regulations have no specific items that relate to WPT systems and those items that apply to temporary imports do not refer to safety of electrical systems. It is unclear how compliance with C&U requirements are demonstrated; compliance may only require evidence if challenged by the enforcement authority.

### *Approval for large scale implementation*

For large scale implementation of DWPT systems, changes to regulations would be required in order to protect vehicle occupants and other road users. These are likely to include, but not be limited to:

- Requirements for shielding performance of the EMF
- Requirements for the EMF strength (the evidence for health effects is contradictory and a precautionary principle might be warranted in relation to the established ICNIRP limits) and measurement points that include inside the vehicle and outside the equipped vehicle
- Ensuring that the tests contained within the existing EMC Directive are appropriate for the control of interference with critical vehicle systems in other vehicles
- Requirements for the primary coil to only be energised when a vehicle equipped with a secondary coil passes over it
- Requirements for the primary coil size; an upper limit might be required to prevent exposure of other non-equipped vehicles.

### *Regulations and standards*

SAE J2954 (Wireless Charging of Electric and Plug-in Hybrid vehicles) (SAE International) is in preparation. Its intent is to establish minimum performance and safety criteria for wireless charging of electric and plug-in hybrid vehicles and to create a technology matrix to evaluate multiple technologies (inductive, magnetic resonance, etc.).

An equivalent standard for heavy duty vehicles is also in preparation. This is SAE J2954/2 (Wireless Power Transfer of Heavy Duty Plug-in Electric Vehicles and Positioning Communication) (SAE International).

SAE J2847/6 (Wireless Charging Communication between Plug-in Electric Vehicles and the Utility Grid) (SAE International) is also in preparation but at a much earlier stage. This is based on SAE J2836/6 (Use Cases for Wireless Charging Communication between Plug-in Electric Vehicles and the Utility Grid) (SAE).

The International Electrotechnical Commission (IEC) is also developing set of technical standards (TC69/JPT61980) for WPT systems:

- 61980-1, Electric vehicle WPT systems Part 1 – General requirements. (IEC Standards)
- 61980-2, Part 2 – Specific requirements for communication between electric road vehicle (EV) and infrastructure with respect to WPT systems. (IEC Standards)
- 61980-3, Part 3 – Specific requirements for the magnetic field power transfer systems (IEC Standards).

There are also a number of standards relating to human exposure to electric and magnetic fields which are applicable as the transmission frequency range of WPT systems falls within their realm. In the USA the relevant standards are prepared by the Institute of Electrical and Electronics Engineers (IEEE):

- IEEE C95.1™-2005 – Safety Levels with Respect to Human Exposure to Radio Frequency Electromagnetic Fields, 3 kHz to 300 GHz (IEEE Standard, 2005)

- C95.3.1™-2010 – Measurements & Computations of Electric, Magnetic, and Electromagnetic Fields with Respect to Human Exposure to Such Fields, 0 Hz to 100 kHz (IEEE Standards, 2010)
- IEEE C95.7™-2005 – Recommended Practice for Radio Frequency Safety Programs – 3 kHz to 300 GHz (IEEE Standards, 2005).

### **6.3 Battery specifications and requirements**

This section defines the battery specifications for a car, medium van and an HGV.

#### **6.3.1 Outline of the methodology**

Battery requirements are dependent on vehicle dynamics, duty cycle and power train technology. Vehicle dynamics include parameters such as power demand, weight restrictions and availability of space to accommodate a battery.

The vehicle model has a major influence on the battery specification for cars and light vans. The vehicle characteristics of cars and light vans are very similar; therefore these two vehicle types were grouped together. It is recognised that duty cycles for cars and vans are likely to be different; however, the purpose of this work was not to assess the possible variations of duty cycles but rather to understand the basic energy requirements from these vehicles, which could then be scaled up for different duty cycles. A car category can be considered for vehicles weighing less than 2 tonnes. In this scenario the Nissan Leaf was chosen for modelling using the TRL energy demand model.

According to the Society of Motor Manufacturers and Traders, a medium sized van is one which weighs between 1.8 tonnes and 3.5 tonnes. For the purposes of this study, the Ford Transit was modelled.

The HGV category covers a range of heavy vehicles weighing from 7.5 tonnes up to 44 tonnes. The parameters of the Scania R-series articulated HGV were used to develop an energy demand model.

The battery specification was considered to depend on a number of factors that were investigated in the study, including:

- Power train
- Regeneration rate
- Discharge rate
- Power transfer rate from the charger
- Duty cycle
- Drive cycle
- Weight and volume
- Route predictability.

#### **6.3.2 Battery specification**

This sub-section gives an overview of the battery specifications required for various vehicle types. The project team has utilised information from suppliers and the battery information review (see Appendix A and Appendix B) in order to develop a model to

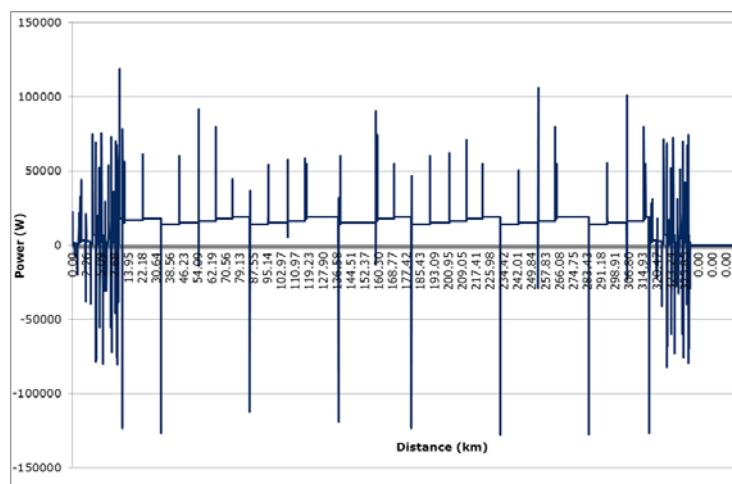
analyse vehicle behaviour. The modelling information and development can be found in greater detail in Appendix C. The routes were modelled to start and end in a city with a motorway journey in between, covering 330 km (~206 miles). The city parts of the trip were approximately 16 km (10 miles) long. The car model was designed to simulate an ideal journey based on the above parameters.

Outcomes from the review of battery technology and the TRL energy demand model were used to develop battery specifications for each vehicle type, as described in more detail in the following sections.

### 6.3.2.1 Car

Figure 18 shows the hypothetical charge discharge rate for an urban and motorway mixed route, including maximum power demand and generation based on the kinematic properties of the vehicle and the route. Vehicle traction demand can be as high as 119kW (139kW discharge from the battery) at acceleration rate of  $2.3\text{ms}^{-2}$ . The average deceleration rate was assumed to be  $3\text{ms}^{-2}$ ; therefore, the regeneration rate can be as high as 126kW at the traction motor. When inefficiencies in the powertrain are factored into the calculation, the battery should be able to charge at a rate of up to 113kW, this is approximately charge rate of  $5\text{C}^1$  (the rate of battery charge or discharge per hour as a ratio of the battery capacity).

The theoretical values above are useful for understanding typical power demand that can be experienced by a vehicle of a size and weight similar to a Nissan Leaf, completing the described route. However, in practice these values are constrained by the capability of the specific parameters of the vehicle’s motor and battery. For the modelled Nissan Leaf, maximum battery charge rate for regeneration was limited to  $1\text{C}$  (approximately 21kW) and maximum discharge rate was limited to 85kW, based on the battery specification. These values were used to determine the representative SoC over the route.



**Figure 18: Nissan Leaf route profile**

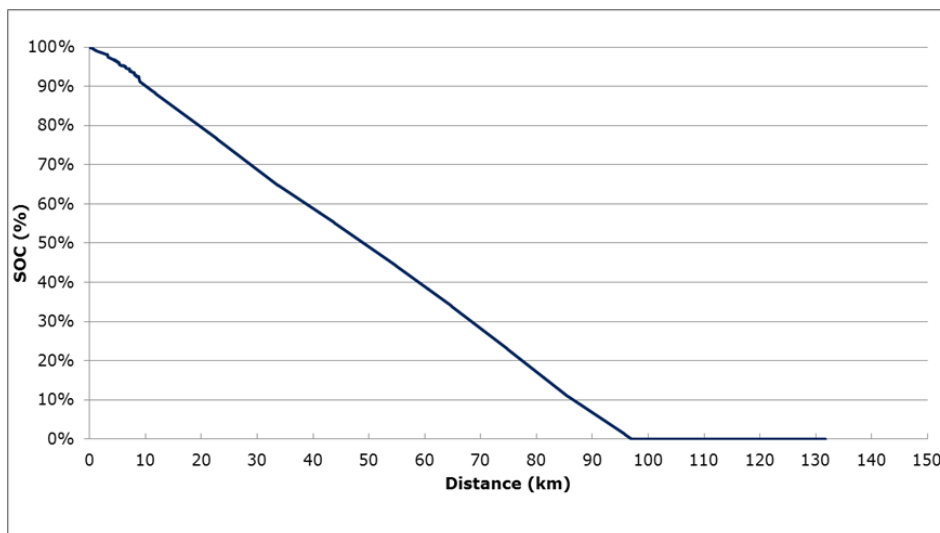
Figure 19 shows the Nissan battery State of Charge (SoC) on a motorway journey, equipped with a 24kWh battery pack (17.8kWh available). The route starts in a city centre where the vehicle drives for 9 km in urban drive conditions. The motorway part of the route is 314km followed by another urban driving section of 7km. As shown, the

<sup>1</sup> A charge rating of  $1\text{C}$  would correspond to a 113kWh battery charging for one hour at a rate of 113kW.

electric range on battery is 60miles (97km). Therefore, the average energy consumption with motorway drive conditions is 0.181kWh/km. However, it should be noted that the energy demand in city drive conditions is 0.15kWh/km, and based on that figure the urban range of a Nissan leaf is 74miles (118km).

The Nissan Leaf needs to be equipped with a battery of at least 60 kWh available capacity in order to complete a 330km (206mile) journey on a single charge. A battery with 60kWh available battery capacity could increase the total weight of a Nissan Leaf to over 2000kg which can be considered as too heavy for a small family car, and could cost over £32,000, so a battery of this capacity will have a significant impact on vehicle cost.

Battery mass is expected to reduce by 30% and costs by 50% by 2020 for the same capacity (Element energy, 2012). Under these conditions, it would be possible to equip a car with a 40kWh battery (32kWh available) without having to compromise on weight and at the same time reducing the cost of the vehicle. The range of a vehicle equipped with 32kWh available capacity is 213km under urban and 176km under motorway drive conditions. This increase in battery capacity would result in a 25% reduction in range anxiety when compared with current electric vehicles (Knutsen, 2013).



**Figure 19: Nissan Leaf SOC**

Table 7 has parameters for a range of electric cars which shows that the average battery capacity is 20.2kWh and the average range is 163km (103miles). The average weight of the electric vehicles is 1334 kg, which is slightly less than the average compact ICE vehicle, which weighs 1354kg. The Tesla Model S was excluded from the average calculations because it is not comparable with compact diesel cars in terms of its weight, power and cost.

**Table 7: Electric car battery state of the art**

Model	Battery capacity	Range (NEDC) km	Weight (Kg) (List of car weights, 2015)	Power (kW)
Standard ICE compact	N/A	800	1354	80
Nissan Leaf	24	175	1521	80
BMW I3	19	190	1270	125
Tesla model S	85	310	2108	310
Renault Zoe	22	130	1468	65
Mitsubishi i-MiEV	16	160	1080	47
Average	20	163	1334	79

Table 8 presents a typical battery specification for a car or light duty van. Energy density and safety are the determinant factors in cars because the users experience range anxiety and vehicles must be safe to drive. However, increasing the range results in a heavier vehicle so weight and volume constraints, as well as cost, determine the upper battery capacity limit. At the time of writing two Li-ion battery chemistries, NMC (Nickel Manganese Cobalt) and LMO (Lithium Manganese Oxide) were found to be the most feasible options for EVs, as they provide relatively good specific energy, power density, high duty cycle and are safe. However, super capacitors can be used to maximise the storage of regenerative energy as the NMC battery with capacity of 24kWh may not be able to charge when the regeneration is above 1C.

**Table 8: Car or light duty van battery specification**

Parameter	Value
Available capacity	20.2kWh (40kWh by 2020)
Charge rate	113kW (max)
Discharge rate	139kW (max)
Duty cycle	3265miles (max)
Nominal voltage (typical for cars and light vans)	150-400V
Car weight	1354kg
Cost	£8,700
Chemistry	NMC, LMO (and NCA (Nickel Cobalt Aluminium Oxide) if safety concerns are solved)

Information provided by vehicle manufacturers which are working on developing future battery technology for cars and light vans confirms that most batteries for EVs, are at present, between 22 and 24kWh, using various forms of Li-ion chemistry, as discussed above. According to developers, the intention is to double the capacity of such batteries, and therefore their range, before 2020. This would result in batteries of around 45kWh capacity that would be able to provide range of around 200 miles (less for motorway driving).

Vehicle manufacturers also raised a concern associated with the development of battery technology. Increasing the size of batteries would require considerably longer charging times using existing static charging infrastructure. This can be illustrated by considering a typical current EV with a battery capacity of 21kWh charging overnight using a typical home charger rated at 3kW. If the vehicle battery is empty, it would require around 7 hours to charge fully. Assuming the same conditions but for a vehicle with double the battery capacity, 42kWh, would require twice as long to charge to full power, 14 hours. This clearly cannot be achieved overnight.

This issue becomes even more challenging when considering en-route charging using rapid chargers. A vehicle with double battery capacity of today's EVs would require around 1 hour to charge the battery to 80% full using the fastest available charging technology, 50kW DC rapid chargers. This would significantly increase the duration of any intercity journey.

The results seem to indicate that as battery capacity increases, helping to improve range and reduce range anxiety, a new issue is introduced concerning the ability to charge EVs within an acceptable time period. For those people with access to charging at home and at work, this may not be an issue, but for others and those attempting to make longer motorway journeys, such long charging times may be considered unacceptable. In this respect, the ability to receive power dynamically through DWPT while driving on the highway could help overcome this concern. This may be of particular importance to commercial vehicle operators who try to minimise the amount of time a vehicle is out of use (as when using a static charging point).

#### *6.3.2.2 Medium van*

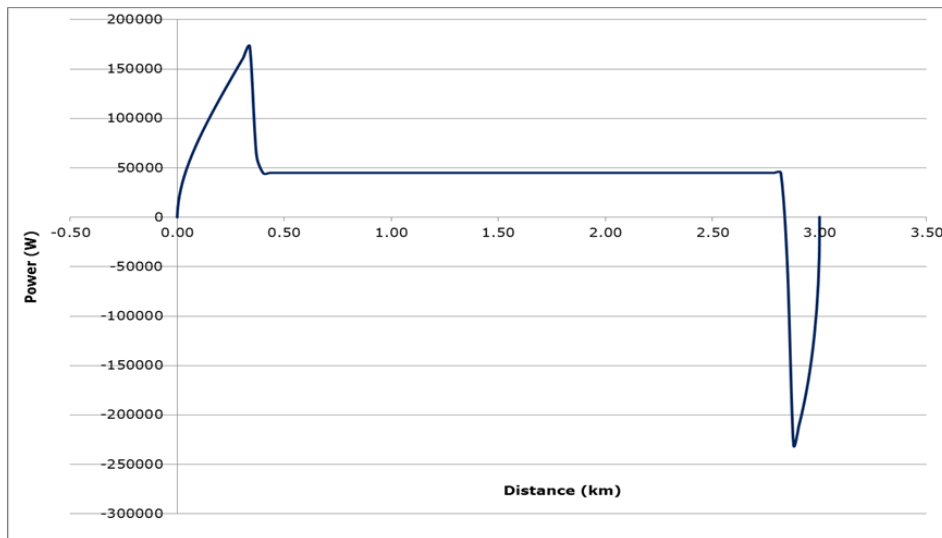
A medium sized electric van with total mass of 3000kg was modelled in urban and motorway conditions. Even though current electric vans are not capable of reaching motorway speeds, for the purposes of this study the model assumed that the electric van could reach speeds up to 70mph in order to understand the power and energy demand requirements. The model shows that energy consumption in urban conditions is 0.27kWh/km and 0.44kWh/km in motorway conditions.

As described in more detail in Appendix B.2, the average daily mileage for a commercial van is 64miles (102km). Assuming that the van drives 78% in urban and 22% in motorway conditions (speed above 55mph), the daily battery capacity should be 40kWh (32kWh available) in order to provide traction for 64 miles. In a purely city driving scenario, on an average day 34kWh (27kWh available) battery capacity should provide a 64mile (102km) range. However, to provide daily average mileage in mainly motorway conditions (at 0.44kWh/km) the vehicle battery capacity should be 56kWh (45kWh available).

Figure 20 shows the van acceleration and deceleration profile. During acceleration from 0 to 70mph (112km/h), the demand from traction motors can be as high as 180kW, and



regeneration can be as high as 220kW during deceleration. The van requires 45kW power from the traction motor in order to maintain a speed of 70mph, and 38.4kW in order to maintain a speed of 65mph.



**Figure 20: Van Acceleration/Deceleration profile**

Table 9 presents the typical battery specification for a medium panel van. The energy and power density are determinant factors as the weight and the volume of the battery has an impact on payload capacity. The minimum battery capacity is 34kWh, which provides a 63mile range in urban conditions. The required battery capacity can be as high as 58kWh in order to achieve a 64mile range in mainly motorway driving conditions. A battery capacity greater than 58kWh could possibly result in reduced payload capacity. The NMC chemistry is the most feasible battery chemistry option as it provides relatively good specific energy, power density, long life time and it is safe. However, if the vehicle mainly operates in urban conditions and aims to recuperate most of the regenerative braking energy, then LMO or LTO (Lithium Titanate Oxide) can be more suitable options, as these battery types are capable of accepting up to 5C charge rates.

**Table 9: Medium van battery specification**

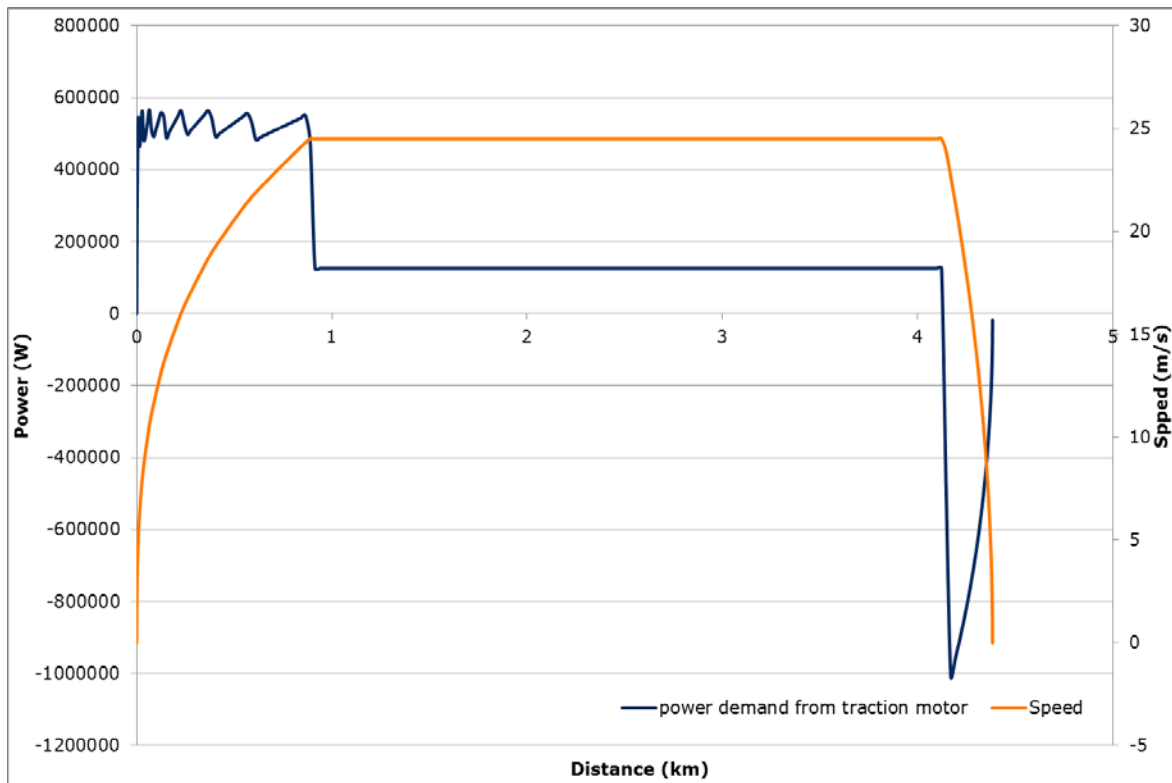
Parameter	Value
<b>Capacity</b>	34 – 58kWh
<b>Charge rate</b>	200kW
<b>Discharge rate</b>	200kW
<b>Duty cycle (assuming life time of 10 years and average daily mileage 64 miles)</b>	2656miles
<b>Nominal voltage</b>	Up to 400V
<b>Vehicle weight</b>	Kerb weight no greater than 2000kg
<b>Volume</b>	Not to effect payload volume
<b>Cost</b>	£14,600 – £25,000
<b>Chemistry</b>	NMC, LMO, LTA

Similar discussion points apply to vans as those for cars around increasing battery sizes and corresponding charging times. As vans have larger batteries and typically have more demanding duty cycles with less idle time for charging, high charging times may be deemed unacceptable.

Use of DWPT may help to reduce the need for prolonged charging periods for vans with larger batteries and could improve their overall utilisation.

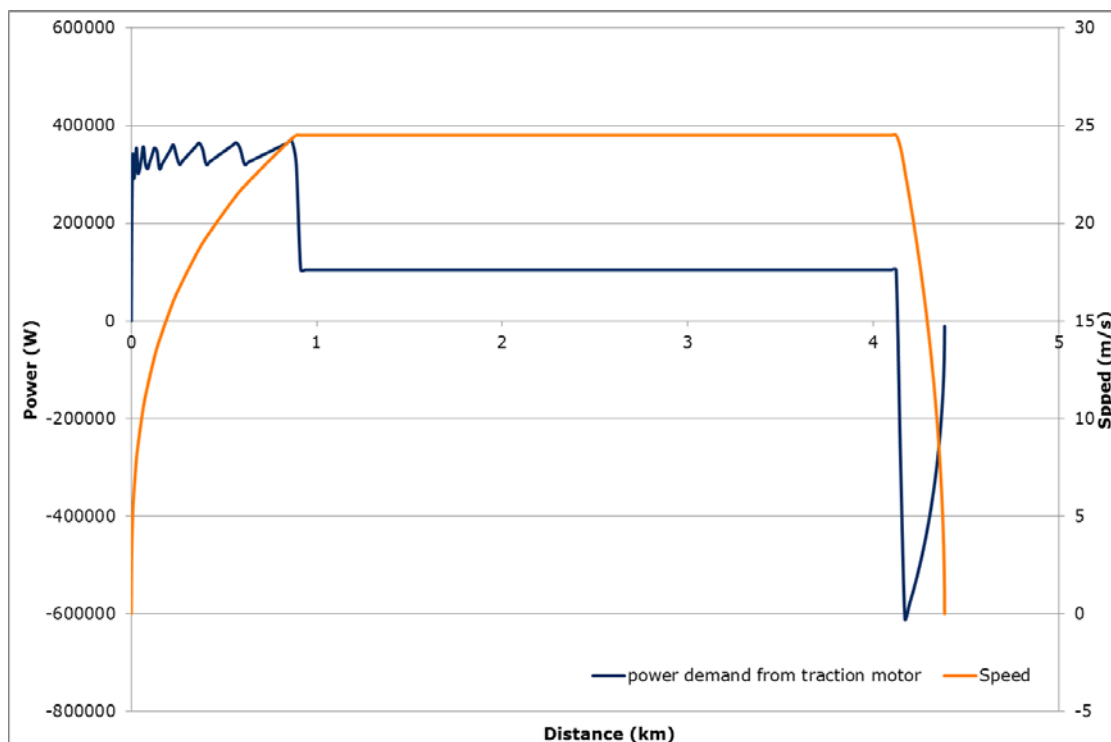
### 6.3.2.3 HGV

Figure 21 shows the traction power demand and supply (blue trace) and the speed profile (orange trace) of a 40tonne truck for one cycle of acceleration through gears to 25m/s (55mph), steady speed and braking to standstill. During acceleration the vehicle demands up to 560kW power. In this case both engine and motor operate at their peak power. During deceleration the energy dissipated, and hence potentially available for regeneration, can be as high as 1MW (but in practice limited to 236kW due to the rating of the motor). In order to operate in electric mode on electrified sections at constant speed, the traction motor should be rated at least 130kW for continuous power. Peak motor power is not expected to be greater than 236kW (560kW total demand-assumed 324kW power from the engine) for such a motor. Therefore, the remaining 70% of braking must be provided by mechanical means. It should also be noted that if the vehicle is fully battery electric, then all of the peak power (560kW) will have to be provided by the traction motor. This would also allow for higher power regenerative braking (up to the rating of the motor).



**Figure 21: Power demand/supply for a 40 tonne HGV**

It should be noted that the demand and generation values during acceleration and deceleration are affected by the weight of the vehicle and for the purposes of this calculation, the weight is assumed to be 40 tonnes. Figure 22 shows the demand and generation values for a 25tonne HGV. The demand has reduced to 360kW and the generation has reduced to 620 kW (but limited to 236kW due to the rating of the motor). This shows that the motor design should be tailored for each vehicle's needs in order to maximise the benefits of using a hybrid powertrain.



**Figure 22: Power demand/supply values for a 25 tonne HGV**

At a steady speed of 55mph, a 40tonne HGV typically requires some 140kW of continuous power. If we assume that the WPT system can supply 100kW, this means that the battery needs to supply an additional 40kW to maintain this speed.

The battery capacity in this case will depend on length of the electrified section. Assuming the HGV can drive for 395km (247 miles) without stopping, and, if 30% of the road is electrified, then the required battery capacity is 68kWh (54kWh available).

The HGV requires very high discharge and charge rates so it is desirable to use a hybrid of super capacitor and Lithium ion battery pack to make sure that all the regenerative energy can be recovered during braking.

**Table 10: HGV battery specification**

Parameter	Value
Capacity	68kWh
Charge rate	208kW (based on peak motor power of 236kW)
Discharge rate	268kW
Duty cycle (Assuming life time of 1,000,000 km)	1250-5000
Nominal voltage	Up to 700V
Vehicle weight	Up to 40,000kg
Volume	The battery volume should not affect payload capacity
Cost	£29376
Chemistry (Possibly hybrid of lithium-ion and super capacitor. Super capacitor in parallel with the lithium ion battery)	LTO or super capacitor/lithium ion hybrid. Li-Polymer

Feedback from vehicle manufacturers shows that most current heavy vehicle battery specifications are based on vehicles used on urban routes. However, this is a good indication of what can be considered to be a reasonable size of battery to include in terms of weight and size.

For buses, battery capacity varies from approximately 50kWh for a hybrid powertrain to 100kWh for a fully electric vehicle. A 100kWh battery weights in the region of 1200kg. The sizes of batteries currently being considered for heavy vehicles seem to be appropriate for DWPT, based on the calculations described above.

If high power DWPT is available of approximately 140kW, and a vehicle operates on a mostly electrified route, then it would be possible to use considerably smaller batteries,

in the region of 10 to 40kWh. For hybrid vehicles, there would be no restriction on using sections of the highway that are not electrified as long as the ICE on board the vehicle is able to cope with the anticipated power demand. Battery electric vehicles would be constrained to operating on largely electrified routes.

### **6.3.3 Recommendations for possible improvements to batteries to cope with DWPT**

DWPT itself is not thought to require any specific improvement to the battery technology used in cars and vans. Use of DWPT for these vehicles will likely require the ability to cope with high power transfer, up to 40kW, which most EVs already have at present to cope with rapid charging at 50kW. Moreover, the ability of DWPT to provide power directly to the vehicle traction motors will likely reduce the need to charge batteries while using the system, or at least allowing charging at lower power levels.

For heavy duty vehicles, battery technology would need to cope with very high power, potentially, up to 140kW. Depending on battery size, this could require charging at up to 2C or 3C. Current battery technology is already able to cope with this level of charging and is used in static WPT applications for charging at up to 200kW. In a similar manner to cars and vans, most of the time, most of the power from the DWPT system is expected to be used by the powertrain directly. Therefore, battery charging would be at lower power in most cases.

Further details on the technologies closest to market can be found in Appendix A.

## **6.4 Specification and costs for installation of systems under the motorway (types of installations to be investigated)**

This section investigates possible construction methods, including a review of tools, and potential costs for installing DWPT systems under a motorway.

### **6.4.1 Power supply system construction approach**

Different approaches to power supply system construction essentially fall into two options: a cast in-situ system or a pre-cast system.

### **6.4.2 Existing construction methods and tools**

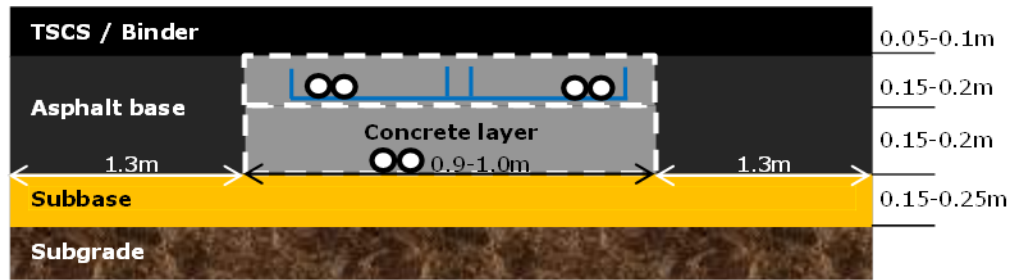
Three construction methods for installation of a DWPT are: trench based construction, full lane construction and full lane prefabricated construction. The following sections will describe some of the machinery that could be used for the three methods, and some of the advantages and drawbacks of each approach.

#### **6.4.2.1 Trench based construction**

This method involves creating a trench in the existing highway, installation of the system (whether in situ or pre-cast), backfilling and laying an asphalt surfacing layer, see Figure 23.

Whilst the option of cutting a trench in the road is likely to be the quickest and cheapest of the options, the introduction of a concrete section within the pavement would almost certainly lead to reflective cracking at the surface at or near to the wheel paths, as well as cracking of the transverse joints where the power supply is taken in from roadside

cabinets.



**Figure 23: Example of a DWPT system embedded using the trench excavation method**

The reflective cracking could potentially be reduced and / or delayed through the use of a SAMI<sup>2</sup> or grid layers between the system and the asphalt layers. Another option that could be considered would be to angle the sides of the trench to reduce the vertical forces.

Such systems have been used in embedded rail systems, where the rail is contained within a concrete structure rather than been constructed on sleepers and ballast, as shown in Figure 24 below, where the rail is held within an elastomer, inside a plastic sleeve. This physically separates the steel rail from the concrete, and reduces vibration and noise.



**Figure 24: Balfour Beatty embedded rail system**

In terms of construction, no particularly specialist equipment or tooling would be required to excavate an asphalt pavement. There are various milling machines, such as the one shown in Figure 25 below that can form trenches to a variety of widths and depths. A web search identified two companies (Roadtec and Wirtgen). Cutting width tends to vary from 0.35m to 2.2m with depths of up to 0.35m. It is understood that a width of 1 metre is required for installation of the components.

The construction method has been discussed with HE contractors. The process involves planing out of the entire lane 1 width (3.65m) to a depth of 0.1m prior to excavating a 1m wide trench or removing the full width of lane 1. Assuming the machine could excavate to a depth of 0.35m, the bottom of the trench would be 0.45m from the original surface level, so would exceed the 0.3m – 0.4m depth required to install the system. It is also likely that a manufacturer could customise a machine for specific width and depth requirements if required.

<sup>2</sup> SAMI – Stress Absorbing Membrane Interlayer



**Figure 25: Milling machine forming trench**

For a scenario where pre-cast units are used, efficiencies in delivery and installation could be gained by using specialist delivery plant. TRL has previously investigated the use of an extendible trailer (also known as a trombone) for installation of pre-cast concrete tram tracks. The trailer would be extended when it was immediately over the location where the device was to be installed, as shown in Figure 26. The pre-cast sections could then be lowered through the extended trailer deck directly to the point where they are required without any interference to pedestrians or traffic on the adjacent carriageway. The vehicle would then move forward the appropriate distance and drop the next section. This process avoids double handling and congestion, and the construction team are protected from collisions with site traffic.



**Figure 26: Example of extendible trailer that could be used for prefabricated sections installation**

Using a pre-cast system in this situation might be preferable as there would be no need to allow concrete to set as would be the case with construction in-situ. This would mean that the asphalt layer could be laid immediately, reducing construction time.

#### 6.4.2.2 Full lane reconstruction

Unlike placing the WPT system within a trench, this option would involve removing the full depth of bound layers from lane 1, and either constructing in-situ or using pre-cast units, followed by construction of a concrete pavement around the units and then by asphalt surfacing.

Whilst this is a more time consuming and expensive construction exercise than the trenching option outlined above, it has the advantage of locating longitudinal construction joints at the edge of the lane. The number of transverse joints would be the same and would extend across the full lane width. However, it is thought that any on-going maintenance requirement may be less with full lane width construction.

In this case, DWPT units and associated connection pipework would be delivered to the site in precast form and the pavement constructed around them. This could potentially avoid the requirement for two concrete pours, and so would accelerate the programme. Lane 1 is excavated to the sub-base and a precast system with non-metallic dowels and anchors is transported to site where it is lowered in place by crane onto four aluminium supports. For a motorway trial, asphalt overlay with a reinforcement grid or SAMI can be applied to reduce noise and match the adjacent construction.

Again, there is no special tooling that would be required for this construction method, simply road planers and concrete mixing plants. A possible concern with this method is that a routine inspection and maintenance policy would have to be enforced, especially with the high number of longitudinal and transverse joints associated with each system.

#### 6.4.2.3 Full lane prefabricated construction

An alternative to the full lane reconstruction outlined above would be to plane out the full lane width of asphalt, but rather than reconstructing the entire lane on site, it would be replaced with a full lane width prefabricated section containing the entire system. This could possibly be finished with asphalt surfacing as above, or by having a porous concrete surfacing already placed on the prefabricated sections.

The significant advantages of this approach, compared with on-site construction, would be an accelerated construction period and factory construction quality. This approach has been trialled in several locations as a general construction approach, albeit not containing WPT devices. One approach that the project team is familiar with is the Modieslab concept, which was developed in response to an innovation call from the Dutch Road Authority, Rijkswaterstaat. It has been deployed on a number of trial sections including on motorways, and can be installed on piles, as shown in Figure 27, or an existing concrete or asphalt road.



**Figure 27: Installation of Modieslab prefabricated section**



This particular system can be produced with a two layer porous concrete surfacing, as shown in Figure 28, with noise reduction of the same level as porous asphalt.



**Figure 28: Modieslab sections in-situ**

For the Modieslab system, it is understood that the moulds are fully adjustable<sup>3</sup> in size and depth to take account of curves and gradients, and they are mobile, with the idea that they would be transported to a depot near the construction site to minimise transport of the sections. In addition, they can be manufactured without reinforcement.

For example, for a 1.6 km (1 mile) section, there would be around 230 vehicle movements to deliver all the sections to site, in addition to the number of vehicles that would be required to remove the milled material. This might actually be less than that required for conventional reconstruction as detailed above where the entire bound layer is removed, as an asphalt layer is a suitable bed for a prefabricated section, i.e. only the depth required to fit the slabs would be required to be removed, not the entire bound layer.

Whilst prefabrication is likely to be the highest capital cost option, there would be significant savings in traffic management costs with the only major concern being the potential disruption caused by the transport of these systems to site. It is understood that potential disruption to road users in transporting these units to site may be a concern to Highways England. This concern should be weighed against the relatively low numbers of loads and the far greater speed of construction and hence greater availability of the network, i.e. an intermittent number of wide loads delivering to site would be less disruptive than a longer lane closure. In addition, there may be ways to mitigate the impact of the deliveries through, for example, delivery during off-peak periods, or potentially developing a frame for the trailer that would carry the slab at an angle to avoid any overhang.

Furthermore, the durability advantages of prefabrication reduces future maintenance; the ability to remove and replace a section in a short time frame could well lead to lower whole life costs.

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<sup>3</sup> The minimum size is 2m x 2m and maximum size is 9m (l) x 4m (w).

#### *6.4.2.4 Future maintenance programme*

For the road owner, the future maintenance programme is highly dependent on the type of construction with the selected power transfer system. It is not expected that the equipment itself will require any maintenance during its service life.

For all construction types that include an asphalt overlay, the expected maintenance will depend on the expected service life of the asphalt overlay and the subsequent effect of the power transfer system on the performance of the asphalt layers. Due to the thermal movement of the concrete, there will inevitably be the risk of reflective cracking in the asphalt above joint locations. Previous experience with overlays to jointed concrete pavements suggests that the use of a SAMI or geo-grid layer between the units and the asphalt layer(s) should be considered. Alternatively, the use of a saw cut and seal in the asphalt surface above the joints in the concrete layer below has been shown to control reflective cracking and should also be considered.

To ensure that these joints are performing and not causing problems with the serviceability of the pavement, a routine inspection and maintenance programme must be put in place. This could involve the use of surveys at traffic speed to monitor the development of any cracking and any changes in pavement ride quality. A maintenance programme which prevents the use of personnel on highly trafficked carriageways is always preferable, and this can be achieved for the most part using the approach above. However, at some stage there may need to be allowances for a walked visual inspection of the joints from the hard shoulder. It is likely that inspection of roadside electrical equipment will be needed periodically and a visual assessment of the carriageway could be made at the same time. To ensure initial success of the performance of the pavement systems, it is suggested that monthly or bimonthly inspections be undertaken for the first two years following installation. Once enough experience has been garnered from the successful installation, operation, and maintenance of these pavement systems, an alternative maintenance programme can be put forward.

Assuming that the asphalt overlay performs as expected (8-10 years of service life), a programme of maintenance will be put forward which will include milling off and replacement of the surface layer (~35-50mm) which can be done at night when traffic volumes are much lower. If maintenance or modification of the power transfer systems is required, then this would be the ideal window to do so, although it would significantly extend the proposed programme of works.

Assuming that an asphalt overlay is not applied, then the maintenance programme would replicate that which is normally associated with jointed concrete pavements, with visual inspections a priority to ensure that there are no defective joints and that the surface is in good condition and provides adequate skid resistance.

#### **6.4.3 Costs**

Discussions on the construction process in broad terms were held with the road construction industry and this has assisted with estimating a 'ball park' figure for a potential installation of 1.6 km section.

There are a significant number of assumptions in making the estimate and apart from the civil engineering construction process, the purchase of induction coils, supply and installation of road side cabinets, roadside trenching for cables to cabinets, project

management, site office and traffic management has also been considered. However, it does not include the cost of connection to the National Grid power supply.

It is recommended that Highways England engage in early contractor involvement in order to better understand actual construction costs and constraints at the outset. The cost estimates below have been provided based on the limited information the project team was able to share with the road construction industry, as well as with project team experience on other construction projects.

Further, it should be noted that the cost of construction of a trial will not be an entirely accurate reflection of potential costs for the roll out of a system, as it will be a slower process, due to the contractor's lack of familiarity with the equipment and specific construction processes. The off-site trial and on-road trial should be used to determine the optimum construction method for larger scale deployment, including the potential to procure specialist, potentially bespoke manufactured, manufacturing and installation equipment to optimise the process as well as training dedicated teams to undertake these tasks.

#### *6.4.3.1 Lean construction*

The cost implications of rolling out wireless power transfer on the SRN are considerable, and will be balanced against considerations such as emissions targets, customer demands and developing the UK's skills in this area, to become a world leading centre of expertise.

A whole life cost assessment should be undertaken to determine the optimum solutions to take account of such factors as initial cost, lifetime of the system, maintenance requirements, speed of installation, traffic management requirements for installation and future maintenance events, as well as customer requirements and network availability.

It is proposed that Lean methodologies be considered at the outset in order help determine the optimum construction option, and should continue through the project in order to make the whole system more efficient, to reduce waste (in terms of activities that do not have benefit) from the programme, leading to cost savings and greater programme certainty.

Business improvement systems such as Lean and Six Sigma became prevalent in Japanese manufacturing following World War 2 as a means to increase quality and produce goods at low cost, when they could not compete on mass production and volume of sales.

It empowers all levels of a business or organisation to work in an efficient manner from planning to execution whilst focussing on five key areas of an organisation: People, Safety, Quality, Cost and Delivery.

Within this, a key focus of the Lean methodology includes the on-going identification and elimination of 'waste' and creating value within any activity, process or business which is defined as "anything that the customer is not prepared to pay for", for example through eliminating double handling, improving construction quality and avoiding reworking, reducing down time and waiting.

The following outlines how a Lean approach can support construction activities:

### **Planning & Management**

- Effective and co-ordinated planning of people, tasks, materials (logistics), and targets to reduce down time/waiting
- People management. Matching skill sets to specific tasks, to have a specialised team where everyone knows their job
- Daily monitoring of plan vs actual status to ensure strict management of programme which supports early identification of problems for swift mitigation
  - Daily materials and logistics auditing to ensure inventory is kept to a minimum thus reducing cost.

#### **Design for construction**

- Modularisation of components to increase the ease of assembly resulting in less resource, and time
  - Key components assembled off-site to reduce installation time and disruption on-site.

#### **Standardisation**

- Identified best practice for optimised assembly and installation
- Repeatable time bound process, simplified monitoring of progress against target
- Reduced variation by carrying out tasks the same way every time
- Built in quality.

#### **Communication**

- Daily communication between Design, Engineering, and Construction to ensure cross discipline alignment
- The use of visual management to simplify lines of communications and provide transparency and problem solving opportunities.

#### **Lessons Learnt**

- Create a forum for regular reflection to create a Continuous Improvement environment.

#### *6.4.3.2 Cost estimates*

Based on the approach outlined above, it was estimated that cost of DWPT-equipped road construction (on existing road) could be between £1.7M and £5.5M, including infrastructure but excluding grid connection. The exact value would depend on a variety of factors such as:

- Location of the road segment
- Construction method
- Cost of Primary DWPT infrastructure.

The cost of the trench-based construction option was identified as likely to be the cheapest. However, this option was not favoured by Highways England Netserv pavements team due to the inclusion of two in-lane longitudinal joints and the potential to cause on-going maintenance needs which could add to the whole life cost of the installation.

#### *6.4.3.3 Assessment of lifting and transportation options*

Depending on the construction option chosen, the transportation of the equipment to site and installation will be significantly different, and this in turn might affect options for

optimising the construction process. The larger the pre-fabricated unit, the greater the cost is likely to be. Additionally, full sized slab could require a full closure for installation.

There are a variety of vehicles with Hiab cranes that would be suitable for lifting sections in the order of the 8–9m. Using an articulated lorry and separate crane, the achievable length of section, using a spreader beam as necessary, would be 13m. Articulated lorries can have integral Hiab cranes, although the additional weight reduces the carrying capacity. In terms of speed of installation and reduction of joints, longer lengths are preferable. There exists a wide range of rigid and articulated lorries with various Hiab cranes. The lifting capacity of a small selection has been collected and is presented below.

**Table 11: Carrying and lifting capacity of selected vehicles**

Type	Truck weight (t)	Carrying capacity (t)	Lifting capacity (t)	Lifting reach (m)	Width (m)	Length (m)
<b>Hiab</b>	18	6.5	4	8	2.5	6.8
<b>Hiab</b>	26	11.5	6.5	12	2.5	8.5
<b>Articulated lorry</b>	~15	≤28	n/a	n/a	2.5	13

For prefabricated channels, any of the Hiab vehicles would be suitable and would be able to lift and carry several sections, and possibly also be configured to drop sections through an extendable trailer as per Figure 26.

For full width reconstruction, only the articulated lorry would be suitable, with an external crane. For a 1.6 km road trial, it is likely that a standard mobile crane could be used, although a crawler crane (a tracked crane) might offer greater manoeuvrability on site.

Should DWPT be rolled out on a large scale across the SRN, bespoke options might need to be considered for speed of installation, to maintain site access. In the rail sector, there are track laying machines as shown in Figure 29, below and there are also mobile 'straddle cranes' used at ports for moving shipping containers.

Neither is likely to be directly appropriate for use with these sections, without at least some modification, although it shows what could be achievable.



**Figure 29: Remtek track laying machine**

The idea in this scenario would be that the crane would straddle lane 1, a lorry delivering a road section would drive beneath it, the crane would lift the section from the lorry, which would then drive back to the depot. The machine would then place the section onto the prepared ground and move forward to be ready for the next section.

The basic requirements for such a system would be that it could move under its own power, have the ability to raise itself sufficiently such that a tractor unit of a HGV could drive beneath it, and lower itself so that it could fit beneath bridges. There would be a requirement to set appropriate weight and axle limits on the machine to prevent damage to the surrounding pavement, although the caterpillar tracks and slow speed should help in this regard.

#### *6.4.3.4 Factory thinking approach*

Many civil engineering contractors are exploring the benefits of off-site prefabrication in delivering improved construction quality and minimising on-site uncertainty. This so called 'factory thinking' approach aims to simplify and standardise the products and systems where products are constructed offsite, leading to a much quicker and safer onsite assembly process. A 'set of parts' philosophy can be employed where there are a limited number of standard parts forming the majority of the configuration, coupled with a limited number of bespoke elements, which could also be manufactured offsite if required.

#### **6.4.4 Key requirements for a road installation tool**

Currently available DWPT systems are manufactured and installed on a small scale, without using any bespoke or specifically developed tools. As described in Section 6.4.3.3, a number of lifting and transportation options already in use in road construction industry are typically used for installing current DWPT systems. This is sufficient for small scale pilot and trial installations but is unlikely to be adequate for high volume manufacturing and installation. For this purpose, dedicated road installation tools could be developed.

The key requirements for a road installation tool might consist of the following topics. A tool kit will only be able to be fully developed once a system has been trialled. Any tool specification will need to be specific to the system and construction method used.

Example topics:

- Minimising disruption of traffic
- Mobility/portability of equipment
- Ability to position and space inductive devices on and within the road
- Ability to install devices within all trunk road pavement structures, e.g. full asphalt construction, thin overlay asphalt, concrete, concrete/asphalt composite
- Ability to install system in areas where the pavement is thinner than usual, e.g. bridge decks
- Ability to install relative to power and cost of installation
- Resilience of tool to motorway environment, durability, expected life
- Need to install equipment that is resilient to temperature, water, traffic wear (especially HGVs)
- Speed and safety of installation
- Ability to detect and work relative to utilities, drainage and other power sources
- Impact of relative positioning of tunnels, bridges, culverts, etc.
- Impact on inspection, repair and replacement requirements of the installed product
- Commercial restrictions, warranty and Intellectual Property for the tool
- Capital and running costs, repairs, supply of consumables and maintenance issues
- Manufacturing and future proofing risks.

## **6.5 Specification for a tool**

The specification for a road installation tool might consist of the following topics.

For example:

- Operational function
- Depth, size and tolerances required for excavation
- Power connection
- Quality of finish, reinstatement and waterproofing
- Durability of installation
- Repair and replacement of product
- Speed of installation
- Future proofing of spare parts to avoid obsolescence
- Cross references to other parts of the MCHW and related documents.

During the project, it was found that at least two DWPT system exist that could be taken through to off road trials. However, neither system has a finalised and thoroughly tested installation method. As such, the exact specifications for a tool can only be developed once the system and construction method have been finalised.



## 7 Process requirements

This section of the report focuses on determining requirements for connecting DWPT systems to the electricity grid in a manner that is compliant with existing standards and for ensuring that electricity can be appropriately recharged back to the user. The requirements are reported under the following headings:

- Power Demand Requirements for each vehicle - this details the power needed by different classes of vehicle while travelling along realistic stretches of the SRN. These requirements will drive the level of power which must be delivered to the in-road infrastructure for the purposes of DWPT
- Commercial drivers and detracting factors – this looks at the costs and benefits to the various actors in the wireless power transfer system. It includes the potential for revenue generation and costs savings for users
- The Network Impact Assessment - this investigates the potential impacts that DWPT could have on the electrical generation and distribution networks
- Finally the inputs to a discounted cash flow model are identified and evaluated.

### 7.1 Power demand requirements for each vehicle

This section describes the power demand requirements for different vehicle types and differing scenarios on the SRN. Power demand requirements were estimated using DfT and TRL data sets in order to understand potential power demand from a DWPT equipped motorway. Using data obtained at earlier stages in the project and data from partner organisations, a high level model was used to understand variations in power demand. A sensitivity analysis was used to understand the variations that will be created by differing traffic conditions (traffic density) by time of day.

It is necessary to understand how much power is required by different vehicle types in order to maintain their speed on the motorway of up to 70mph. In order to be useful, DWPT systems will need to be able to supply power at least at this level to the vehicles. If less power is available then the vehicle will need to use additional power from other sources, such as an on-board ICE, rechargeable energy storage system (REES) or a Fuel Cell. This would result in the vehicle either not being able to maintain 100% electric traction, thereby using additional fuel, or, using energy stored in their REES. If more power is available than the vehicle requires, then it is possible that an on-board REES can be charged while providing full traction to the vehicle.

#### 7.1.1 Car and HGV requirements

The power requirements from a typical modern EV family car (the Nissan Leaf is used as a representative vehicle) at different constant speeds were calculated and are shown in Table 12. This shows both the power required for traction to maintain the constant speed, and the power required from the grid, which accounts for the various losses incurred between the grid and the traction motor. The wheel to grid efficiency is assumed to be 73% when the DWPT is used to provide traction power to the vehicle. At constant speed, the variation in the kinetic energy is zero, and the energy required for acceleration is not included in the table. It can be observed that at 50 mph the vehicle requires about 12 kW from the grid to maintain a constant speed, and that the power

requirement more than doubles if the speed rises to 70 mph. This is due to a non-linear increase in air resistance with higher vehicle speed, thus requiring more power to maintain the speed.

**Table 12: Car or light vehicle energy demand under various constant speeds**

Speed (mph)	Speed (m/s)	Power requirement for traction (kW)	Traction energy per km (kWh)	Power demand from the grid (kW)
10	4.5	1.1	0.067	1.5
20	8.9	2.2	0.067	3.0
30	13.4	3.7	0.076	5.0
40	17.9	5.8	0.090	7.9
50	22.3	8.8	0.11	12.0
55	24.6	10.7	0.12	14.6
60	26.8	12.8	0.13	17.6
65	29.1	15.8	0.15	21.7
70	31.3	18.1	0.16	24.8
75	33.5	21.3	0.18	29.2
80	35.8	24.9	0.19	34.1

Air resistance is even more important for HGVs, due to the less aerodynamic shape of the vehicle. As the speed increases, the air resistance increases and becomes the dominant cause of energy consumption beyond 55 mph. The Scania R-series truck was used as a typical HGV for which, as shown in Table 13, the power demand from the grid is about 175 kW when travelling at 55 mph.

**Table 13: HGV energy demand under various constant speeds**

Speed (mph)	Speed (m/s)	Power requirement for traction (kW)	Traction energy per km (kWh)	Power demand from the Grid (kW)
10	4.5	11.7	0.73	16.1
20	8.9	25.6	0.80	35.1
30	13.4	44.3	0.92	60.7
40	17.9	70.2	1.09	96.2
45	20.1	86.6	1.20	118.7

50	22.3	105.7	1.31	144.7
55	24.6	127.8	1.44	175.0
57	25.5	137.6	1.50	188.4
60	26.8	153.1	1.59	209.7
65	29.1	182.1	1.74	249.5
70	31.3	214.9	1.91	294.4

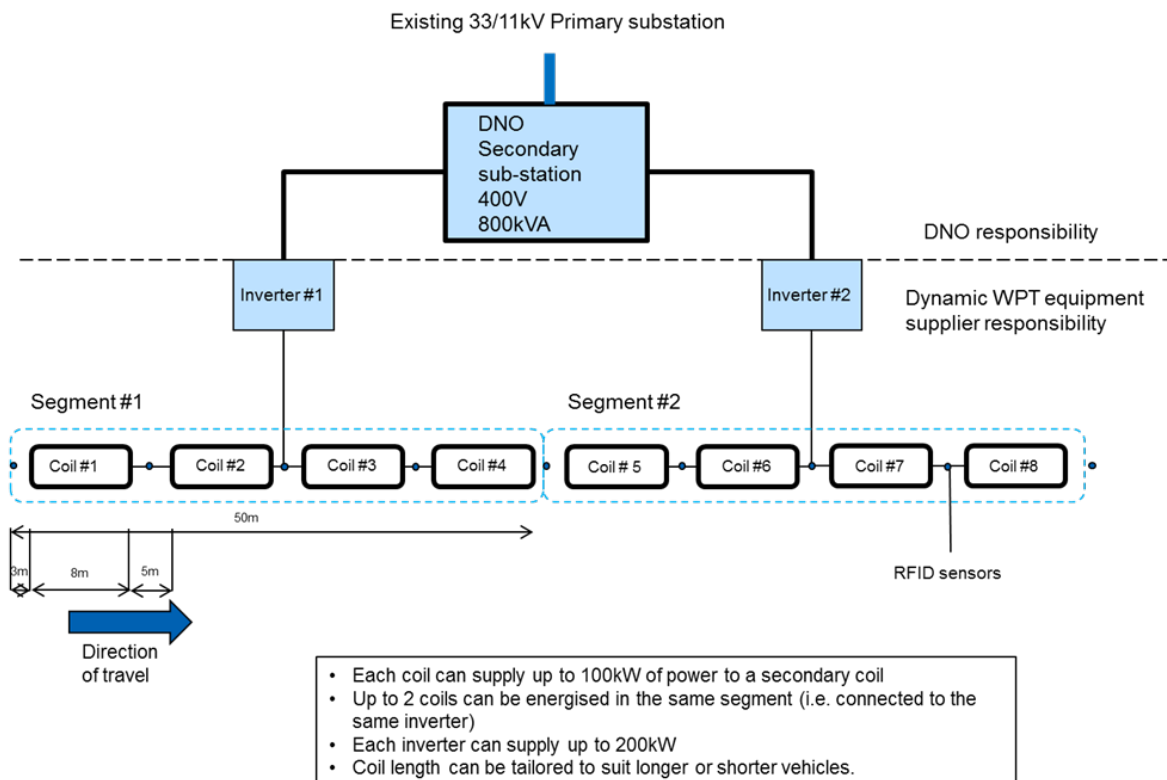
### 7.1.2 Power transfer rate from DWPT

In order to explore what power is to be provided by the grid, it is important to consider not only the power requirements of the vehicles but also the maximum power that can be delivered by a DWPT system. Based on the information available about the systems reviewed, it is apparent that for different systems there is a different combination of power supply, power transfer segment length (that can only be occupied by a single vehicle) and gaps between power transfer segments.

Two different topologies for system layout are described below.

#### 7.1.2.1 DWPT system layout 1

In the example layout shown in Figure 30, each segment can be occupied by up to two different vehicles, separated by approximately 25 m.



**Figure 30: Example of DWPT system layout 1**

Each vehicle can receive a maximum of 100 kW. Because the analysis is focussed on future scenarios, an assumption is made that both light vehicles and heavy vehicles can use the same infrastructure, which would result in them drawing different levels of power from the grid. These are summarised in Table 14 below. It should be noted that a more detailed investigation of how a vehicle powertrain could deal with the amount of power provided by DWPT can be found in Section 6).

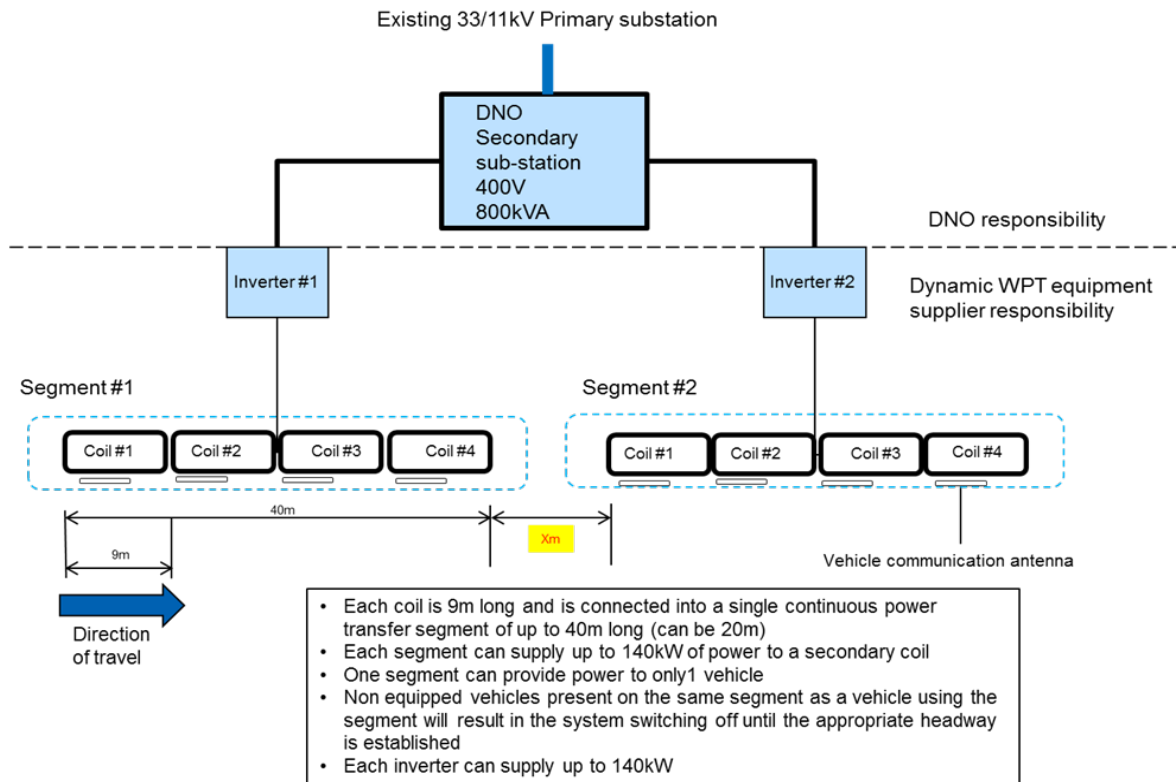
The table shows that light vehicles similar to the Nissan Leaf would use 14.6 kW for maintaining 55 mph speed on the motorway. Vans and larger light vehicles would likely require more power to maintain speed. The model assumes that up to 40 kW is transferred to the on-board vehicle coil. Power that is not used for maintaining speed would be used to charge the battery. For HGVs, 175 kW of power is required to maintain this speed. This is more than is available from system layout 1.

**Table 14: Example of DWPT system layout 1 power transfer assumptions**

Vehicle class	Traction power required from grid at 55mph	Assumed power received by secondary coil	Assumed power drawn from the grid	Comments
<b>Light vehicles (car or van)</b>	14.6kW	Up to 40kW	51kVA	The traction power value is based on a car (specifically the Nissan Leaf). Vans would likely require more traction power than the stated 14.6kW. Any spare power is assumed to be used for charging batteries on the move.
<b>Heavy vehicles (Trucks or coaches)</b>	175kW	100kW	118kVA	This category includes a large variety of vehicles. Medium sized trucks and coaches are likely to not require more than 100kW. Very heavy vehicles, such as articulated lorries will likely need an additional source of power on-board the vehicle.

### 7.1.2.2 DWPT system layout 2

In the example layout shown in Figure 33, each segment can be occupied by up to one vehicle only. The distance between segments is short compared to the segment length, of the order of 2 to 5 m.



**Figure 31: Example of DWPT system layout 2<sup>4</sup>**

The gap between vehicles has to be maintained at 40 m in order to avoid the system switching off due to the presence of a non-equipped vehicle. Each vehicle can receive a maximum of 140 kW. As previously, an assumption is made that both light vehicles and heavy vehicles can use the same infrastructure, which would result in them drawing different levels of power from the grid. These are summarised in Table 15. It should be noted that a more detailed investigation of how a vehicle powertrain could deal with the amount of power provided by DWPT can be found in Section 6).

**Table 15: Example of DWPT system layout 2 power transfer assumptions**

Vehicle class	Traction power required from grid at	Assumed power received by secondary	Assumed power drawn from the	Comments
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<sup>4</sup> Distance between individual segments has not yet been confirmed by the technology developer but is expected to be between 2m and 5m.

	55mph	coil	grid	
<b>Light vehicles (car or van)</b>	14.6kW	Up to 40kW	to 51kVA	The traction power value is based on a car (specifically the Nissan Leaf). Vans would likely require more power than stated 14.6kW. Any spare power is assumed to be used for charging batteries on the move.
<b>Heavy vehicles (Trucks or coaches)</b>	175kW	140kW	184kVA	This category includes a large variety of vehicles. Medium sized trucks and coaches are likely to not require more than 140kW. Very heavy vehicles, such as articulated lorries will likely need an additional source of power on-board the vehicle.

### 7.1.2.3 Further assumptions

In order to estimate total power demand it is necessary to define a specific use case by making a series of assumptions about how a DWPT system may be deployed in an operational environment. The use case situation we have chosen to illustrate is listed below:

- A single lane of motorway is equipped with a WPT system (left lane)
- Only data from three lane motorways is used in order to maintain consistency with maximum traffic density
  - Data from MIDAS points on M6, M42, M69, M6 toll are used
- Maximum vehicle flows are the maximum number recorded within one hour of data
- Secondary coil to grid efficiency is 80%
- Power factor is 0.972
- All vehicles are prepared to travel at 55mph maximum speed when charging.

### 7.1.3 Method used for analysis of traffic flow data

Data from inductive motorway (MIDAS) loops (in one minute sets) for the entire data set is grouped into one hour "banks". The average and maximum values for each hour is determined and a 24 hour profile created.

When data is collected using MIDAS, the data is sorted into four bins based on vehicle length. The thresholds are 5.2m, 6.6m and 11.6m. Bin one is less than 5.2m and bin four is greater than 11.6m.

To calculate vehicle types, it is assumed that light vehicle counts are equal to the sum of length bins one, two and half of three. Heavy vehicle counts are equal to the sum of length bin four and half of bin three.

The values are taken from data collected on Monday 7<sup>th</sup> October 2013. The data is from a weekday and is likely to be during school term-time (traffic flow data for school holiday periods is noted to be lower than data taken during term-time). A weekday was chosen as there is a significant drop in HGV traffic at weekends. For simplification of analysis, a single day of data was chosen rather than a large selection of days.

The average data is taken from the MIDAS flow data for each motorway. Speed, vehicle counts and time are the primary collected. The data is summed up for each minute during the day. The flow data is the count of vehicles in each bin above. At this point the data are broken into light vehicle and HGV "banks". Vehicle per mile flow rate is estimated using the one minute flows and average speeds, assuming vehicles are equally spaced within the minute. The average is taken from the sum of each minute in each hour, which enables an hourly average flow rate to be calculated.

The maximum flow is simply the maximum number of vehicles recorded per minute at each MIDAS loop. The maximum on each motorway per hour is the value used in calculations.

This traffic data was incorporated into the power demand model using the assumptions stated previously in Section 7.1.2.3.

#### **7.1.4 Assessment of power requirements**

One of the largest sources of uncertainty in this analysis is the assumed penetration rates of equipped vehicles. There is no data on which the penetration can be estimated as there are no precedents for the adoption of such vehicle technology. Therefore, two scenarios were created that represent a medium level of take up and a high level of take up of the technology by vehicle users and operators. Furthermore, it also assumed that the deployment of DWPT systems would be targeting the users that could benefit most from the technology. As the provisional findings from the preliminary benefits to cost ratio analysis suggest that the benefit of the system is proportional to the total annual mileage driven, vehicles with the highest mileage could therefore benefit the most. As a result, an assumption is made that a higher proportion of high-mileage fleet vehicles (such as long haul trucks and heavy coaches) will be equipped with DWPT capability than cars and vans. Assumptions for DWPT capability penetration rates are summarised below:

- Scenario A (medium penetration)
  - Light vehicles: 30%
  - Heavy vehicles: 50%
- Scenario B (high penetration)
  - Light vehicles: 50%
  - Heavy vehicles: 75%.

The sections below describe the expected power demand for each scenario based on the assumptions and the method outlined in preceding sections.

7.1.4.1 Scenario A (medium penetration)

Figure 32 and Figure 33 below illustrate power demand profiles for layout 1 and layout 2.

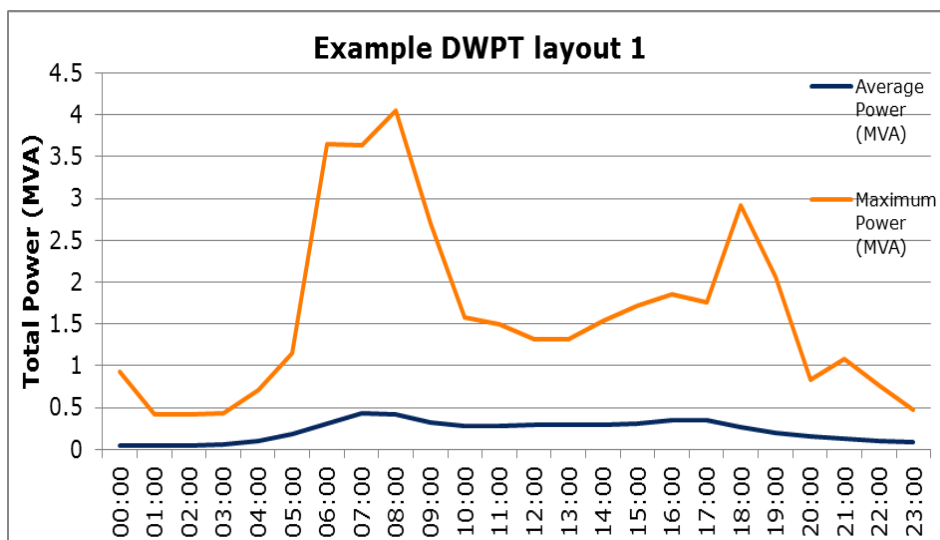


Figure 32: Power demand per mile of motorway for 30% light vehicle and 50% heavy vehicle penetration at 55 mph, DWPT system layout 1

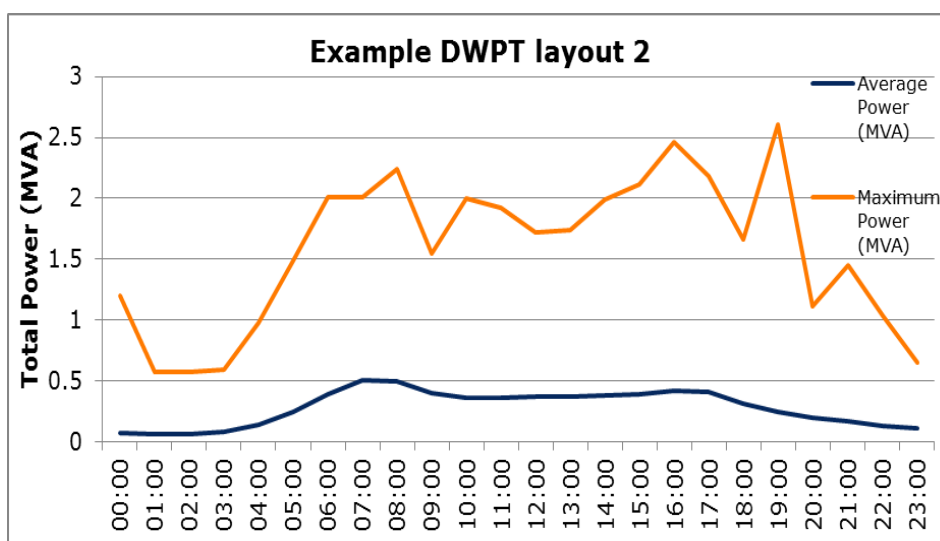


Figure 33: Power demand per mile of motorway for 30% light vehicle and 50% heavy vehicle penetration at 55 mph, DWPT system layout 2

The vehicle flow values are incorporated into the power demand model using the assumptions stated previously. The model uses the following factors to calculate the average and maximum power demands:

- Vehicle flows
  - Light vehicle
    - Average flow
    - Maximum flow



- HGV
  - Average flow
  - Maximum flow
- Number of charging segments per mile
- Power demand for each type of vehicle for each system at 55 mph
- The power factor (0.97)
- Number of lanes of motorway (this analysis only uses three lane sections, but only one is assumed to be equipped with DWPT).

Analysis of the expected demand profiles shows that the average power demand generally follows the same profile as road traffic, with an increase during the morning peak and then continued demand at a lower baseline with another increase towards the evening peak and then a drop towards night time. It should be noted that the average demand profile is very similar for both DWPT system layout examples, having similar peak values at around 0.5MVA and is constant through the day between 0.3 and 0.4MVA per mile.

However, the maximum power demand profiles are substantially different between the two system layout examples. In the case of system layout 1 (Figure 32), there is a very pronounced morning peak, reaching 4MVA per mile, and then a sharp drop to around 1.5MVA followed by a smaller evening peak of approximately 3MVA. This profile suggests that system layout 1 is sensitive to fluctuations in vehicle densities per mile section of the motorway. Due to the relatively high number of individual power transfer segments in this layout, up to 64 segments per mile, vehicle density becomes the dominant factor determining maximum power demand. Closer examination of the results shows that the highest utilisation of power transfer segments is 82% (equivalent to approximately 53 of the available power transfer segments being occupied during that hour). As the vehicle density reduces, so does the total maximum power demand.

System layout 2 generates a different maximum power demand profile, as seen in Figure 33. This is more uniform between the morning and evening traffic peaks, with the maximum power demand in the morning reaching just over 2MVA, continuing at around 2MVA for the rest of the day and increasing towards 2.5MVA in the evening peak before dropping at night. The maximum power demand is lower than for system layout 1. This is due to layout 2 having fewer (but longer) individual power transfer segments per mile of motorway, up to 36 segments. Therefore, the system reaches high levels of utilisation more quickly, and on numerous occasions reaches a point where more vehicles require power transfer than there are available segments. This is the limiting factor for system layout 2 where 100% utilisation is reached between the hours of 7am and 10am. So, although there are more vehicles present on that stretch of the motorway able to use the system, they are not able to draw power due to lack of available power transfer segments. This is an important limitation to bear in mind because during later stage of adoption when DWPT vehicle penetration is high, inability to guarantee power to vehicles using DWPT because of close proximity of other vehicles may have a significant negative impact on battery electric vehicle range relying on the DWPT system.

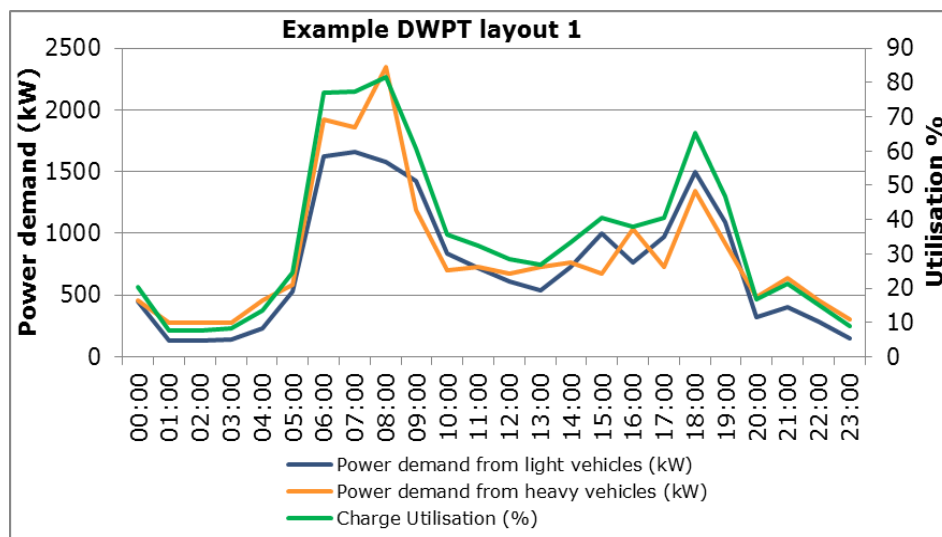
The difference between the two example layouts only manifests itself when considering maximum power demand because there are instances under these conditions when utilisation exceeds 100%. When looking at average power demand, the profiles are very

similar because utilisation is far below 100% on average, meaning that it does not become a limiting factor for either layout and so the profiles are similar to that of average vehicle flow rates. System layout 2 has a slightly higher average power demand due to the slightly higher power transfer capability per segment.

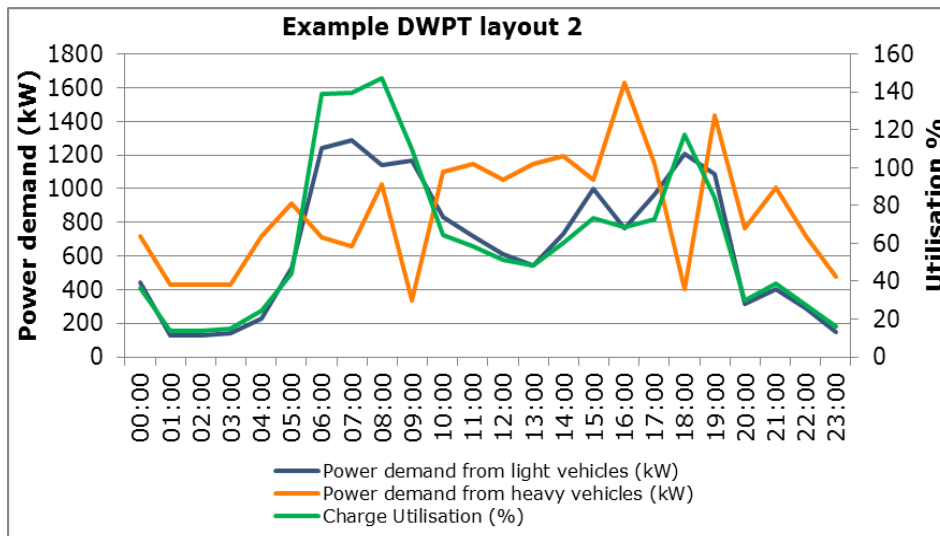
These values depend on all vehicles using the DWPT lane travelling at 55mph. This speed has been selected as a limiting factor in that, above this speed, overcoming air resistance becomes the dominant power draw. This is also the approximate speed limit for HGVs on the UK road network. In assuming this value for HGVs, and that there is a single lane equipped with DWPT technology, it becomes the case that light vehicles must also travel at this speed if they are to using this lane to charge.

### Comparing utilisation and vehicle types

Another parameter to which both system layout power demand profiles are sensitive is the relative proportion of heavy vehicles to light vehicles using the systems. Fluctuations in power demand can arise not only due to the total number of vehicles, but also due to the proportion of heavy vehicles present, as heavy vehicles draw more power from the systems. It is therefore possible to have a situation where the overall utilisation of the system is reduced but the maximum power demand increases due to a higher proportion of heavy vehicles. This is illustrated in Figure 34 and Figure 35 below.



**Figure 34: Comparison of light vehicle and vehicle power demand with total utilisation for Scenario A-system layout 1**



**Figure 35: Comparison of light vehicle and vehicle power demand with total utilisation for Scenario A-system layout 2**

Figure 34 and Figure 35 show that, although the profile of total system charge utilisation remains the same for each system layout (as this depends on vehicle flow); utilisation in layout 2 regularly exceeds 100%. For the purposes of modelling total power demand in such situations, as shown in Figure 32 and Figure 33, power demand was limited to the maximum possible during 100% utilisation, allocated according to the respective share of light and heavy vehicles.

In the case of layout 1 (Figure 34), maximum power demand from light and heavy vehicles is very similar, with light vehicles representing the majority of the demand during the morning peak. However, in the case of layout 2 (Figure 35), the power demand profile for heavy vehicles is substantially different from that of light vehicles as it is constantly modulated by the limit on total available utilisation. Furthermore, as the power demand for individual heavy vehicles in layout 2 is more than three times greater than that for individual light vehicles, there are large variations in power demand as the system attempts to allocate available power transfer modules to vehicles once utilisation has exceeded 100%.

#### *Summary of scenario A*

Assessment of Scenario A has shown that under average traffic conditions, both example system layouts perform similarly and produce a similar average power demand profile. However, under heavy traffic conditions, system layout 1 was able to cope with the overall demand, but results in high power demand spikes during peak times. System layout 2 reached the maximum possible utilisation and was not able to provide sufficient power for all vehicles on that one mile section. However, it should be noted that layout 2 provides higher power for heavy vehicles than layout 1. During times of high demand, prioritising use of the system for heavy vehicles may be appropriate. Doing so would also result in higher maximum power demand.

It should also be noted that during high demand it is more likely that unequipped vehicles will be present within charging segments. Due to safety limitations for human and vehicle exposure of magnetic fields, it is likely that segments with other vehicles present on them would not be activated and would not transfer power. System layout 2 is particularly susceptible to this, due to the length of each charging segment being 40m.

Although the length of a charging segment in layout 1 design is approximately 25m, each coil activated at any given time is only 8m long. It is therefore unlikely that the system functionality would be affected until vehicle headway is reduced to within 9m.

Variations between maximum and average traffic flows used for this assessment were derived from MIDAS loop data from multiple locations on the network. It is therefore important to understand how representative these values are of different motorways (see section 7.1.5).

#### 7.1.4.2 Scenario B (high penetration)

This scenario assumes 50% light vehicle and 75% HGV take-up. Figure 36 and Figure 37 below illustrate power demand profiles for layout 1 and layout 2.

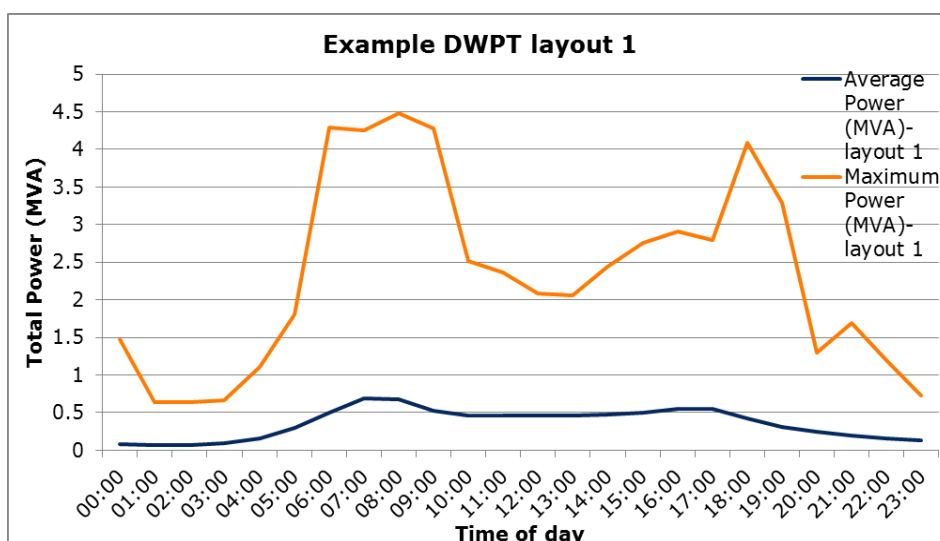


Figure 36: Power demand per mile of motorway for 50% light vehicle and 75% heavy vehicle penetration at 55mph, DWPT system layout 1

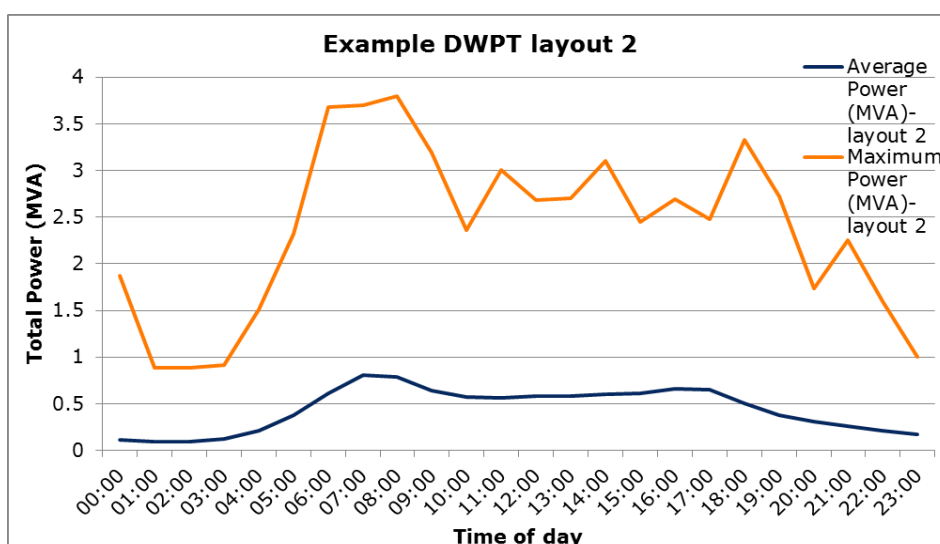


Figure 37: Power demand per mile of motorway for 50% light vehicle and 75% heavy vehicle penetration at 55mph, DWPT system layout 2

Analysis of the expected demand profiles shows that average power demand generally follows the same profile as road traffic; there is an increase during the morning peak and then continued demand at a lower baseline with another increase towards the evening

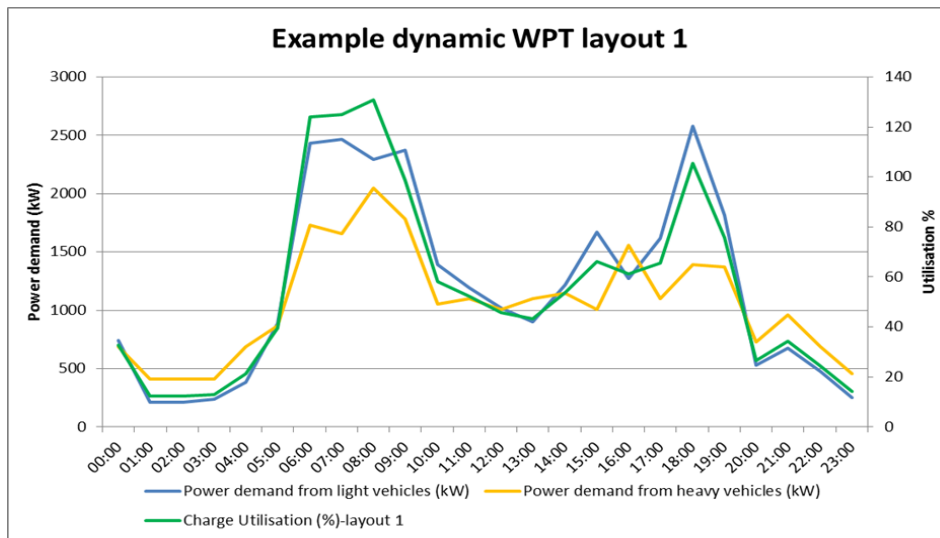
peak and then a drop towards night time. It should be noted that the average demand profile is very similar for both DWPT system layout examples, having similar peak values at around 0.7MVA and 0.8MVA respectively for layout 1 and 2. Through the day, layout 1 remains at approximately 0.5MVA; layout 2 is approximately 0.6MVA per mile.

The maximum power demand profiles are substantially different between the two system layout examples. In the case of layout 1 (Figure 36), there is a pronounced peak around the morning rush hour, reaching just over 4MVA per mile, and then a sharp drop to around 2MVA followed by a smaller evening peak of approximately 3.3MVA. As in scenario A, this profile suggests that system layout 1 is sensitive to fluctuations in vehicle densities per mile section of the motorway. Due to the relatively high number of individual power transfer segments in this layout, up to 64 segments per mile, vehicle density becomes the dominant factor for maximum power demand. Closer examination of the results shows that the highest utilisation for power transfer segments was 131%. (This is equivalent to approximately 84 power transfer segments being occupied during that hour, which is greater than the total number available per mile.) As the vehicle density reduces, the total maximum power demand reduces accordingly.

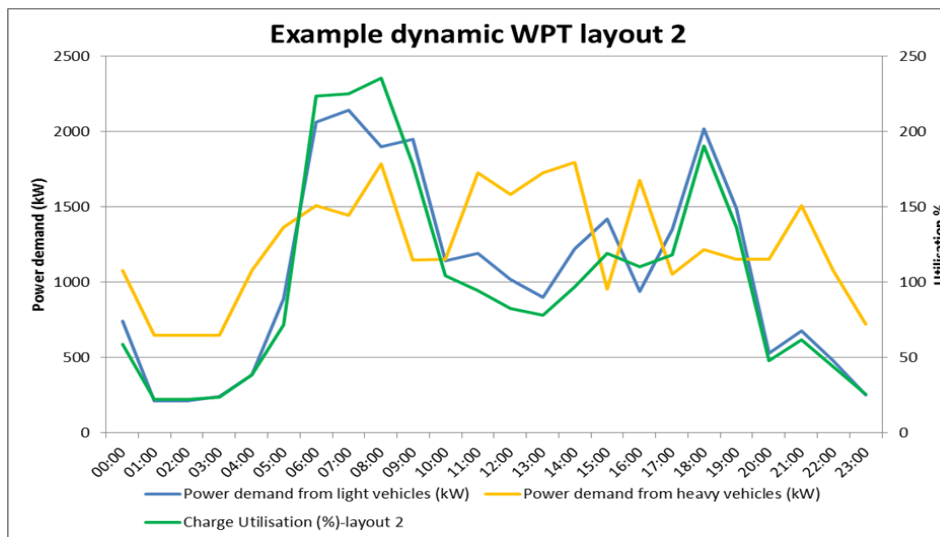
System layout 2 generates a different maximum power demand profile, as seen in Figure 37. This is more uniform between the morning and evening traffic peaks, but with intermittent peaks of approximately similar demand. The maximum power demand in the morning reaches just over 3.5MVA, and then varies between 1.5MVA and 3MVA throughout rest of the day. The evening peak is less than the intervening daytime peak power demand at 2.7MVA before dropping at night. The maximum power demand is lower than for system layout 1, but only during the morning and evening peak traffic flows. This is due to DWPT system layout 2 having fewer (but longer) individual power transfer segments per mile of motorway, up to 36 segments. Therefore, the system reaches high levels of utilisation more quickly. On numerous occasions it reaches a point where more vehicles require power transfer than there are available segments. This is the limiting factor for system layout 2, where 100% utilisation is reached between the hours of 7am and 10am. Thus although there are more vehicles capable of using the system present on that stretch of the motorway, they were not able to draw power due to lack of available power transfer segments.

#### *Comparing utilisation and vehicle types*

The other parameter to which both system layout power demand profiles are sensitive is the relative proportion of heavy vehicles and light vehicles using the systems. Fluctuations in power demand can arise not only due to the total number of vehicles but also due to the proportion of heavy vehicles present, as heavy vehicles draw more power from the systems. It is therefore possible to have a situation where the overall utilisation of the system is reduced but the maximum power demand is increased due to a higher proportion of heavy vehicles. This is illustrated in Figure 38 and Figure 39 below.



**Figure 38: Comparison of light vehicle and vehicle power demand with total utilisation for Scenario B-WPT Layout 1**



**Figure 39: Comparison of light vehicle and vehicle power demand with total utilisation for Scenario B-WPT Layout 2**

Figure 38 and Figure 39 show that the profile of total system utilisation remains similar for each system layout, as this depends on the vehicle flow. Utilisation in layout 1 exceeds 100% during the morning and evening peak hours (06:00-08:00, 18:00-19:00). System layout 2 also exceeds 100% utilisation during the morning and evening peak, but for a greater length of time (06:00-10:00, 15:00-19:00). For the purposes of modelling total power, the model was limited to the maximum possible power during 100% utilisation, balanced to the respective proportions of light and heavy vehicles. In the case of system layout 1 (Figure 38), maximum power demand from light and heavy vehicles is very similar, except during peak morning and evening traffic flows, where light vehicle traffic presents a higher demand. Heavy vehicles represent a majority of the demand overnight. In the case of system layout 2 (Figure 39), the power demand profile for heavy vehicles is substantially different from that of light vehicles as it is constantly modulated by the limit on total available utilisation. The demand profile shows light vehicles dominating during the morning and evening peak, but HGVs dominating during the inter-peak in the middle of the day and overnight. Furthermore, as the power

demand for individual heavy vehicles in system layout 2 is more than three times greater than that for individual light vehicles, there are large variations in power demand as the system attempts to allocate available power transfer modules to vehicles once utilisation has exceeded 100%.

#### *Summary of scenario B*

Assessment of Scenario B has shown that under average traffic conditions, both example system layouts perform similarly and produce a similar average power demand profile.

System layout 1 requires slightly less total power than system layout 2. System layout 1 shows high power demand spikes during peak times. This is also shown in the case of system layout 2, but these demand spikes last for longer. Using the percentage of charge utilisation figure, it can be seen that system layout 1 exceeds 100% for only four hours of the day. In the case of system layout 2 the utilisation exceeds 100% for ten hours of the day, with a peak utilisation of more than 230%. The equivalent maximum power demand utilisation spike for system layout 1 is 130%.

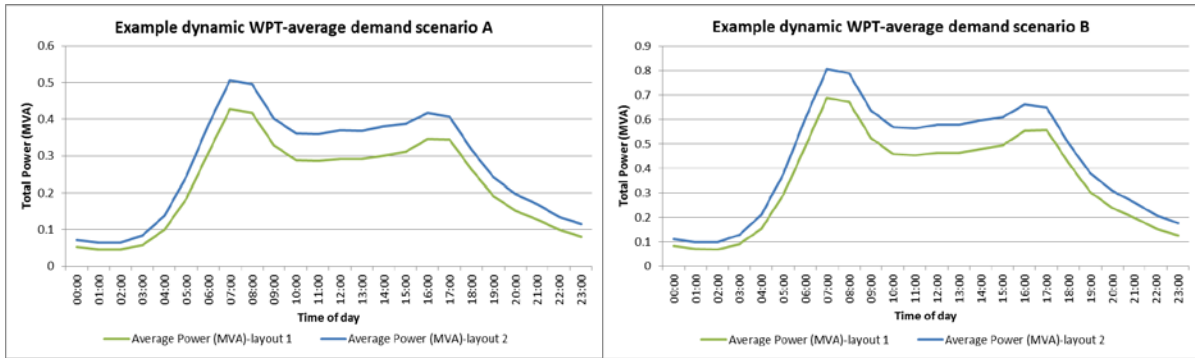
#### *7.1.4.3 Comparison of scenarios*

Charging demand in these scenarios tends to be specific to the type of vehicle at certain times of day. During the morning and evening peak traffic times, the demand comes primarily from light vehicles. At other times, the demand is mostly from HGVs.

In scenario A for system layout 1 (Figure 32) the power demand levels were similar to traffic levels, but in the high take-up scenario B, they are much less alike in peak traffic times. This is most notable during the evening rush hour period, where HGV demand reduces significantly for two hours. For system layout 2 there is a similar reduction in HGV demand at peak traffic times, but there is more significant HGV demand at other times, notably during the middle of the day, which is shown to be the time of highest HGV power demand.

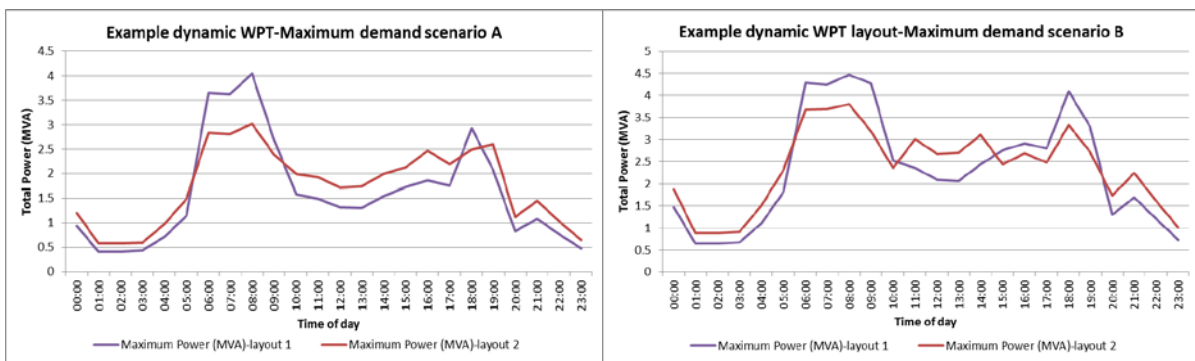
In scenario B it is less likely that unequipped vehicles will be present in the charging segment as the take-up levels are higher than in scenario A. System layout 2 is more susceptible to reduction in charging capacity as the segments are greater in length than system layout 1, which means there are less chargers per mile.

The power demand profiles seen above are linked to the traffic flow levels, hence their similar outputs. In scenario A the average power demand reaches 0.42MVA for system 1 and 0.5MVA for system 2, whereas in scenario B system 1 is 0.69MVA and system 2 is 0.8MVA (Figure 40). The average power demand peak consistently occurs between 07:00 and 08:00, with the next highest demand occurring consistently from 08:00-09:00.



**Figure 40: Average power demand for each layout in scenarios A and B**

As shown in Figure 41, the maximum power demand in scenario A for system 1 is 4.05MVA, between 08:00 and 09:00. For system 2 the maximum is 3.0MVA between 08:00 and 09:00. For scenario B the maximum for demand system 1 is 4.5MVA between 08:00 and 09:00. For system 2 the maximum is 3.8MVA between 08:00 and 09:00. The maximum power demand occurs less consistently than the average power demand. This behaviour is largely due to HGV traffic flow variability, due to the higher power demand of HGVs.

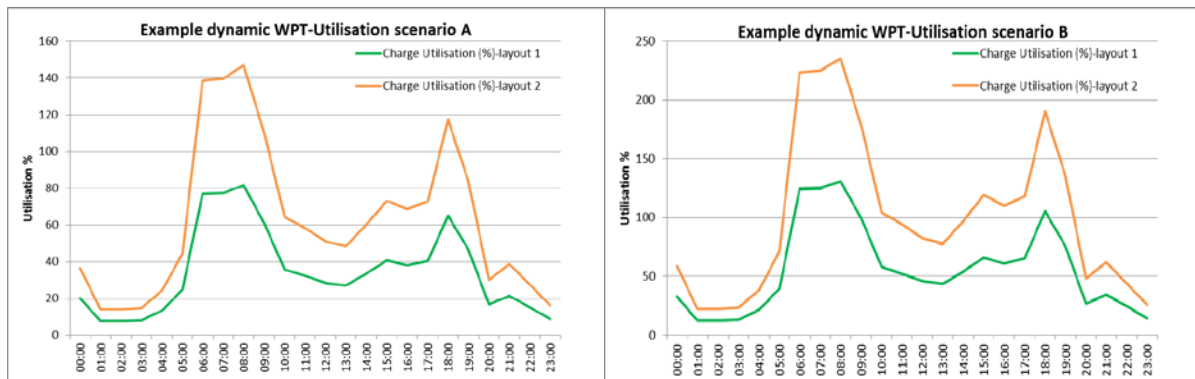


**Figure 41: Maximum power demand for each layout in scenarios A and B**

Figure 42 shows utilisation for each scenario. In the case of system layout 1 in scenario A, the maximum utilisation reaches a peak of 82% in the period of 08:00-09:00. In the case of system layout 2 the peak utilisation reaches 147% during this time. Utilisation exceeds 100% for five hours of the day, 06:00-10:00 and 18:00-19:00.

In the case of scenario B system 1, maximum utilisation reaches 131% between 08:00 and 09:00. The system is above 100% utilisation for four hours of the day, 06:00-09:00 and 18:00-19:00. In the case of system layout 2, the peak utilisation is 235% between 08:00 and 09:00. The system exceeds 100% utilisation for ten hours of the day, 06:00-11:00 and 15:00-20:00.





**Figure 42: Charge utilisation for each system in scenarios A and B**

### 7.1.5 Investigation of variations in vehicle flows

Earlier in the chapter, assumptions for traffic flow were outlined (see Section 7.1.3). These data were used as an input into the power demand model and are key to the overall power requirements calculations. A more in-depth analysis of vehicle flows used was carried by the project team in order to fully understand the sources of the variations. Peak power demand values calculated in the preceding sections were based on the total number of vehicles per mile of motorway. These numbers were calculated based on an average of several different motorways, which give a broad selection of traffic flows. The peak demand in the busiest locations is likely to be much higher than on quieter sections of motorway. Furthermore, HGV traffic shows more variability of flow depending upon time of day and motorway. Since HGVs are largely responsible for maximum power demand spikes, each motorway should be treated individually when considering installation of DWPT.

### 7.1.6 Conclusions on power demand

Work presented in this section shows that DWPT systems would be susceptible to high peaks and variations in power demand which will be dependent on traffic conditions at the time. Furthermore, the exact layout of the DWPT system and its maximum power supply capability will also have a substantial impact.

Analysis undertaken during this task focused on two different example layouts for DWPT systems as described in Section 7.1.2.

The analysis showed that under different traffic conditions and an assumed scenario for vehicle and technology penetration, average demand from DWPT systems can be as high as 400kVA to 500kVA (0.4MVA to 0.5MVA) per mile for system layouts 1 and 2 respectively. Under these conditions, when utilisation of the system does not approach the maximum value, the expected demand is similar across both layouts. The number and length of segments under these conditions does not have an impact on total power demand as the number of power transfer segments that can be occupied is limited by the number of vehicles on the road. Demand from system layout 2 is higher than from layout 1 due to the higher power transfer capability for heavy duty vehicles.

However, during times of maximum demand, maximum power requirements per mile can vary between approximately 4MVA and 4.5MVA throughout the day, with the highest values occurring during the morning and evening traffic peaks. These are considerably higher than during average demand because the number of vehicles is higher, so more power transfer segments can be occupied at any given time. Because the total power

demand depends on the number of vehicles using the system, the demand profiles follows a similar profile to vehicle flows. However, because different vehicle types are assumed to have different power demand from the system, systems can vary in terms of maximum power transfer capability. Furthermore, the number of power transfer segments per mile varies depending on the system layout, so very different power demand profiles are seen for high traffic flow cases between system layouts 1 and 2.

The analysis also highlighted that the demand from heavy duty vehicles tends to dominate the variations in overall power demand. However, power demand in these scenarios tends to be specific to different types of vehicle at certain times of day. During the morning and evening traffic peaks, demand comes primarily from light vehicles as there is a sharp increase in numbers of these vehicles and the proportion that they make up on the network. At other times, demand is mostly from HGVs as these continue to operate throughout the day.

Furthermore, system layouts with longer DWPT segments can reach peak utilisation before maximum road capacity is reached. In the case of system layout 1, utilisation only rarely exceeds 100% even under maximum demand scenarios, whereas with system layout 2, utilisation is either close to 100% capacity or is exceeded throughout the day. For system layout 1 in scenario A (medium penetration, see Section 7.1.4), the maximum utilisation reaches a peak of 82% during the period 08:00-09:00. For system layout 2 the peak utilisation reaches 147% during this time. There is utilisation of more than 100% for five hours of the day, 06:00-10:00 and 18:00-19:00.

In scenario B (high penetration, see 7.1.4) for system 1 the maximum utilisation reaches 131%, between 08:00 and 09:00. The system is above 100% utilisation for four hours of the day, 06:00-09:00 and 18:00-19:00. For system layout 2, the peak utilisation reaches 235% between 08:00 and 09:00. The system is above 100% utilisation for ten hours of the day, 06:00-11:00 and 15:00-20:00.

The take up assumptions used were based on the following:

Initial % WPT HGV	5%
Initial % WPT light vehicle	10%
Annual EV take-up rate HGV	5%
Annual EV take-up rate LV	5%
Maximum penetration allowed for HGV	75%
Maximum penetration allowed for LV	30%

Using these figures, it can be estimated that it would take approximately 5 years to reach light vehicle penetration of 30% and 9 years to reach 50% penetration, assuming a starting point of 10% penetration. Note that it is not anticipated that light vehicle DWPT penetration will exceed 30% in the case of a single lane of motorway being equipped, but for the purpose of maximum power transfer, this scenario was considered as it is theoretically possible. Similarly for HGVs, reaching a penetration of 50% and 75% under the baseline assumption would take 10 years and 15 years respectively. It should be noted that although for the purpose of the cost benefit and payback calculations, a conservative approach was taken to DWPT vehicle penetration, whereas for the purpose of understanding power demand, a more optimistic approach was

adopted in order to ensure the worst case scenario can be represented for power demand, in Scenario B.

Based on information gathered so far, it is apparent that DWPT systems are being designed to only transfer power to a single vehicle per one primary coil segment in order to mitigate the risk of exposure of other unprotected vehicles or road users to magnetic fields. Some of the systems investigated do not have an active control for this and rely on using shorter primary segments to mitigate the risk of multiple vehicles occupying the same segment. However, it could still be possible for multiple vehicles to occupy the same primary segment during particularly dense traffic conditions and low speeds, where vehicle headway is reduced to below 10m. This will be exacerbated in the proposed platooning technology for future HGVs. Other systems have a functionality based on either on-board or roadside radar systems that will switch off power transfer if more than one vehicle is detected on the same primary segment. This will result in the system being switched off and not providing any power transfer to the equipped vehicle. The risk of this happening increases as the traffic builds up and vehicle headways reduce. Therefore, some vehicles will likely be unable to use the DWPT system or, the system may not function at all due to a safety override preventing the system from energising coils with multiple vehicles present.

This suggests that systems with shorter segments (similar to the length of the vehicle, i.e. 10m or less) will be better suited for meeting higher anticipated levels of demand and provide more flexibility around when the systems can be used, but is also likely to lead to higher power demand fluctuations which will likely result in requiring higher specifications for power supply equipment and higher costs for making the electric connection to mitigate any undesired impacts on the grid. Systems with longer primary coil segments provide more predictability of demand and lower overall power requirements, but may not work effectively when traffic levels are high if currently proposed safety features are implemented.

## **7.2 Commercial drivers and detracting factors**

In this feasibility study, two types of commercial organisation are considered, the DWPT service provider and the EV fleet operator. In this section the main focus is on EV fleet operators when discussing commercial opportunities and possible detracting factors for transmitting electricity from EVs back into business premises.

The commercial benefits, which have the potential to increase revenue, are discussed in terms of their applicability, advantages and disadvantages to the types of commercial organisations considered, namely businesses owning and operating fleets of EVs. Strictly speaking, such opportunities are not exclusive to WPT or DWPT enabled vehicles, but are applicable to all users of EV fleets. Therefore, these findings are not only applicable to DWPT enabled vehicle fleets but also to all plug-in vehicle fleets. However, where use of DWPT is identified to have a possible benefit, this is stated.

### **7.2.1 Logistics provider revenue**

Often delivery services, such as white good deliveries, grocery drops to customers of major supermarkets or business courier services, have allotted time slots or deadlines where deliveries can take place. These delivery slots can vary from four hours to one hour windows, in which the goods must be delivered or a penalty is incurred. Usually, this involves the loss of the delivery fee for the courier and delivery service or loss of

sale for white goods. There is also a reputational risk associated with missing a promised delivery schedule.

Clearly, every business is different, so a range of delivery revenues, size and weight of goods and delivery time constraints apply. However, there are general trends for certain types of delivery service.

#### *7.2.1.1 Domestic grocery deliveries*

Across the four major supermarkets, each delivers between 08:00 and 23:00, six days a week and 08:00 to 22:00 on Saturdays. Delivery charges vary from £1 to £7 and are highest at times when domestic customers are in their homes. 08:00 to 11:00 Saturdays and Sundays incur the highest charges, at ~£7, with late week nights and week days incurring the lowest charges of ~£1.

If the grocery fleet converted from ICEVs to EVs, then charging at off peak times or overnight would incur the least delivery and custom revenue loss. Having access to DWPT could improve the number of EVs available to be deployed at peak delivery times without using either battery swaps or excess EV fleet capacity to meet demand.

#### *7.2.1.2 Business courier services*

Business courier services offer time critical delivery products ranging from Next Day Before (NDB) 10:00 and NDB 12:00, which are premium services. Lower cost services are Next Day (ND), Two Day (TD) and Weekend delivery products, which offer more flexibility and time to the EV fleet operator.

By offering time constrained premium services, the most profitable delivery times yield an increase of between 83% and 127% delivery charge revenue for NDB 10:00 compared with TD delivery. Charging EVs or suffering range constraints during these times could impact on the profitability of such a business. Having access to DWPT during these peak times and charging off peak would be an advantage. Due to the varied nature of delivery business models, what the DWPT unit rate should be in order to encourage use by delivery companies is beyond the scope of this feasibility study. However, estimating this unit rate for charging or dynamic power transfer could be investigated in future analysis or feasibility studies.

#### **7.2.2 Energy prices/tariffs**

To exploit many of the potential primary revenue drivers, a half hourly (HH) meter is a requirement. An EV fleet operator is likely to have a service import capacity agreement with their DNO in excess of 100kW, since a single Medium Goods Electric Vehicle (MGEV) can draw at least ~43kVA at 63A on a 3 phase supply, with an inductive power factor of 0.97, while charging statically at the depot or base. Any import capacity agreement in excess of 100kW requires a HH meter, together with an appointed HH Meter Operator (MOP) and HH Data Collector. A MOP is responsible for installing and maintaining metering and communications equipment, and passes the technical meter details to the Data Collector to enable collection of consumption data. A Data Collector is responsible for collecting HH consumption data from the meter. This data is then validated and passed to the supplier for invoicing.

Most energy suppliers, for large commercial customers, will not display tariff rates openly. Energy suppliers tailor the various utility charges, based on location and

consumption/export profiles. Therefore, without knowing the detailed operations of EV fleet operators, it is only possible to provide an illustrative example for a selected business location.

For this study, a typical energy bill has been created using time bands and illustrative energy tariffs as shown in Table 16. Table 18 shows typical prices of an electricity bill, broken down into its constituent parts. Explanations of the various contents of the bill are shown in Table 17. Drawing energy at low power levels, for longer periods, at off peak times, can reduce the energy tariff costs considerably. Exporting electricity can also potentially lead to revenues by importing at off peak times and discharging the batteries at peak times. This process is known as energy arbitrage. For larger supplies, an energy supplier will most often offer a “seasonal time of day” (STOD) tariff which breaks down the energy costs into a basis which more closely reflects the variations in wholesale energy prices.

**Table 16: Seasonal Time of Day (STOD) bands and illustrative energy prices based on 2012 values**

STOD time periods	From	To	Day	Months	Illustrative energy Prices p/kWh
Night Units	0030	0730	Monday to Sunday	January to December	6.87
Other Units	2000	0030	Monday to Friday	November to February	8.17
Other Units	2000	0030	Monday to Friday	March to October	8.17
Other Units	0730	0030	Saturday & Sunday	November to February	8.17
Other Units	0730	0030	Saturday & Sunday	March to October	8.17
Nov & Feb Peak Units	1600	1900	Monday to Friday	November & February	17.85
Dec & Jan Peak Units	1600	1900	Monday to Friday	December & January	19.38
Nov & Feb Winter WD Units	0730	1600	Monday to Friday	November & February	9.55
Nov & Feb Winter WD Units	1900	2000	Monday to Friday	November & February	9.55
Dec & Jan Winter WD Units	0730	1600	Monday to Friday	December & January	10.09
Dec & Jan Winter WD Units	1900	2000	Monday to Friday	December & January	10.09
Summer WD Units	0730	2000	Monday to Friday	March to October	9.97

**Table 17: Half Hourly supplier bill item breakdown and description**

Bill Item	Description
<b>Electricity Consumption</b>	The number of kWh electricity units consumed within the billing period. This value is multiplied by the Line Loss Factor (LLF), which accounts for the energy lost through the distribution system before it reaches the customer.
<b>Transmission Use of System Charges</b>	Based on location within the UK, with two charges for peak power consumption and generation are calculated from HH meter readings. Appears as cost per kW on the HH bill.
<b>Distribution Use of System Charges</b>	<p>This is the charge added to the bill by the Distribution Network Operator (DNO). It comprises:</p> <ul style="list-style-type: none"> <li>• Capacity Availability Daily Charge – A fixed daily charge relating to the site Maximum Import Capacity (MIC); the agreed maximum power consumption between the DNO and the consumer. Billed in £/kVA.</li> <li>• Consumption Charge – A unit charge based on electricity used. This reflects the consumer’s use of the distribution system at various voltage levels. The charges varied based on the time of day and split into three categories: Red (highest charge) 16:00 – 19:00 Mon – Fri; Amber – 07:30 – 16:00 Mon – Fri and Green (Lowest Charge) at all other times. Billed in £/kWh.</li> <li>• Excess Reconciliation Charge – Charges from exceeding MIC billed in £/kVA.</li> <li>• Fixed Charge – A fixed daily charge independent of energy use covering administration and consumer account costs. Billed as £/day.</li> <li>• Reactive Power Charge – Only applicable if the customer exceeds a predefined limit, set by the DNO. The charges are imposed to account for losses due to wasteful reactive power flows due to poor consumption power factors (p.f.).<sup>5</sup></li> </ul>
<b>The Climate Change Levy</b>	A government levy to encourage more efficient energy usage. A per unit charge not based on time of use. Exemption can be acquired if business buys renewable energy or implements energy saving measures. Billed as £/kWh.
<b>Value Added Tax (VAT)</b>	An additional taxation on the value of sale.
<b>MOP Fee</b>	Cost of installing, setting up and collecting data from a HH meter.

<sup>5</sup> The power factor represents the ratio of real and apparent power.

**Table 18: Illustrative energy tariffs for a small to medium EV Fleet operator**

Item	Cost
<b>Unit Rate</b>	12.5 p/kWh 07:30am – 12:30 am 8.5 p/kWh remainder
<b>Transmission Use of System</b>	33.8 £/kW consumption and 3.54 £/kW generation
<b>Distribution Use of System Charges</b>	<ul style="list-style-type: none"> <li>• Capacity Availability Daily Charge – 2.31 (LV) – 3.97 (HV) p/kVA/day</li> <li>• Consumption Charges – <ul style="list-style-type: none"> <li>○ (HV) Red ~6.69 p/kWh, Amber – ~0.13 p/kWh, Green – ~0.004 p/kWh;</li> <li>○ (LV) Red ~9.1 – 10.4 p/kWh, Amber – ~0.30 – 0.42 p/kWh, Green – ~0.01 – 0.24 p/kWh;</li> </ul> </li> <li>• Generation Charges – <ul style="list-style-type: none"> <li>○ (HV) Red ~-4.05 p/kWh, Amber – ~-0.22 p/kWh, Green – ~-0.011 p/kWh;</li> <li>○ (LV) Red ~-5.48 – -6.24 p/kWh, Amber – ~-0.44 – 0.22 p/kWh, Green – ~-0.03 – 0.01 p/kWh;</li> </ul> </li> <li>• Excess Reconciliation Charge – 2.31(LV) – 3.97 (HV) p/kWh/day;</li> <li>• Fixed Charge – 6.24 (LV) – 63.57(HV) p/MPAN/day</li> <li>• Excess Reactive Power Charge – Only applicable to 0.95 p.f. loads and below. 0.358 (LV) – 0.196 (HV) p/kVArh</li> </ul>
<b>The Climate Change Levy</b>	0.541p/kWh
<b>VAT</b>	20%
<b>MOP Fee</b>	£600/year to 350/year based on 1 and 5 year plans respectively.

A DWPT service provider is likely to connect at a higher voltage level than the EV fleet operator and have a much greater power requirement. Therefore, for a connection on a WPD network, the energy tariffs in Table 18 will not apply. Where connections are at a higher voltage, the DNO calculates a site specific use of system charge, taking into account the actual EHV assets used to deliver the service. It is therefore only possible to ascertain a likely Distribution Use of System (DUoS) tariff by contacting the DNO directly. However, looking at a user with a similar usage profile, it can be seen that the following rates apply:

- Fixed Charge – 48.10 – 76.30 £/day
- Import Capacity Charge – 1.76 – 8.51 p/kVA/day
- Import Exceeded Capacity Rate – 1.76 – 8.51 p/kVA/day.

There are no 'time of use' DUoS charges as for Extremely High Voltage (EHV) customers except for 'super red band', which is between the hours of 16:00 and 19:00 Monday to Friday, November to February. A super red band charge is not always applied, but ranges from 0.29 to 1.4p/kWh for some sites.

#### *7.2.2.1 TRIAD avoidance*

In the United Kingdom, the means by which industrial and commercial electricity consumers pay for the electricity Transmission System (TS) is partly met by the Triad charging system, which also serves the function of a peak load management mechanism. The cost of owning and operating the TS is linked to its capacity to satisfy peak demand and this cost is high where local generation is insufficient to meet demand (as it is the case of the South East area). Therefore, the Triad charging system is designed to penalise consumption during periods of high network demand especially in high demand areas with insufficient generation.

Electricity Suppliers and licensed Generators all pay Transmission Network Use of System (TNUoS) charges to National Grid (NG), of which Triad charges are a part. An EV fleet operator and DWPT service provider will pay Triad charges as part of their bill; these are passed on by their supplier as part of the TNUoS charges, where Electricity Suppliers pay for the consumption on behalf of their commercial and industrial customers.

The Triad charge is retrospective, in that the periods which are considered to be peak demand are calculated after the Triad season is over; this runs from the beginning of November to the end of February. The calculation involves reading Half Hourly meters of all industrial and commercial customers and determining the three maximum demand HH periods. These periods must be separated by at least 10 days.

Since the DWPT service provider cannot shift their consumption patterns outside of the likely peak time, due to demand stemming from the timing of peak traffic flows, it is unlikely they will benefit from Triad avoidance, unless they employ some sort of EES and/or a charging tariff incentive. This makes Triad avoidance more suitable to the EV fleet operator as a benefit.

The potential saving to the EV fleet operator can be measured in £/kW of demand reduction during the likely Triad periods. To calculate the Triad charge, the average power consumption over the three Triad periods is calculated. This average Triad period peak demand is multiplied by the Triad charge for the regional zone. Table 19 shows that the Triad charge is highest in the south east, where demand is greatest.



**Table 19: 2013 - 2014 Triad season zonal charges**

Network Zone	Triad charge (£/kW)
<b>Northern Scotland</b>	£5.87
<b>Southern Scotland</b>	£11.22
<b>Northern</b>	£14.52
<b>North West</b>	£18.43
<b>Yorkshire</b>	£18.34
<b>Merseyside and North Wales</b>	£18.89
<b>East Midlands</b>	£20.93
<b>Midlands</b>	£22.69
<b>Eastern</b>	£21.84
<b>South Wales</b>	£22.52
<b>South East</b>	£24.63
<b>London</b>	£26.76
<b>Southern</b>	£25.49
<b>South Western</b>	£26.06

#### 7.2.2.2 *Commercial opportunities*

Because the cost of owning and operating the GB TS is partly recovered in the three Triad periods, an EV fleet operator can save and earn from the Triad system. Battery installations that avoid charging during Triad periods, whether by reducing charging or by discharging, save money for their Electricity Suppliers.

A battery installation wishing to exploit this opportunity requires:

- Flexibility in charging or discharging
- An appropriate tariff – For charging, the Triad charges must be explicit, not hidden in the unit rates. When discharging, a share of the Triad benefit must be negotiated with the Supplier.
- Triad warnings – Because Triad periods are not known in advance, they must be predicted from demand and weather forecasts, and previous experience.

Most suppliers and many energy bureaux provide Triad warning services. These service providers would notify the EV fleet operator when they are consuming in a likely Triad period. The savings from Triad avoidance could range from £5.85 to £26.06 for each kW of load reduction, during peak times, annually. These times are most likely to be between 16:30 and 18:00 Monday – Thursday, November to February. In addition, the savings could increase up to ~±10% if Line Adjustment Factors (LAF) are used.

### 7.2.2.3 *Demand side response services*

Demand Side Response (DSR) is a customer (energy consumer) focused set of measures that deals with Dynamic Load Management. The set of measures usually requires a change in consumer behaviour. It involves changes to Business as Usual energy consumption patterns using: interruptible loads, scheduled loads, standby generation and fuel substitution.

Energy consumption patterns can be changed in terms of quantity, energy type and time of use. DSR is context specific in that in every scenario to which it is applied, the following questions must be answered:

- What is the problem to be solved?
- Who is responsible for the problem?
- What is the cause of the problem?
- At what scale does the issue apply, i.e. local or national?

Organisations that are responsible for problems that DSR can solve are usually NG, DNOs, Energy Suppliers and Commercial Aggregation Service Providers (CASPs).

NG is ultimately responsible for balancing the electrical supply and demand, so DSR poses an alternative to flexible and reserve generation. DSR could be attractive to NG because DSR can be national in scale, with provision currently being met by large industrial users.

DNOs are responsible for maintaining security and quality of supply on their network and must design their networks accordingly as part of their network licence. DSR can be used to solve local network issues at HV or the LV level, however, the response needs to be tailored for each location where issues occur. Currently, DSR is in early stages of development with DNOs, occurring within Office of Gas and Electricity Markets (Ofgem) funded innovation projects such the Low Carbon Networks Fund (LCNF). During these types of projects, industrial, commercial and domestic customers have participated in DSR schemes.

Energy suppliers are responsible for balancing the energy market financially i.e. electricity traded should balance every trading period (half-hour). They achieve this by varying the price of electrical energy throughout the day. This includes discouraging use at peak times by imposing charges. Current supplier DSR measures include Time of Use (ToU) tariffs.

CASPs are facilitators of DSR as opposed to a DSR service buyer. The DSR service CASPs supply involves providing a coordinated and targeted response from multiple clients to meet NG or DNOS requirements. CASPs take a share of the payments from DSR buyers before distributing the remaining revenue to their DSR client base.

For this feasibility study, DSR buyers from an EV Fleet operator would be the local DNO and the energy supplier, and possibly the National Grid through Frequency Control by Demand Management (FCDM). Because the likely load and discharge capacities will in the 100s of kW range, a CASP is likely to facilitate. FCDM is discussed in detail in 7.2.2.5.

### 7.2.2.4 *Common distribution charging methodology*

Electrical energy transmission involves transferring electrical power from power plants to substations or between substations at very high voltage levels, typically 132kV up to

400kV. These circuits are usually "point to point" with sophisticated relay protection schemes on both ends. The load levels are several hundred to a couple of thousand amps per circuit. Within Great Britain, the TS is owned and maintained by three regional transmission companies, while the system as a whole is operated by a single System Operator (SO), namely National Grid Electricity Transmission plc (NGET) who is responsible for ensuring the stable and secure operation of the whole transmission system.

The interface between the TS and the 12 Distribution Network (DN) license areas is via a series of about 500 Grid Supply Points (GSP) (England and Wales) or Bulk Supply Points (BSP) (Scotland), where the TS voltage is stepped down to 132, 33 or 11kV.

The twelve distribution licence areas are operated by six DNOs who are responsible for the operation of such distribution networks, on a regional basis. Such networks comprise overhead lines, underground cables, sub-stations, transformers and a miscellany of other plant, ultimately connecting to individual "feeders", which run through neighbourhoods serving individual customers along their length. Distribution voltages are in the range of 132kV to 400V. The voltage is stepped down to the customer's utilisation voltage through the use of transformers. Typical feeder loads are a few hundred amps. The DNs are owned and operated by DNOs who are licenced to distribute electricity in their license region. This section looks at the charges incurred for commercial and industrial consumers at the distribution level by the DNOs.

The Common Distribution Charging Methodology (CDCM) estimates the costs involved in meeting a 500MW increment in network capacity. These costs can be broken down as asset costs and operating costs; the latter includes network rates and a contribution to transmission exit charges<sup>6</sup>. The CDCM is a common methodology used by all mainland GB DNOs.

To estimate the total asset costs, a notional network model was constructed. This network is designed to provide 500MW of simultaneous maximum load at the grid supply point at each network level. The assets of the notional models are costed in terms of their modern equivalent asset value and their cost is annuitised. Applicable network levels include the voltage/transformation level of supply and all network levels above this.

Operating costs, network rates and exit charges are forecasts for the charging year. Forecasts are based on historical data coupled with the licensee's (i.e. GB DNOs) estimates of future trends.

Costs are allocated to the different network levels as follows:

- Asset costs are allocated according to the network level of the assets
- Operating costs and network rates are allocated to each network level according to its share of modern equivalent asset value (asset replacement cost)
- Exit charges are allocated to the transmission exit level.

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<sup>6</sup> Transmission exit charges are levied on DNOs in respect of the costs of connecting the distribution network to the transmission network and represent a charge for specific connection assets at the interface between the transmission and distribution networks.

Following cost allocation to network levels, the yardstick costs of the load at each network level in £/kW/year are derived. This is achieved by dividing network level costs by the simultaneous maximum load at that level. This number will be different from 500MW due to loss and diversity adjustments.

For each user, the network level unit and standing charges are then derived, which are based on user characteristics e.g. coincidence factors and agreed standing factors<sup>7</sup>. The unit charges are determined on the basis of the user's contribution to simultaneous maximum load (i.e. in reference to a coincidence factor). The capacity charges are allocated according to agreed capacity charge factors and would apply to both the DWPT service provider and the EV fleet operator. Fixed charges are allocated according to agreed fixed charge factors.

For each user, the unit and standing charge elements across the applicable network levels are aggregated. The charges obtained are the pre-scaled charges.

Pre-scaled charges and consumption forecast data are used to determine revenue shortfall or surplus relative to the regulatory allowed revenue. The pre-scaled charges are scaled up or down to match recovered revenue with allowed revenue. The charges obtained are the final charges to the network customer.

#### *7.2.2.5 Ancillary services*

Within the UK, the transmission system frequency must be held at the nominal value specified in the 'Electricity Supply Regulations' of 50Hz±1% at all times except in abnormal or exceptional circumstances, such as a large power station being out of service or the switching of a large load. National Grid ensures this happens by offering commercial frameworks that incentivise energy consumers or generators to curtail consumption or export at the appropriate times. The ancillary services considered in this report are Short Term Operating Reserve (STOR), Fast Frequency Response (FFR), Firm Frequency Response (FFR) and FCDM.

NG's control centre keeps the system in balance using a team of specialist system operators that forecast the demand for electricity. This is done by taking into consideration factors such as: the weather forecast; the time of day, month and year; historical data, events such as 'TV pickups'<sup>8</sup>. From this information NG issues calls to service providers at various time of the day, 365 days a year.

#### *Short term operating reserve*

Certain types of generators or Electrical Storage System (ESS) are known as fast-acting. These Fast-Acting Units (FAUs) can be held in readiness so that NG can dispatch them quickly to maintain system frequency to within ±1% of 50Hz nominal. These FAUs are incentivised to generate when called upon by NG, especially during events such as sudden demand peaks or a failure of one or more large power stations.

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<sup>7</sup> Two of the tariffs (Related MPAN and unmetered supply customers) have only a unit charge component

<sup>8</sup> These are caused by popular television programmes or major televised sporting events such as the Olympics or World Cup ending or having advert breaks. Consumption then spikes when appliances such as kettles are switched on at the same time.

STOR is required all year round, on a 24 hours basis from a range of providers. NG sources these providers through a tri-annual competitive tender process. National Grid is free to accept or reject a tender, but offers fixed term contracts for STOR service providers.

A STOR provider must be able to:

- Offer a minimum of 3MW or more of generation or steady demand reduction. This can be from more than one site and from a collection of smaller providers through a CASP or Demand Response Aggregator (DRA)
- Deliver full MW within 240 minutes or less from receiving instructions from National Grid
- Provide full MW for at least 2 hours when instructed.

In assessing the benefit of acceptance of a STOR tender, the value and costs of that tender are considered and then compared with the economic costs of procuring that same volume of reserve from alternative sources.

Participants are paid in the form of:

- Availability Payments (£/MW/h): service providers are paid to make their unit/site available for the STOR service within an Availability Window. This is a firm payment;
- Utilisation Payments (£/MWh): service providers are paid for the energy delivered as instructed by National Grid. This includes the energy delivered in ramping up to and down from the Contracted MW level.

For example, a 3MW committed contract, based on 100% availability and service delivery (utilisation) would provide:

- A £66k availability revenue (6 seasons yr 1) – Firm revenue
- A £36k-54k (50 – 80 1hr utilisation in yr 1) – Variable revenue
- A total revenue of between £102k and £120k per year.

Availability is paid during key 'windows' set by National Grid. These windows vary seasonally, but currently fall within the periods 07:00 to 22:30, and amount to roughly 11 hours per day. Most STOR utilisation occurs within these windows.

Clearly, an EV fleet operator is unlikely to be able to dispatch or curtail 3MW of power across multiple sites and may not be likely to interrupt their core business when called upon by NG.

A range of CASPs which allow groups of smaller capacity STOR providers to provide STOR services, where they can, within the availability window when called upon is shown in Appendix E. The minimum power capacity is usually ~100kW and STOR requests can be overridden at inconvenient times outside the availability window. The trade-off is that the STOR payments are lower than when directly dealing with NG with larger power capacities.

For a 900kW generator, a typical example of aggregated revenues from a STOR CASP, provide revenues of around £12,000/yr. This is at £13.33/kW/yr capacity with a service provider compared with £34 – £40 /kW/yr with a NG contract.

To obtain a detailed revenue breakdown and capital investment requirements to set up as a STOR provider, several CASPs should be approached, with details of EV fleet charge/discharge capacities and vehicle availability.

### *Frequency response*

To maintain system frequency, generation and demand must be kept in balance in real time. In the case of a rare event, Frequency Response (FR) is designed to cope with the loss of two 660MW generator sets in quick succession. In the UK there is approximately 2.5GW of frequency service loads available, covering a peak demand of around 60GW. National Grid will balance the grid by using generators, including renewables such as wind, solar or hydro. These sets come online or go offline and vary their output, depending on demand. NG pays for generation FR services in advance, or procures from the balancing mechanism (BM) a few hours ahead of requirement.

Frequency response can be split into two distinct types. The first is a continuously provided service used to manage the normal second by second changes on the system, known as Dynamic Frequency Response (DFR). The second is usually a discrete service triggered at a defined frequency deviation from 50Hz; this is known as Non-Dynamic Frequency Response (NDFR). Here three separate frequency balancing services are examined.

### *Mandatory frequency response*

Within the Grid code, it is a requirement that all large generators to have the capability to automatically control their active power output in response to grid frequency changes. This service is known as Mandatory Frequency Response (MFR). Thus, large generators connected to the grid help NG to fulfil its obligation to ensure that sufficient generation and/or demand is held in automatic readiness to manage all credible frequency change contingencies.

MFR can be sub categorised into Primary Response and Secondary Response, which are defined as follows:

- Primary Response – provision of additional active power (or a decrease in demand) within 10 seconds after an event and can be sustained for a further 20 seconds
- Secondary Response – provision of additional active power (or decrease in active power demand) within 30 seconds after an event and can be sustained for a further 30 minutes.

Further qualifying criteria are aimed at the characteristics of traditional generation sets, such as droop characteristics and synchronisation time since MFR is only open to large grid-connected generation. Therefore, this service would not be applicable to an EV fleet operator through a CASP. This is not the case for FFR and FCDM.

### *Firm frequency response*

FFR is the firm provision of Dynamic or Non-Dynamic Response automatically to changes in Frequency. FFR is open to Balancing Mechanism Unit (BMU) and non-BMU providers<sup>9</sup>, and new providers. NG procures the services through a competitive tender process, where tenders can be for low frequency events, high frequency events or both.

There are three subcategories of FFR which are:

- Primary response – an initial increase of generation, with sustained output from 10 seconds to 30 seconds following a loss of 0.8Hz
- Secondary response – an increase in generation, in response to system frequency still being lower than target frequency, with sustained output from 30 seconds to 30 minutes for a loss of 0.5Hz
- High response – a decrease in generation, in response to system frequency being higher than target.

FFR is suitable for EES and it is possible for an EV fleet operator to act as a FFR service provider. To provide FFR services a provider must:

- Have suitable operational metering, usually HH
- Pass the FFR Pre-Qualification Assessment
- Deliver minimum 10MW Response
- Operate at their tendered level of demand/generation when instructed (in order to achieve the tendered Frequency Response capability)
- Have the capability to operate (when instructed) in a Frequency Sensitive Mode for dynamic response or change their MW level via automatic relay for non-dynamic response
- Communicate via an Automatic Logging Device
- Be able to instruct and receive via a single point of contact and control where a single FFR unit comprises of two or more sites located at the same premises

FFR has a five part payment structure, though FFR providers do not have to tender for all payments. Participants are paid in the form of an:

1. Availability Fee (£/hr) – for the hours for which a provider has tendered to make the service available
2. Window Initiation Fee (£/window) – for each FFR nominated window that National Grid instructs within the Tendered Frames
3. Nomination Fee (£/hr) – a holding fee for each hour utilised within FFR nominated windows
4. Tendered Window Revision fee (£/hr) – National Grid notifies providers of window nominations in advance and, if the provider allows, this payment is payable if National Grid subsequently revises this nomination

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<sup>9</sup> Balancing Mechanism (BM) participants are generally transmission connected generation from large power station sites while non-BM participants are generally small transmission or distribution connected generation and demand.

5. Response Energy Fee (£/MWh) – based upon the actual response energy provided in the nominated window.

Utilisation volumes are determined by NG in accordance with the system frequency and the characteristics of the response service.

For FFR to be a lucrative option for an EV fleet operator, they must be able to interrupt their charging demand instantaneously for short periods of time when called upon by NG. The minimum threshold of 10MW can be overcome by using a CASP, similar to STOR. The CASPs will often pay and assist with setting up the equipment required to qualify as a FFR service provider.

Indicative revenue from FFR service provision is ~£50 – 60 per kW, per year, split over the tendered fees above. A CASP is likely to take a proportion of this revenue and therefore the revenue per kW per year will likely be lower.

#### *Frequency control by demand management*

FCDM is similar to FFR in that it is a commercial frequency response service provided through automatically disrupting electricity demand when the frequency drops. This service is specifically aimed at preventing the grid frequency falling below the statutory limit of 49.5Hz and is triggered at 49.7Hz. FCDM provides frequency response through interruption of large demand customers, through a low frequency detection relay which automatically interrupts demand when the system frequency transgresses the low frequency relay setting on site.

An EV fleet operator who wishes to provide the FCDM service, must be prepared to have charging interrupted for a 30 minute duration, curtailing their declared capacity. Statistically, interruptions are likely to occur between approximately ten to thirty times per annum.

An FCDM provider must:

- Discharge to capacity in under 2s
- Deliver for a minimum of 30 minutes
- Deliver a minimum of 3MW, which may be achieved by aggregating a number of small loads at the same site, at the discretion of National Grid or using a CASP
- Have suitable operational metering, usually HH
- Provide an output signal into National Grid's monitoring equipment.

Availability is required 24 hours daily, 365 day a year. FCDM has a very strict requirement that capacity must not fail. If 100kW of capacity is declared available, there must be delivery of 100kW in the event of a frequency dip without fail. NG will remove the site/capacity from service immediately if the FCDM service is not provided, stopping payment; the site will not be eligible to participate again.

For FCDM, the capacity can be profiled over HH periods, so for example a EV fleet operator can declare 500kW from 09:00 – 18:00 and then 1MW 18:00 – 22:00 and then 1.1MW from 22:00 – 09:00, depending on their requirements.

FCDM is remunerated on an availability basis (there is no payment for utilisation, as this is very low). For each site, where Availability has been accepted by NG in a Settlement



Period, an Availability Fee (£/MW/h) is paid against the Metered Demand in the Settlement Period of the site specified in the Agreement. Payment from FDCM when using a CASP is around £26 – 30 per kW per year.

### **7.2.3     *Detracting factors***

#### *7.2.3.1     Existing vehicle licensing arrangements*

There are 24 road vehicle licence categories as of Oct 2012, each with their own restrictions, including weight. The categories of road vehicles which are of interest to the DWPT project, are cars (B), medium sized vehicles (C1), Large Vehicles (C), Minibuses (D1) and buses (D).

Non-electric HGVs have Vehicle Excise Duty (VED) bands based on the number of axles, weight, vehicle emissions and suspension type. Weights range from 3.5 to 40 plus tons with VED varying between £165 and £1531 per annum respectively. Having road friendly suspension, a Reduced Pollution Certificate (RPC) and lower axle count reduce the annual VED. Savings of over one third are available if the vehicle qualifies for a RPC grant.

#### *7.2.3.2     Impacts of vehicle fleet electrification*

The congestion charge (CC) is another cost associated with running a vehicle within London. At the time of writing, this charge is £11.50/day. At six days/week running 52 week per year gives a total annual spend of up to ~£3,600 per year. This fee can be waived if the vehicle qualifies for the Ultra-Low Emission Discount (ULED), which includes vehicles with fuel types registered as electric. Congestion charges are only applied in London, making CC benefits of fleet electrification geographically limited. In addition to the CC, some London boroughs will be penalising diesel-engine road vehicles (DERVs) due to high levels of diesel related pollution, with even Euro 6 class diesel engines due to be penalised. The London ultra-low emission zone (ULEZ) is due to be in effect from 2020.

The high capital cost of an EV is a major barrier to adoption. This is primarily due to battery costs. Table 20 shows details of electric vehicles, including weight and capacity in each licence class applicable to this project. It also contains the details of one or more ICE equivalent in each class.

**Table 20: Commercially available fleet electric vehicles**

Category	Make & Model (A "*" after the model name denotes an ICE vehicle)	Kerb Weight (kg)		Goods or Passenger Capacity	Capital Cost Excluding grants or battery leasing including VAT
<b>B</b>	Nissan Leaf	1,474 – 1,541	–	4 passengers/595kg	£26,490 – £30,590
	Renault Zoe	1,428		4 passengers/434kg	£22,328 – £24,393
	Nissan Note*	1,040 – 1,216		4 passengers/ 395 – 415kg	£9,995 – £17,870
	Renault Clio*	980 – 1,204		4 passengers/ 425 – 438kg	£10,995 – £19,995
<b>C1</b>	Nissan eNV200 Van	1,517 – 1,606	–	703kg/4.2m <sup>3</sup>	£21,775 – £25,410
	Kangoo EV Range	1,426 – 1,553	–	2 – 5 passengers 650 – 740kg/2 – 3m <sup>3</sup>	£25,517 – £28,518
	Nissan NV200 Van*	1,272 – 1,286	–	714 – 728kg/4.2m <sup>3</sup>	£13,890 – £16,025
	Kangoo Range*	1,280 – 1,441		2 – 5 passengers 650 – 740kg/2 – 3m <sup>3</sup>	£13,760 – £21,515
<b>C</b>	Smith Newton	4,260 – 5,059		2,762 – 7,508kg	>£78,400
	Renault D10 10T*	4097kg		5,903kg	£35,741
<b>D1</b>	Smith EV Minibus	~3,500kg		7 passengers/1,220kg	£57,556 – £69,957

Most electric vehicles use a derivative of the Lithium Ion battery. The energy density and specific energy of a lithium ion battery are 0.25 – 0.62kWh/l and 0.1 – 0.265kWh/kg respectively. This is far lower than that of petrol which has an energy density and volumetric energy density of ~11 – 12kWh/kg and 8.7 – 9.1kWh/l respectively. To make up for this low energy density, EV batteries are larger and heavier than fuel tanks containing equal level of energy contained in fuel. Despite this, EVs rarely match ICEVs in terms of energy stored on board.

Table 21 shows the energy storage characteristics of ICEVs and EVs.

**Table 21: Comparison of different ICE and EV energy carriers**

Energy Store	Energy Density kWh/kg	Volumetric Energy Density kWh/L	High Level Estimate of Total Efficiency	Energy Store Utilisation
<b>Petrol</b>	12.1	9.12	18%	100%
<b>Diesel</b>	11.8	9.97	22%	100%
<b>Battery (lead-acid)</b>	0.03	0.06	80%	80%
<b>Battery (NiMH)</b>	0.06	0.15	80%	80%
<b>Battery (LiFePO4)</b>	0.1	0.15	80%	80%
<b>Battery (LiPo/LiCo)</b>	0.135	0.25	80%	80%

It can be seen that despite needing bigger batteries, EVs have a greater efficiency when converting stored energy into energy at the wheels, than ICEV equivalents. In fact, even if Lithium Polymer batteries have ~90 times less energy density and ~35 times less volumetric energy density than petrol, an EV power train only requires ~25 and ~10 times the storage mass and volume than that of an ICEV for every 1kWh of energy delivered to the wheels.

Without DWPT and keeping vehicle volume constant, EVs manufacturers can either reduce range or internal volume capacity (volume of the usable internal compartment of the vehicle for carrying occupants or goods) compared with ICEV equivalents. Alternatively, it is possible to increase range by adding battery packs which will either lower internal volume capacity or increase frontal area, increasing aerodynamic drag, if vehicle volume is increased to compensate. EV manufacturers optimise battery capacity and vehicle space to meet a range of requirements. However, most current EVs are comparable in size to similar ICE vehicles thus, their range is considerably lower.

#### *7.2.3.3 Distribution network capacity (potential reinforcement)*

For an EV fleet operator, a Point of Connection application (POC) may not be required near urban centres, since converted or new EV fleets will likely be operating from sites with existing power supplies in strong network areas. Changes to power requirements at an existing site are highly likely to be incurred if a vehicle fleet becomes electrified, since a source of major energy use is switching from a fossil fuel delivery network to the electricity network, which has not been designed to cater for transport energy requirements. Therefore an increase in Maximum Import Capacity (MIC) will likely be required, which will increase the capacity availability daily charge. The DNO will then carry out any reinforcement works if required. The cost of this will be met by the DUoS

charges paid for by customers on the network, including the EV fleet operator. These charges are site specific.

Some depots are situated far from urban centres to take advantage of reduced land costs compared with urbanised sites. Setting up EV fleet charging sites at these locations may incur POC reinforcement costs, since rural DNs are often weak.

For the DWPT service provider, a POC application will often be required since the system will require new infrastructure to connect to the grid. During this process, the DNO outlines contestable and non-contestable works required to carry out the connection to the DN. The DNO then puts together a quote of non-contestable works to the DWPT service provider which they must pay to the DNO in order to be connected to the DN. The DWPT provider is free to approach a third party for any contestable works to receive a more competitive quote. Traditionally DNOs operated a '1<sup>st</sup> in' system, meaning that any spare capacity is given free of charge to the first POC in the system when spare capacity is available, while late comers pay for reinforcement if spare capacity is not available or has been used up.

#### **7.2.4 Charging unit identity**

The identity assignment of the charging unit is an essential tool to manage two primary business processes which are fundamental to the Business Case:

- Charge Session Authentication
- Billing and Settlement.

The charging unit identity can be assigned to the driver or the vehicle. Identity assigned to the driver is the simpler case. Assigning identity to the vehicle is more complicated. There are two scenarios:

- Where the unique identity invokes non-chargeable services i.e. Vehicle Identification Number (VIN) used by manufactures detail elements of the vehicle
- Where the unique identity invokes chargeable services

Non-chargeable services such as VIN are not always linked to a contracted payment entity. Currently every chargeable service from vehicle duty to fuel purchase is linked to a settlement entity because a sale is a contract as well as in some cases a statutory requirement – Vehicle Excise Duty (VED) etc.

The challenge for any form of dynamic DWPT will be in the method of identification of the parties involved in the Charge Session Authentication and therefore the billing and settlement ability.

##### *7.2.4.1 DWPT automatic vehicle identification*

Automatic Vehicle Identification (AVID) falls in four broad categories, which includes:

- Automatic Number Plate Recognition (ANPR)
- Radio Frequency Identification (RFID) Ultra High Frequency (UHF) reader using passive or powered tag. This is effective at a range of up to 4m at low or zero vehicle velocity
- Microwave Frequency Identification (MFID) reader using a passive or powered tag. Effective at a range of 10m at a vehicle velocity of up to 125 mph

- In-road loop and transponder (IRLT) system, effective at high vehicle speeds with a range of 1 m above the road surface.

For DWPT, the low speed short range UHF system would not be appropriate unless a dedicated lane with a toll-like gate at the start or end was adopted. ANPR would only be effective if the number plates of vehicles could always be read. This may not be possible on slip roads, where traffic congestion can cause cars to drive slowly, and close together, which can block the line of sight to car number plates.

The UHF and microwave tag readers and in-car transponders require installation of specialised equipment within the vehicle. The MFID and IRLT systems appear to be the most appropriate for DWPT, since they can be used at high speeds and do not require line of sight. Table 22 shows a summary of the AVID technologies with their respective advantages and disadvantages.

**Table 22: Vehicle identification categories summary table**

Technology	Advantages	Disadvantages	Capital Cost
<b>ANPR</b>	<ul style="list-style-type: none"> <li>• No vehicle equipment installation</li> <li>• Tamper proof</li> <li>• Works at high speeds</li> </ul>	<ul style="list-style-type: none"> <li>• Requires number plate line of sight</li> <li>• Susceptible to poor weather conditions</li> </ul>	Low
<b>RFID UHF Tag</b>	<ul style="list-style-type: none"> <li>• No line of site required</li> <li>• Works in all weather conditions</li> </ul>	<ul style="list-style-type: none"> <li>• Vehicle equipment installation required</li> <li>• Low speeds</li> <li>• Short range</li> </ul>	Med
<b>MFID Tag</b>	<ul style="list-style-type: none"> <li>• High Speeds</li> <li>• Med range</li> </ul>	<ul style="list-style-type: none"> <li>• Vehicle equipment installation required</li> </ul>	High
<b>IRLT</b>	<ul style="list-style-type: none"> <li>• High speeds</li> <li>• High range with large or multiple loops</li> </ul>	<ul style="list-style-type: none"> <li>• Vehicle equipment installation required</li> <li>• Road surface modification required</li> </ul>	High

#### 7.2.4.2 Links from vehicle to user identity

In the DWPT system, the vehicle will have to communicate with the in-road charging unit in order to start the power transfer. This functionality will already be part of the DWPT system. The equipment that provides this functionality could be used to identify the vehicle as a charging coil is activated.

Should ANPR be used, either alone or in conjunction with MFID or IRLT, linking the registration to the vehicle owner may be desirable as a further check against fraud i.e. a user who has tampered with their on-board AVID equipment. The standard method of doing this is to go through the DVLA website, complete a V888 form and pay a nominal £2.50 fee. This would be impractical every time a user uses the DWPT system; however, it could be used as an initial check to validate a user account upon registration.

### *The TAG system*

A system that is in use in the UK which uses user accounts for billing and payment services is in operation on The Second Severn Crossing. The TAG system is a method of identifying users in moving vehicles via UHF RFID. To take part in this system, users must apply for a 'Season' or 'Trip TAG' user account. A Season TAG account allows unlimited journeys for periodic payments within the covered period via various payment methods, including direct debit.



**Figure 43: Second Severn Crossing TAG system Toll sensors and in car TAG unit**

#### *7.2.4.3 Energy charging and metering considerations*

In the domestic, commercial and industrial environments, the consumer is charged a price per kWh based on a number of factors. Most bills can be broken down into the following categories:

- Wholesale Cost
- Distribution Charges
- Transmission Charges
- Environmental Charges
- VAT.

Charges can vary with location, due to the costs associated with transmission and distribution. When loads are far from places of generation, the customer pays more for losses in the network through charges imposed on their supplier by DNOs and TNOs.

Any metering schemes will have to be used in conjunction with a user identification system as discussed in Section 7.2.4.2.

#### *Scenario 1 - Meter Attached to Vehicle*

With a meter fixed to the vehicle, all energy delivered to the battery via the charging coil is metered; a major advantage to in-road in metering. This metering would not account for energy losses due to sub optimal positioning of the vehicle when charging. Therefore, the cost of the energy losses will be placed on the DWPT service provider unless the power delivered to the coils is also metered and/or a Misalignment Loss Factor is statistically calculated from all DWPT users for use within the DWPT billing methodology. This MLF could then be multiplied by each user's kWh usage to remove the cost to the DWPT service provider. Additionally, the DWPT control system could disable the DWPT

when the lane position is out of tolerance. This would avoid excessive losses in the process.

In the on-board meter scenario, the meter is fixed to the vehicle with a unique identification number similar to an MPAN and anti-tamper measures. The meter would differ from traditional meters in that it would need to be powered by the vehicle battery and have internal Electrical Energy Storage (EES) for an internal clock and data storage. Data transfer from the vehicle can take place at the user premises, when connected to the power supply, and/or at the entry and exit to the slip road via wireless data transfer.

Potential issues with attaching a meter to vehicles are:

- The meter would be subject to the full vehicle Noise, Vibration and Harshness spectrum and environmental conditions, requiring the on-board meter to be more robust than conventional consumption meters
- The meter could be open to tampering, leaving the DWPT system open to fraudulent use
- Time and expense are required for installation and maintenance
- Requires the design of an on-board metering solution that fits and works with the majority of vehicles whilst adhering to automotive design standards
- The meter creates a parasitic load in terms of fuel use, through increased vehicle weight and electricity use.

#### *Scenario 2 - meter as part of DWPT system*

Virtual meters can exist within the user charging and accounting system when used in conjunction with the in-road DWPT system. It is assumed that an AVIDS will be in use and this must be in operation in order for the charging coils to activate. Each coil would have to have its own meter or energy monitor in order to identify how much energy each charging coil has used and which DWPT user accessed it. A computer controlled relay to each coil would only close if the AVIDS was active and a registered vehicle was passing over the coil. The energy meter would then assign the energy consumed by inductive power transfer to the registered user for each activated coil and add it to their virtual meter reading.

Any near road monitoring equipment would be subject to temperature variation, environmental factors and vibration from heavy traffic. The energy accounting system must therefore be designed to be robust, and to require minimal maintenance and equipment replacement.

Roadside metering has the drawback of not accounting for misalignment losses, with the amount of energy received by the secondary coil remaining an unknown. This would be a problem for a DWPT user, as the DWPT would be supplying the required energy, but the vehicle would be receiving lower levels due to misalignment and WPT inefficiencies. The DWPT user may perceive an issue with the DWPT system, rather than their driving misalignment. Therefore, a Misalignment Loss Factor, statistically calculated from all DWPT users could be used to show the energy used by the operator and transmitted to the user. Thereby, showing the overall system efficiency. To minimise energy losses the DWPT control system could disable the DWPT power transfer when the lane position or efficiency is out of tolerance specified by the operator.

### 7.3 Infrastructure Management System (IMS)

The purpose of the IMS is to act in a Supervisory Command And Data Acquisition (SCADA) and data processing capacity and to provide overall system level logical controls to the physical charging systems. The system may include both software and hardware components in varying amounts based on the chosen system architecture.

Any IMS architecture will of course include certain core, top-level requirements such as customer identification, authorization, metrology and billing/account management, but below these core requirements are a series of equally important functional requirements which will be determined by the selected DWPT architecture.

In order to adequately address all of the back office requirements, a review of the operational considerations is presented. This is followed by a complete summary of the top-level system requirements and more detailed functional requirements. The DWPT system data flow is summarised in Figure 44.

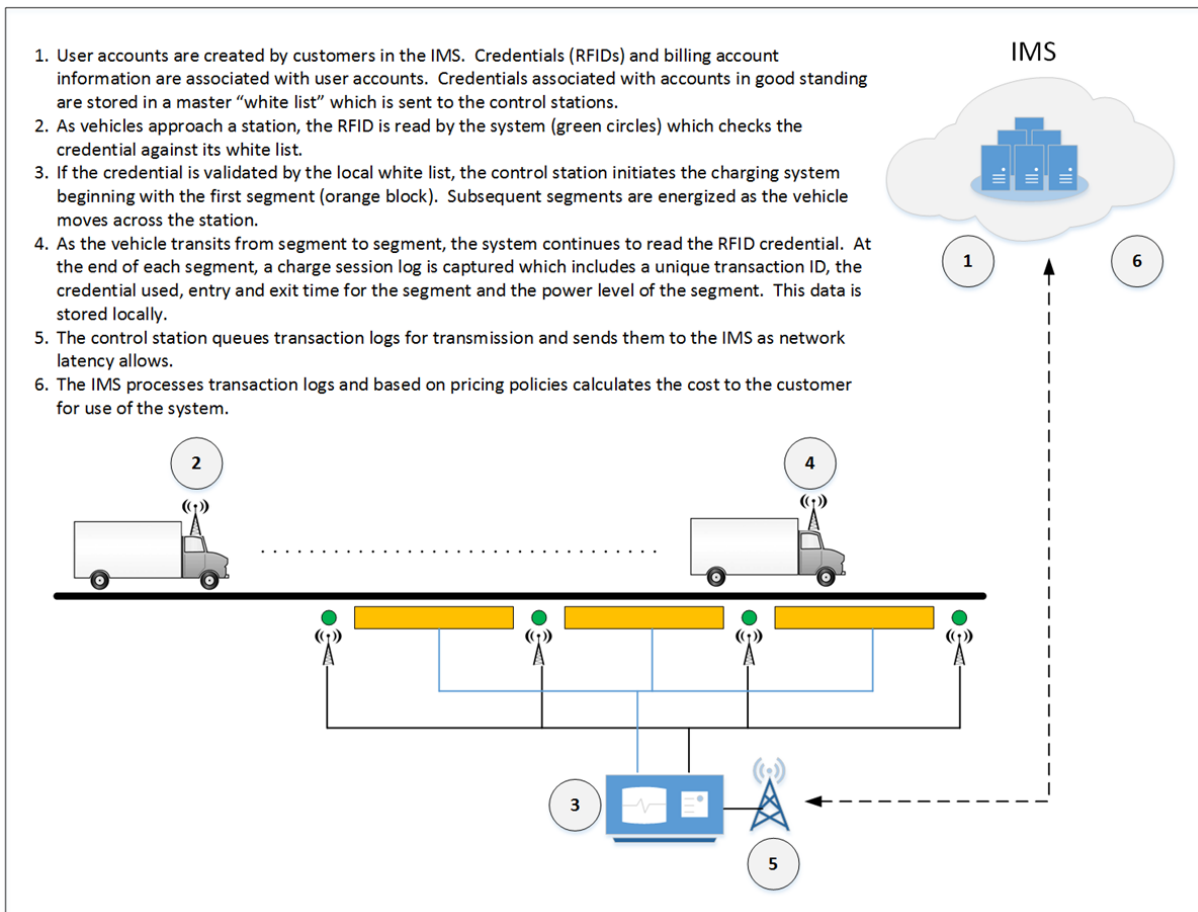


Figure 44: IMS – DWPT System Data Flow

#### 7.3.1 Operational considerations

##### 7.3.1.1 User identification

Identification of vehicles and/or drivers is a basic requirement for control and monitoring of the DWPT infrastructure. The various technologies to achieve this are discussed in



7.2.4. It enables starting and stopping of the in-ground systems, allows throttling of power based on different user charging needs and also provides a mechanism by which to store, query, aggregate and report on system usage. Finally, it provides a mechanism for connecting a vehicle or driver to a billing account.

It is a given that every vehicle or driver (or both depending on billing scenario) will require a unique identifier. However, the form of this identifier and means by which it is communicated to the backend system for purposes of tracking and billing is an open question.

RFID transponders are commonly used as vehicle/driver identifiers in transportation applications because they are:

- Proven technology with more than a decade of in-field use
- Inexpensive (production units typically costing less than £15 per unit in the aftermarket)
- Capable of carrying additional simple data payloads along with their unique identifier
- Independent of the vehicle and completely portable
- Very lower power so battery life is measured in years.

Under an RFID scenario, the vehicle or driver might set the transponder to request charging at a predefined power level and the transponder would automatically provide the vehicle credentials and the user preference (charge and at what power level, or do not charge) to the RFID receiver whenever it was about to enter a WPT location.

Another option for vehicle identification is a customized mobile application loaded onto a driver's mobile device or (in the future) their vehicle's in-dash operating system. One can envisage a scenario in which the driver sets the app to request a charge and then the mobile device or the vehicle autonomously broadcasts a notice to the WPT system based on its current location informing the system to power the vehicle. Charging would continue at each WPT location until such time as the vehicle reached a certain SOC or the driver intervened and instructed the app to discontinue charging.

#### *7.3.1.2 WPT system size*

The size and configuration of the in-ground systems is a key driver in the development of backend system architecture. If the in-ground system were large – say, an inductive coil that is a mile long – then dwell time of a charging vehicle over the system would be long enough to support lower latency network connections such as could be expected in a system that employs cellular technology.

By contrast, in-ground systems of shorter length – say, on the order of 10 to 30 metres – would produce very short dwell times by charging vehicles travelling at highway speeds. In these cases, the network latency would either need to be very low or a more distributed monitoring and control architecture would be required to manage the system.

As the system envisaged will consist of segments of between 2m and 20m in length, a distributed monitoring and control architecture will be required.

#### 7.3.1.3 *Power start/stop*

It is estimated that each WPT charging station will provide between 40kW and 140kW of power to the vehicle. At the high end, the corresponding power drawn from the grid will be in the range of 185kW due to intrinsic system losses. A system of hundreds or even thousands of such stations would consume a considerable amount of energy and, if left to run when no vehicles were charging, would put a considerable strain on the grid. Thus, it is critical that the system be capable of turning the stations on and off quickly and consistently to minimize grid loads and energy costs.

Additionally, it is important that the system be smart enough to recognize incompatible or inadequately shielded vehicles and turn off power accordingly. Fortunately, most systems currently in development only switch on when a compatible secondary coil is detected and is present to complete the circuit of the coupled system.

Controls for both of these situations are the domain of the on-site system and have little to do with the IMS.

A third consideration in regard to turning power on and off is in case of roadway emergencies and this is where the IMS can and should participate in the control of the in-ground system. In these circumstances, the ability to remotely command the in-ground systems to power down until further notice may be crucial to the safety of drivers and rescue personnel.

#### 7.3.1.4 *Metrology*

The variable cost of operating the WPT system is the cost of the energy that it uses and not how efficiently the vehicle can turn the inductive load into energy to power the electric motor. Thus, for the purposes of billing, the only logical way to meter the amount of energy used in charging a vehicle is to measure the amount of energy consumed by the station or segment during the period when the vehicle is drawing power from it.

Since the WPT system will constantly measure the local power, the simplest way to calculate the energy used in servicing the vehicle is to simply multiply the power by the amount of dwell time over the station. This assumes that the rate of power transfer remains constant during the dwell time – a more complex measurement will be required if the power transfer is not substantially constant during power transfer. By summing the incremental meter readings of each segment and each station, the total energy consumption for a trip can be calculated by the IMS and billed as appropriate.

It should be noted that this metering process is completely dependent upon two things: accurate measurement of the power (presumably by the station itself) and accurate measurement of the dwell time (calculated from time of entry and time of exit from the station). It does, however, have the advantage that it enables measurement of actual (not nominal power consumption) and can provide very accurate readings of dwell time by the station.

The meter could be attached to the vehicle or it could be part of DWPT system:

- 1) Meter fixed to the vehicle

All energy delivered to the battery via the charging coil is metered. This metering will not account for energy losses due to sub optimal positioning of the vehicle when charging. Therefore, the cost of the energy losses will be placed on the

DWPT service provider unless the power delivered to the coils is also metered and/or a Misalignment Loss Factor (MLF) is statistically calculated from all DWPT users for use within the DWPT billing methodology. This MLF could then be multiplied by each user's kWh usage to remove the cost to the DWPT service provider. Additionally, the DWPT control system could disable the DWPT when the lane position is out of tolerance. This would avoid excessive losses in the process.

In this scenario the meter is fixed to the vehicle with a unique identification number similar to a Meter Point Administration Number (MPAN) and anti-tamper measures. The meter would differ from traditional meters in that it would need to be powered by the vehicle battery and have an internal EES for an internal clock and data storage. Data transfer from the vehicle can take place at the user's premises, when connected to the power supply, and/or at the entry and exit to the slip road via wireless data transfer.

Potential issues with attaching the meter to vehicles are:

- The meter would be subject to the full vehicle Noise, Vibration and Harshness spectrum and environmental conditions, requiring the on-board meter to be more robust than conventional consumption meters
- The meter could be open to tampering, leaving the DWPT system open to fraudulent use
- Meters require time and expense for installation and maintenance
- Requires the design of an on-board metering solution that fits and works with the majority of vehicles whilst adhering to automotive design standards.

## 2) Meter as Part of DWPT System

Virtual meters can exist within the user charging and accounting system when used in conjunction with the inroad dynamic wireless charging system. It is assumed that an Automatic Vehicle Identification System (AVIDS, see Appendix F) is used and this must be in operation in order for the charging coils to activate. Each coil would have to have its own meter or energy monitor in order to identify how much each charging coil has used. A computer controlled relay to each coil would only close if the AVIDS was active and a registered vehicle was passing over the coil. The energy meter would then assign the energy consumed by inductive power transfer to the registered user for each activated coil and add it to their virtual meter reading.

Any near road monitoring equipment would be subject to temperature variation, environmental factors and vibration from heavy traffic. The energy accounting system must therefore be designed to be robust and require minimal maintenance and equipment replacement.

This method has the drawback of not accounting for misalignment losses, with the amount of energy received by the secondary coil remaining an unknown. Therefore, a Misalignment Loss Factor, statistically calculated from all DWPT users is again required to show the DWPT provider is not excessively charging users for DWPT system inefficiencies. Again, the DWPT control system could disable the DWPT when the lane position is out of tolerance i.e. greater than ~15cm from the lane centre.

#### 7.3.1.5 *Data collection & transmission*

Data collection is best handled by the WPT system without interference from the IMS. However, it is important that the mechanism by which data is transferred to the IMS includes considerations for transmission and back-up.

The conduit through which transaction data is communicated to the back office should conform to industry standards. The current standard most commonly used in Europe (though not elsewhere) is Open Charge Point Protocol (OCPP) version 1.5, and it defines all of the required messages to both run the system as well as to report transactions and charging data to the back office. These messages include:

- Boot Notification
- Authorize Transaction
- Start Transaction
- Status Notification
- Stop Transaction
- Station Heartbeat
- Meter Reading.

In the future, support for OCPP v 2.0 may be desirable, but is not strictly required. Note that OCPP is designed for static conductive charging stations, but the protocol is sufficiently general to encompass the requirements of dynamic wireless power transfer.

In order to ensure that all data is faithfully collected, recorded and audit-ready, multiple layers of data storage redundancy are recommended. At a minimum, the charge station should be able to send a message and verify that the message has been received by the IMS. Fortunately, this is a component requirement of the OCPP standard.

In addition, the station should be able to:

- Resend messages (repeatedly, if necessary) when a proper confirmation is not received
- Store messages for a period of at least several weeks
- Enable remote access to collect data logs as necessary

#### 7.3.1.6 *Remote monitoring*

As with any system of this size and complexity, the ability to remotely monitor and triage issues is a key success factor.

OCPP enables remote health monitoring through a system of regular heartbeats. It also provides an architecture in which fault specific information can be passed on from the local station to the IMS for remedial action.

In order to perform remedial actions remotely, a different level of access is generally required. This can be as simple as the ability to send a hard reset command (to completely power cycle and reboot the station) or a soft reset command (to clear a fault and allow the system to attempt to return to normal function). It may also require higher levels of access to assess the current state of various parameters, manually override system parameters or patch software or firmware.

#### *7.3.1.7 Accounting & billing*

In contrast to data collection and transmission, account management and billing is best managed by the IMS. Here, data can be aggregated and usage and pricing policies can be applied to determine the proper amount to bill the customer.

Account management and billing can be handled in several ways:

- 1) A private merchant gateway can be built directly into the IMS, and accounting and billing can be handled within the IMS
- 2) A commercial merchant gateway can be integrated with the IMS, and accounting and billing can be handled within the IMS
- 3) The IMS can be integrated with a third-party billing system which manages both accounting and billing exclusive of the IMS

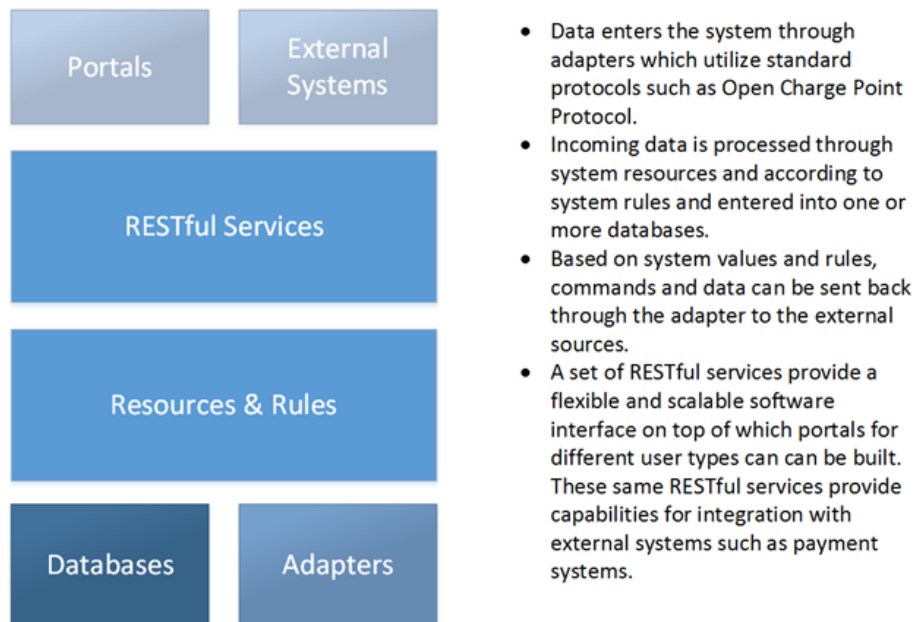
Each of these approaches has advantages and disadvantages; however, the most commonly chosen option is option number 2. While the processing fees are generally a little higher than for the other options, the commercial merchant gateways are the least expensive to implement, most robust and feature rich, and are already certified for compliance with the Payment Card Industry Data Security Standard (PCI DSS) to guarantee that customer financial and transaction data is secure.

### **7.3.2 IMS requirements**

This section presents general requirements for the IMS. These include system architecture, communication protocols and various functional requirements. It also details requirements for the Administrative and Driver/Fleet User Interfaces which assist stakeholders in managing their interactions with the back-office systems.

#### *7.3.2.1 General system architecture*

Software industry best-practices for enterprise level, scalable web-based systems of the type likely to be utilised in a DWPT IMS have evolved to a common model over the last decade. This common model includes a set of core databases populated in near real time from external sources via configurable adapters and exposed to users via portals or external systems integrations built on top of Representational State Transfer (“RESTful”) services. This general architecture is shown in the diagram in Figure 45.



**Figure 45: Common Enterprise Software Architecture**

The benefits of this type of architecture are:

- Performance, i.e., the ability to respond to a large number of transactions efficiently
- Scalability to support large numbers of components and interactions among components
- Simplicity of interfaces
- Ability to modify components to meet changing needs (even while the application is running)
- Visibility of communication between components by service agents
- Portability of components by moving program code with the data
- Reliability, i.e., the resistance to failure at the system level in the presence of component failures.

#### *Distributed control*

Due to the predicted low dwell times over any given WPT segment, it is recommended that the IMS opt for a distributed control approach wherein the individual stations are provided with vehicle access control and approval information and have the ability to start and stop power autonomously. This will effectively eliminate network latency issues by pre-seeding approved credentials at each station and enable the station to quickly recognize a vehicle token to authorize charging.

#### *Communication protocols*

As the established standard in the Electric Vehicle Supply Equipment (EVSE) industry, Open Charge Point Protocol (OCPP) is the recommended protocol for communication between the WPT and the back office.

OCPP v1.5 is currently believed to support all of the monitoring and management functions required of the overall system including:

- Station on-boarding via boot notifications
- Station start/stop transactions
- Heartbeats
- Meter readings
- Station status/fault notifications

OCPP v2.0, which is planned for release in mid- to late-2015, adds some functionality in pricing controls and other non-core functions, but the primary purpose of this release is to port the protocol to a Java-based architecture which includes web-socket technology. While the long term goal should be to build a system on OCPP v2.0 and take advantage of its more extensible and robust architecture, for the present, v1.5 is field tested (for plug-in charging), reliable and sufficient.

#### *Customer & asset identification*

One of the key aspects of control within any system is the account. Within the IMS, every customer must have an account with a unique account identifier.

Every vehicle (or driver) should have a unique identifier associated with it or the identification device that it carries. There may be a case for both vehicle and driver to have a unique identifier.

The account identifier should be capable of association with one or more vehicle identifiers and one or more driver identifiers – as would be common in fleets. This will facilitate access controls, pricing controls as well as billing and payment.

#### *Charge sessions*

Charge sessions – defined here as the period of time during which a vehicle dwells over a DWPT – should have unique identifiers. Every charge session should include the following information:

- Transaction ID
- Asset identifier (RFID or credential)
- Start and end time stamp of event
- Power reading (kW)

#### *Access control*

For the DWPT, access control is best handled close to the actual charging location. The back-office system should maintain a “master white list” of approved credentials (those whose accounts are in good standing) and update the station controls points with “local white lists” on a regular basis – at least once daily.

#### *Data aggregation*

Since it would be impractical and expensive to for users to pay separately for each charge session on the WPT system, the IMS should be capable of collecting data,

aggregating many charge sessions over a period of time and then processing all sessions in a single transaction.

The IMS should allow the account holder to determine over what period of time the charge session data is aggregated.

The IMS should also have the ability to break out aggregated data into its component sessions for auditing purposes.

#### *Data storage*

The IMS should have sufficient data storage capabilities to keep at least three years' worth of charge session data plus as much memory as is necessary to store account and billing information.

All data should be stored in properly structured, secure and redundant databases.

#### *Billing & payment integration*

The IMS should support integration with third party, certified PCI-DSS compliant, merchant gateways to enable credit card based payment options.

The system should also support customer account invoicing for large fleet accounts.

The system should support a pre-paid billing mechanism where accounts can add credits to their account and then debit against the account over time.

#### *Messaging/communication*

The IMS should be capable of communicating with all stakeholders based on their data requirements. Communication should include both email and SMS options.

The types of communication required should include:

1. System to administrator – supports emergency warnings and identifies when charging assets require attention
2. System to account holder – supports communication of account specifics including usage, credits, scheduled demand response events, and related data
3. System to driver – supports dynamic pricing and real-time demand response notifications
4. System to external party – supports communications between third parties and service stations.

#### *System security, monitoring redundancy*

All components of the IMS should be monitored 24 hours per day for security and uptime.

All system components/servers should be fully redundant, configured for load balancing, scalable on demand, and enabled for fail-over to ensure maximum reliability.

All system components should have both, automatic and manual remote restart capabilities to ensure maximum availability.



### *Application programming interface (API)*

The IMS should have a complete API for all key functions including:

- Accounts
- Stations – location, status, pricing
- Assets/Vehicles
- Drivers
- Charge sessions/Transactions
- Access control
- Pricing
- Usage reporting.

The API should be fully documented to ensure ease of development.

#### *7.3.2.2 Administrative portal*

The following section describes the administrative portal, i.e., the interface through which administrative users interact with and configure the IMS. This portal provides access to location and station data, account/vehicle/driver information, access and pricing controls, and reporting.

General requirements for the administrative portal include:

- Simplicity
- Easy-of-use
- Minimization of training
- Conformance to web browser standards
- Feature extensibility.

### *System configuration*

The admin portal should provide users with the ability to add, modify or remove *locations* from the system. It should also provide mechanisms to organize and aggregate locations into logical groupings for the purposes of access control, pricing and reporting.

The admin portal should provide users with the ability to add, modify or remove *stations* or WPT elements from the system. It should also provide mechanisms to organize and aggregate stations into logical groupings for the purposes of access control, pricing and reporting.

The admin portal should provide users with the ability to add, modify or remove *customer, vehicle and driver accounts* from the system. It should also provide mechanisms to organize and aggregate vehicle and driver data for the purposes of access control, pricing, billing and reporting.

### *Access control*

The admin portal should provide administrators with the ability to specify access to locations or stations by account, vehicle or driver.

The admin portal should provide a mechanism by which access control parameters (white lists) can be pushed to station control points on either a regularly scheduled basis (say, once per day) or immediately at the administrator's discretion.

### *Reporting*

The admin portal should provide administrators with the ability to quickly generate relevant and useful reports. Typical reports include:

- Usage by location or station including vehicles, dwell time, power consumed
- Usage by account, vehicle or driver including dwell time, power consumed and billed amount
- System faults by location or station

The admin portal should support the ability of administrators to schedule any predefined reports for delivery on a weekly, monthly quarterly or annual basis.

### *Remote access*

The admin portal should provide users with the ability to remotely start or stop a station in real time. It should also provide users with the ability to override the station's automatic mode to turn it on or off. The override should persist until it is removed by another user and the automatic station state is restored.

#### *7.3.2.3 Network Operating Centre (NOC) interface*

The NOC is a portal designed for monitoring the overall system, and identifying, triaging and fixing system issues.

In contrast to the Administrative Portal, the NOC's intended audience is system support and IT support professionals whose job it is to identify and resolve issues in the shortest time possible.

The NOC does not include management capabilities such as those required for location, station, account, access, pricing and reporting. Instead, the NOC should present a dashboard which highlights issues and provides an ability to rapidly drill down from a system level to a location level to a station level in a matter of clicks.

### *System map*

The NOC should include an overall system map which displays the components of the system aggregated into groups that share a logical connection. This should include separate groups for locations or supersets of locations, and IMSs (servers).

The NOC should provide an ability to grade issues by colour codes. One such schema could be:

- Red: critical issues requiring immediate attention
- Yellow: non-critical issues that has not reached a critical level
- Green: no issues identified.

Examples of critical (red) issues include:

- Power failure at a location or station

- Incident on the road that requires system shut down
- Failure of one or more of the servers in the IMS
- Recurring faults of a similar type over some period of time.

Examples of non-critical issues which do not require immediate interaction include:

- Communication loss to a location or station (this might be escalated to red if it persists for longer than an hour)
- Warnings from servers of higher than average CPU usage or insufficient memory allocation.

The NOC map should be live and provide users with the ability to select a color-coded area and immediately descend to a lower level in the system hierarchy where additional details of issues may be examined. This process should be enabled for recursive searching down to the lowest level of the system (stations or controllers).

#### *Issue log*

The NOC should provide a searchable log of system messages and warnings so that operators can identify issues and link to them directly without drilling down through the map interface. The tabular listing should conform to the same colour coding standards as the map interface.

#### *Real time system usage*

The NOC should provide near real time system usage statistics including:

- Active charge sessions
- Active vehicles
- Average power consumption
- Max power consumption.

The NOC should also provide options for week-, month- and year-to-date usage statistics including:

- Total charge sessions
- Total vehicles
- Total power consumed
- Peak power consumed
- System uptime
- GHG emission savings
- Electric miles provided.

#### *7.3.2.4 Driver/fleet user portal*

The driver/fleet user interface is intended for use by the account holder. As such, it should be much simpler and less functional than the administrative portal.

### *Account setup*

The driver fleet portal should include an ability to autonomously create a new account. The account should be associated with a unique account ID (an email address, account number or user name are usually employed).

In addition, every account should include the following:

- Admin name
- Admin email address
- Admin phone number
- Admin mailing address.

Optional information associated with the account should include:

- Additional contact names
- Additional contact email addresses
- Additional contact phone numbers.

The IMS should place safeguards in the system to prevent automated account creation by malicious web-bots.

New account creation should include a verification step which requires the new account to verify their email address and/or contact phone number.

### *Account modification*

The driver/fleet portal should provide account holders with an ability to add, modify or delete their account including admin details and contact emails.

### *Vehicle/driver credentials*

The driver/fleet portal should provide account holders with an ability to add, modify or delete vehicle and driver profiles.

The portal should allow account holders to associate one or more credentials (RFIDs or other identifiers, see Appendix F) with any vehicle or driver.

The portal should allow account holders to maintain credentials which are not associated with any vehicle or driver.

The portal should allow account holders to request new credentials that are automatically associated with their account.

The portal should allow the account holders to turn on or off the association of a credential with a vehicle or driver without deleting it completely from the vehicle or driver profile.

The portal should allow account holders to aggregate vehicles, drivers or credentials for the purposes of tracking, billing and reporting.

### *Billing setup/modification*

The driver fleet portal should provide a mechanism by which an account holder can select their method of billing and payment. The methods should include credit/debit card, prepaid account and invoice (optional) options.

The billing module should allow account holders to set up multiple accounts to assist in management, tracking and reporting of system usage.

The credit card billing setup should conform to all applicable security standards and all credit card information should either not be stored within the system (i.e., they are stored external to the system in a PCI-DSS compliant merchant gateway system) or stored in an encrypted format which cannot be accessed with highest system privileges.

Prepaid account setup should provide a mechanism by which account holders can add credits to their account. Options should be provided to add credits in suitable increments (say, £100) and to pre-configure replenishment of the account when it reaches a certain threshold.

### *Reporting*

The driver/fleet portal should provide account holders with the ability to quickly generate the following reports:

- Usage by location or station including vehicles, drivers, dwell time, power consumed
- Usage by account, sub-account, vehicle or driver including dwell time, power consumed and billed amount
- Usage by account, sub-account, vehicle or driver cross-referenced against time of day or cost of service
- Billing by location or station
- Billing by account, sub-account, vehicle or driver.

The driver/fleet portal should support the ability of account holders to schedule any predefined reports for delivery on a weekly, monthly quarterly or annual basis.

### **7.3.3 System costs**

As with any enterprise-level system, the costs of development of the IMS are not expected to be trivial; however, these costs – and the associated development time – can be mitigated by identifying and selecting a pre-existing platform on top of which application-specific features can be developed.

While it would be expected that development from scratch of a system which meets the requirements described herein would take approximately 12 months and a team of at least five experienced IT professionals, modification of an existing platform could more than halve the development resources required.

IT professionals of the type and experience required for a project of this nature are typically compensated at £70,000 to £100,000 per year. Thus, development costs for the IMS can be estimated to be between £350,000 and £500,000 if the project is developed from scratch or roughly half this if built on top of another commercially available platform.

In addition to personnel costs, the development activities require hardware and communication infrastructure. This will include servers, routers and related hardware for both development/test and production environments. These are best and most economically sourced as a hosted solution, for example from Amazon Web Services (AWS) or any of a number of similar companies.

Estimates of the server and communication costs for the IMS as described above would be on the order of £3,000 - £5,000 per month or £36,000 - £60,000 per year initially. As the number of stations increases over time, the data traffic and CPU load will increase proportionally and this will require scaling the system to meet demand. It can be expected that the number of servers will increase by 50% for every 1,000 – 1,500 new stations.

Ongoing operation, support and maintenance of the IMS would require a staff of at least three full time IT systems personnel to perform monitoring and management functions on a 24x7 basis. These personnel are typically compensated in the range of £50,000 - £60,000 per year.

In summary, the IMS should be expected to cost:

- Development: £175,000 - £500,000
- Operation: £186,000 - £240,000 per year

Note that this estimate does not include any one-time or annual software licensing fees that might be due to a platform provider as described above.

#### **7.3.4 Commercial drivers and detracting factors summary**

This chapter set out and described the qualitative identification of the principal relevant inputs required for the development of a model which would analyse the cost benefits of fleet electrification and associated revenue services, relative to the impact on existing revenues, from passenger or goods transport. These various facets, described in the sub sections above, are now summarised in Table 23 below.

**Table 23: Summary of principal inputs to Energy Revenue Services/Logistics Revenues model development**

Potential DWPT Revenue Services	Impact on Logistics Revenues
<b>Positive effect on Revenues (+)</b>	
<b>Large energy customer commanding a lower market rate for electricity consumed</b>	STOR, Demand Side Response Services, Triad Avoidance, Off peak charging, FFR, FCDM
<b>STOR, Demand Side Response Services, Triad Avoidance, FFR, FCDM if service not offered during peak network times</b>	Fuel Costs
<b>Potentially</b>	Vehicle maintenance costs and higher reliability
	Congestion charge and VED savings
<b>Negative effects (Deficits) (-)</b>	
<b>POC costs due to high “peaky” power demand profile</b>	Vehicle availability
<b>Exclusion from STOR, Demand Side Response Services, Triad Avoidance, FFR, FCDM if service offered during peak network times</b>	DUoS charges increases
<b>Cost of capital due to high project risk and capital outlay</b>	Capacity availability charge increases
<b>Capacity availability charges</b>	Vehicle capital increases
<b>Long term revenue reduction due to monopoly regulation</b>	Potential network reinforcement costs increases
	Tonne miles per annum per vehicle reductions
	Impacts of sub optimal delivery routes (to incorporate DWPT SRN or charge point access)
	Metering cost increases (due to HH meter requirement)

#### **7.4 DWPT network impact assessment**

The addition of a dynamic charging system on to the Distribution or Transmission Network has the potential to impact significantly on the existing infrastructure.

The output of Section 7.1 has been used as the starting point from which to assess the impact of a DWPT system on the electricity network. Demand levels for a given section of the SRN were established in Section 7.1 and discussion and analysis for the worst

case scenario of high traffic volume periods have been used in the network analysis. Consideration of partial section outages has been identified and discussed.

A 'typical' section of SRN, between junctions 5 and 6 on the M6, in the West Midlands, was selected as an example DWPT SRN section and a basic Network System Study has been performed.

#### 7.4.1 Working assumptions

In order to establish the power requirements of 1km of DWPT SRN, some assumptions about the vehicles passing through the DWPT system have been made in the previous sections. Table 24 shows the various traction power requirements to maintain vehicle velocities for cars, small vans and HGVs. This represents a worst case for vehicles moving at a constant speed.

For the purposes of designing the electricity network, the worst case peak load needs to be catered for, so the electrical load for a Heavy Goods Electric Vehicle (HGEV), drawing 180kW in the secondary coil, has been considered. It was assumed that the worst case for DWPT user penetration is 16 HGEVs per 1km of SRN. The system efficiency is assumed to be 75% at a power factor, p.f., of 0.95. Therefore the total power drawn for the 1km DWPT SRN is 4.04MVA, utilising 16 out of 20 secondary coils simultaneously.

**Table 24: Traction and real power demand from DWPT charging vehicles of different classes. Energy values are calculated for each km.**

Vehicle	Sec. Coil Load (kW)	Avg. Speed (mph)	Traction Power (kW)	Traction Energy (kWh)	Sec. Coil Power (kW)	Battery Charge per km (kWh)
Car	40	70	18.14	0.16	40.0	0.19
Small Van	40	70	18.14	0.16	40.0	0.19
HGV	180	55	127.80	1.44	180.0	0.59

Table 25 shows the assumptions used to calculate the power drawn. If the DNO owns the network at the LV level, the power flow requirements for each 50m segment, comprising four coils, needs to be considered. Each segment, which is connected to one AC-AC converter each, can charge one HGEV at a time. The maximum power drawn from the grid, through an AC-AC converter, will be 253kVA.



**Table 25: Network impact assessment working assumptions**

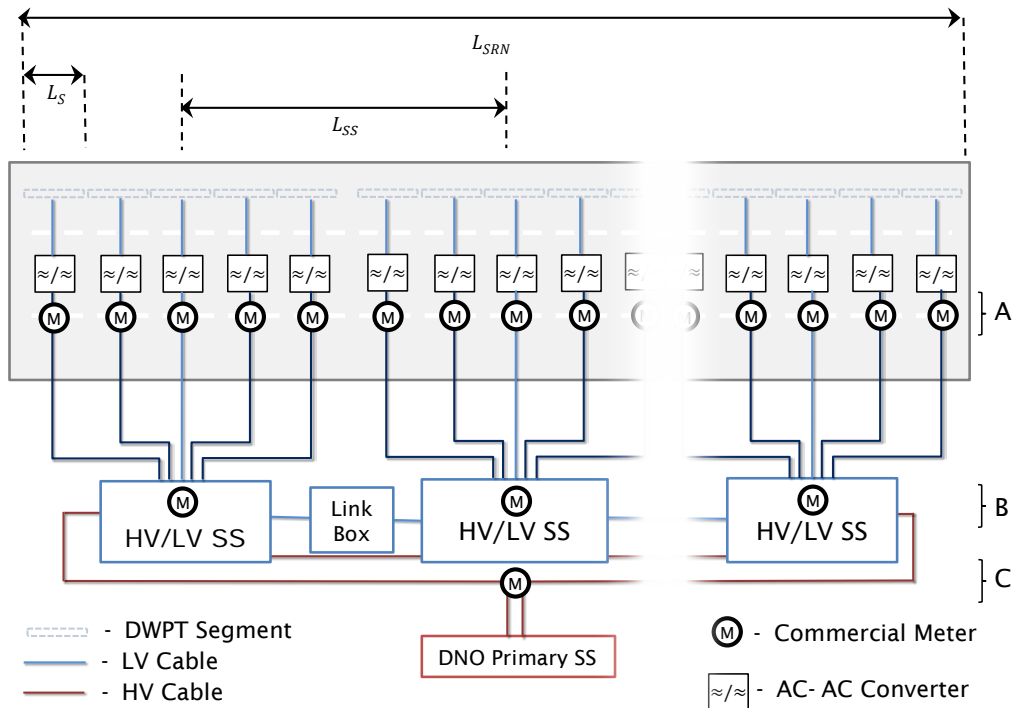
Parameter	Assumption
No. EVs per 1km stretch of road	16
Distance between LV substations ( $L_{SS}$ )	250m
No. of vehicles per segment	0.8
DWPT segment length ( $L_S$ )	50m
No. of Segments per SS	5
No. of Sub Stations per km	4
Vehicle Type	HGEV
Vehicle Electrical Load	180kW
Total Secondary Coil Load per km of SRN	2.88MW
DWPT Charging Efficiency ( $\eta_{DWPT}$ )	75%
Power Factor p.f.	0.95
AC-AC converter load (single HGEV)	253kVA
Apparent Load per km of DWPT SRN	4.04MVA

Figure 46 shows an illustration of network ownership for the DWPT supporting network. DNO network ownership ends at the meter point, so any asset below the meter is the responsibility of the DWPT provider. Three options for meter placement are displayed.

Option A involves the minimum levels of network ownership, with a 300kVA cut-out and 253kVA supply capacity agreement for each meter. This option would require the DWPT operator to own 20 commercial HH meters per km of DWPT SRN. This would incur higher metering costs due to the number of meters involved, but would involve the minimum levels of network asset management and ownership.

Option B lowers the number of HH meters required from 20 to 5 per km of DWPT SRN. The meters are placed on the LV side of the HV/LV substation, meaning that the HV/LV substation is the responsibility of the DNO. This option heavily reduces the metering requirement, while only incurring a small increase in LV asset ownership.

Option C requires only 1-2 half hourly meters after the HV substation, for a 1km section, and it is likely that longer sections of DWPT SRN can be used. The meters are placed on the LV side of the HV/LV substation, meaning that the HV/LV substation is the responsibility of the DNO. This option increases asset ownership requirements to include 4 x 1 MVA substations, Link Boxes, associated switchgear, bus bars and HV lines. The use of Link Boxes would provide additional security for maintenance purposes, but this would need to be carried out at low traffic times to avoid overload.



**Figure 46: An illustrative example of a 1km DWPT section of SRN with supporting electrical network infrastructure. Options (A), (B) and (C) represent three different scenarios of network ownership dependent on where the supply meter(s) sit(s) in the network.**

#### 7.4.2 Defining the supply voltage

In this feasibility study, for the chosen location, a network model was not required to define the Point of Connection (PoC), since the supporting infrastructure to supply sufficient peak power demand from the 132kV level is close to the 1km of SRN. This scenario is likely to be reproduced in other locations due to the large power swings in load profile from each DWPT segment. Figure 47 shows an illustrative example of a load profile seen at the AC-AC converter as HGEVs pass over the secondary coil the converter is attached to.

In the illustration, it is assumed that:

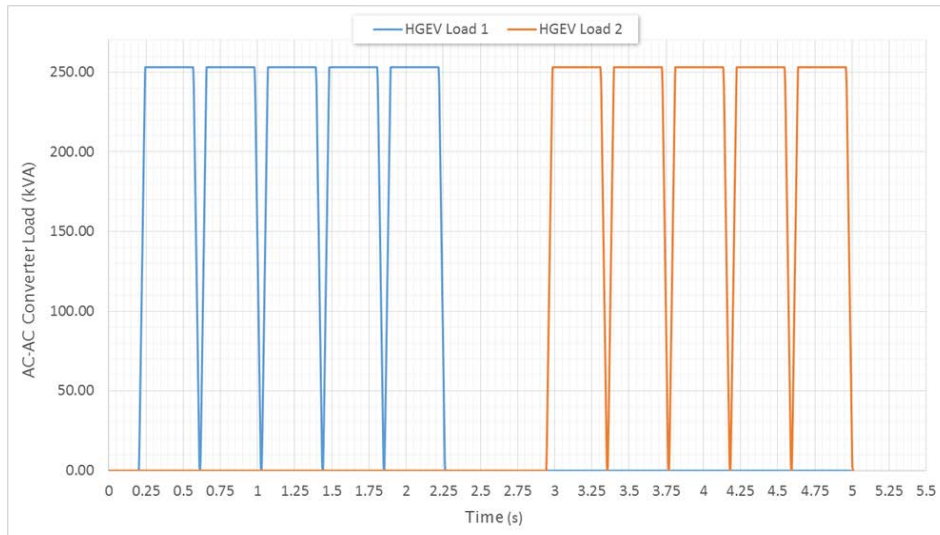
- The primary coil is 9m long, with 1m spacing
- The secondary coil length is 1m
- The HGEV length,  $L_{HGEV}$ , is 16.5m
- The HGEVs are moving at  $v_{HGEV} = 55\text{mph}$  ( $24.5 \text{ ms}^{-1}$ ).

The load ramp rate shown is linear, depicting the secondary coil as it moves completely within and away from a primary coil, five of which are in each road segment. This ramp rate may not be linear in practice. The frequency of load peaks is set by the spacing of the primary coils and the HGEV speed. The frequency of the profile, with 16 HGEVs travelling at  $24.5 \text{ ms}^{-1}$ , is  $\sim 2.48\text{Hz}$  with a ramp time of  $\sim 41\text{ms}$ . Each HGEV initiates 5 load cycles in the AC-AC converter. The time between the 5 load cycles is  $\sim 0.67\text{s}$  set by the HGV length, minimum HGEV spacing and speed. This represents a worst case for

constant vehicle velocity, as this corresponds to vehicles spaced at the Highway Code two seconds minimum moving at a constant speed of 55mph.

Another scenario could introduce higher power requirements, where HGEVs are moving at very low speeds, tightly packed together and then accelerating suddenly.

It is recommended that in future trials, a slow moving, but quickly accelerating, densely packed HGEV fleet scenario is analysed to assess the associated peak power requirements.

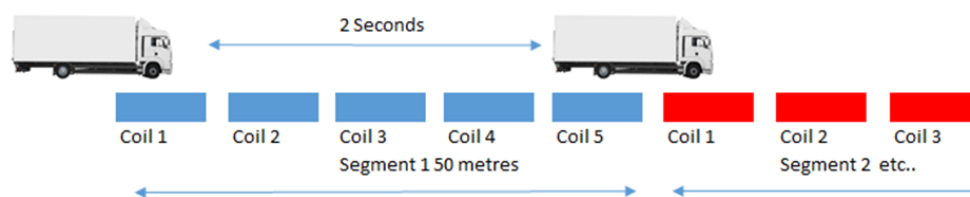


**Figure 47: Illustrative example of a load AC-AC DWPT converter load profile for a HGEVs travelling at 55mph or  $24.5 \text{ ms}^{-1}$ .**

#### 7.4.2.1 Vehicle speed, spacing and coil activation

In the illustration, each AC-AC converter supplies 50m of roadway, with a peak demand of 253kVA. If each coil, plus spacing, is 10m then each convertor supplies 5 of these coils, and it is essential that only one of the coils is energised at a time, otherwise the AC-AC converter will be overloaded. At 55mph, ( $24.5\text{ms}^{-1}$ ) the vehicle will traverse the 50m in 2.04s, so if a second vehicle is two seconds behind, plus the length of the HGEV, then it will be able to pick up power from the segment, because the HGEV secondary coil to secondary coil spacing is greater than 50m.

The 2 second rule means the gap between HGEVs secondary coils is given by  $L_{\text{gap}} = V_{\text{HGEV}} \cdot 2 + L_{\text{HGEV}}$ . If  $L_{\text{HGEV}}$  is 16.5m, then any speed less than 37mph ( $16.75\text{ms}^{-1}$ ) causes  $L_{\text{gap}} < 50\text{m}$  and a following HGEV will not be able to pick up power; this is due to a coil already being utilised in that DWPT segment by another HGEV, even though each vehicle will draw less power at these lower speeds. Any speed greater than 37mph increases  $L_{\text{gap}}$  above 50m and the DWPT can satisfy all moving vehicles.



**Figure 48: Illustration of HGEV vehicle spacing**

#### 7.4.2.2 Power quality

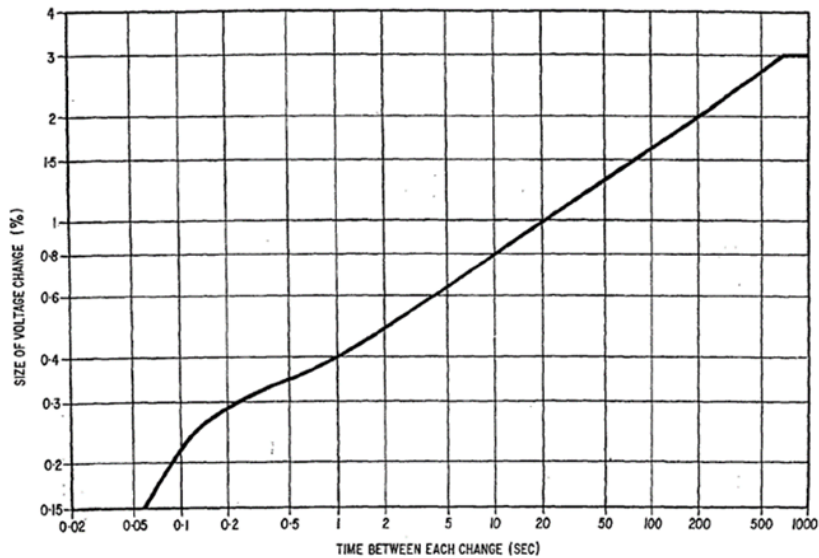
The addition of a DWPT system on to Distribution Network has the potential to impact significantly on the existing infrastructure. As a result, a network impact study assessment forms a part of this feasibility study. Several options of network configuration exist; however, in order to narrow the options down it is worth considering the effect of 'flicker' as described in Engineering Recommendation (ER) P28.

ER P28 is based on variation in brightness, as perceived by the human eye, due to voltage changes in Tungsten filament lamps, which were the most sensitive lighting source at the time of publication of ER P28 (1989). A 3% general maximum voltage change limit is applied in ER P28, which stems from the accepted practice of controlling excessively low system voltages.

Large peak loads, with short ramp times, can lead to sudden voltage drops which can affect other customers that are connected on the same circuit. The recommended limit for the maximum size of % voltage change,  $V_D$ , with respect to the minimum time between occurrences,  $\Delta T_{\min}$ , is given in Figure 49. For the worst case scenario of 16 HGEVs per km, it is shown that for  $\Delta T_{\min}=2.68\text{s}$ , a limit of  $V_D=0.55\%$  applies. In order to comply with stage 2 in ER P28, the short term flicker severity is  $P_{st}\leq 0.5$ , with no requirement to check the existing background flicker severity at the point of common coupling. The value of  $P_{st}$  depends on network location and other customers on the same feeder. The value of  $P_{st}$  at any point on the network can be calculated through network modelling or having a flicker meter placed in the network to record to voltage profile at a high sampling rate.

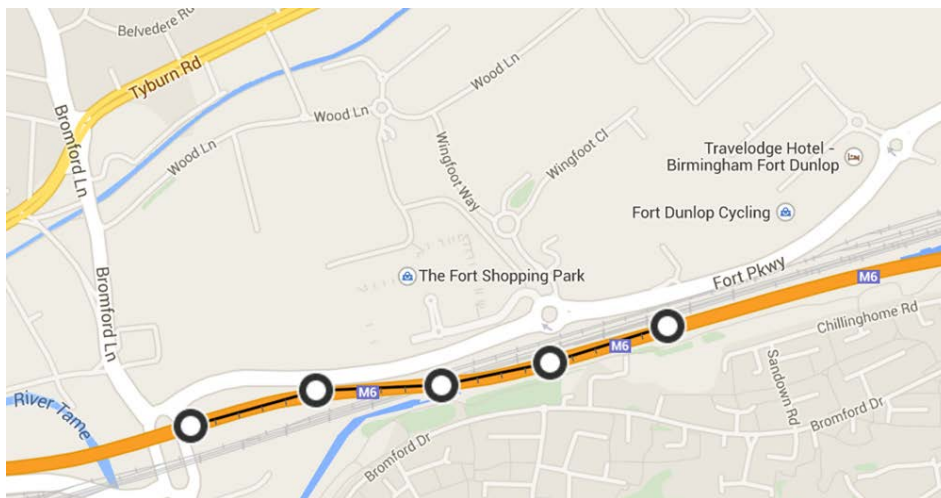
The DNO will conduct a flicker analysis when considering any application to connect new customers, in order to assess  $V_D$  and  $P_{st}$ . With large 'peaky' loads, as seen in Figure 47, it is likely that the DNO will opt to connect a DWPT system at HV levels, and install a new section of isolated network or simply allow a private network connection at that point. This would minimise network effects on quality of supply for other network customers, as the size of  $V_D$  will be lower.

Therefore, the higher the voltage at the PoC, the lower the distribution or transmission network impact on other parts of the network. This is a major consideration for the DNO or Transmission Network Operator (TNO) and the DNO is likely to want to isolate part of the DWPT supporting network from their other network assets. This would involve installation a new section of network, connected to existing assets, at the high voltage level.



**Figure 49: Recommended limits for the size of step voltage changes with respect to the time between each change.  $P_{st}=0.5$**

To select a grid supply point, the same section of motorway, between junction 5 and junction 6, in the West Midlands, is considered, shown in Figure 50. It begins where Bromford Lane intersects with Fort Parkway and ends 1km east of that point along the M6. This location lies very close to sizable commercial and industrial area with numerous 11kv/400V distribution substations and two 132/11kV primary substations, Erdington and Dunlop.



**Figure 50: The 1km stretch of road network studied is situated between Junctions 5 and 6 on the M6. The total distance between these two junctions is ~ 4.5km. (Image courtesy of Google Maps)**

The 11kv/400V distribution substations are of insufficient capacity for a 4.04MVA load, though they are likely to have sufficient capacity for at least 1 AC/AC converter load. Due to anticipated network effects, it is likely to be necessary to run a new network from either Erdington or Dunlop using 4MVA capacity from an existing or new 132/11kV transformer. A major cost when installing new sections of network is the civils work required to lay new cable. To minimise the length of cable run and provide some system security against faults, a single legged HV Ring Main Unit (RMU) is assumed to be

installed at the primary substation, with 11kV HV cable run in a ring main connecting four 1MVA 11/400V distribution substations as shown in Figure 50.

### **7.4.3 Network modelling**

The network model is based on a new network laid from the Erdington 132kV/11kV primary substation to four 11kV/0.433kV 1MVA transformers. All network data is contained in Appendix G and has values in line with the E.ON Central Networks Network Design Manual for the elements used. All input network values can be found in Table 48 to Table 51.

Fault levels and network impedances at the network supply point were provided by WPD and can be seen in Table 51. The HV cable lengths are approximately 1.5km from the primary substation to the HV/LV substations, assuming that a cabling arch over the rail line can be used for the 11kV cabling. The HV/LV substations are spaced apart by 250m. The first and last road segment will be 125m west and east from the first and last substation, assuming that the DWPT system is placed on the Eastbound side of the motorway. The LV (Low Voltage) cabling from the LV busbar to the segment AC/AC converter has not been included in the IPSA (Interactive Power System Analysis) model.

Load flow and a fault level assessment were carried out using the network model, with results shown diagrammatically in Figure 61, Figure 62 and Figure 63. For the load flow analysis, four loads per LV busbar are drawing 253kVA at 0.95 power factor. All voltage levels remain within statutory limits at each point of the network at both the 11kV and 0.4kV voltage levels. The maximum power drawn through each transformer is 1.041MVA at a 0.93 power factor. At a transformer tap setting of -2.5%, the LV bus bars are close to a nominal voltage with a voltage of 0.398kV. The results displayed in Figure 61 show a transformer setting of 0% at worst case HGEV loading. The power drawn at the primary substation is 4.142MVA at power factor of 0.94, which accounts for power losses in network assets. No power flows through the LV cabling, due to the LV breakers being set as Normally Open Points (NOPs).

Fault level calculations have been carried out to replicate both 'Break' and 'Make' fault level conditions, in line with standard UK distribution network practice. The 'Make' fault level has been calculated as peak fault current at 10ms (Figure 62) and the 'Break' fault level as the symmetric RMS (Root Mean Square) fault current at 100ms (Figure 63). Prospective three phase fault current for both 'Break' and make conditions have been calculated and the results are presented in Table 26.

**Table 26: Three phase fault level results for all busbars**

Name of Busbar	Break Fault Level AC Magnitude (kA)	Make Fault Level $\phi$ – Red AC Magnitude (kA)
400 V - 1	3.816	5.593
11 kV - 2	4.200	6.143
11 kV - 3	4.200	6.144
11 kV - 4	4.201	6.144
11 kV - 5	4.200	6.143
11 kV - 1	4.203	6.149
400 V - 2	3.817	5.593

#### 7.4.3.1 Network costs

All costs for this Section have been provided by WPD and do not include the cost of digging and back filling trenches, which can be a significant cost to any infrastructure project. Figure 46 shows three different network ownership scenarios. These translate to three different costs of connection scenarios due to different levels of DNO expenditure on network assets required to connect the DWPT system. This section shows costs provided by WPD, the Distribution Network Licence holder for the West Midlands area.

#### Option A

Option A involves the minimum levels of network ownership by the DWPT operator and a one off PoC cost. The DNO would own and charge for approximately 1km of 11kV 300mm<sup>2</sup> aluminium cable, four 1MVA substations, 3 link boxes, 1km of 300mm<sup>2</sup> Combined Neutral and Earth (CNE) LV cable and 20x3 phase supply services, with total costs shown in Table 27.

**Table 27: Cost table with WPD providing HV and LV infrastructure to the meter points in option A**

<b>Item</b>	<b>Description</b>	<b>Cost</b>
<b>LV Cable</b>	1km of 300mm <sup>2</sup> Combined Neutral and Earth (CNE) LV cable, ducted, with civils costs excluded. Includes cost for 3 off LV link boxes.	£25,000
<b>HV Cable</b>	1km of 11kV 300mm <sup>2</sup> aluminium cable, ducted, with civils costs excluded.	£30,000
<b>4 off 1MVA substations</b>	11kV/0.4kV 1 MVA substations.	£120,000
<b>HV cabling Security of Supply</b>	A length of HC cable laid from the primary substation and an extra Ring Main Unit (RMU) provides security of supply and back feeding capability in case of a network fault.	£200,000
<b>20 off 3 Phase Supply</b>	250kVA 3 phase service (cable and cut-out).	£50,000
<b>Total Cost</b>		£425,000

### *Option B*

Option B lowers the number of HH meters required from 20 to 5 per km of DWPT SRN. The meters are placed on the LV side of the HV/LV substation, meaning that the HV/LV substation is the responsibility of the DNO. This option heavily reduces the metering requirement, while only incurring a small increase in LV asset ownership.



**Table 28: Cost table with WPD providing HV to the meter points in option B**

<b>Item</b>	<b>Description</b>	<b>Cost</b>
<b>HV Cable</b>	1km of 11kV 300mm <sup>2</sup> aluminium cable, ducted, with civils costs excluded.	£30,000
<b>4 off 1 MVA substations</b>	11kV/0.4kV 1MVA substations.	£120,000
<b>HV cabling Security of Supply</b>	A length of HV cable laid from the primary substation and an extra Ring Main Unit (RMU) provides security of supply and back feeding capability in case of a network fault.	£200,000
<b>Total Cost</b>		£ 350,000

*Option C*

Option C would require roughly 1km of HV cable laid from the nearest primary substation, a new primary breaker and a new HV HH metered Ring Main Unit (RMU) fed from a single HV leg, which would provide no redundancy in case of a fault. The interface between the DNO and the private network would require a private building or large enclosure to house the RMU, protection equipment and HH meter.

**Table 29: Cost table with WPD providing HV to the meter points in option C**

<b>Item</b>	<b>Description</b>	<b>Cost</b>
<b>HV cabling Security of Supply</b>	A length of HV cable laid from the primary substation and an extra Ring Main Unit (RMU) provides security of supply and back feeding capability in case of a network fault.	£170,000
<b>Building Cost</b>		£10,000 - £20,000
<b>Total Cost</b>		£ ~190,000

**7.4.4 Stakeholder cooperation**

In order to identify how working arrangements with the local Distribution Network Operators will be established, the following sources have been reviewed (see Appendix H for further details):

- Planning Act 2008
- National Infrastructure Plan 2013

- Energy National Policy Statements for Electricity Networks
- Transport National Policy Statements for Roads & Rail Networks
- GB Electricity Distribution Licence Agreements.

Similar cooperation between “Regional” Electrical Network Operators and National Operators, notably the Rail Industry, has already been established and this cooperative model has been referenced as an output of this work.

#### **7.4.5 Outputs**

A ‘typical’ electrical network system study, based on the outputs from Section 7.1 and assumed designs for a given section of the SRN, has been carried out. This has highlighted the areas of significant change and impact on the existing electrical infrastructure.

Recommendations have been given regarding working with cooperating partners / stakeholders within existing planning legislation and operating agreements.

### **7.5 Qualified inputs for a discounted cash flow model**

Using the outputs from Sections 7.2 and 7.3, the process for charging for consumption of electricity by road users by the DWPT provider on behalf of Highways England can be informed by development of a Discounted Cash Flow (DC) model. To this end, high level input variables are identified in Section 7.5.1.

Section 7.5.1.1 contains a discussion on the sensitivities that will affect future cash flows such as DWPT user penetration, purchase cost of energy and DWPT road user electricity charge levels. It also provides recommendations as to how a DCF model can be developed with functionality that will allow the Highways England to calibrate the high level input variables, in order to identify the likely per kWh or per km cost to charge DWPT road users for using the DWPT SRN.

#### **7.5.1 High level input variable identification and qualification**

The high level input variables identified are: design/development, infrastructure costs/initial capital expenditure (including technological life of charging assets), installation, indirect Costs (IDC) & Commissioning, Operation & Maintenance (O&M) costs.

##### *7.5.1.1 Design and development*

Where significant uncertainties and impacts on future cash flows are involved, cost benefit analyses may be useful. The most pressing decisions at this stage of the project are around the metering arrangements and the selection of the network ownership.

A fair accounting of project costs should apportion “one-off” R&D and demonstration costs to the initial R&D budget and not to the business DCF (Discounted Cash Flow) valuation. After the R&D phase and a sufficient demonstration project, subsequent project specific design costs can be added to the DCF model.

Following the feasibility phase of the project towards an active demonstration, all design decisions must be taken. Where significant uncertainties and impacts on future cash flows are involved, cost benefit analyses should be conducted. The most pressing

decisions at this project stage are around the metering arrangements and the selection of the network ownership.

Metering considerations revolve around whether the meter should sit in the vehicle, at the road side or both, and whether the billing units should charge per unit length of DWPT SRN travelled by a user or per kWh hour of energy consumed. This will affect the design of meters, sensors and remote telemetry unit (RTU) requirements.

Network ownership considerations involve where in the network the supply meter(s) should lie. This affects who designs, builds, maintains and operates the network past the main HV Ring Main Unit (RMU). Both design considerations have the potential to impact future cash flows.

Table 30 shows the likely DCF input variables for DWPT system design and development. The costs associated with the items are mainly one-off costs, but making informed decisions at this early stage will affect future costs.

**Table 30: Design and development cost items for DWPT system installation**

<b>Input Variable (Cost Item)</b>	<b>Description</b>	<b>Lifetime</b>
<b>Design</b>		
<b>Selection of metering system</b>	The selection of the metering system should be done at the design stage. In-road or in vehicle; billed/kWh or per/km based on vehicle type. This could include a cost benefit analysis.	N/A
<b>Selection of Network ownership</b>	Decision on whether the electrical supporting network should be private (DWPT provider owned) owned or DNO owned. This could include a cost benefit analysis.	N/A
<b>System specification and design</b>	Following the choices on metering and asset ownership, the system can be design physically and electrically: what equipment, what location, configuration etc.	N/A
<b>Geographic/Electrical CAD plans</b>	The records with positions of equipment and any supporting private network should be produced at this stage and updated when system modifications/upgrades take place.	15-20 years
<b>Design and selection of back-office system, supporting software of database</b>	The design of the back-office system from concept to how it will be implemented in practice, along with the procurement of database software and data security.	N/A
<b>Project management and planning</b>	To bring all the design and development elements together, the various tasks and responsibilities will need to be coordinate to compete the stage on time and on budget.	N/A
<b>Design of communications, sensor and metering systems</b>	How the vehicles will be identified, energy use logged and attributed to each DWPT user should be finalised and designed at this stage, following inputs from the selection of the metering system.	N/A
<b>Administration Cost</b>	The production and filing of documents such as CAD drawings, design philosophy reports, equipment specification sheets, method statements and risk assessments	N/A
<b>Development</b>		
<b>Safety case</b>	This should be conducted well in advance of the installation and should inform the design stage.	N/A
<b>Back-office software</b>	Selection and market research into the most appropriate software and support systems should be done at this stage. This may involve a cost benefit analysis if cost is prohibitive.	N/A
<b>Support Staff training</b>	Key staff need to be trained on how to use the billing systems, databases and customer engagement. A recruitment and training plan should be developed at this stage.	2-3 yrs based on staff turnover

7.5.1.2 *Infrastructure costs & installation CAPEX*

From the information available to the project team, it appears that Highways England does not own any private electricity network. In the case of DWPT installations, this is likely to remain the case, with the exception of the cable runs from the charging coils to the inverters. Therefore, no cost items for capital expenditure (CAPEX) and installation have been entered in Table 31 based on this assumption. The infrastructure costs and installation CAPEX have been broken down into road work, DWPT system installation, DN connection, and ancillary equipment as shown in Table 31. The types of cost in this table are mainly one-off costs. The lifetime of the DWPT system is a suitable period for assessing the discounted cash flows as the replacement of this system is a major business cost. For this feasibility study this has been assumed to be 25 years.

**Table 31: Infrastructure and CAPEX cost items for DWPT system installation**

<b>Input Variable (Cost Item)</b>	<b>Description</b>	<b>Lifetime</b>
<b>Road work</b>		
<b>Traffic management labour and equipment</b>	Includes traffic cones, road works signage, average speed cameras, temporary barriers and lane construction etc.	N/A
<b>Project management and planning</b>	Before and during the installation project, several months of planning will be required which will involve procuring goods and services from third parties to set up a safe site to carry out the DWPT installation on the SRN. This also involves writing method statements and risk assessments to ensure compliance with H&S and environmental regulations.	N/A
<b>Road excavation labour and equipment</b>	Lay the DWPT system in the road, excavation and removal of roadway material will be required. This will involve the use of heavy machinery and skilled operators.	N/A
<b>Road resurfacing, materials, labour and equipment.</b>	Returning the road surface to a fit state will require infill of concrete and relaying the road surface. This will involve the use of heavy machinery, skilled operators and materials.	25 years
<b>Road painting and temporary road side signage materials and equipment.</b>	To guide traffic during the installation phase, temporary signage and lanes will need to be put in place. This may involve removing existing paint and repainting the road surface.	N/A
<b>Use of Highways England roadside vehicles</b>	A 1km long site will require the use of Highways England fleet vehicles to transport site personnel.	
<b>DWPT System Installation</b>		

<b>Input Variable (Cost Item)</b>	<b>Description</b>	<b>Lifetime</b>
<b>DWPT Product</b>	This includes all equipment that is to be laid within the road, plus supporting equipment, such as power electronics and control systems, i.e. all equipment supplied by the DWPT manufacturer.	25 years
<b>DWPT Installation inc. labour and materials</b>	This includes the cost of labour and specialist ancillary equipment required, but not supplied by third party contracts or the WPT manufacturer.	N/A
<b>Cable run excavation labour and materials</b>	The cabling from the coils to the road side cabinets would be included in the DWPT product costs. The cost for excavation, cable laying, and back filling, heavy machinery, any ducting and labour would have be accounted for.	25 years
<b>Project management and planning</b>	After a space for installation has been made by the road works, the installation of the DWPT system needs to be planned and managed, including the development of Risk Assessments and Methods Statements and well as procuring goods and services from third parties.	N/A
<b>DN Connection</b>		
<b>POC Costs</b>	Non contestable works costs will be supplied by the DNO. These costs will be for connecting the DWPT to the DNO network. Contestable works will also need to be paid for and carried out by either the DNO or a third party provider.	N/A
<b>Network Reinforcement Costs</b>	These costs will apply if there is not enough spare network capacity in the area of installation. The DWPT provider will therefore have to bear some of these costs.	N/A
<b>Project Management and Planning</b>	The DNO must be liaised with, provided with equipment data and may ask to witness asset connections to their network. Managing these tasks will be a cost to the project.	N/A
<b>Ancillary Equipment</b>		
<b>Roadside cabinets</b>	The procurement and installation of road side equipment housing. This will house any ancillary equipment.	N/A
<b>Energy meters</b>	Suitable energy meters must be procured and installed. Assessment of the number and position of meters required would be informed by the system design stage.	N/A

<b>Input Variable (Cost Item)</b>	<b>Description</b>	<b>Lifetime</b>
<b>Road side &amp; in road sensors</b>	The system design stage will inform the number, type and position of sensors required for the AVID system and DWPT coil activation and power control.	N/A
<b>Communications equipment</b>	The system design stage will inform the required communication equipment (RTUs) required to relay charging data to the DWPT back office.	N/A
<b>IT equipment, software and database plus support staff recruitment</b>	This will concern the support equipment and software required for the billing system and data security.	N/A

### 7.5.1.3 Indirect costs and commissioning

The electrical load caused by DWPT is likely to have a novel profile, not encountered before by a UK DNO. They are therefore very likely to wish to witness the DWPT system commissioning and testing before allowing normal operational use of the DWPT system on their DN. Therefore a test schedule will need to be produced and followed during the commissioning phase and any requested data regarding equipment specification will have to pass to the DNO. Liaison of this nature will involve significant time and resources and should be factored into the DCF model. Table 32 shows a summary of significant cost items for commissioning. Also included are indirect costs such as DWPT provider company overheads and site specific costs for DWPT system installation.

**Table 32: Indirect & commissioning cost items for DWPT system installation**

<b>Input Variable (Cost Item)</b>	<b>Description</b>	<b>Lifetime</b>
<b>Commissioning Costs</b>		
<b>Witness testing of electrical installation (staff and third party costs)</b>	To commission the entire DWPT system, the system must be energised and tested to ensure all equipment functions as designed. The maximum power drawn from the DN may be tested using moving test vehicles. Staff costs and commissioning equipment will need to be factored in.	NA
<b>Test vehicle(s) hire or purchase cost</b>	Depending on how long the tests are to be carried out, test vehicles will need to be fitted with secondary coils, on-board meters and other diagnostic equipment.	NA
<b>Staff Labour for offsite system checks</b>	Back office staff may be required to support onsite staff during tests to check the metering and billing system is functioning as designed.	NA

<b>Input Variable (Cost Item)</b>	<b>Description</b>	<b>Lifetime</b>
<b>Project Management and Planning</b>	System commissioning testing will require planning of a testing schedule, the development of Risk Assessments and Method Statement and liaison with the DNO. This cost item accounts for staff time and equipment required to achieve these tasks.	NA
<b>Indirect Costs</b>		
<b>Administrative</b>	The running of Highways England requires day to day running of the business. Part of this overhead should be a cost item to the DWPT project.	NA
<b>Advertising and marketing</b>	Public and stakeholder engagement will require an advertising and marketing budget for the project initiation.	NA
<b>Installation staff expenses</b>	Staff expenses such as hotels, meals and hire car use will need to be accounted for within the DCF model.	NA
<b>Site security</b>	During construction, expensive pieces of equipment needing to be left on site may require protection from theft.	NA
<b>Equipment Storage</b>	The procurement of shipping containers for equipment storage.	NA
<b>Liability insurance</b>	An insurance requirement to protect the Highways England from liabilities imposed by lawsuits and similar claims for incidents at site involving members of the public.	NA
<b>Roadside assistance</b>	The cost of providing roadside assistance to vehicles broken down in the 1km stretch of roadwork.	NA

#### 7.5.1.4 Operation & maintenance (O&M) costs

The DWPT has components that will not last the lifetime of the system. The discounted cash flow requires equipment life time data and likely future replacement costs. The costs should then reoccur in the model cash flows at regular intervals. Table 33 shows a range of cost items requiring replacement or maintenance. Non equipment related operational costs are also included.

**Table 33: Summary of likely operation and maintenance costs**

<b>Input Variable (Cost Item)</b>	<b>Description</b>	<b>Lifetime</b>
<b>Equipment Replacement</b>		
<b>Energy Meter replacement</b>	Meters will likely need replacing at least once during the DWPT system lifetime	15 years



<b>Input Variable (Cost Item)</b>	<b>Description</b>	<b>Lifetime</b>
<b>DWPT primary coil replacement</b>	Due to road side vibrations, weather conditions and heating cycles, the induction coils will eventually need replacing.	30 years
<b>DWPT Road resurface and repair</b>	It is unclear whether the road surface would be treated as a conventional road and have maintenance funded through general taxation. A contingency cost should be included.	15 years
<b>Cable replacement</b>	Due to heating cycles and the elements, cabling and jointing will eventually need replacing.	40 years
<b>Traffic management labour and equipment</b>	Any work carried on and at the road side will require traffic management, including traffic cones, road works signage, average speed cameras, temporary barriers and lane construction etc.	5 years
<b>DWPT power electronics replacement</b>	All power electronics equipment fails after a certain period. Replacement time is variable.	15 years
<b>Communications equipment replacement</b>	Communications equipment will likely contain power electronics which have a lifetime similar to other DWPT power electronics on the SRN.	15 years
<b>Charging control equipment replacement</b>	Coil activation relays will also eventually need replacement.	15 years
<b>Road side &amp; in road sensors</b>	Due to the elements and impacts from vehicle caused vibrations, in road and road side sensors will eventually need replacement.	20 years
<b>Repainting road surface and signs</b>	Due to wear and tear on the road surface caused by passing vehicles, the DWPT surface will need to be repainted for DWPT users.	5 years
<b>O&amp;M Project management</b>	Equipment replacement will require planning, procurement and the development of method statements and risk assessments.	NA
<b>Operational</b>		
<b>Advertising and marketing</b>	In order to keep attracting new DWPT users and to ensure penetration growth of DWPT enabled vehicles, advertising to private and commercial SRN users' needs to be carried out.	Ongoing
<b>Complaints and customers services</b>	Any commercial entity directly dealing with a customer base will have complaints. Provision for dealing with customer's issues will be an ongoing business cost.	Ongoing
<b>Metering and billing administration</b>	This is a cost of business to recover revenues and DWPT user debts.	Ongoing

Input Variable (Cost Item)	Description	Lifetime
<b>DWPT system inspection and testing</b>	A regular inspection and testing regime should be accounted for in the DCF model in order to show that system is safe to use and is working as designed.	Ongoing

## 7.5.2 Cost estimates

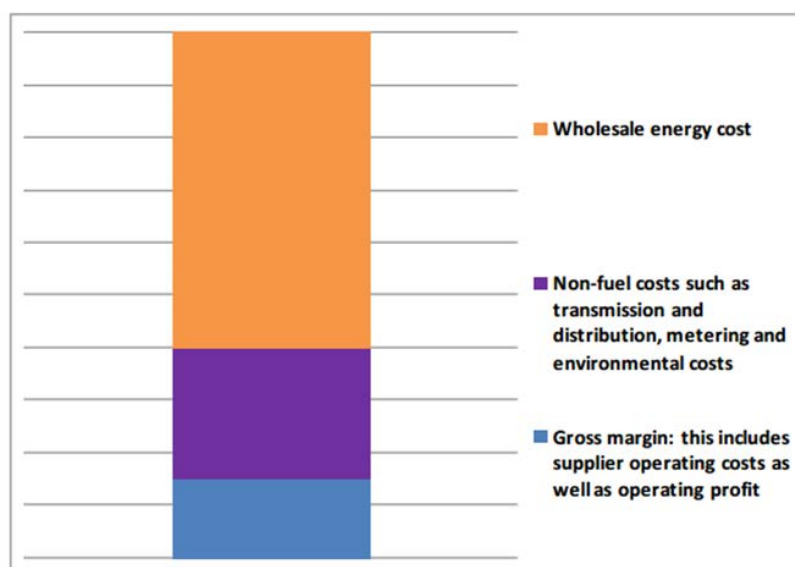
### *Future operating costs*

The cost of business for the DWPT service company will involve salaries, cost of electricity provided, and general administrative expenses as well as maintenance and replacement costs. For a full list see Table 33. Operating cost changes into the future can be multiplied by the Retail Price Index and informed by price changes in supplied equipment. Sensitivity analysis of the changes in Operation & Maintenance costs should be conducted to assess how sensitive Free Cash Flows are to operating cost assumptions.

#### 7.5.2.1 *Estimated purchase cost of energy*

The UK electricity market is a wholesale and retail electricity market. The role of the wholesale market is to allow trading between generators, retailers and other financial intermediaries both for short-term delivery of electricity (spot price) and for future delivery periods (forward price). The wholesale electricity market spot price has been historically volatile. This market price is reduced in volatility, on behalf of the retail consumer, when the supplier participates in hedging in the wholesale electricity market.

The retail cost of electricity is linked to the wholesale cost of electricity, but it is not a direct relationship. Figure 51 shows the average retail customer bill breakdown, which shows a significant proportion of a consumer's bill goes towards meeting wholesale costs. Historically, non-fuel costs have remained relatively stable and the gross margin enjoyed by suppliers has fluctuated between £50 and £130 per customer/year.



### **Figure 51: Average retail consumer bill breakdown (ofgem, 2009)**

Wholesale electricity costs are volatile and can vary sharply from day to day. Retail consumers have historically preferred stability in energy prices, preferring the protection from electricity market volatility through suppliers forward-purchasing electricity. To pass this benefit on to retail consumers, Electricity Suppliers use various hedging strategies which generally have two effects:

- Smoothing out changes in wholesale electricity costs
- Introducing a time lag between the wholesale and retail price of electricity.

The UK faces a combination of factors which are likely to increase energy prices. These include increasing dependence on gas imports, ambitious environmental targets and the need to replace ageing power stations.

The amount of electricity the UK produces from gas is likely to increase to around 60 per cent between now and 2020 as coal-fired power stations close. This will come at a time when many European and Asian countries will also need more gas. This could put pressure on wholesale prices, depending on whether new sources of supply become available globally. These will all put increasing pressure on the wholesale electricity price over the medium and long term. Conversely, energy consumption has generally fallen, in part due to more efficient use, which reduces typical retail bills.

Due to the previously discussed uncertainties, it is not possible to predict the changes in wholesale costs throughout the lifetime of the DCF model period. It is therefore recommended that a sensitivity analysis be undertaken, over a 25 year DCF modelling period, using annual wholesale electricity price increases between 4 – 8%.

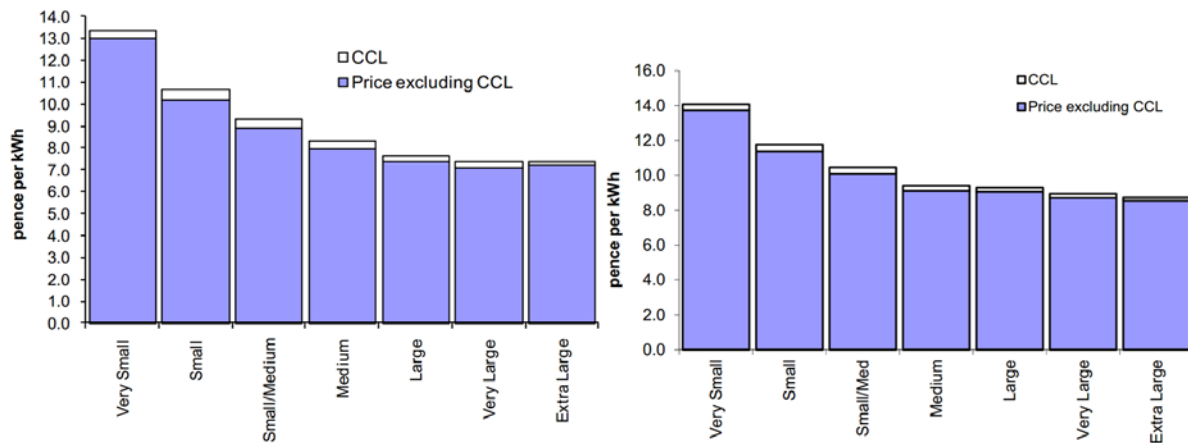
Assuming that the average power demand over 24 hours from 1km of the DWPT system is 0.2MVA, including off-peak periods, the annual energy consumption would be ~1,800MWh/yr.

In Section 7.2, the cost breakdown of a commercial electricity bill was discussed and an illustrative example shown for a business operating in the WPD DN area. The cost break down included the non-domestic retail cost of electricity.

This consumption rate classifies a 1km DWPT SRN section, covered by a single meter, as a small to medium energy consumer, which will face marginally higher unit rates than the largest consumers of electrical load.

Figure 52 shows that there is a descending unit cost of electricity between the large and small electricity consumers. This difference between the unit rate for small consumers and the medium or large consumer rate is the margin that a DWPT provider can exploit in their DWPT user-charge. This margin could be increased (i.e. to a DWPT user-charge above the very small consumer unit rate) due to the benefits of charging on the move. This benefit is greater for larger businesses like haulage companies.

How much this benefit allows DWPT charges to be set higher than the small consumer retail rate should be assessed in the R&D stage of the project.



**Figure 52: Average UK non-domestic electricity prices Q4 2011 (on the left) and 2014 (on the right). Small 20 – 499MWh/yr, Small/Med – 500 – 1,999MWh/yr, Med – 2,000 – 19,999MWh/yr, Large - 20,000 - 69,999MWh/yr, V Large – 70,000 – 150,000/yr. (Source Quarterly Energy Prices, Office of National Statistical, 2012)**

#### 7.5.2.2 Network ownership

Taking supply from the DNO at a higher voltage level reduces:

- The likelihood of system disturbances from harmonics and flicker affecting other connected customers
- The DNO Point of Connection (POC) costs
- The Distribution Use of System (DUoS) charge.

However, it increases:

- The capital costs of the DWPT system and private network installation (due to additional transformers and switchgear being paid for by the DWPT operator and not the DNO)
- O&M costs (since the O&M of all this equipment will have to be carried out by the DWPT provider or its contractors and not the DNO).

Conversely, taking supply at a lower voltage from the DNO increases POC costs and DUoS charges, but reduces O&M because the DNO is responsible (and recovers this through DUoS charges).

Whatever the approach, similar values of capital and operational expenditure will occur mainly through either POC and DUoS charges, or private network installation and O&M costs. The choice will come down to whether the DWPT operator wishes to be responsible for carrying out and bearing the risk of designing, building and managing the private network. The advantages of private network ownership at high voltage levels are that the DWPT operator will benefit from any cost savings and has control over the design and access of the supporting network.

To perform a cost benefit analysis, detailed costs for private network ownership, at varying voltage levels of private network, need to be carried out as part of the R&D stage of the project.

### 7.5.2.3 Security of supply

As part of a DNO license, the DNO must plan and develop its Distribution System in accordance with a standard not less than that set out in the Energy Networks Association (ENA) Engineering Recommendation (ER) P.2/6. Failure to comply with ER P.2/6 effectively means that the DNO is in breach of its license. One aspect of ER P.2/6 is the minimum restoration time following a fault.

Electricity consumers and generators are grouped together in groups known as Group Demand<sup>10</sup>. Group demand is currently ill defined. However, each DNO has a methodology when grouping loads together, which is used to inform network design considerations. The DNO's estimate of the maximum demand of the group being assessed for ER P2/6 compliance sets the minimum supply restoration time. For an isolated 1km DWPT section, it is possible for the load to be classed as a Type B supply.

Table 34 shows that a restoration time of within 3 hours applies for the Group Demand of up to 12 MW minus 1 MW, which represents the worst case reconnection time for 1 km of DWPT SRN connected via a single meter. Combining more sections of SRN under one meter could lead to a worst case scenario of a 15 minutes outage, i.e. a 16.2MVA capacity for 4km of DWPT SRN (a class C supply type). Alternatively, multiple meter points could be used, with a commercial contract with the DNO ensuring a quick restoration of supply in case of a fault. This would probably lead to increased DNO charges in return for the lower system restoration time requirement. Regardless of the supply restoration time, a fault may still occur on a network owned by the DWPT SRN provider, which will need to be cleared by them.

**Table 34: Table 1 from ER P.2/6**

Class of supply	Range of Group Demand	Minimum demand to be met after		Notes
		First Circuit Outage	Second Circuit Outage	
A	Up to 1MW	In repair time: Group Demand	Nil	Where demand is supplied by a single 1000kVA transformer the "Range of Group Demand" may be extended to cover the overload capacity of that transformer.
B	Over 1MW and up to 12MW	(a) Within 3 hours: Group Demand minus 1MW (b) In repair time: Group Demand	Nil	
C	Over 12MW and up to 60MW	(a) Within 15 minutes: Smaller of (Group Demand minus 12MW); and 2/3 of Group Demand (b) Within 3 hours: Group Demand	Nil	Group Demand will be normally supplied by at least two normally closed Circuits or by one Circuit with supervisory or automatic switching of alternative Circuits.
D	Over 60MW and up to 300MW	(a) Immediately: Group Demand minus up to 20MW (automatically disconnected) (b) Within 3 hours: Group Demand	(c) Within 3 hours; For Group Demands greater than 100MW: Smaller of (Group Demand minus 100MW); and 1/3 Group Demand (d) Within time to restore arranged outage: Group Demand	A loss of supply not exceeding 60 sec is considered as an immediate restoration. The Recommendation is based on the assumption that the time for restoration of Group Demand after a Second Circuit Outage will be minimised by the scheduling and control of planned outages, and that consideration will be given to the use of rota load shedding to reduce the effect of prolonged outages on consumers.
E	Over 300MW and up to 1500MW	(a) Immediately: Group Demand	(b) Immediately: All consumers at 2/3 Group Demand (c) Within time to restore arranged outage: Group Demand	The provisions of Class E apply to infeeds to the distribution system but not to systems regarded as part of the interconnected Supergrid to which the provisions of Class F apply. For the system covered by Class E consideration can be given to the feasibility of providing for up to 60 MW to be lost for up to 60 seconds on First Circuit Outage if this leads to significant economies. This provision is not intended to restrict the period during which maintenance can be scheduled. The provision for a Second Circuit Outage assumes that normal maintenance can be undertaken when demand is below 67%. Where the period of maintenance may be restricted paragraph 3 of section 2 applies.
F	Over 1500 MW	In accordance with the relevant transmission company licence security standard		

<sup>10</sup> Group Demand is presently defined as the sum of the Measured and Latent demands, where Latent demand is the increase in demand which would be observed if all distributed generation (DG) in the group were not producing any output.

Alternatives to DNO focused fault ride-through solutions include energy storage in the form of EES or back up diesel generators. Each scenario described here could form a basis for NPV comparisons, using DCF models with different inputs for each of the scenarios.

Input cost data for these scenarios could be gathered from DNO and energy storage manufacture quotes during the R&D stage of the project. At this point, decisions need to be taken on the level of security required for the DWPT supplies through a risk assessment on the effect of a power failure on motorway traffic being powered by the DWPT.

## 8 Preparing for off-road trials

The installation of new infrastructure into the road structure has many unknowns, hence it is important that these are investigated and the implications fully understood before any systems are installed on the road network.

This covers the development of laboratory and test track trials requirements. These trials are considered to be an important precursor to any on-road trials. It is presented in two parts:

- 1) Section 8.1 presents the requirements, with justification, for laboratory trials of the in-road components of a selection of DWPT systems. It is proposed that these trials are undertaken in a controlled, accelerated road assessment environment such as TRL's Pavement Test Facility (PTF). These trials will provide an in-depth understanding of the physical implications of installing wireless power transfer equipment in the road surface, particularly with respect to the potential deterioration of the road structure when realistic loads are repeatedly driven over the in-road equipment.
- 2) Section 8.2 presents the requirements for follow-on track trials. Assuming that the laboratory trials show that in-road DWPT equipment can safely be installed in the road surface, this section will go on to develop the requirements for track trials where real DWPT systems will be installed in a test track and trialled. The object of these trials concentrates more on the power transfer elements of the systems, but will also to a certain extent validate the findings of the laboratory trials for road installation and provide useful experience with implementing grid connections.

Before running any trials, irrespective of whether these are on-road, off-road or in a laboratory, it is a vital to undertake a risk assessment of the trial. This mitigates any risks to staff or equipment.

For a description of the DWPT system see Appendix D.

### 8.1 Laboratory trials

The aim of this section is to discuss suitable options for trialling DWPT systems in a laboratory environment and present the possible construction methodologies for each option.

The options presented can be divided into three categories:

#### 1. In-situ cast power systems

In-situ power systems are constructed in the field. There are different methods of construction, depending on whether a full lane width construction or a trench excavation and construction method is selected.

#### 2. Pre-cast power systems

These systems are constructed off-site and then transported to site. Two power supply systems have been considered for this approach. There are different methods of construction and installation for both of these systems, depending on whether a full lane width pre-cast slab or a trench pre-cast slab is selected.

### 3. Transition sections – In-situ/Pre-cast

Transition sections are the areas between the power supply systems that contain the aluminium pipes that

- Connect adjacent power supply systems
- Connect to roadside equipment.

The reason for proposing this section for trials is due to the presence of the aluminium pipes and the potential to cause weakness/movement in the surrounding pavement materials, which could lead to premature cracking and failure. Each of the options listed thus far can be sub-divided further into categories based on the proposed thickness of the overlaying asphalt layer:

- Thin Surface Course System (TSCS) only
- TSCS and binder course (100mm).

Previous experience with overlays to jointed concrete pavements suggests that the use of stress absorbing membrane interlayers (SAMI) or grid layer between the units and the asphalt layer(s) should also be considered. Alternatively, the use of a saw cut and seal in the asphalt surface above the joints in the layer(s) below should be considered.

## 8.2 Track trials

### 8.2.1 Overview of the track trials

The track trials are a precursor to a full on-road trial of selected DWPT systems on the strategic road network.

Test track trials should be designed to answer a number of specific research questions; these are:

- What are the implications of installing this type of equipment in the road surface? This will particularly investigate the effect of the installation on the normal functioning of the road, both during and after installation.
- How efficiently can power be transferred from the infrastructure to moving vehicles?
- What are the safety implications of using wireless power transfer in a dynamic environment? Including, risks from EMF and from driver behaviour being potentially influenced by the use of DWPT.
- What are the implications on the grid if this type of power transfer system is installed on a significant portion of the network?
- Does the evidence support the business case for the installation of DWPT systems on the SRN?

By investigating these issues in a track trial, it will be possible to go to a full on-road trial with reasonable confidence that the on-road trials will be successful and safe to implement.

Areas that cannot be fully addressed without off-road trials are:

1. Full understanding of safety issues under representative conditions



Although some evidence already exists to show the systems are safe, they have never been trialled in the UK motorway environment. Furthermore, apart from one system, no existing DWPT system fully meets the necessary emission limits for human exposure to magnetic fields. It is also difficult to be sure what limits are met without doing the necessary testing in the UK under controlled test track conditions. Before on-road trials of any system can be implemented, it is vital to ensure that these systems are thoroughly tested under controlled conditions.

2. Better understanding of issues associated with integration of systems under the road, including any impacts on road deterioration or integrity

There are no DWPT installations anywhere in the world that have existed for a sufficiently long time to determine what impact these installations have on the structural integrity of the pavement or how susceptible these systems are to deterioration after a prolonged period under the road surface, particularly in the motorway environment. It is crucial that these elements can be understood in detail before the feasibility of using such technology on the SRN can be determined. In order to achieve this, accelerated wear and degradation testing is necessary in a dedicated pavement test facility.

### **8.2.2 Safety**

It is critical to understand the safety risks associated with DWPT systems in order to determine whether their use on the SRN is feasible. If a fundamental safety flaw is identified that cannot be addressed cost effectively through further development, then such systems are unlikely to be suitable for use on public roads. TRL has identified a number of key safety areas and investigated the safety issues related to those, as described in more detail in the sub-sections below. No issues were identified that suggest this technology is not feasible. However, a number of issues were specifically identified as requiring off-road and on-road trialling in order to fully understand their implications for the feasibility of this technology.

A risk assessment was undertaken to assess the risks associated with the implementation, use, maintenance and decommissioning of DWPT. The risk assessment aims to identify the potentially hazardous events, the persons at risk, and the controls that will be considered and implemented, to ensure that risks are as low as reasonably practicable for the next stage of the research. The risk assessment will be used to conclude whether the control measures are likely to reduce the identified hazardous events sufficiently to proceed with further trials and testing, and whether there are any unacceptable risks that are unlikely to be controlled once additional research has further increased expert understanding of DWPT.

The risk decisions made are the expert opinion of the safety expert assessor, informed by relevant literature and the opinion and experience of specific technical experts. It must be noted that an additional risk assessment will be required prior to undertaking off and on road trials.

The high level hazard categories identified are:

1. Wireless magnetic field emissions in relation to human health
2. Driver behaviour in response to DWPT
3. Vehicle safety and reliability

4. Implications of primary systems under the road surface
5. Implications of road side equipment
6. Electrical safety
7. Environment
8. Stakeholder impact and compliance.

Below are summary findings from the risk assessment.

#### *8.2.2.1 Impacts of magnetic field emissions on human health*

DWPT systems operate using coupled magnetic fields. Precise limits exist in existing standards that limit the allowable human exposure to such fields in the frequency range where DWPT systems operate, up to 100kHz. These limits have been defined by the ICNIRP and have been adopted by the World Health Organisation (WHO) and the Health Protection Agency (HPA) in their guidelines. The stated limit for human exposure to a Magnetic field for systems operating in the frequency range 3kHz to 10MHz is  $2.7 \times 10^{-5} \text{T}$ <sup>11</sup>. This is applicable to all technologies currently being considered for DWPT<sup>12</sup>.

For the technologies selected for this feasibility study, no barriers associated with the risk to human health were identified which would prevent Highways England from proceeding to off-road trials.

#### *8.2.2.2 Impacts of magnetic field emissions on vehicle safety systems*

High-intensity alternating magnetic fields can have two effects on metallic parts of vehicles:

- A current can be induced in any conductors exposed to an alternating magnetic field. If these conductors are being used to carry important signals (e.g. the CAN bus), this could severely disrupt the vehicle's safety systems
- The magnetic fields can induce circulating currents into metal surfaces, causing localised heating.

Both of these effects can be detrimental to the vehicle's safety systems. These systems can be protected by shielding sensitive components, or by shielding the entire underside of the vehicle with an aluminium plate.

Therefore all suppliers wishing to take part in the trials will be required to provide test information about how their vehicles are protected against intense alternating magnetic fields, and what practical measures have been implemented in the vehicle to protect its safety systems from magnetic interference.

#### *8.2.2.3 Electrical safety*

Electrical safety is critical in any public installation. All systems utilise well understood and relatively common components, packaged together in a way that meets the

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<sup>11</sup> <http://www.icnirp.org/cms/upload/publications/ICNIRPLFgdl.pdf>

<sup>12</sup> Note that there is considerable variation in limits, e.g. a commonly quoted limit at frequency between 3 – 150kHz, is a  $6.25\mu\text{T}$  based on earlier ICNIRP guidelines

necessary Ingress Protection (IP) rating. The exact properties of the housing are to be determined, but the experience of all current technology providers from the development and deployment of other electrical equipment suggests this should not be an issue. As the coil housing is buried under the road surface, there is no risk of electrocution to any road users or staff.

Installation of electrical devices at the road side is also common among DNOs and contractors, with clear guidelines and regulations in place. Advice from contacted DNOs suggests that this is not expected to be an issue.

Specific Electro-Magnetic Compatibility (EMC) standards need to be met for any equipment which is fitted onto the vehicle. Automotive EMC Directive 2004/104/E states that frequencies below 30MHz are considered which means that DWPT technology is not expected to interfere with vehicles' electronic systems. However, it would be good practice to undertake the relevant testing in any case, in order to check for any unexpected harmonics. A number of DWPT and WPT systems have been fitted to vehicles around the world and no problems have been reported to date.

## **8.3 Test-track trial Methodology**

### **8.3.1 Installation**

This will evaluate how time consuming and complex the installation processes are. Of particular interest will be the amount of time that the road needs to be closed and the likely disruption that will be caused by the installation.

It is recognised that for some suppliers who may be installing prototype equipment, or who have little experience at installation, the time taken may not be fully representative of the installation time in a real on-road environment. Nevertheless, by observing the installation process, it will be possible to be able to gauge the relative complexity of the different systems being installed and obtain an indication of the time required for a real installation in the future. This information will be valuable for planning the on-road trials phase of the project.

During this evaluation, the following will be recorded:

- Time taken for the installation
- Any particular difficulties encountered by the installation team
- Any practices or techniques used which would be inappropriate during a real installation on the strategic road network.

### **8.3.2 Road degradation**

The road structure and surface should be measured, partially verifying the results found in the laboratory trials described in Section 8.1.

While it is accepted that the amount of traffic which will use the trial road section is small compared with a real road, lessons can be learned from any degradation which does take place. It is therefore proposed that the road will be surveyed by visual inspection by pavement specialists, for example using the Highways England Road Research Information System (HARRIS), a road surface survey vehicle, at the start and end of the trials to evaluate any deterioration in the condition of the road.

It is also recommended that the installations are instrumented with strain gauges to gather more information on the expected strains that these installations would typically experience under standard loads.

### 8.3.3 Measurement of power transfer efficiency

These tests will measure the efficiency of power transfer from the grid to the electrical load in the vehicle at various speeds and alignments.

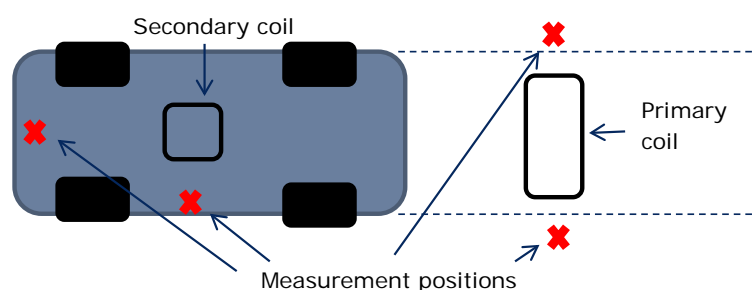
The power being supplied to the DWPT infrastructure from the grid will be measured, as well as the power supplied to the secondary load in the vehicle. Additional measurements at two other strategic points will make it possible to evaluate the efficiency of the inductive power transfer itself, separate from the control electronics.

### 8.3.4 Emissions

During power transfer, an intense magnetic field is generated above the primary coil, potentially well above safety limits for humans. In power transfer systems, these fields are intended to only exist in the space between the primary and secondary coils; however any misalignment between these coils may result in leakage of magnetic fields, posing a health hazard to people. The shape and intensity of these fields may vary considerably between different DWPT solutions.

The objective of these tests is to measure the level of magnetic radiation in the vicinity of the DWPT equipment to ensure that any field leakage is within acceptable limits.

The test will be carried out by placing magnetic field measurement probes alongside the primary coils on the primary side, and on the underside of the vehicle on the secondary side.



**Figure 53: Magnetic Field Measurement Positions**

The proposed positions of the magnetic field measurement probes are shown by the red crosses in Figure 53, with two probes each on the vehicle and on the road outside the line of travel of the vehicle. The vehicle-mounted probes will measure the field intensity on the underside of the vehicle, while the road mounted probes will measure the field to which pedestrians may be exposed as a vehicle drives by.

### 8.3.5 Effect on the grid

The effect on the grid supply will be measured during the trials by monitoring the following parameters of the grid supply:

- Grid voltage, to detect voltage drops due to the load, measured at the 3-phase input to the DWPT equipment
- Load current
- Frequency
- Power Factor of the load presented by the DWPT equipment, to ensure the load does not fall outside power factor limits
- Total Harmonic Distortion (THD) Voltage, to ensure harmonic introduced by the DWPT systems fall within limits. Complex loads such as DWPT systems can generate high levels of harmonics which can be fed back into the grid.

It is envisaged that the local DNO will be invited to take part in the evaluation of the effect on the grid, because a significant roll-out of dynamic power transfer systems could have a marked effect on the grid supply.

It is however recognised that because of the limited scope of these trials, the effect on the grid cannot be fully evaluated, but the trials will give valuable data to be used in future simulations.

### **8.3.6 Communications**

Communications are required between the various components, particularly between the vehicle and the infrastructure. This is an important element for a number of reasons:

- Identification of the vehicle – is this vehicle able to accept power from the infrastructure?
- Billing purposes – does this vehicle have a valid account?
- Safety – does this vehicle have the ability to safely accept power in its current situation? This includes such things as alignment, speed etc. Some systems will only transfer power to a vehicle which is travelling above a certain minimum speed, thereby ensuring that people are not able to be exposed to high levels of magnetic fields
- Efficiency – to improve alignment
- Negotiation of power levels – it is possible that there is a mismatch between the power the infrastructure can supply (either its maximum power, or less due to transient effects), and the vehicle is able or wants to accept. Therefore, as part of the communications between the vehicle and infrastructure, an agreed power transfer level needs to be negotiated.

It is not intended to directly monitor the communications within the systems as there are likely to be a range of solutions, and some may not even require a communications link between the vehicle and the infrastructure. However, where communications are required, the effect of communications failures will be evaluated to ensure that the system safety is not compromised. Details of these evaluations can only be completed once the equipment to be trialled is finalised.

## **8.4 Test scenarios**

To ensure that the trials cover the widest possible range of use cases, six test scenarios have been defined, each with five sub-scenarios. For each scenario, the power to be

transferred must be varied according to the requirements of the vehicle, as well as the capabilities of the DWPT infrastructure.

In all the power transfer scenarios, it is important that the infrastructure does not supply more power than the vehicle is capable of receiving. The most common architecture used in wireless power transfer applications is where the power source at the secondary end is a constant current supply. This architecture simplifies the power electronics required in the vehicle, and leaves the responsibility for power control with the infrastructure. While efficient in terms of power control, it does mean that the infrastructure must be aware of the maximum power that the secondary side is able to accept without damage. To ensure the safety of the vehicle and its occupants, the secondary system must include technology which detects excessive power being supplied by the infrastructure and invokes a safety procedure.

## **8.5 Trials design**

The trials could be undertaken in the following phases:

1. Development of a comprehensive safety case to ensure all risks are fully understood and mitigated
2. Selection of DWPT suppliers. While supplier selection is outside the scope of this document, detailed trials design cannot be completed until the DWPT suppliers have been selected
3. Detailed trials design – once the supplier equipment is known, a detailed design can be undertaken. This will include:
  - a. Physical design
  - b. Power supply design, in cooperation with the local electrical supply company, to suit the suppliers which have been selected
  - c. Final track selection, based on the most appropriate track for the suppliers, electrical supply, costs and availability
  - d. Planning of road installation, including gaining any planning consent which may be required
  - e. Day by day run sheets for trials
  - f. Detailed evaluation criteria
4. Installation on track. The monitoring of the installation process will provide the first results of the trials.
5. Vehicle integration
6. Validation of track and vehicle installation
7. Validation of grid connection
8. Proving trials and training, to show that the equipment operates as expected. This also includes pilot runs for the actual trials
9. Track trials using a stepwise process, with trials building on each other in complexity
10. Results evaluation and reporting.

For all the trials, a full set of measurements will be taken. The trials will be repeated for a range of vehicles, including cars, heavy vehicles and buses. As it is expected that the suppliers of the DWPT equipment will also supply the vehicles, the exact mix of vehicle cannot be defined at this stage. The measurements to be taken are detailed in the following section.

## **8.6 Measurements**

The measurement which will need to be taken during the track trials are discussed below. The tests which are required to enable these measurements and the test methodologies will be defined during the trial design phase.

### **8.6.1 Vehicle parameters**

The following vehicle parameters will be measured for each test run:

- Vehicle speed over the DWPT coils at the time of power transfer
- Vehicle alignment over the coils:
  - Lateral alignment
  - Longitudinal alignment (stationary cases only)
  - Angular alignment (varying lateral alignment)
  - Air-gap between primary and secondary coils.

The above parameters are also controlled variables in tests of power transfer and efficiency, where we will measure the power transferred at different speeds and alignments.

### **8.6.2 Power transfer parameters**

- Power requested by the vehicle: The power transfer rate requested by the vehicle at the start of the power transfer
- Power or energy transferred: The amount of energy transferred from the primary to the secondary coil while a vehicle passes over the power transfer segment
- Efficiency between primary and secondary coils: Power transfer efficiency between DWPT infrastructure and the vehicle
- Efficiency from grid to the secondary coils: Power transfer efficiency from the grid transformer to the vehicle secondary
- Coupling time (also called dwell time): Total time energy transfer occurs
- Start power transfer location: Location of the secondary coil with respect to the primary when power transfer begins
- End power transfer location: Location of the secondary coil with respect to the primary when power transfer ends.

### **8.6.3 Grid parameters**

The effects of significant loads on the grid are well understood by the electricity supply industry. They are required to supply a stable, reliable supply to residential and

commercial customers while coping with the very large and disruptive loads from some industrial users (arc furnaces for example). However, the load presented by a DWPT system is not typical. The power transfer coils embedded in the road infrastructure need to supply very short bursts of power (as short as a few milliseconds at a time), at levels as high as 100kW or more. This kind of highly irregular pulsed load is unusual and possibly unique.

Various projects have speculated on possible solutions to the potential disruption these types of DWPT systems may generate; for example by supplying local energy storage in the form of second-use battery systems for power smoothing.

While this project will not attempt to trial power compensation and smoothing systems, if indeed they are even required, it will measure the effect of these loads on the local supply grid.

#### **8.6.4 Emissions and other safety parameters**

Most current dynamic power transfer systems, and all those which will be considered for this trial, transfer power using resonant magnetic coupling. Intrinsicly, this generates intense magnetic fields in the air gap between the primary and secondary coils. It is one of the design aims of all such systems to contain the magnetic field as much as possible, both to maximise efficiency and ensure safety limits are adhered to.

The ICNIRP has proposed limits for magnetic field strengths (ICNIRP, 2010). In the frequency range 3kHz to 10MHz that these types of systems fall into, this limit is  $2.7 \times 10^{-5}T$ . It is noted that this limit is for “unperturbed rms values” of radiation, implying that in short bursts other, presumably higher, limits may be applied. Nevertheless, this should be considered to be an absolute maximum level of radiation allowed as no limits for short term exposure have been found.

To ensure that these systems are safe to deploy on public roads, magnetic field strengths will be measured, both alongside the primary coil and in the vehicle, while power is being transferred to ensure the ICNIRP guidelines are not breached.

While the above tests will determine the safety of DWPT systems while operating normally, it is also crucial that the systems are safe under abnormal operating conditions. An important aspect here is the air gap between the primary and secondary coils where intense magnetic fields exist. A number of techniques exist for ensuring that human and other living bodies are not exposed to these fields. The most common are:

- Foreign body detection systems, which attempt to detect any unexpected objects in the air gap between the primary and secondary coils. These should detect not only living objects (hands, small animals etc.), but also other objects which may affect the efficiency of power transfer, particularly some metallic objects
- For dynamic systems, ensure that they only operate above a certain minimum speed, above which it is unreasonable to expect any living object to be on the roadway, and only when the vehicle is directly over the primary coil. This does not, of course, prevent small inanimate objects lying on the roadway from affecting the DWPT system.

The trials will test the operation of the safety systems, with tests appropriate to the technology used. So for those systems using foreign object detection, various types of foreign objects will be introduced onto the primary DWPT coil to see if they are detected.



Animate objects will not be used for safety reasons, but will be substituted by dummies. For systems which rely on the vehicle being in motion during power transfer, this will be tested by attempting to initiate power transfer below the target speed.

#### **8.6.5 Power transfer system parameters**

This will evaluate the ability of the DWPT system to operate in a reliable and consistent manner, by monitoring how the DWPT infrastructure interoperates with the vehicles. The following parameters will be monitored:

- Registration of vehicle with power transfer infrastructure, i.e. does the infrastructure correctly identify its client vehicles?
- Do the infrastructure and vehicle consistently set up a valid power transfer session?
- Does the infrastructure correctly ignore all vehicles other than those it has a valid power transfer relationship with?

The correct identification of vehicles which are eligible and able to use the DWPT system requires that the infrastructure reliably and consistently detects these vehicles. Registration of vehicles can be done in a number of ways, but is most reliably achieved by making use of a secure communications channel between the vehicle and the infrastructure.

### **8.7 Selection of track**

Crucial to the success of the track trials is the identification of a suitable test track. There are a number of tracks with a wide range of capabilities and facilities in England; however the requirements for this trial are quite specific and require careful investigation of track facilities to ensure that the track selected is suitable.

The core requirements for the track are as follows:

- Ability to install one or more (probably not more than three) trials systems into a road which is representative of a typical UK road in terms of construction etc.
- Over a period of 3-5 months, run a series of trials on the installation
- As the installation will require installation of equipment into the road surface, this will involve considerable civil works (digging, installation, making good etc.) Exclusive use of the track for the duration of the trial would be highly beneficial, if not essential
- Ideally vehicles should be able to reach motorway speeds, or at least come close to this, while running over the test sections
- All solutions would be expected to be covered by tarmac or concrete
- The trial will require a grid power supply capability which is expected to be of the order of 200kW. It is understood that this is likely to exceed the capabilities of most test tracks, so reinforcement of the supply is envisaged. In order to simulate grid connections as close to the real-world connection as possible in order to maximise lessons learned about costs and complexity of connection, it is proposed to ensure a minimum power capability of 800kVA for the trials. Use of generators is not acceptable as the effect on the grid is part of the research.

A HV grid would supply to a local sub-station which converts the HV to 3-phase Low Voltage (LV). The LV would be distributed to the Road Side Units (RSU) of the various DWPT suppliers. These units would typically be situated close to the road edge to minimise losses incurred in transferring the power from the RSUs to the in-road primary coils. The distribution of the power from the RSUs to the primary coils is likely to vary between suppliers; some may have more than one RSU, and some may embed some of the control electronics in the road rather than in the RSU. It will be the responsibility of the suppliers in this trial to provide full technical installation requirements to ensure their equipment is correctly installed. The siting of the sub-station is not critical. The track itself could be a loop or a single straight with turning areas at each end.

The above options for track installation have been considered and discussed with a number of test tracks, and several suitable solutions have been identified. The operators of the tracks have shown enthusiastic support for the project.

## 9 Costs and Impacts

This section discusses the costs and benefits that would need to be quantified as part of the process of developing a business case for a DWPT scheme.

The chapter first provides an overview of the principal impacts that would be expected, following the categorisation set out in the DfT's Transport Appraisal Guidance (TAG<sup>13</sup>), identifying those impacts that, on the basis of available evidence, would be expected to be worth more detailed assessment.

To demonstrate how such an assessment might be undertaken, a spreadsheet model was developed to calculate the emissions, fuel and energy consumption changes per km of motorway on which one lane has been equipped with DWPT. Different traffic flow conditions were considered, corresponding to real traffic data from some selected sections of motorway, as are a range of different DWPT up-take scenarios. Where possible, the outputs from the model were then monetised according to TAG

Uncertainties and limitations in the model used leave some information gaps that will need to be considered in future work in this area, in particular getting an improved understanding of:

- The costs of installing DWPT and connecting it to the electricity supply grid.
- The costs of DWPT equipped vehicles in comparison with both conventional ICE and EV and hybrid vehicles; taking account of how the availability of DWPT might influence these other technologies.
- Which user groups will be most likely to adopt DWPT, based on operational considerations such as annual vehicle mileage on motorways, and other potential incentives for adopting EVs, such as pressure to use zero emission vehicles in urban centres.

It will also be necessary to increase the range of vehicle types that are taken into account, in particular vans.

### 9.1 Identification of potential impacts (costs and benefits)

An initial assessment was undertaken to identify potential impacts, and then to consider the extent to which they can be quantified using available information. As the intention was to understand how cost-benefit analysis of DWPT would be undertaken, the assessment was structured around the categories described in the TAG Appraisal Summary Table (AST). This uses four top level categories of impact:

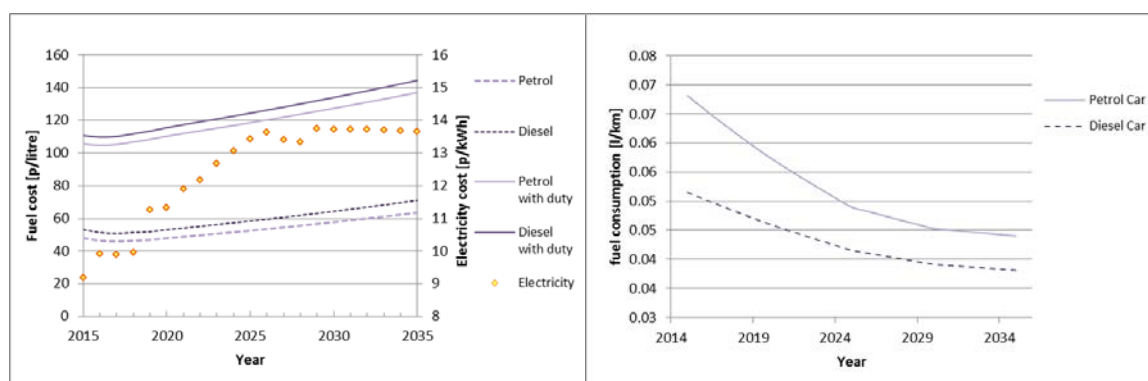
- Economy – for example time savings or fuel cost savings to businesses
- Environment – e.g. reductions in emissions of CO<sub>2</sub> or local air pollutants
- Social – e.g. cost impacts on members of the public
- Public Accounts – impacts on transport budgets, such as that of Highways England, and on taxation revenues

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<sup>13</sup> [www.gov.uk/transport-analysis-guidance-webtag](http://www.gov.uk/transport-analysis-guidance-webtag)

Impacts under each of these headings are discussed in the sub-sections below, identifying the individual impacts that are considered in the detailed analysis, the basis for the calculations, and the data sources used.

Much of the information required is available in government forecasts as set out in the TAG Data Book and Defra's National Atmospheric Emissions Inventory emission factors<sup>14</sup>. The technical assumptions used in the study are described in greater detail later. Forecast trends in fuel and electricity prices and fuel efficiency are shown in Figure 54 (source: DfT TAG Data Book). For HGVs a constant (0.356 l/km) is forecast, this is because there is currently limited potential for significant improvements in fuel efficiency using current technology. Note that these are shown to illustrate how the expected trends compare, no assumptions are made about the cost per unit that DWPT users would pay.



**Figure 54: Forecast trend in energy prices (left) and in car fuel efficiency (right)**

### 9.1.1 Economy (impacts on businesses)

#### 9.1.1.1 Running cost savings

The principal implications for businesses arise from the costs of buying and operating the DWPT-equipped vehicles. It would be expected that these vehicles would be more expensive than conventional vehicles, so there would need to be lower running costs for operators to have an incentive to use them. The running costs savings arise from the difference between the cost of fuel for an equivalent vehicle and the cost of buying electricity from the DWPT system. To assess these impacts, information is therefore needed on:

- Expected capital costs of a DWPT-equipped vehicle in comparison with a conventional ICE vehicle
- Forecast fuel consumption on petrol or diesel and energy consumption for the comparable DWPT vehicle when running on electricity
- Future costs of petrol, diesel and electricity

<sup>14</sup> <http://naei.defra.gov.uk/data/emission-factors>

#### *9.1.1.2 Ability to meet zero-emissions requirements*

In addition to reduced operating costs arising from the lower cost of running on electricity rather than petrol or diesel, it is important to bear in mind that the business case for using an EV is also likely to be driven by other factors, in particular avoiding emissions in urban areas. If future restrictions on emissions (or even noise) mean that operators will find themselves having difficulty being able to gain access to urban centres with conventionally fuelled vehicles, then the case for investing in EV technology becomes significantly stronger. Although such benefits are likely to be harder to quantify than running costs, having an additional DWPT capability would then become a complementary part of a wider business case, meaning that DWPT would not then by itself need to justify the full additional cost.

#### *9.1.1.3 Changes in demand for transport arising from changes in cost*

If running costs are reduced then it would normally be assumed that users would respond by increasing their use of the road, following elasticities of demand. This would lead to increased traffic growth on top of forecasts, making scenarios with DWPT significantly more complex than the 'do nothing' scenario. Understanding the implications of such changes would require complicated demand modelling, which is beyond the scope of this project. As a necessary simplification therefore, in this study it is assumed that changes are not sufficiently large to have a significant impact on demand for road transport. In the early years of introduction, when uptake levels are relatively low, and DWPT equipment comparatively expensive, overall cost savings to users are likely to be relatively low. As will be seen later, electrification of road transport raises a number of implications for government revenues through the taxation of road users, which may require very different approaches to be taken in the future. It is not unreasonable, therefore, to consider that DWPT is implemented alongside other changes that would compensate for any increased demand that DWPT might lead to.

#### *9.1.1.4 Changes in journey time and reliability*

Changes in journey time and reliability are usually very significant impacts on business users in transport appraisal. DWPT systems could influence journey time if it is implemented in a way that affects speed, or encourages some other effect on driver behaviour that might affect traffic flow or capacity. However, currently proposed systems would operate at average traffic speeds, so this should not be a particular constraint. There is a minimum spacing between vehicles required before the DWPT will operate, which could influence behaviour under heavily congested traffic flows, however the response would be complex, theoretically reducing capacity while encouraging smoother traffic flows. There may be a case for operating DWPT as part of a traffic management system alongside speed and lane management, however this would be a complex study in itself, beyond the scope of the current project. It was therefore concluded that this study would assume no particular impacts on user behaviour.

It is also assumed that (as a necessary condition of large scale introduction) the DWPT-equipped vehicles are as reliable as conventional vehicles, and are either hybrids or fitted with range-extendors, so that users would not have concerns about range limits.

#### 9.1.1.5 *Impacts on manufacturing and the supply chain*

The very large investment involved in buying and installing DWPT equipment over a large proportion of the SRN would be expected to create a significant number of jobs and stimulate the manufacturing supply chain. However, it is not clear how much of the equipment could be manufactured in the UK and how much would need to be imported.

As the in-vehicle equipment would start to become mass produced and integrated into the vehicle production lines, it is likely that the impact on jobs would not be large. Installation of roadside infrastructure on the other hand would be expected to be more labour-intensive, and new jobs would have to be based in the UK.

#### 9.1.2 *Environmental*

The environmental benefits that were identified and could be considered with the available information were:

- CO<sub>2</sub> emissions reductions resulting from vehicles transferring to EV
- Air quality benefits arising from Oxides of Nitrogen (NO<sub>x</sub>) and Particulate Matter (PM) emissions local reductions resulting from vehicles transferring to EV

Calculating CO<sub>2</sub> emissions requires consideration both of the direct emissions saved from vehicles that would otherwise run on petrol or diesel, and the additional emissions from the additional electricity power generation required to power the vehicles running on DWPT. The 'carbon intensity' of power generation, i.e. the amount of CO<sub>2</sub> per kWh generated, is dependent upon the mix of sources used to generate it. Coal fired power generation has a very high carbon intensity, while gas-fired generation is much lower (both because of higher energy efficiency and the lower carbon content of the fuel) and nuclear and renewable sources have effectively zero carbon intensity. Forecasts for the carbon intensity of power generation in future years are available from Defra.

To calculate CO<sub>2</sub> emissions from conventionally fuelled vehicles it is necessary to know future trends in the use of different fuels, as well as in their fuel efficiency. It is expected that fuel efficiency will continue to improve over the next 20 years or so as vehicle technology enables greater efficiency and European emissions legislation imposes higher standards. Clearly, if decarbonisation of electricity power generation does not improve as quickly as vehicle fuel efficiency then the comparative advantage of electrical vehicles over conventional vehicles will be eroded. The Defra Emissions Forecasting Tool (EFT<sup>15</sup>) was used in this study, as this takes into account future predictions for energy efficiency and the composition of the vehicle fleet.

The benefits of reduced CO<sub>2</sub> emissions can be monetised in transport appraisal, using carbon pricing. As there is no current market in carbon pricing for transport, the 'non-traded' values are used to value the reduced emissions from vehicles, whereas the 'traded' carbon price is used for the increased emissions from power generation. Non-traded carbon prices are included in the TAG Data Book, traded-values from DECC (Department of Energy & Climate Change, 2014).

The other major environmental benefit from electrical vehicles is the reduction in emissions of local and regional air pollutants, principally Oxides of Nitrogen (NO<sub>x</sub>) and Particulate Matter (PM). Both these are associated with impacts on health and are

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<sup>15</sup> <http://laqm.defra.gov.uk/review-and-assessment/tools/emissions-factors-toolkit.html>

subject to local limits and standards. As with CO<sub>2</sub> emissions, there is an extent to which a shift to electrical vehicles involves displacement of emissions from the roadside to power stations. However, because the impacts of air pollution are mostly localised, power station emissions have far less impact on exposed populations. Emissions of both PM and NO<sub>x</sub> are forecast to decline significantly in future years, in line with tighter emission standards and improved technology. In the study, the Defra EFT was used to predict future emissions from conventionally fuelled vehicles.

Emission reductions of PM and NO<sub>x</sub> can also be monetised in transport appraisal, reflecting the societal benefits of reductions in their adverse impacts on health. However, as the impacts are highly localised, depending upon the extent to which there is an exposed population and how badly this population is affected by other sources of air pollution, accurate quantification of the benefits at a particular location requires detailed modelling. For this study 'damage cost' values, taken from the TAG Data Book were applied as an approximate value for the benefit of NO<sub>x</sub> reduction in areas not affected by exceedances of the NO<sub>2</sub> limit value, which would be broadly representative of the majority of the SRN. Where limits are exceeded, the much higher 'abatement' cost should be used. As a sensitivity test, a calculation was made using the abatement cost to assess what the monetised benefits are likely to be in sensitive locations.

As noted in the earlier discussion on business benefits, it is important to note that the air quality benefits delivered by EVs could form a significant part of the case for buying and using such a vehicle in urban areas. Therefore, although the emission reduction benefits of DWPT-equipped vehicles are not as beneficial on most of the SRN, the ability to combine low-emissions in urban areas with long-distance EV capability could help support a stronger case for the purchase of DWPT vehicles than either benefit would by itself.

#### *9.1.2.1 Environmental impacts not considered further in the study*

It was concluded that other categories of environmental impact identified on the AST would not be taken forward for more detailed consideration.

- **Noise:** at above 50km/h tyre noise is the dominant source of noise from road vehicles<sup>16</sup>, so at the higher speeds found on the Strategic Road Network a change to EVs would not have a significant impact in most locations.
- **Landscape:** there is a potential adverse impact from additional overhead power lines and pylons where roads pass through sensitive landscapes; however this would require assessment at a local level, and can be mitigated through sensitive routing and greater use of underground cables.
- **Townscape:** as above.
- **Historic Environment:** no impacts would be expected.
- **Biodiversity:** no impacts would be expected.
- **Water Environment:** there is a small potential positive impact if the DWPT equipment can be used to de-ice roads, as this would reduce the need for

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<sup>16</sup> See for example [www.dft.gov.uk/vca/fcb/noise.asp](http://www.dft.gov.uk/vca/fcb/noise.asp)

road salt. However, there is insufficient information available for this to be evaluated.

### **9.1.3**     *Social*

#### **9.1.3.1**     *Impacts on private road users*

The principal social impact would arise from the cost implications for private road users. These would be the potential cost savings from running on electricity set against the greater cost of purchasing DWPT equipped vehicles. These impacts can be calculated in the same way as for business users, with an important difference being that private users pay VAT on fuel, electricity and vehicle purchases.

#### **9.1.3.2**     *Other social impacts*

Following initial consideration of the other categories of impact considered in TAG, it was concluded that the following would not be taken forward for more detailed assessment.

- **Physical activity:** no impacts are expected on active modes of transport, in particular no modal shift to or from them, in particular because the journeys made on the SRN tend to be longer distance and hence walking and cycling are least likely to be practical alternatives.
- **Journey quality:** no impacts would be expected.
- **Accidents:** it was assumed that there is no particular reason for any changes to occur to accident rates, as long as DWPT provision is sufficient to avoid significantly influencing driver behaviour. However, it is important to note that in this study the focus is on scenarios where only one lane is equipped, which could lead to changes in behaviour such as increased lane changing. The potential impact is not currently quantifiable, and a limit is imposed on the maximum uptake rate amongst light vehicles to minimise its impacts. As previously discussed, there may be benefits if DWPT is implemented alongside traffic management systems, which has the potential to reduce accidents, however no information was identified to enable this to be assessed.
- **Security:** consideration would need to be given to ensuring that DWPT user data and payments are secure; however, this would not be considered to present greater challenges than for a road user charging system, for example. There are no implications for perceptions of personal security for road users.
- **Access to services:** it is assumed that provision of DWPT does not affect the location of essential services, nor the availability of transport to them. As discussed later, it is possible that the introduction of DWPT on the SRN could improve the case for the purchase of EVs for use in urban areas, which could become important if, in the future, greater restrictions are placed upon vehicle emissions in city centres, making it easier for services to be maintained in such locations.
- **Affordability:** any cost implications are already covered. As DWPT is new technology, likely to cost more than conventional vehicles, it would not be expected that low income groups would be amongst the early adopters.
- **Severance:** no potential impacts have been identified.



- **Option and non-use values:** road users may attach a value to the availability of DWPT on the SRN, potentially influencing their willingness to purchase an electrical vehicle in the future by giving them confidence they can use it for longer distance journeys. As with the earlier discussion about business users, the availability of DWPT on the SRN could help justify the case for buying an EV that is mostly intended for use in urban areas. However, a more detailed assessment would require market research and willingness to pay surveys amongst potential users, and this information is not currently available.

#### 9.1.4 Public accounts

##### 9.1.4.1 Cost to broad transport budget (impacts on Highways England budgets)

DfT's guidance on cost-benefit analysis (TAG Unit A1.1) states that impacts in this category are those that directly affect 'the public budget available to fund transport schemes'. In this case this will refer to the costs affecting Highways England to construct, maintain and operate the system.

The major capital cost items are:

- Purchase of the DWPT equipment (power converters, control gear and communication systems, induction loops)
- Installation of the equipment into the road
- Providing a suitable connection to the electricity supply grid

There is currently very little information available on which to base robust estimates of the infrastructure costs. Information has been provided by a manufacturer, suggesting that a cost for the equipment of approximately £0.6M per km is achievable. Drawing upon experience in other highway schemes, an estimate has been made by TRL of £1M per km to install the equipment in the road (assuming cheapest installation method). It is expected that it would be possible to combine the installation of the DWPT coils as part of routine resurfacing that would take place anyway, avoiding additional costs for managing lane closures. This leads to an estimated cost to buy and install the DWPT equipment of £1.6M per km (for one lane).

The cost of providing a connection to the supply grid will be dependent upon the distance between the section of road being electrified and a suitable connection point, as well as on the maximum power demand. There are a number of different approaches to electrification that could be considered, such as providing a separate connection to the grid for each km of road, or providing a single very high power connection at a small number of locations with a local supply network then provided alongside the road, analogous to how rail electrification systems are connected. For the purpose of this report the first case has been considered, with an estimate of £455k per km provided by the DNO.

Given the significant uncertainties in the above estimates, and the fact that there is not yet any UK experience of installing DWPT on a large scale, an 'optimism bias' of 60% has been added to these costs in the analysis described later in this report.

In addition to the above there would be significant revenue impacts arising from:

- Ongoing maintenance

- Administration and management costs for any user registration and payment system
- Electricity charges paid to the supplier

In the absence of any empirical evidence for the cost of maintenance, a figure of 1% of the initial capital costs was applied annually over the period being assessed.

There would also be 'back office' costs for user administration. No information was available on what these might be, so the model used an assumption that administration costs would be 5% of the electricity costs, thereby providing some link to the number of users. It is hard to identify existing comparable systems, however the Dutch government specified a 5% administration cost in specifications it issued for road pricing schemes (Ministerie van Verkeer en Waterstaat, 2006).

#### *9.1.4.2 Transport budget impacts not quantified in this study*

There are a number of other possible impacts on costs and revenues. However insufficient evidence was available to enable any detailed consideration to be undertaken.

It has been assumed that there are no wider implications on highway maintenance, however there is a possibility that changes in how vehicles use the road could have implications for wear and tear. As noted in the discussion on economic and social benefits, it is assumed that cost changes do not lead to significant changes in demand for transport, and hence traffic volumes or composition. However, consideration does have to be given to potential implications such as the diversion of traffic from non-equipped to equipped routes, in particular of heavy vehicles, and, in the case where only one lane is equipped, a shift in the usual distribution of traffic flows increasing the proportion in Lane 1. All of these could lead to greater wear of the road surface. Furthermore, there is a possibility that if automated systems are used to maintain a central position in the lane, to maximise charging efficiency, then rutting could increase along the path taken by the wheels.

As noted previously, there is a possibility that the coils embedded in the road could assist with de-icing, thereby reducing gritting requirements and saving costs. There is very limited information on the extent to which this might work, and it should be noted that the scenarios considered in this study are largely focused on only a single DWPT equipped lane.

There is a potential application of the communication infrastructure as a means of providing high speed broadband to road users. However it would likely be dependent upon use of existing mobile services such as 4G (or 5G in the future) and it is not clear that delivery via the DWPT system would be more cost effective. The extensive power distribution network needed could potentially be used to carry broadband signals, either directly or using optical fibres attached to the structures, but further work, involving discussions with the power distribution and telecommunication industries, will be needed to assess the extent to which this would provide significant additional revenues.

As the DWPT system involves direct communication to individual vehicles there is a possibility that it could replace the need for roadside information signs, if provision is made for this, including development of suitable 'in cab' displays connected to the DWPT

communication systems. It could therefore in principle assist with the development of managed motorways and active traffic management. However, the potential cost savings only arise if it is able to remove the need for roadside signs and equipment, which would require full uptake, and probably having all lanes DWPT equipped. Similarly, the system would be able to provide high quality information on traffic flows and speeds, replacing roadside systems; if sufficiently high penetration rates are achieved.

#### *9.1.4.3 Indirect tax revenues (impacts on central government budgets)*

Transport appraisal has to take account of impacts a scheme may have on indirect taxation, as these can have a significant impact on central government finances that is quite separate from their direct impacts on transport budgets. As is the case for any method of electrification of road transport, there is a switch from petrol and diesel, on which significant rates of duty and VAT are charged, to electricity which has no duty and is only VAT rated at 5%. This has implications for how the results of cost-benefit analysis should be interpreted, because under current appraisal methods, any scheme that shifts consumption from petrol or diesel to electricity will show a poor, or even negative, Net Present Value because of its impact on indirect tax revenues.

## **9.2 Modelling costs and environmental impacts**

### *9.2.1 Overview of modelling approach*

A spreadsheet model was developed to assess the costs to HE and the monetisable environmental benefits of installing DWPT on 'representative' 1km sections of motorway over a 20 year appraisal period (for one lane only, and in a single direction). This considers both the cost implications for the Highways England and the broader range of societal impacts considered by central government.

It is important to note that in neither case do the models refer to a specific scheme proposal: the 'representative' sections are assumed to be part of a wider network of sufficient size for economies of scale to apply and to support the take-up rates applied. We have not assumed that particular sections of the road network are equipped, or that particular groups of users have adopted DWPT. Scenarios relate to different penetration rates within the fleet, varying traffic flows and compositions, and, for users, different proportions of the roads they use being equipped; however, no attempt has been made to try to model uptake as a response to the rate of implementation of a DWPT network.

As far as is possible, costs and benefits have been assessed and reported in accordance with WebTAG. The detailed assumptions and technical parameters used in the models are described in the rest of this section.

### *9.2.2 Technology and power requirement*

To simplify the models, power and fuel consumption requirements were used for illustrative vehicles, rather than attempting to model the full range of vehicles in the fleet. Very little information is available to enable a robust assessment to be made of what the equivalent DWPT vehicle would be for each type of current petrol or diesel vehicle that might be considered. Currently, existing electric cars are probably more comparable with smaller, lighter petrol or diesel cars. There are very few electric vans in existence and no commercially available electric HGVs. For early adoption it seems reasonable that DWPT cars will continue to be more representative of current EVs, so

values for models such as the Nissan Leaf provide a realistic example. For other vehicle types an estimate can be made of the equivalent power requirement by using current fuel consumption data, and assumptions about engine and transmission efficiency (40% for diesel, 28% for petrol), to estimate the power required 'at the wheel', and hence to estimate the equivalent under electrical propulsion. Given the limited information available, in particular on larger electric vans, the analysis was restricted to two categories of vehicle: a HGV and a car, with light vans treated as for cars. This provides examples at two extremes of the power requirement spectrum. The assumed values are shown in Table 35.

**Table 35: Assumed energy consumption for ICE and DWPT compared**

Vehicle	Fuel consumption l/km	Equivalent electricity consumption kWh/km
<b>Car (petrol)</b>	0.068	0.2
<b>Car (diesel)</b>	0.052	0.2
<b>HGV</b>	0.356	1.9

NB – fuel consumption figures quoted above are the current values. As technology improves and emission standards are tightened, future fuel efficiency is expected to improve. For future years, average fuel economy forecasts were used in the model, these were taken from the TAG Data Book. NO<sub>x</sub>, PM and CO<sub>2</sub> emissions were forecast using the Defra Emission Forecasting Tool (EFT).

The electrical power consumption figures include allowances for the efficiency of the electrical vehicle and for transmission through the DWPT system.

To provide some basis for evaluation a simplification has been made, assuming that:

- All DWPT cars and light vans are either full EVs, or equipped with range extenders
- All DWPT HGVs are diesel hybrids which can run on electrical only power under DWPT

It is assumed that the price paid to the electricity supplier will be an industrial tariff, and for this study the TAG Data Book value for electrified railways was used. This is lower than the retail tariffs that users would expect to pay at home, or at commercial premises.

### 9.2.3 *Scenarios modelled*

It was felt that it would be helpful to base calculations on some real traffic flow and composition data for three motorways that could be considered to be likely candidates for initial roll out of a DWPT system.

Using DfT's published Annual Average Daily Flow data, some example sections of motorway were identified and the traffic flows and proportion of HGV traffic used in the calculations. The examples chosen were a section of the M20 between the M25 and the Channel Tunnel, a section of the M1 north of the M25, and the M6 in the West Midlands. These are all on busy corridors that carry long distance road freight, a market that would be considered to be early adopters for this technology. Annual Average Daily Flow

(AADF) for HGVs and light vehicles are summarised in Table 36. This is the total annual traffic flow in both directions, divided by 365 days, taken from the Highways England's traffic counter data available to TRL.

**Table 36: Annual Average Daily Flows for HGVs and light vehicles on example motorway sections**

	M1	M20	M6
<b>AADF HGV</b>	15656	8136	18055
<b>AADF LV</b>	164493	45984	110035

Average speeds were assumed to be: 68mph for cars and LGVs, 56mph for HGVs.

The model focused on cars and light vans (light vehicles, LV), and HGVs. The numbers of these in the traffic were taken from the DfT AADF data for the first year of the scenario. The model spreadsheet enables a range of starting conditions, uptake rates and final maximum penetration rates, as well as overall traffic growth to be assumed. A linear traffic growth of 2% was used as an approximation to 40% growth between 2010 and 2030, taken from DfT's 2013 Road Traffic Forecasts.

When considering the DWPT uptake that might be achieved, a higher initial value for take-up by light vehicles was used on the basis that hybrid and full EV cars are already available in the marketplace so adoption of DWPT for these vehicles is nearer to the market. However, given that the current study is focused on a single lane of DWPT, which imposes capacity constraints on the number of users, this imposes a lower maximum penetration rate of around 30%.

The uptake rates used in the charts below were based upon the following scenario in Table 37:

**Table 37 - Vehicle take-up**

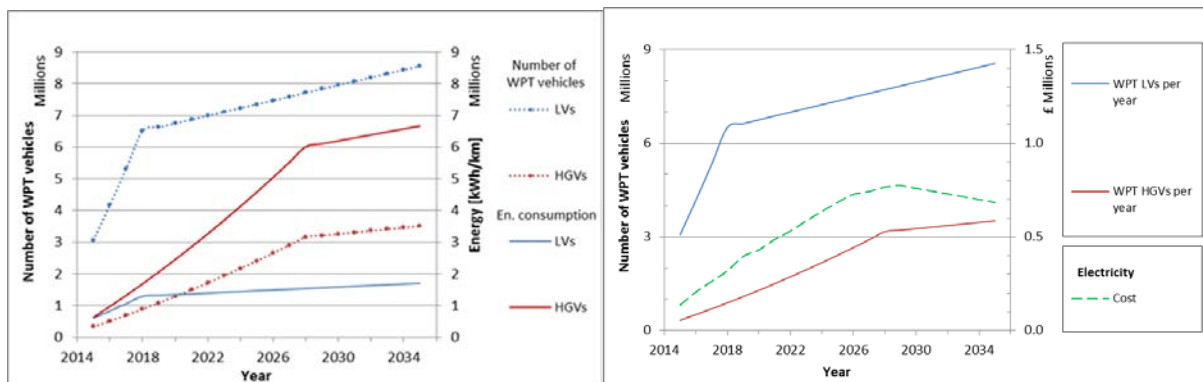
<b>Initial % DWPT HGV</b>	5%
<b>initial % DWPT LVs</b>	10%
<b>Annual EV take-up rate HGV</b>	5%
<b>Annual EV take-up rate LV</b>	5%
<b>Maximum penetration allowed for HGV</b>	75%
<b>Maximum penetration allowed for LV</b>	30%

When considering the outputs from the model it is important to note that the scenario begins with low penetration, i.e. it is showing a steady 'ramp-up' in the use of DWPT in the years following its introduction. This will inevitably show a much worse return on the initial outlay than a scenario that starts with an already established market for DWPT, and hence a large population of DWPT users from the start. This will be discussed in greater detail later in the chapter.

### 9.2.4 Growth of vehicle numbers and power consumption with time in Scenarios

The left-hand chart in Figure 55 shows how the number of DWPT LVs and DWPT HGVs increases with time under the scenario and the resulting annual electricity power consumption. The chart shows that while the number of HGVs is lower than the number of LVs (noting that the latter is capped), they consume more power.

In the right-hand chart the number of electric light vehicles and HGVs with time and the corresponding total annual electricity cost is shown. Note that the values are Present Values and calculated from forecast electricity prices, so the decline in future year costs reflects the limit to uptake being reached and the discount factor applied to future costs.



**Figure 55: Number of vehicles and energy consumption over time (left) and Number of DWPT vehicles and electricity cost (right)**

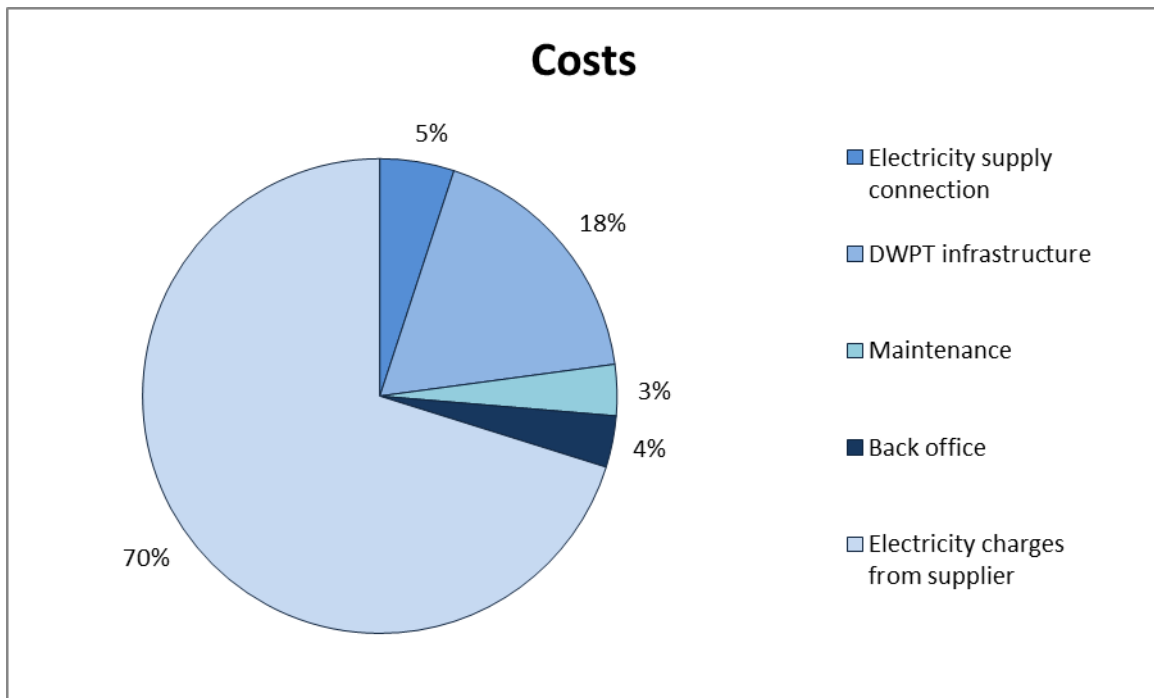
### 9.2.5 Overall summary of costs

In transport appraisal total costs and benefits are usually calculated as the Net Present Value over the appraisal period, and expressed in 2010 prices. Future benefits are discounted at 3.5% per year, reflecting the reduced 'present value' attached to benefits in the future compared with the present year. The NPV per km of the cost items discussed above are summarised in Table 38 and Figure 56<sup>17</sup>.

**Table 38: Summary of NPV costs per km to Highways England over 20 years**

Cost item	NPV (per km) over 20 years
DWPT infrastructure	£3,046,400
Electricity supply connection	£866,320
Maintenance	£595,219
'Back office'	£600,431
Electricity charges from supplier	£12,008,613

<sup>17</sup> Please note that costs that do not already include VAT are increased by the 'indirect tax correction factor' (1.19) to reflect that impact that increased public expenditure from direct taxation has on consumer spending and hence indirect taxation. See TAG Unit A1.1



**Figure 56: Breakdown of the NPV costs per km over 20 years under the chosen scenario**

#### 9.2.6 Impacts on indirect taxation

The model was used to calculate the total value of petrol and diesel saved over the 20 year period and, using assumptions about fuel duty and VAT from the TAG Data Book, it is possible to calculate the effect of reduced duty and tax revenues to the Treasury. As explained previously, indirect taxation impacts have to be calculated under the current appraisal methodology.

Any additional VAT on electricity (at 5% according to TAG Data book) that would be payable is not included in this analysis. The cumulative NPV VAT and Duty impacts over 20 years are shown in Table 39.

**Table 39: Indirect taxation impacts of switch to DWPT**

Indirect taxation impact	NPV per km over 20 years
<b>Fuel Duty reduction (business users)</b>	£10,057,950
<b>Fuel Duty reduction (private users)</b>	£2,851,495
<b>VAT revenue reduction (private users)</b>	£1,058,864

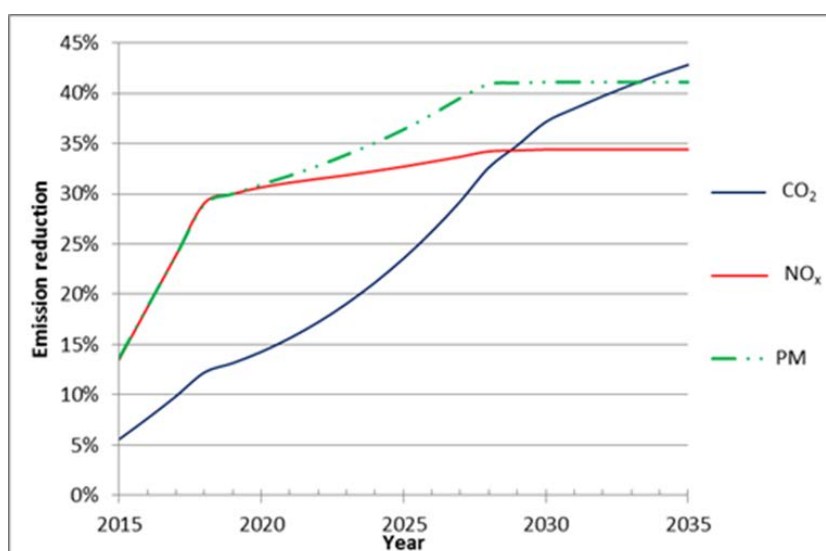
#### 9.2.7 Monetisation of Environmental Impacts

In line with DfT's appraisal guidance (TAG Unit A1.1) air quality and carbon reduction benefits are valued using the damage cost and non-traded carbon price values given in the TAG Data Book. In line with Defra advice, the PM and NO<sub>x</sub> damage costs are

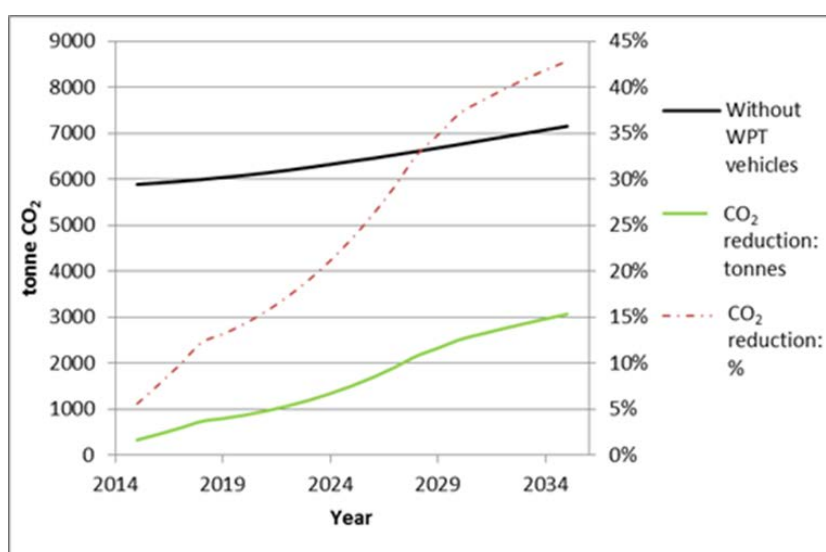
increased by 2% annually in future years to reflect the greater value attached to air quality improvements that would be expected as the economy grows.

The spreadsheet model was used to forecast the total reductions in the amount of CO<sub>2</sub>, NO<sub>x</sub> and PM over the 20 year period, and the monetised values of those reductions, using the appropriate carbon prices; and NO<sub>x</sub> and PM damage prices. The total values for emission reductions arise from the cumulative total of the emissions in each year. To illustrate the changes in emissions year on year the annual reductions are shown in Figure 57 as a percentage of the business as usual emissions. Figure 58 shows total and % CO<sub>2</sub> savings by year.

Over 20 years, cumulative CO<sub>2</sub> savings (taking account of CO<sub>2</sub> emissions from power generation) add up to 34,686 tonnes, with a monetised value of £1,986,347. In the final year, with highest penetration of DWPT vehicles, annual CO<sub>2</sub> savings are worth £162,627.



**Figure 57: Annual percentage reduction of CO<sub>2</sub>, PM and NO<sub>x</sub> over appraisal period**



**Figure 58: CO<sub>2</sub> emission reductions in tonnes saved and % change**



The values used to monetise the benefits of reduced emissions vary according to the extent to which exposed populations are affected by air pollution. In areas where NO<sub>2</sub> limits are exceeded the 'abatement' cost should be used, rather than the much lower 'damage' cost that applies elsewhere. To illustrate this, the above calculations were applied to a hypothetical section of road in an urban area affected by exceedances of the NO<sub>2</sub> limits, so that the abatement cost was used, together with a higher value for the damage cost of the PM emissions that is used in urban areas. The effects on the NPV of the total monetised benefits are shown in Table 40. As can be seen, this adds over a million pounds to the NPV, at such locations.

**Table 40: How the value of emission reductions varies by location**

<b>Pollutant</b>	<b>Total emission reductions per km over 20 years</b>	<b>NPV benefits per km (typical motorway section)</b>	<b>NPV benefits per km (sensitive urban location)</b>
<b>NOx</b>	55,886 tonnes	£52,413	£1,190,939
<b>PM</b>	572 kg	£27,821	£67,607

### 9.3 Conclusions and discussion

Following a review of the impacts that would need to be taken into account in a cost-benefit analysis of DWPT, it was concluded that a full appraisal would need to consider the following:

- Costs to the 'broader transport budget' (Highways England):
  - The DWPT equipment costs and installation
  - A connection to the distribution grid
  - Maintenance
  - User administration and 'back office costs'
  - Electricity charges from the grid
- Indirect taxation impacts on central government finances:
  - Loss of fuel duty
  - Loss of VAT on fuel saved by private users
- Business impacts:
  - The cost of DWPT vehicles in comparison with conventional ones
  - Fuel cost savings
- Social impacts:
  - The cost of DWPT vehicles in comparison with conventional ones
  - Fuel cost savings
- Environmental impacts:
  - The 'non traded' carbon price of CO<sub>2</sub> savings (taking account of CO<sub>2</sub> emissions from electricity production)
  - The monetised benefits of reduced NO<sub>x</sub> and PM emissions (which vary according to the exposed population and background air quality)

For the purpose of this report costs to business and users were not calculated. Such a calculation would also require information on the likely cost of DWPT vehicles, for which

there is currently very little robust information. This report therefore focuses on assessing what the costs of providing a DWPT system might be under a chosen scenario, to both transport budgets and central government finances, and the monetised environmental benefits from reduced emissions.

For the chosen scenario, based on steadily increased penetration of DWPT vehicles into the traffic mix of representative sections of motorway, the following conclusions were reached (for a 20 year appraisal period):

- The Net Present Value of construction and operating costs, per km, would be £17 M, of which infrastructure costs (which includes the 60% 'optimism bias') account for 30% and electricity 70%.
- In this scenario, the NPV of monetised CO<sub>2</sub> savings would be nearly £2M per km, equivalent to half the capital cost. This corresponds to approximately 45% reduction in emissions compared with the 'without DWPT' case.
- Local emissions of NO<sub>x</sub> and PM would be reduced, in this scenario, by approximately 35% and 40% respectively. The NPV monetised value of these reductions would be less than £100k, except in areas where populations are exposed to poor air quality. Where the NO<sub>2</sub> limit is exceeded, the value of NO<sub>x</sub> reductions would rise to over a million pounds per km over the appraisal period, although this would not be expected to apply to more than a few locations on the SRN.
- There would be a reduction of around £14M in central government revenue, because of the 'loss' of fuel duty and VAT from reduced fuel consumption. This is greater than the capital costs of the fixed infrastructure.

A number of other potential impacts were identified qualitatively, but were not considered further because of a lack of information. However, some would require further investigation as part of any assessment of a proposed scheme, in particular any relating to the maintenance implications of the road, and potential changes in road user behaviour, or demand for transport that might occur.

#### *Uncertainties and limitations in the model*

It is important to bear in mind that the model outputs are based upon current forecasts of fuel and electricity prices, assumptions that could change significantly in the longer term, particularly if, for example, the need to reduce carbon emissions more quickly leads to the introduction of carbon pricing in transport.

As noted above, the costs to users have not been assessed in this report. To do this it will necessary to understand more about the DWPT vehicles themselves, both in terms of their performance as well as their costs:

- The technology is not yet commercially developed so a market price has not yet emerged. Whatever the technologies adopted, unit costs will be significantly lower than those in any experimental vehicles, especially at the high uptake rates used in the later years of our scenarios.
- It is not clear what will be the 'baseline' vehicle against which DWPT costs should be compared. If tighter emissions regulations in the future make ICE

vehicles more expensive, or lead to a greater push towards hybrid and EV technology, then the price 'gap' to DWPT capability will be greatly reduced.

- The model is based upon representative values for only two vehicle types: HGV and light vehicles, the latter being based upon power consumption for a car. There remains considerable uncertainty on how LGVs might be adapted for DWPT, whether as compatible EVs, as is assumed for cars, or as hybrids, as assumed for HGVs.
- The widespread availability of DWPT could influence the design and hence costs of EV and hybrid vehicles, potentially reducing the size of the battery needed for full EVs or the maximum diesel engine power needed for a hybrid, if motorway running could be largely shifted to DWPT operation.

There are other drivers that could support a business case, in particular the growing need for low and zero emission vehicles in urban areas. If a broader environmental case such as this is being made for buying an EV or plug in hybrid, then the availability of DWPT on motorways will support that case, as the running costs per km will be lower than for a conventional vehicle even at the higher mark-ups on electricity charges considered in this study.

## 10 Summary of Conclusions

### 10.1 Stakeholder engagement

WPT technology is a utility that requires consumers to adopt supporting technology (i.e. a WPT-enabled electric vehicle). Thus it is possible for WPT technology to drive EV uptake, and conversely for vehicle uptake to drive use of WPT technology. The current level of EV adoption in Great Britain is low, thus public knowledge and experience of them is also low. The survey of consumers sought to explore early attitudes towards WPT technology (within the context of EV adoption) among private individuals who had some experience of driving an electric powered vehicle (through taking part in a trial in which they had been loaned an EV).

Two hundred participants were contacted and asked to complete an online survey; 80 complete responses were returned, which is a reasonable response rate for an on-line survey of individuals. The sample was fairly representative of private new (or nearly new) car purchasers in Great Britain, but compared with the general population had a higher than average level of income, which is only to be expected in a sample of private new (or nearly new) car purchasers.

Despite having previous experience with EVs, a third of drivers stated that they felt uninformed about them. This is possibly symptomatic of the current lack of market penetration of electric powered vehicles.

Drivers' general attitudes to driving suggest that they enjoy driving, and that the car is a necessary and preferred mode of transport. Symbolic attitudes towards EVs were positive although responses to instrumental items suggest that for the majority of the sample, EVs are perceived to be too expensive and are not thought to offer enough range to be useful.

Awareness of WPT prior to the survey was low. This was reflected in the responses to a number of items which suggest that many had not acquired enough information, or had not had enough time to process the information, in order to develop positive or negative attitudes.

While respondents did not report that WPT was a breakthrough technology they were waiting for, there were positive indications that WPT could encourage EV adoption. It is possible that WPT is seen as addressing barriers such as limited range, although there was some evidence of concern about how it would be priced for consumers.

There was some indication that WPT was seen as benefiting businesses more than private drivers, but about half of respondents were undecided. However there were no clear differences in the responses to this question, between people with different levels of business and private mileage.

When asked to consider ownership of a WPT-enabled vehicle and with the infrastructure installed on roads they use regularly, respondents appeared to trust the technology and the majority were not concerned about safety. However, a large proportion of respondents would still be worried about running out of charge, suggesting that range anxiety may be an ongoing barrier that may need to be addressed through marketing, information, technological advances and/or further experience.

Drivers reported that they would be more likely to use a WPT enabled vehicle, particularly for short trips, suggesting a potential unintended consequence of modal shift towards the car for trips traditionally undertaken on foot, by bicycle or by public transport.

Participants were generally positive about EVs, but were unlikely to have an EV as a main car in the next five years. The introduction of WPT on motorways does little to change this although wider access (i.e. all roads) increases likelihood. These responses may be tempered by the expectation that a DWPT-enabled vehicle would be more expensive than current EVs, which are already considered to be more expensive than current diesel cars (it should be noted that the cost of EV technologies is expected to reduce with increased market penetration and economies of scale). Nevertheless, there is an indication that WPT availability could play an important role in influencing consumer decision-making and behaviour.

The surveys of both private and commercial road users highlight the 'chicken and egg' issue which arises with the adoption of new technologies: the results show that vehicle purchasing decisions by both industry and consumers will depend on the wide availability of WPT charging, but the business case for investing in the technology is weak without demand from users.

The small survey of industry stakeholders associated with the project workshop indicated that there is some support for the view that Highways England should deploy and own the DWPT infrastructure on the Strategic Road Network, but that the charging system should be operated by a third party.

Availability of charging infrastructure is not the only factor working against the take up of DWPT charging. The improved performance new Euro VI light and heavy duty engines is seen by some operators as meeting the requirement to reduce emissions without increasing risk to businesses, while competing alternative fuel technologies create an investment risk. Residual value is also a dissuading factor in decisions on replacing commercial vehicles.

Commercial operators require a return on investment within 18 months to three years. Thus any additional cost of leasing or purchasing vehicles would need to be balanced by savings on operating costs to offset these additional costs over this relatively short time period. Industry stakeholders indicated that important factors in investment decisions related to WPT technology would be automation and user-friendliness of the WPT system, practicality and simplicity of charging and the level of CO<sub>2</sub> reduction.

The survey of consumers who had some previous experience of using an electric vehicle indicates that although participants were mainly positive about EVs, they are unlikely to have an EV as a main car in the next five years; for the majority of the sample, EVs are seen as too expensive and not offering enough range to be useful at present. It should be noted that these comments are related specifically to battery EVs, REEVs or plug-in hybrids are not perceived to have the same range issue. Furthermore, the opinion is based on current pricing of vehicles, which is likely to reduce with economies of scales and higher market penetration.

Consumer respondents appeared to trust the WPT technology and only a minority had concerns about safety, but a large proportion said they would still be worried about running out of charge, suggesting that range anxiety continues to be a barrier to be addressed.

Industry stakeholders indicated that they were more likely to purchase an EV if it were possible to use DWPT on equipped sections of the Strategic Road Network. Similarly, the responses from consumers indicate that introducing WPT on motorways would increase the likelihood of having an EV as their main car in the next five years, and that the likelihood would increase if WPT were introduced on main roads as well as motorways.

Thus while respondents did not report that WPT was the breakthrough technology they were waiting for, there were indications that WPT could encourage EV adoption among private motorists. It is possible that WPT is seen as addressing barriers such as limited range, although there was some evidence of concern about how much consumers would be expected to pay to charge their vehicles using WPT. There are indications therefore, that WPT availability could play an important role in influencing consumer decision-making and behaviour.

The third of respondents who thought that WPT would benefit businesses more than private drivers provides an indication that people who drive regularly for business may be more likely to be early adopters of WPT-enabled vehicles than those who drive predominantly for private purposes.

Even this group of consumers with previous experience of using an EV included a substantial minority who felt uninformed about EVs. Having been provided with background information about WPT, the responses indicate that respondents had not yet developed positive or negative attitudes, with many neutral responses to some questions. There is clearly more to be done to extend public knowledge and experience of EVs in general, and WPT in particular, in order to overcome some of the perceived barriers to EV adoption.

## **10.2 Functional requirements**

The project has investigated a number of possible WPT technologies focusing on those able to function as DWPT systems. In total seventeen WPT systems were investigated, eight of which had a dynamic capability. Each system that is capable of dynamic functionality was evaluated by the project team against a number of metrics covering: power transfer level, operational speed, suitability for different vehicle types and availability for trials. An assessment of technology readiness and manufacturing readiness was carried out and showed that most DWPT technologies score between TRL 4 and 8, while manufacturing readiness is lower, between 3 and 7.

Other services that could be provided by DWPT systems were also investigated. The value of any benefits is likely to be insignificant compared with the cost and benefits of the actual installation and operation of the DWPT system itself. However, a number of potential additional services were identified and described. These included installation of MIDAS road loops as part of DWPT sections of motorway, which could result in savings of up to £4,900 per km for Highways England. Using DWPT technology to support autonomous vehicle functionality on the SRN was also found to be possible and could help to improve safety.

Other services, such as provision of wireless communication and integration with Smart Motorways, were found to be unlikely to generate any direct benefit to Highways England.

An investigation of how DWPT could affect other services on the SRN revealed that there are two key areas where DWPT systems may have an impact. These are conductive disturbances and radiated disturbances.

The two main conductive disturbances likely to be caused by WPT equipment are (1) current and voltage fluctuations caused by frequent switching on and off of the WPT equipment as vehicles pass over the primary coils, and (2) harmonics generated by the power electronics of the WPT systems. Experience from trials of static WPT systems indicates that these problems are not insurmountable and will likely involve dedicated connections from the DNO specifically for the WPT installation, possibly at high voltage, to provide a degree of separation from other customers and harmonic filters to deal with any excess harmonics.

The second conclusion relates to radiated disturbances caused by the electromagnetic fields (EMFs) generated by the DWPT equipment which, unlike existing static installations, may extend beyond the perimeter of the vehicles. This does not prevent connection to the public electricity system as it is outside the scope of the DNO connection requirements. However, it does potentially impact on safety and electromagnetic compatibility with other equipment. It is therefore important that the manufacturer of the equipment demonstrates compliance with the EMC standards to ensure safe operation.

### **10.3 System performance requirements**

The key components were identified and their technology readiness level assessed. There are no production WPT systems currently available on the open market; however, several are in advanced trials, and demonstration systems exist in a number of countries. Projects like FABRIC and others are actively working on live demonstration systems.

Various options for fitting of WPT equipment into vehicles were considered, including factory fit, manufacturer aftermarket fit and third party aftermarket fit, with and without manufacturer support. Third party fitment without manufacturer support is not considered viable, and is not recommended. Several case studies are presented showing different fitting options.

The implications for safety were considered. For factory fitted systems, safety is not considered an issue as all vehicles are required to meet stringent safety requirements before they are allowed to be sold in Europe. The safety of aftermarket fitted systems is more of an issue. It was clear that DWPT systems could not be safely retrofitted to vehicles without vehicle manufacturer support. For vehicle manufacturers to approve the use of a DWPT system with their vehicles, the systems would need to be extensively tested and validated. A DWPT system fitted to a trailer may reduce some of the risk for vehicle manufacturers, but would still require their support to define the necessary interfaces to the vehicle and its systems.

Finally, a number of relevant international standards have been identified and listed. Various standards bodies are in the process of developing standards for the use of wireless power transfer systems, both static and dynamic.

The requirements for batteries are dependent on vehicle dynamics, usage duty cycles and power train technology. The requirements for cars, medium duty vans and HGVs were considered. Both cars and vans could viably be used in fully electric mode, with

DWPT increasing range and/or reducing required battery capacity. The increased distances driven by HGVs, together with their much greater energy requirements, means that fully battery electric HGVs are not feasible. However, benefits can be expected from hybridisation, and these benefits are increased by DWPT. If sufficient SRN coverage can be achieved with high power DWPT systems (>140 kW), fully electric HGVs would become viable.

Three types of construction were considered, these being trench-based constructions (where a trench is excavated in the roadway for installation of the DWPT primary coils), full lane reconstruction (where the full depth of bound layers are removed, the primary coils installed and the whole lane resurfaced), and full lane prefabricated construction (where the full depth of bound layers are removed and replaced by pre-fabricated full lane width sections containing the complete in-road system).

The first two methods were both found to be viable. Identification of the most appropriate method would require trials. The full lane pre-fabricated method is likely to be prohibitively expensive, although further investigation is required as this is a relatively new construction technique.

The types of machinery which would be required was also considered, and key requirements for some specific road installations tools identified. However, given that an exact method of installation for DWPT systems does not yet exist and requires to be developed, tested and validated, a definitive set of tools and respective specifications cannot be identified at this stage.

#### **10.4 Process requirements**

The project showed that DWPT systems would be susceptible to high peaks and variations in power demand which will be dependent on traffic conditions at the time. Furthermore, the exact layout of the DWPT system and its maximum power supply capability will also have a substantial impact.

Two different example layouts for DWPT systems were considered:

- System layout 1: This consists of individual power transfer segments of up to 8m long which are combined into power transfer sections of up to 50m long (consisting of 4 segments with a gap in between each segment). Up to 2 segments can be energised in any given 50m section. The power transfer is limited to 40kW for light vehicles and to 100kW for HGVs or coaches. Each 50m segment can supply two vehicles with power.
- System layout 2: This consists of individual power transfer segments of up to 40m long. A gap exists between adjacent segments. The length of this gap is in the region of 5m. Each 40m segment can supply power to one vehicle. Power transfer is limited to 40kW for light vehicles and to 140kW for HGVs or coaches.

It should be noted that the analysis is hypothetical because an assumption is made that the same primary infrastructure can supply power at two different levels to different vehicle types (e.g. 40kW for cars and vans, 140kW for Coaches and HGVs). The ability of any system to do this in practice has not yet been demonstrated. However, for the purpose of understanding potential future worst case power demand, this was assumed to be possible.



The analysis showed that under different traffic conditions and an assumed scenario for vehicle and technology penetration, average demand from DWPT systems can be as high as 500kVA (0.5MVA) per mile for system layouts 1 and 2 respectively. Under these conditions, when utilisation of the system does not approach the maximum value, the expected demand is similar across both layouts. The number and length of segments under these conditions does not have an impact on total power demand as the number of power transfer segments that can be occupied is limited by the number of vehicles on the road. Demand from system layout 2 is higher than from layout 1 due to the higher power transfer capability for heavy duty vehicles.

However, during times of maximum demand, maximum power requirements per mile can vary between approximately 4MVA and 4.5MVA throughout the day, with the highest values occurring during the morning and evening traffic peaks. These are considerably higher than during average demand because the number of vehicles is higher so more power transfer segments can be occupied at any given time. Because the total power demand depends on the number of vehicles using the system, the demand profiles follows a similar profile to vehicle flows. However, due to the fact that different vehicle types are assumed to have different power demand from the system, systems can vary in terms of maximum power transfer capability; as the number of power transfer segments per mile varies depending on the system layout, very different power demand profiles are seen for high traffic flow cases between example system layouts 1 and 2.

The analysis also highlights that the demand from heavy duty vehicles tends to dominate the variations in overall power demand; however, power demand in these scenarios tends to be specific to the type of vehicle at certain times of day. During the morning and evening traffic peaks, the demand comes primarily from light vehicles as there is a sharp increase in numbers of these vehicles and the proportion that they make up on the network. At other times, the demand is mostly from HGVs as these continue to operate throughout the day.

Scenarios A and B were used to help understand how the system utilisation and power demand may depend on total DWPT vehicle penetration. These two scenarios are based on the following assumptions:

- Scenario A (medium penetration)
  - Light vehicles: 30%
  - Heavy vehicles: 50%
- Scenario B (high penetration)
  - Light vehicles: 50%
  - Heavy vehicles: 75%.

Furthermore, system layouts with longer DWPT segments can reach peak utilisation before maximum road capacity is reached. For system layout 1, 100% utilisation is largely not exceeded even under maximum demand scenarios, whereas with system layout 2, utilisation is either close to 100% capacity or is exceeded throughout the day. For system layout 1 in scenario A, with medium levels of penetration of equipped vehicles in the fleet, the maximum utilisation reaches a peak of 82% for the period of 08:00-09:00. For system layout 2 the peak utilisation reaches 147% during the period

08:00-09:00. Utilisation exceeds 100% for five hours of the day, 06:00-10:00 and 18:00-19:00.

In scenario B, with high levels of penetration of equipped vehicles in the fleet, for system 1 the maximum utilisation reaches 131%, between 08:00 and 09:00. The system is above 100% utilisation for four hours of the day, 06:00-09:00 and 18:00-19:00. For system layout 2, the peak utilisation reaches 235% between 08:00 and 09:00. The system exceeds 100% utilisation for ten hours of the day, 06:00-11:00 and 15:00-20:00.

In order to assess power requirements, assumptions were made about the take up of the technology in the fleet. These were based on the following:

**Table 41 - Vehicle take-up**

<b>Initial % WPT HGV</b>	5%
<b>Initial % WPT light vehicle</b>	10%
<b>Annual EV take-up rate HGV</b>	5%
<b>Annual EV take-up rate LV</b>	5%
<b>Maximum penetration allowed for HGV</b>	75%
<b>Maximum penetration allowed for LV</b>	30%

Using this figures, it was estimated that reaching light vehicle penetration of levels of 30% and 50% would take approximately 5 and 9 years respectively, assuming a starting point of 10% penetration. Note that light vehicle DWPT penetration is not expected to exceed 30% in the case of a single lane of motorway being equipped, but for the purpose of maximum power transfer, this scenario was considered as it is theoretically possible. Similarly for HGVs, reaching a penetration of 50% and 75% under the baseline assumption would take 10 years and 15 years respectively. It should be noted that although for the purpose of cost benefit and payback calculations, a conservative approach was taken to DWPT vehicle penetration, for the purpose of understanding power demand, a more optimistic approach was adopted in order to ensure the worst case scenario can be represented for power demand, in Scenario B.

Based on information gathered so far, it is apparent that DWPT systems are being designed to only transfer power to a single vehicle per one primary coil segment in order to mitigate the risk of exposure of other unprotected vehicles or road users to magnetic fields. Some of the systems investigated do not have an active control for this and rely on using shorter primary segments to mitigate the risk of multiple vehicles occupying the same segment. However, it could still be possible for multiple vehicles to occupy the same primary segment during particularly dense traffic conditions and low speeds, where vehicle headway is reduced to below 10m. Other systems have a functionality based on either on-board or roadside radar systems that will switch off power transfer if more than one vehicle is detected on the same primary segment. This will result in the system being switched off and not providing any power transfer to the equipped vehicle. The risk of this happening increases as the traffic builds up and vehicle headway reduces. Therefore, some vehicles will likely be unable to use the DWPT system, or the system may not function at all due to a safety override preventing the system from energising coils with multiple vehicles present.

This suggests that systems with shorter segments (10m or less) will be better suited for meeting higher anticipated demand and provide more flexibility around when the systems can be used, but is also likely to lead to higher power demand fluctuations which will likely result in requiring higher specifications for power supply equipment and higher costs for making the electric connection to mitigate any undesired impacts on the grid. Systems with longer primary coil segments provide more predictability of demand and lower overall power requirements, but may not work effectively when traffic levels are high if currently proposed safety features are implemented.

An investigation into possible opportunities for EV fleet owners to benefit from the utilisation of EV charging at depots was carried out. This showed that there are a number of mechanisms to deliver additional financial benefits including:

- Triad avoidance
- Demand side response services
- Common distribution charging methodology
- Short term operating reserve
- Frequency response
- Frequency control by demand management.

Actual benefits that could be derived from the above services will depend on the specific type and number of vehicles, the times of day when they would be connected to a charger at the depot and the flexibility of the charging regime based on the vehicle duty cycle. As such information is not available at present, possible magnitudes of the benefits for each mechanism were described.

The evaluation also considered the potential effects of:

- Energy prices and tariffs, and the likely effects and impacts of pricing models
- Opportunities presented by the Triad system
- Demand side response through dynamic load management
- Various ancillary services.

Various detracting factors were also considered; for example, the current vehicle licensing arrangements, the cost of fleet ownership, and other impacts of fleet electrification (e.g. exemption from paying the congestion charge).

It was found that large fleet operators could benefit from having EVs in their fleet by making use of revenue services described above. In particular, making use of seasonal time of day bands, Demand Side Response Services (DSRS), Triad avoidance could help reduce the costs of electricity for the operator while Firm Frequency Response (FFR) and Frequency Control by Demand Management (FCDM) could help generate additional revenue by making the vehicles and their batteries available to service providers during charging. Although this could result in additional revenue for fleet operators of up to £50 to £60 per kW per year (in the case of FFR) or £26 to £30 per kW per year for FCDM, it requires a commitment to make those vehicles available to the service during agreed periods.

Finally, back office was considered, including the requirement to securely and robustly identify the user (be it the driver or vehicle owner), as well as the operational

requirements. It was found that a DWPT back office system could be created based on existing EV charging back office solutions and existing vehicle identification and communication technology. Although no such complete system exists at present, it is believed that it could be developed with largely off-the shelf components. A set of requirements for such a back office system were described.

A specific example of a stretch of the M6 motorway was used in order to collect appropriate DNO data provided by WPD, and feed into a free cash flow calculation model. This was used to determine a possible process for recharging users for electricity from the DWPT system. Apart from purely technical considerations, this also looked at “softer” implications, considering planning laws and the relationship to the National Infrastructure Plan and other statutory instruments. A specific recommendation is made to include cooperation with the rail industry as there are distinct parallels with respect to network implications between rail electrification and DWPT.

Costs for setting up connections from the electricity grid to DWPT systems were analysed for the M6 example. It was found that the cost for 1 km stretch of DWPT could vary between £350,000 to £425,000 depending on the exact layout of the DWPT infrastructure and the asset ownership models used.

## **10.5 Preparation for off-road trials**

Investigation of road construction methods showed that the in-situ full width lane reconstruction was the preferred option for the off-road trial and suitable on in-service Highway England roads. Other methods of installation such as, trench-based construction, should also be investigated during the trials in order to fully understand possible strengths and weaknesses of the different approaches. In order to achieve this, it was proposed that a set of laboratory trials should be undertaken using a pavement test facility and which should include the following:

- Trafficking along the joint between the concrete and asphalt interface which would represent the interface between lanes 1 and 2
- Trafficking the adjacent construction which represents the wheel path (outside the width of the system)
- Trafficking directly above the top of the system to observe how the material surrounding the system behaves (i.e. structural integrity of the slab with coil system).

The use of instrumentation in the test sections with strain gauges and thermocouples is also recommended. This would make it possible to gather more information about the expected strains that these construction types would typically experience under standard wheel loads. Such information could potentially reduce the design thickness of the pavement or the concrete section surrounding the unit itself.

Requirements for test track length, DWPT segment length, power provision requirement and the need for additional facilities, such as vehicle storage hangars, were evaluated and described. A track length of approximately 1km was identified as being necessary in order to support tests of up to 100km/h for trial vehicles with at least 2 lanes, each of 3.5m wide. Power supply of up to 800kVA was deemed to be necessary, both to support testing of up to three systems simultaneously, and to understand the complexities of undertaking grid connection for the systems.

The track trials were demonstrated to be an important precursor to eventual on-road trials, significantly de-risking them and providing valuable learning, so it is recommended that they be implemented. One of the key outputs of the trials would be to understand in detail possible safety risks of an on-road deployment.

## 10.6 Impact assessment

Following a review of the impacts that would need to be taken into account in a cost-benefit analysis of DWPT, it was concluded that a full appraisal would need to consider the following:

- Costs to the 'broader transport budget' (Highways England):
  - The DWPT equipment costs and installation
  - A connection to the distribution grid
  - Maintenance
  - User administration and 'back office costs'
  - Electricity charges from the grid
- Indirect taxation impacts on central government finances:
  - Loss of fuel duty
  - Loss of VAT on fuel saved by private users
- Business impacts:
  - The cost of DWPT vehicles in comparison with conventional ones
  - Fuel cost savings (after electricity costs are included)
- Social impacts (impacts on private users):
  - The cost of DWPT vehicles in comparison with conventional ones
  - Fuel cost savings
- Environmental impacts:
  - The 'non traded' carbon price of CO<sub>2</sub> savings (taking account of CO<sub>2</sub> emissions from electricity production)
  - The monetised benefits of reduced NO<sub>x</sub> and PM emissions (which vary according to the exposed population and background air quality)

For the purpose of this report costs to business and users were not calculated. Such a calculation would also require information on the likely cost of DWPT vehicles, for which there is currently very little robust information. This report therefore focuses on assessing what the costs of providing a DWPT system might be under a chosen scenario, to both transport budgets and central government finances, and the monetised environmental benefits from reduced emissions.

A scenario was developed in which the proportion of DWPT vehicles using a representative section of motorway equipped with a single DWPT lane was increased steadily over 20 years. In the scenario, the proportion of light DWPT vehicles increased from 10% to 30%, constrained by having only one DWPT lane, while the proportion of heavy DWPT vehicles from 5% to 75%. A spreadsheet model was used to quantify some of the costs and impacts that arise from this scenario, giving the following conclusions:

- The Net Present Value of construction and operating costs, per km, would be £17M, of which infrastructure costs (including a 60% 'optimism bias') account for 30% and electricity 70%.
- In this scenario, the NPV of monetised CO<sub>2</sub> savings would be nearly £2M per km, equivalent to half the capital cost. This corresponds to approximately 45% reduction in emissions compared with the 'without DWPT' case.

- Local emissions of NO<sub>x</sub> and PM would be reduced, in this scenario, by approximately 35% and 40% respectively. The NPV monetised value of these reductions would be less than £100k, except in areas where populations are exposed to poor air quality. Where the NO<sub>2</sub> limit is exceeded, the value of NO<sub>x</sub> reductions would rise to over a million pounds per km over the appraisal period, although this would not be expected to apply to more than a few locations on the SRN.
- There would be a reduction of around £14M in central government revenue, because of the 'loss' of fuel duty and VAT from reduced fuel consumption. This is significantly greater than the capital costs of the fixed infrastructure.

A number of other potential impacts were identified qualitatively, but were not considered further because of a lack of information. However, some would require further investigation as part of any assessment of a proposed scheme, in particular any relating to the maintenance implications of the road, and potential changes in road user behaviour, or demand for transport that might occur.

There are other drivers that could support a business case, in particular the growing need for low and zero emission vehicles in urban areas. If a broader environmental case such as this is being made for buying an EV or plug in hybrid, then the availability of DWPT on motorways will support that case, as the running costs per km will be lower than for a conventional vehicle even at the higher mark-ups on electricity charges considered in this study.

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## Appendix A Battery requirements

Continuous deep charge/discharge cycles can impact battery life but micro-charging (e.g. between 50% and 80% SOC) can be advantageous and reduce the need to take the battery to low and high SOC where degradation can occur.

For short durations of dynamic charging, a high level of charge acceptance is needed which may impact the design of the battery cooling system and the choice of battery technology (see A.1).

The end of life of the battery is typically accepted as occurring when it is only able to reach around 80% of its original capacity (or only able to deliver 80% of its original function (current output).

The more energy throughput there is per cycle, the greater the impact on battery life. Conversely, the lower the energy per cycle, the less the impact on battery life.

With dynamic charging there is potential to extend battery life by ensuring charge/discharge cycles are kept relatively shallow and are in the mid SOC range, away from the stress points.

The choice of battery voltage and battery capacity would be independent of whether dynamic charging would be supported or not. This choice would be made dependent on the required vehicle performance and the required maximum range under battery power.

The battery requirements for current vehicles are dependent on many factors but, with the exception of Tesla, they essentially fall into two groups with a maximum range of about 100 miles:

- Small cars: typical battery rating is 300 – 400V, 16 – 18kWh
- Medium cars: typical battery rating is 300 – 400V, 22 – 27kWh

These battery packs are designed to accommodate level 2 charging (i.e. single or three phase supply that can deliver up to 20kW)<sup>18</sup> and some offer the capability of direct fast charge from a DC source.

Tesla vehicles are designed to have a range much closer to cars with combustion engines and have battery packs rated between 50 and 85kWh.

### A.1 Review of battery types

The vehicle requirements for energy and power density, charge and discharge rates as well as safety and duty cycles determine the suitable battery chemistry. The batteries types studied are:

- Nickel-metal Hydride (NIMH)
- Lithium-ion
- Alternative battery technologies which are near market

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<sup>18</sup> Level 1 consists of single phase ac supply that can deliver up to 3.3kW, while Level 3 is direct dc current or “fast” charging from a dc source of up to 240kW of power.

### *Nickel-metal Hydride (NIMH)*

#### Strengths:

- Currently used in approximately 2 million vehicles
- Life time of up to 10 years
- Contains no toxic materials
- Relative low cost of manufacture when compared with the Lithium chemistry

#### Weaknesses:

- The patents for large NIMH battery technology (Ovonics) are owned by a stream of owners and are currently with BASF; this has led to “Patent Encumbrance” which has so far limited further developments of the battery technology and production of battery units
- Cannot be fast charged below 5°C to prevent hydrogen venting
- Poor performance in cold weather.

### *Lithium-ion*

The lithium chemistry batteries use migration of lithium ions between electrodes through the electrolyte. The lithium-ion batteries have high specific energy density, therefore are an ideal power source for an EV. A vehicle battery is made up from a number of units:

- Cell – A single unit made up of electrodes, electrolyte and separator
- Module – A set of cells linked together to act as a unit to be part of a larger unit
- Battery pack – Either a set of cells or modules acting as one battery pack

A lithium-ion battery has higher energy and power density when compared with NIMH, but it also costs more. However, lithium based systems have lower charge/discharge rate and load cycle when compared to the flywheel or super capacitors, whereas, super capacitors and flywheels have very low energy density.

#### Strengths:

- High energy density
- High efficiency
- Low rate of self-discharge
- Low maintenance

#### Weaknesses:

- Uses Lithium salts which is a limited and finite material
- Low charge discharge cycle
- Lithium batteries are expensive
- Special packing and protection to minimise fire risk.

There are various Lithium-ion based batteries, such as: Lithium Cobalt Oxide (LCO), Lithium Nickel Manganese Cobalt Oxide (NMC), Lithium ion Manganese Oxide LiMn<sub>2</sub>O<sub>4</sub> (LMR/LMO) and Lithium iron phosphate LiFePO<sub>4</sub> (LFP).

Table 42 shows the lithium based battery scores out of four on seven criteria, with four being the best score (Boston Consulting Group) (Element energy, 2012). The NMC, LFP and NCA scored the highest total points. The NMC and LFP have good energy and power density and relatively low cost. The LTO chemistry has low specific energy but this type of battery has a very high charge and discharge rate, a high duty cycle as well as low cost, so this chemistry can be a suitable option for the vehicle types with high traction power and high regeneration characteristics.

**Table 42: Lithium type battery score**

Battery Type	Specific energy	Specific power	Safety	Performance	Life span	Temperature	Cost	Total Score
Lithium Cobalt Oxide (LCO)	4	2	2	3	2	2	3	16
Lithium Nickel Manganese Cobalt Oxide (NMC)	4	3	3	3	3	2	3	19
Lithium ion Manganese Oxide $\text{LiMn}_2\text{O}_4$ (IMR/LMO)	3	3	3	2	2	1	3	16
Lithium iron phosphate ( $\text{LiFePO}_4$ ) (LFP)	2	3	4	3	4	3	3	19
Titanate batteries ( $\text{Li}_4\text{Ti}_5\text{O}_{12}$ ) (nLTO)	2	3	4	4	4	2	1	18
Lithium Ion Nickel Cobalt Aluminium ( $\text{LiNiCoAlO}_2$ ) (NCA)	4	4	2	3	4	4	2	19

#### *Alternative battery technologies which are near market*

There is a considerable amount of research into battery chemistry at present. The technologies closest to market are: advanced high Nickel Oxide content mixed metal oxides (MMO), Nickel Manganese Cobalt (NMC), Silicon anode technology, Lithium Sulphur.

## **A.2 Battery cost**

Table 43 shows the battery cost based on various sources. The cost of a battery is on average £432/kW.

**Table 43: Battery cost**

Source	Cost £/kWh	Reference
Nissan Leaf	300	(How Improved Batteries Will Make Electric Vehicles Competitive, 2014)
DOE	429	(DOE, 2012)
Transdev	234	(Transdev, 2014)
VTT	783	(centre, 2014)
McKinsey	396	(Amsterdam Roundtables Foundation, 2014)
Business insight	357	(Business Insight, 2012)
SAE	525	(SAE international, 2012)

## Appendix B Review of vehicles and driving patterns

The vehicle and drive cycle parameters and their impact on battery specification have been reviewed. The section is divided into three subsections: car, medium van and HGV.

### B.1 Car

The power train layout for cars can range from ICE through various levels of hybrid power train to full battery electric and fuel cell. There are number of manufacturers that mass produce full electric drive train cars, including Nissan, Tesla, BMW, Mitsubishi and Renault. Therefore using data from these vehicles, a battery specification can be developed for a full electric power train.

#### B.1.1 Weights and power demand

Table 44 shows the vehicle weight for a standard compact ICE and various electric cars. The Tesla Model S weight is noticeably higher, as it is equipped with 85kWh battery, while Mitsubishi iMiEV is lighter, as it is equipped with 16kWh. The average weight of the electric vehicle considered (excluding the Tesla as it cannot be considered a compact vehicle) is 1335kg. It can be seen that a compact ICE vehicle weighs approximately same as the average compact electric car. Hence it is considered impractical to increase the battery capacity until there are significant improvements in specific energy density.

**Table 44: car weight**

Model	Weight (kg)
Standard ICE compact	1354 (List of car weights, 2015)
Nissan Leaf	1521
BMW I3	1270
Tesla model S	2108
Renault Zoe	1468
Mitsubishi i-MiEV	1080

According to the TRL energy demand model from previous projects, a Nissan Leaf demands 18.1kW power at the wheel in order to maintain 70mph (115km/h). At motorway speeds, the energy consumption at the wheel is approximately 0.16kWh/km.

The Nissan Leaf accelerates from 0 to 100km/h in 11.2s (Nissan Leaf, 2015), which means that average acceleration rate is  $2.3\text{ms}^{-2}$  when accelerating at the maximum rate. Expected acceleration rates for cars range between 1 and  $3.5\text{ms}^{-2}$  and the expected deceleration rate is  $3\text{ms}^{-2}$  (HA acceleration and deceleration profiles). The Nissan Leaf is equipped with an 80kW (continuous rated power) motor and this rating can be considered as the maximum charge/discharge rate, although vehicle demand can exceed the rated motor power for short periods of time.



### ***B.1.2 Driving range***

An average car journey is 37km per day, only 2% of the total trips are over 50 miles and the majority of these long journeys are either business or holiday trips (DfT, 2015).

A study carried out by the Technology Strategy Board states that European private users perceive 206 miles (330km) as an acceptable range for all of their journeys (Technology Strategy Board, 2011). The results from surveys on the acceptable long driving range show that the value fluctuates between 308 and 353km in Europe (note that, since this research project concerns the UK, the European requirements are taken into consideration for developing a model).

The routes used by private cars are essentially unpredictable. There could be situations where the car operates on a predetermined route, for example Heathrow airport pods.

### ***B.1.3 Power transfer rate from the infrastructure***

The available space under the car is limited therefore, based on the current "state of the art" technology, the power transfer rate for a car is limited to about 40kW. The power demand from traction motor at 70mph is 18.1kW. When all the inefficiencies from the motor, gearbox and power electronics are considered, the power demand from the secondary coil for traction is 20.3kW. Therefore 19.7kW spare power can be used to charge the vehicle battery.

## **B.2 Van**

The LCVs (light commercial vehicles) make up 14% of all traffic in the UK (DfT, 2015).

Electric power trains do exist for light vans such as Renault Kangoo, Nissan e-NV200, Peugeot partner and Citroen Berlingo. However, these electric vans are light duty vans, and for the purposes of this study medium sized vans were considered.

### ***B.2.1 Weights and power demand***

Mercedes Vito is a full electric van equipped with 36kWh battery and 60kW motor. Iveco daily is also an electric medium sized panel van equipped with 21.2kWh battery, with the electric range up to 128km (Contact hire and Leasing).

The Smith Edison panel van is a full electric van which uses a Ford Transit chassis. The battery capacity is between 36kWh and 51kWh. The Smith Edison is equipped with 90kW motor. It should be noted that Mercedes, Iveco and Smith Edison are not capable of reaching 70mph. These vehicles are primarily designed for urban drive conditions.

Eaton Corporation has developed parallel hybrid vans for UPS, with motor power of 44kW and battery capacity of 1.8kWh.

The Smith Edison gross weight capacity is 3500kg and the unladen weight is 2480kg. The unladen weight for the similar conventional Ford Transit is 1950kg (Ford Transit Technical specifications, 2015). This indicates that the battery weight has a significant impact on vehicle weight; the converted vans reduce the payload weight by 200-700kg (Element Energy Limited, 2012).

About the 66% of vans in use in the UK are less than half full in terms of its payload capacity (RAC Foundation, 2014). For modelling purposes medium sized vans were considered to be 50% full, which means the total weight is 3000kg.

### ***B.2.2 Driving range***

Average daily mileage for a conventional diesel van is 64 miles, where 22% of the mileage is at speed above 50mph, while a hybrid van averages 42.5 miles per day, with 13% of the total mileage occurring at speeds above 50mph (Lammert, 2009).

The annual mileage can range from 15 to 40,000 miles, with an average of 17,000 miles per year (Element Energy Limited, 2012)). The life time of a van is approximately 10 years (RAC Foundation, 2014).

Electric vans are mainly used for urban delivery. However, vans and light trucks below 12 tonnes are increasingly used on motorways. About 80% of the distance travelled by vans is within the same region and 44% of all the vans registered in the UK visit London at least once a year (RAC Foundation, 2014).

### ***B.2.3 Power transfer rate from the infrastructure***

The available space under medium sized vans and small trucks is dependent on the length of the wheel base. A medium sized van can be equipped with a 40kW pickup coil. It may be possible to equip medium vans with larger pick up coils, but that arrangement is dependent on the dimensions of the pickup coil and the additional weight that it adds onto the vehicle.

## **B.3 HGV**

HGVs contribute to 23% of the carbon emissions due to transport in the UK. The hybridisation of HGVs could reduce the carbon emissions by 5-8% (Volvo, 2007).

Geesink Norba group and Volvo have developed a plugin refuse truck which uses an electric motor to drive the lifting and compacting mechanism. Thus the electric power in these vehicles is used to power auxiliary demand rather than to provide traction.

The majority of electric trucks are parallel hybrids. The parallel motor is used to support the diesel engine. Newton Smith is the only full electric truck, but this is specifically designed for local deliveries. Hence, the top speed is limited to 50mph. Also, it has lower vehicle payload when compared to conventional diesel vehicles (Ricardo, 2009).

The "state of the art" review shows that a full electric HGV is not a feasible option for trucks in near future due to the requirement for a very large battery (Daimler, 2013). The hybrid systems for HGVs are aimed to operate on uphill sections or during start-stops in order to ensure higher engine efficiency, therefore for modelling purposes a parallel hybrid system was used and the battery specification was develop accordingly.

### ***B.3.1 Weights and power demand***

The review shows that the battery capacity for existing hybrid HGVs is no greater than 10kWh for hybrid HGVs. The entire hybrid system for the MAN TGL weighs 400kg. In comparison, a full electric HGV would require approximately 600kWh batteries which could weigh approximately 7200kg, with a consequent reduction in payload capacity. Batteries of this size would also take a significant volume of space.

A 40 tonne HGV requires 127kW traction power at the wheel in order to maintain a speed of 55mph on the motorway. This equates 1.44kWh/km of energy consumption. The variation in motor size is dependent on how the traction motor is used. In the dynamic power transfer case it is ideal to provide all electric traction on electrified

sections of the road, therefore the motor should be able to supply a continuous power transfer rate of 130kW (236kW maximum power) at its maximum efficiency.

The MAN TGX parallel hybrid is equipped with a 326kW engine and a 130kW electric motor. However, full diesel HGV engines can be as high as 560kW (750hp). It should be noted that a 130kW electric motor can provide peak power up to 300kW for short periods of time, depending on the design. So, in order to maximise regeneration efficiency and provide maximum support for the diesel engine, peak motor power is assumed to be 300kW and the diesel engine is assumed to provide 326kW power.

### ***B.3.2 Driving range***

According to the EU laws the daily driving shift for commercial vehicles must not exceed 9 hours with at least one 45 minute break in between. Assuming that an HGV travels at an average speed of 55mph, the vehicle range can be as high as 495 miles (790km) per day. The annual mileage for a HGV can range 50-150,000 miles (80,000-240,000km).

The HGV drive cycle is mainly on motorways and A roads; HGVs cover very little mileage in urban driving conditions. The HGV spends 66% on SRN, 25% on local major roads and 9% on local minor roads. The HGV route is not predictable, but the general drive pattern is 55mph on the motorway with a maximum of 4.5 hours between stops.

### ***B.3.3 Power transfer rate from the infrastructure***

It is possible to equip HGVs with 100kW or 140kW secondary coils to provide electric traction in electrified sections. As stated, the HGV requires 127kW traction power to maintain 55mph. However, in order to provide full electric traction, the secondary coil should be rated at 142kW. The 100kW systems can provide 89kW to the traction, and the remaining 38kW must be provided by either engine or battery. The battery capacity in this case is dependent on the length of the electrified section in between two plugin charge events in service stations.

## Appendix C Model development for each vehicle type

This section uses the information from the review section to determine vehicle and route parameters in order to develop a model to analyse the vehicle behaviour.

The routes for cars and vans are designed to start and end in the city. The running speeds have been set in order to simulate real world driving conditions. The journey starts in a city and continues in this environment for 8.7km. Then, the vehicle enters a motorway where it stays for 310km (193miles) with speeds, for a car, ranging between 60mph and 71mph. For the final part of the journey the vehicle leaves the motorway and goes back to city driving conditions for 8.4km.

It should be noted that this is an ideal long journey for a car. However, this route, or parts of the route, can be used to model vans to simulate intercity travel. The HGV can drive up 4.5 hours without having to stop. A suitable drive train arrangement for an HGV is parallel hybrid, therefore the battery size is dependent on regenerative braking and conditions in which electric power is used. In this case, the regenerative sections such as city drive conditions and deceleration from motorway speeds to zero were considered when specifying a battery capacity.

### C.1 Car

The average distance travelled per day is approximately 23-26 miles (37-41km). However, drivers consider 92 miles (147km) to be an adequate range for daily use and 330km to be a sufficient range for all trips. Therefore, the model is based on a 206 mile (330km) city to city journey. The majority of long trips, that is over 90 miles (144km), can be for either business trips, holidays or to visit friends and they may occur on average 12 times per year (Technology Strategy Board, 2011).

The free flow speed on the motorway can range between 53mph and 69mph, thus the model will operate in this speed range. The free flow speed of a car or a van is 69mph.

The review showed that a full electric vehicle available on the market is capable of meeting daily demand. As a result the car battery requirement was based on an assumption that the car power train is full electric. Nissan Leaf parameters were used for modelling purposes. The reason for choosing Nissan leaf is that it is a representative state of the art electric car at an affordable price. Table 45 shows the parameters used in order to calculate power demand and energy consumption of a Nissan Leaf.

### C.2 Van

There are medium sized full electric vans available such as Smith Edison and Iveco daily even and, even though the take up is low, the state of the art shows that the technology is ready. Therefore full electric vans were used for modelling purposes. The review stated that average daily drive range for a conventional diesel van is 64 miles (102km), therefore with a sufficient battery capacity it can be possible to drive in full electric mode. Table 45 shows the input parameters for modelling the car and van.

**Table 45: Modelling parameters for the car and the van**

Parameter	Car	Van
Vehicle power train	Full Electric	Full Electric
Mass	1521kg	3000kg
Drag coefficient	0.28	0.37
Surface area	2.29m <sup>2</sup>	5.6m <sup>2</sup>
Rolling resistance	0.012	0.007
Motor power	80kW	90kW
Gearbox efficiency	97%	97%
Motor efficiency	95%	95%
Power electronics efficiency	97%	97%
Battery charge/discharge efficiency	95%	95%
Air-conditioning	OFF	OFF
Heating	OFF	OFF
Battery capacity	24kWh	54kWh
Available battery	17.7kWh (U.S. Department of Energy)	43kWh

### C.3 HGV

The review showed that it is not possible to design a full electric HGV with current battery technology, therefore for the modelling purposes Scania R-series HGV parameters were used along with MAN TGX power train to model a parallel hybrid HGV. For the purposes of this study it was assumed that the HGV is equipped with a 130kW motor in parallel hybrid power train mode.

The free flow speed for an HGV can be between 53 and 60mph, depending on the truck type and the load. In this case, the average motorway speed of an HGV is assumed to be 55mph.

**Table 46: Scania R-series parameter**

Parameter	Value
Vehicle power train	Parallel Hybrid
Mass	40000kg
Drag coefficient	0.75
Surface area	5.6m <sup>2</sup>
Rolling resistance	0.006
Motor power	130kW (236kW maximum)
Engine power	358kW
Gearbox efficiency	97%
Motor efficiency	95%
Power electronics efficiency	97%
Battery charge/discharge efficiency	95%
Air-conditioning	OFF
Heating	OFF

## Appendix D Description of Dynamic Wireless Power Transfer systems

### D.1 Background to vehicle technologies

All vehicles convert some form of fuel into energy that powers the drivetrain. In internal combustion engine (ICE) vehicles, a liquid fossil fuel (typically petrol or diesel) is delivered to the vehicle via a fuel pump from a fuel station and is stored in an on-board fuel tank. This fuel is then combusted inside the internal combustion engine where chemical energy stored in the fuel is converted to heat energy, which is then converted to movement of the crank shaft and then the drive shaft via transmission, providing all the necessary kinetic energy to move the weight of the vehicle. All energy used by the vehicle is provided by the liquid fuel that originated from outside the vehicle. Due to the numerous energy conversion steps and the principles of thermodynamics, ICE vehicles have a low overall efficiency of converting chemical energy stored in the fuel to traction energy, depending on specifics of the vehicle, ranging between 15% and 25% efficiency.

Electric Vehicles are more efficient as they could require fewer energy conversion steps and electric motors are much more efficient at converting electrical energy into motive power than ICE. Typically, electric motors are around 90% efficient and overall efficiency of converting electricity delivered to the vehicle to traction energy can be around 75%.

For an EV, electric energy is usually provided via some sort of charging mechanism from an external plug to the vehicle. This energy can then be either fed directly into the electric motor or stored in some on-board storage medium (e.g. battery) and then fed into the electric motor. Storing the energy on board the vehicle can result in additional losses reducing the overall energy efficiency to around 65% to 70%. Vehicles with on-board energy storage can also benefit from energy recovery via regenerative braking. This allows some braking energy to be recovered via a generator and used to top up on-board rechargeable energy storage system (RESS).

It is also possible to have a combination of ICE and EV by combining the powertrains into a hybrid powertrain that can use either energy from the fossil fuel or electrical energy from the grid/regenerative braking. The Energy efficiency of such vehicles can vary considerably depending on the drive cycle and powertrain set-up. Due to increased weight of such vehicles they are unlikely to have efficiency as high as a pure EV but will have better efficiency than ICE vehicles. There are two main types of plug-in hybrid vehicles, a parallel hybrid and a series hybrid (also known as electric range extender). The key difference between the two is that a series hybrid always uses electric power and the electric motor is rated to provide all the power required by the vehicle. Whereas, parallel hybrid can use either electric power or power from the ICE and the electric motor is typically rated at a lower level as it is expected to be supported by the ICE to provide all the necessary power. In practice, there are various permutations and sometimes combinations of these hybrid powertrains.

In all of the options for electrified vehicles described, a vehicle can make use of a power transfer system to charge the on-board RESS or to provide power to the electric motor. Typically these systems are plug-in electric chargers that charge the vehicle batteries at varying levels of power (usually between 3kW and 120kW) while the vehicles is stationary and turned off. However, it is also possible to use wireless power transfer to charge the batteries while stationary. Both of these solutions are adequate for charging at home or in car parks but still require the vehicle to stop in an appropriate location to

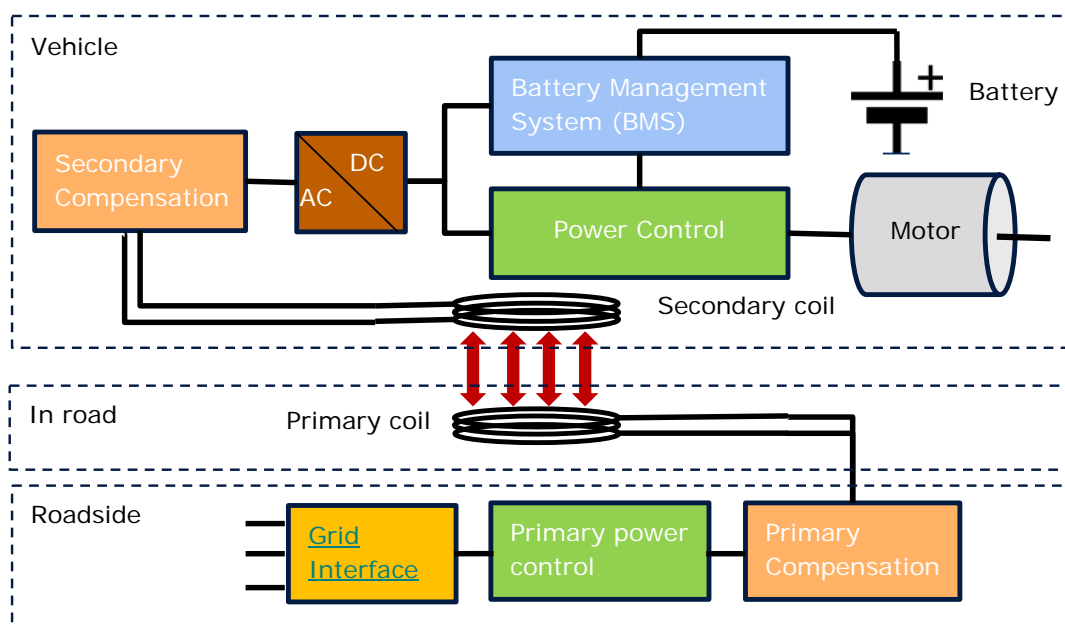
charge the battery. Dynamic power transfer is another option for supplying power to electrified vehicles and, as it can be used while the vehicle is moving, it can help to reduce or eliminate issues with restricted range. Dynamic power transfer can be either conductive or wireless. It can also be used to supply the electric motor with power directly or to charge the on-board RESS, or both.

Conductive dynamic power transfer is only practical for vehicles of a certain size (in the case of pantograph solutions) and requires a considerable amount of over ground infrastructure and cables which could present a considerable maintenance challenge and a potential safety hazard. In the case of in-road conductive rail systems, there are some substantial issues associated with electrical safety and operational durability of such systems if deployed in the motorway environment. Therefore, for the purpose of this project, the feasibility of WPT systems only is considered. However, it is recognised that other potential options exist and it is recommended that they are monitored and where appropriate evaluated as part of future work.

## D.2 Principles of WPT

The most advanced techniques in WPT are based on electrostatic and magnetic induction. In this section only the latter method is presented since it is the most promising one at present.

Inductive wireless power transfer works on the same principal as a transformer. An inductive WPT system (static or dynamic) for EVs can be summarised at high level as shown in Figure 59.



**Figure 59: Layout of a WPT system, static and dynamic**

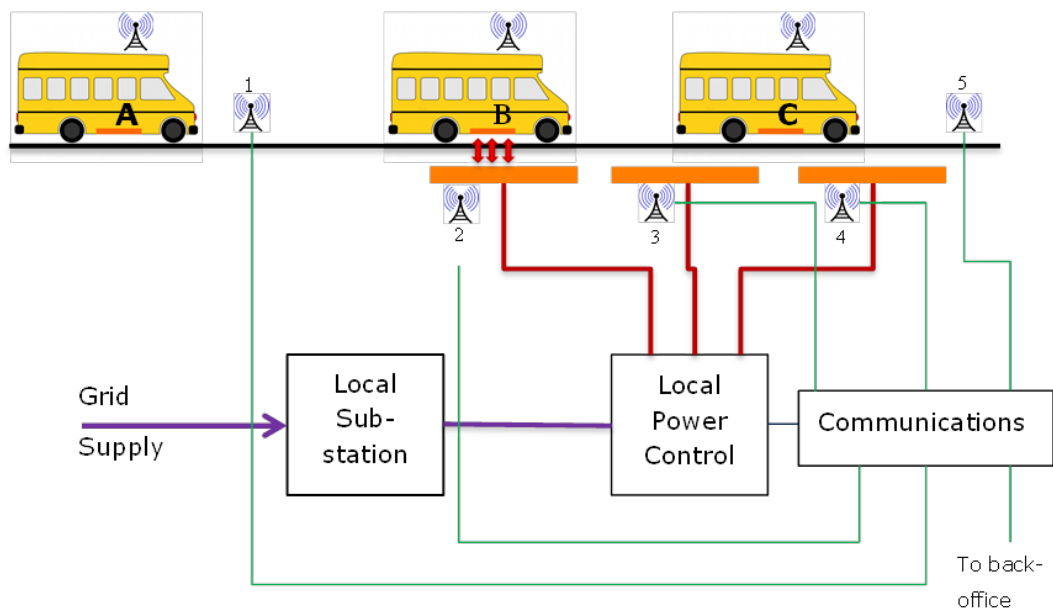
- The AC from the grid is converted to a higher frequency suitable for inductive coupling through an air gap by the power control circuit
- It feeds the primary circuit, which is located under the road surface



- Primary and secondary compensation circuits ensure the two coils are tuned at the same resonant frequency. This is carried out by varying the capacitance of the circuits
- The power is transferred by magnetic induction to the secondary circuit placed on the vehicle
- The current is then converted into direct current (DC) which feeds the battery or is fed directly into the electric motor
- Finally, the stored power can be used by the motor and electronics.

The principle of inductive wireless power transfer is the same for static and dynamic environments, but the dynamic environment places more stringent requirements on the systems, particularly with respect to emissions, efficiency and grid load.

Extending a WPT system to a dynamic environment requires that the system copes with the fact the vehicles may be moving. In a dynamic power transfer scenario, a series of primary coils are deployed along the driving lane. For the on-road system to start emitting power when the EV is over it, there must be a communication system that recognises the approaching vehicle and activates the power transmission at the opportune time. Moreover, it must be interfaced with the electric grid for managing the energy supply and payment information. It could also provide assistance to the driver for optimising the process; for example giving indication about the location of the electrified sections and the manoeuvres for adjusting the speed and alignment.



**Figure 60: Layout of a typical DWPT system layout**

Figure 60 shows a typical DWPT system. A vehicle approaches the DWPT segments (orange blocks below road surface), the secondary coils on the vehicle are shown in orange between the wheels. Grid power is supplied to the DWPT system's local power control via a local sub-station (purple lines). The power control system is in contact with a DWPT back office for control and billing purposes. Figure 60 also shows a means for the infrastructure to communicate with the vehicle before (antenna 1), during (antennas

2-4) and at the end of the DWPT segment (antenna 5). Not all DWPT systems will necessarily include this type of communications link.

As a vehicle equipped with DWPT approaches a segment of road equipped with the necessary power infrastructure, the infrastructure needs to recognise that a suitably equipped vehicle is approaching. This normally implies a communications channel exists between the vehicle (A) and the infrastructure (antenna 1). In the example shown in Figure, this is achieved by a radio channel. This recognition could in principal also be achieved without a communications channel, for example using an ANPR camera. Once the infrastructure has recognised the vehicle, it will have the basic information it needs to transfer power, i.e.:

- What the power transfer capabilities of the vehicle are
- Whether a valid account exists to pay for the power
- Whether the vehicle requires power (the batteries may be fully charged)
- How much power the vehicle requires (if the batteries are fully charged, the vehicle may still want to accept enough power to directly power the traction motors).

The last two points may not be possible for a recognition system which does not employ a communications channel between the vehicle and the infrastructure.

Also shown in Figure 60 are regular communications antennas which will enable the infrastructure to continually monitor the vehicle to ensure that the power transfer is continuing correctly. As before, this is not used by all DWPT systems, so cannot be assumed to exist. Any systems which do not include the regular exchange of information between the infrastructure and the vehicle must demonstrate that fault conditions are adequately coped with.

Assuming the infrastructure has determined that power needs to be supplied to the vehicle, it must now determine when to turn on the primary power coils. It is normally required that the primary coils are only energised when the secondary coils are a position which allows them to couple fully with the primary coils (vehicle B). This maximises both efficiency and safety by containing the magnetic fields within the space between the primary and secondary coils. It is important however to understand that not all systems may work in this way, so this cannot be assumed.

Power will now be transferred while the vehicle drives over the primary coils. When the vehicle is not in a position which allows inductive coupling between the primary and secondary (e.g. Vehicle C), no power should be applied to the primary coil.

## Appendix E Commercial Aggregation Service Providers (CASPs)

There are a range of CASPs, shown in, that allow groups of smaller capacity STOR providers to provide STOR services, where they can, within the availability window when called upon.

Company	Contact Name	Telephone	E-Mail
GDF SUEZ Energy UK	Randy Pryce	0113 3062100	<a href="mailto:randy.pryce@gdfsuezuk.com">randy.pryce@gdfsuezuk.com</a>
Flexitricity	Jill Cox	0131 221 8102	<a href="mailto:jill.cox@flexitricity.com">jill.cox@flexitricity.com</a>
Npower Ltd	David Powell	07989 481144	<a href="mailto:david.powell@npower.com">david.powell@npower.com</a>
EnerNOC UK Ltd	Peter Holzaepfel	001 617 692 2056	<a href="mailto:peter.holzaepfel@enernoc.com">peter.holzaepfel@enernoc.com</a>
KiWi Power Ltd	Yoav Zingher	0845 519 4054	<a href="mailto:info@kiwipowered.com">info@kiwipowered.com</a>
ESP Response Ltd	Arthur Probert	07814 009762	<a href="mailto:a.probert@energyservicespartnership.co.uk">a.probert@energyservicespartnership.co.uk</a>
Matrix – Sustainable Energy Efficiency	Stuart Hutchison	0141 425 2870	<a href="mailto:stuart.hutchison@matrixsee.co.uk">stuart.hutchison@matrixsee.co.uk</a>
Open Energi	Steven Clarke	07939 462000	<a href="mailto:steven.clarke@openenergi.com">steven.clarke@openenergi.com</a>
UK Power Reserve Ltd	Sam Wither	0121 712 1975	<a href="mailto:sam.wither@ukpowerreserve.com">sam.wither@ukpowerreserve.com</a>
Tezla Energy Ltd	Operations Manager	+44 (0)2032 941 687	<a href="mailto:info@tezlaenergy.com">info@tezlaenergy.com</a>
EDF Energy	Karen Anderson	0845 300 9146	<a href="mailto:smartresponse@edfenergy.com">smartresponse@edfenergy.com</a>
Cynergin Projects Ltd	Howard Stone	+44 (0)845 257 7080	<a href="mailto:STOR@cynergin.uk.com">STOR@cynergin.uk.com</a>
Energy Pool / Schneider Electric	Peter McGee	07770 654 119	<a href="mailto:contact.uk@energy-pool.eu">contact.uk@energy-pool.eu</a>
REstore	Dirk Collin	+44 (0)7787 893 663	<a href="mailto:dirk.collin@restore.eu">dirk.collin@restore.eu</a>
Limejump Ltd	Ning Zhang	020 7127 5308	<a href="mailto:info@limejump.com">info@limejump.com</a>
Stor Generation Ltd	Armando Ferro	0203 179 2100	<a href="mailto:AFerro@questjfinvestments.com">AFerro@questjfinvestments.com</a>
Endeco Technologies	Michael St Leger	01923 431 638	<a href="mailto:michael.stleger@endeco-technologies.com">michael.stleger@endeco-technologies.com</a>

## Appendix F DWPT automatic vehicle identification

Automatic Vehicle Identification (AVID) falls into four broad categories:

- Automatic Number Plate Recognition (ANPR) using a camera and image recognition software/hardware.
- Radio Frequency Identification (RFID) through an Ultra High Frequency (UHF) reader using a passive or powered tag. This is effective at a range of up to 4m at low or zero vehicle velocity.
- Microwave Frequency Identification (MFID) reader using a passive or powered tag. This is effective at a range of 10m at a vehicle velocity of up to 125mph.
- In-road loop and transponder (IRLT) system. This is effective at high vehicle speeds with a range of 1m above the road surface.

Table 47 shows a summary of the AVID technologies with their respective advantages and disadvantages.

**Table 47: Vehicle identification categories summary table**

Technology	Advantages	Disadvantages	Capital Cost
ANPR	No vehicle equipment installation Tamper proof Works at high speeds	Requires number plate line of sight Susceptible poor weather conditions	Low
RFID UHF Tag	No line of site required Works in all weather conditions	Vehicle equipment installation required Low speeds Short range	Med
MFID Tag	High Speeds Med range	Vehicle equipment installation required	High
IRLT	High speeds High range with large or multiple loops	Vehicle equipment installation required Road surface modification required	High

Should ANPR be used, either alone or in conjunction with MFID or IRLT, linking the registration to the vehicle owner may be desirable as a further check against fraud i.e. a user who has tampered with their on-board AVID equipment. The standard method of doing this is to go through the DVLA website and use a V888 form and pay a nominal £2.50 fee. This would be impractical every time a user uses the DWPT system; however, could be used as an initial check to validate a user account upon registration.

A system in use in the UK that uses user accounts for billing and payment services is in operation on The Second Severn Crossing. The TAG system is a method of identifying

users in moving vehicles via UHF RFID. To take part in this system, users must apply for a 'Season' or 'Trip TAG' user account. A Season TAG account allows unlimited journeys for periodic payments within the covered period via various payment methods including direct debit.

## Appendix G Network model data

### Electrical System Data

**Table 48: LV network model data for LV network cable**

$S_{base}$ (MVA)	0.243	$I_{base}$ (A)	0	$Y_{base}$ (S)	1.51875
$V_{base}$ (kV)	0.4	$Z_{base}$ ( $\Omega$ )	0.65844		

Run	Network Element	Length (m)	@ 20°C											
			Resistance / m		Reactance per m		Suseptance / m		Resistance		Reactance		Suseptance	
			$\mu\Omega/m$	p.u.	$\mu\Omega/m$	p.u.	nS/m	p.u.	$\Omega$	p.u.	$\Omega$	p.u.	mS	p.u.
Inter SS 1,2 & 3	300 mm LV cable	250	117	1.78E-04	63	9.57E-05	170.00	1.12E-07	2.93E-02	4.44E-02	1.58E-02	2.39E-02	4.25E-02	2.80E-05

**Table 49: HV network IPSA model data for HV network cable**

$S_{base}$ (kVA)	5.81	$I_{base}$ (A)	0	$Y_{base}$ (S)	0.05
$V_{base}$ (kV)	11	$Z_{base}$ ( $\Omega$ )	20.8262		

Run	Network Element	Length (m)	@ 20°C											
			Resistance / m		Reactance per m		Suseptance / m		Resistance		Reactance		Suseptance	
			$\mu\Omega/m$	p.u.	$\mu\Omega/m$	p.u.	nS/m	p.u.	$\Omega$	p.u.	$\Omega$	p.u.	mS	p.u.
East HV Run	300 mm HV	1446	116	5.57E-06	77	3.70E-06	223.00	4.64E-06	1.68E-01	8.05E-03	1.11E-01	5.35E-03	3.22E-01	6.72E-03
West HV Run	300 mm HV	1523	116	5.57E-06	77	3.70E-06	223.00	4.64E-06	1.77E-01	8.48E-03	1.17E-01	5.63E-03	3.40E-01	7.07E-03
HV SS Run	300 mm HV	250	116	5.57E-06	77	3.70E-06	223.00	4.64E-06	2.90E-02	1.39E-03	1.93E-02	9.24E-04	5.58E-02	1.16E-03

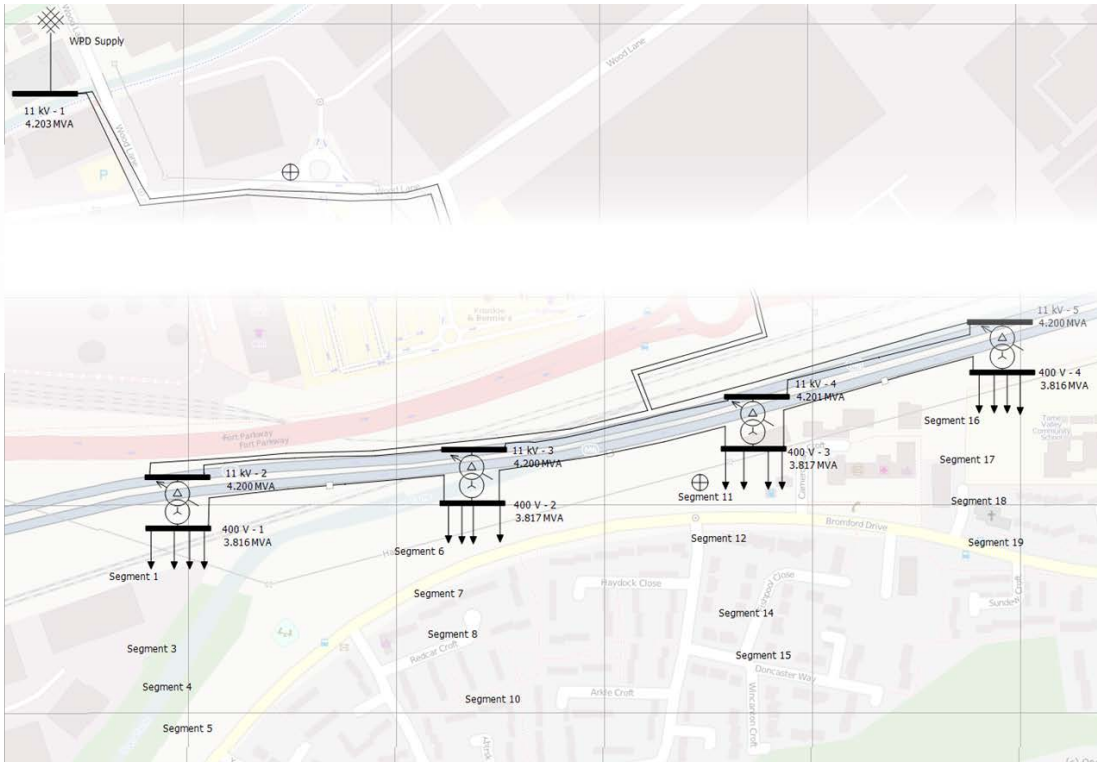
**Table 50: Transformer details from model database**

Network Element	Resistance p.u.	Reactance p.u.	Min Tap (%)	Max Tap (%)	Rating (MVA)	Base (MVA)
11kV-0.433kV Transformer	7.80E-3	46.86E-3	-5	5	1	1

**Table 51: WPD network primary substation infeed data**

Group	IPSA Node Name	Voltage (kV)	Equipment Rating		Short Circuit Currents				System impedance		X/R	Peak LLL (MVA)	RMA LLL (MVA)
			3ph. Make (kVA)	3ph. Break (kVA)	3ph. Make		3ph. Break		React. X1	Resist. R1			
					2014	STRESS	2014 70ms	STRESS					
Nechells	ERDI113B	11	32.8	9.3	24.494	74.68%	8.3	89.81%	0.631	0.017	37.668	0.467	0.158





**Figure 63: Symmetric RMS fault level at 100ms fault current from ISPA 2 1km DWPT SRN network model**



## Appendix H Stakeholder cooperation

In order to identify how working with the local DNOs will be established, the sources introduced in this appendix have been reviewed.

### H.1 Planning Act 2008

The Planning Act 2008 contains many clauses. In this subsection, the most relevant aspects of the Planning Act, to a DWPT project, are discussed, without providing an exhaustive list of all potentially relevant clauses. The relevant section of the Planning Act 2008 will become clearer at the development stage of the DWPT project. To be subject to the Planning Act of 2008, a project must be listed as nationally significant, which can consist of any of the following:

- a) The construction or extension of a generating station
- b) The installation of an electric line above ground
- c) Development relating to underground gas storage facilities
- d) The construction or alteration of an LNG facility
- e) The construction or alteration of a gas reception facility
- f) The construction of a pipe-line by a gas transporter
- g) The construction of a pipe-line other than by a gas transporter
- h) Highway-related development
- i) Airport-related development
- j) The construction or alteration of harbour facilities
- k) The construction or alteration of a railway
- l) The construction or alteration of a rail freight interchange
- m) The construction or alteration of a dam or reservoir
- n) Development relating to the transfer of water resources
- o) The construction or alteration of a waste water treatment plant, the construction or alteration of a hazardous waste facility

Two categories are applicable to DWPT charging which are h) and potentially b), but only if the DWPT SRN section is situated near a small town or in a rural location which requires the erection of overhead lines. Erected electric lines need to be at the 132kV Voltage level for them to be deemed a nationally significant project. It is therefore likely that sub clauses relating to h. are applicable for DWPT infrastructure projects.

A DWPT SRN section is likely to be an improvement or an alteration to the existing highway. As a DWPT scheme is unlikely to have a significant effect on the environment when in operation, the DWPT is likely to satisfy all requirements in subsection 14. (22). (4) since the Highways England acts on behalf of the Secretary of State for Transport. A DWPT project taking place within Wales, Scotland or Northern Ireland are not subject to the Planning Act, though similar legislation will likely be applicable for most devolved administrations.

For DWPT projects in England, an order granting consent may only be granted if an application is made, which must be made to the Infrastructure Planning Commission (IPC). An application for an order granting development consent must:

- Specify the development to which it relates
- Be made in the prescribed form
- Be accompanied by the consultation report
- Be accompanied by documents and information of a prescribed description
- Declare any intention to Toll road users at the point of application

The DWPT provider would have to consult with:

- The local authority, which could be the county council, National Parks authority or the Broads Authority
- A person or person prescribed by the infrastructure planning commission
- An owner, lessee or tenant of any occupying or has interests in land affected by the project

The decision-maker is under a duty to decide an application for an order granting development consent by the end of the period of 3 months beginning with the day after the start day, which is usually when the application has been received. The 3 month deadline may be extended by the deciding party or Secretary of State; however, the former must provide reasons for doing so.

At the decision date, the decision-maker must either make an order granting development consent or refuse development consent and provide reasons and conditions for the order made in the form of a written statement. Copies must be provided to each person who is an interested party.

Supporting features of a DWPT project may include:

- The resulting ability of the use of land within the local authorities planning area to help mitigate climate change
- The person or body must (in particular) have regard to the desirability of achieving good design

Should the order refusing development consent be passed, the applicant will be allowed to appeal within 6 weeks of the order. If development consent is granted, a fixed time frame for development work will be provided, during which the installation of the DWPT SRN must take place. This will include all supporting work required at the site.

It is possible, for a nationally significant project, to override extinguishment of rights, and removal of apparatus, of statutory undertakers, though this is unlikely to be required for a DWPT project unless overhead lines at 132kV are erected.

It is recommended that the Planning Act 2008 be considered in full to identify all relevant clauses for DWPT demonstration and commercial projects following this feasibility stage.

## H.2 National Infrastructure Plan 2014

The National Infrastructure Plan 2014 (NIP 14) sets out an infrastructure vision for the next parliamentary period and beyond the year 2020. It is intended to reinforce the acting government's commitment to investing in infrastructure and improving its quality and performance. It is underpinned by a budget of over £460 billion of planned public and private investment including oil and gas infrastructure development.

The intention of the coalition government was to prioritise the public funding infrastructure and put in place policy frameworks to provide investors in long term projects confidence that will see return on their investments. Several announcements in NIP 14 reinforce the likelihood of higher level of penetration of electric vehicles. These are:

- **Ultra-low emission vehicle research and development** – the government announced up to £50 million, between 2017-18 and 2019-20, to support innovation in manufacturing of ultra-low emission vehicles in the UK, based on a government contribution of £25 million for which it will seek match-funding from industry
- **Ultra-low emission vehicles in London** – the government will provide an additional £10 million between 2017-18 and 2019-20 to increase ultra-low emission vehicles in London, in support of the ambition to introduce an Ultra-Low Emission Zone by 2025
- **Support for ultra-low emission vehicles** – the Roads Investment Strategy (RIS) has set aside £15 million, between 2015-16 and 2020-21, for a national network of charge points for ultra-low emission vehicles on the SRN; the government has also announced further details of three funds, totalling £85million, to support ultra-low emission taxis, buses and cities

Further announcements, pertaining to increased ease of use in the planning process are:

- **Establishing the principle of development** – the government planned to take forward measures to ensure that the principle of development need only be established once
- **Section 106 negotiations** – the government planned to take steps to speed up section 10 negotiations, to reduce delays to the planning process
- **Speed of decisions** – the government planned to keep the speed of major decisions under review, with minimum performance thresholds increasing to 50% of major decisions made on time as performance improves

The NIP 14 also outlined currently planned and future investment in the road and energy infrastructure within the UK. The coalition government announced it was taking steps to revolutionise the way that it planned and delivered roads investment, including:

- Publishing the Road Investment Strategy (RIS1) covering 2015-16 to 2019-20, which set out the national priorities and plans for the SRN
- Replacement of the Highways England with a new strategic highways company

- Creating a new highways monitor, charged with ensuring that taxpayers' money is well spent and the new highways authority is delivering efficiencies during the RIS 1 period and beyond

These changes were underpinned in legislation, through the Infrastructure Bill, which was passed by Parliament in 2015.

In relation to DWPT schemes, the most relevant announcements for Roads in NIC 2014 were:

- The establishment of 5 designated funds - Worth £900 million to address a range of specific issues. The focus of this funding was to ensure that the Strategic Highways Company is at the cutting edge of innovation in road construction and network management. The funds were:
  - Environment
  - Cycling, Safety and Integration
  - Innovation
  - Air Quality
  - Growth & Housing
- To support delivery of its objectives for the roads sector - The government included the following within its Top 40 priority infrastructure investments:
  - Accelerated Road Schemes
  - Strategic Roads New Capacity
  - Smart Motorways

From the above it can be seen that two of the funds, environment and innovation, could possibly be accessed for a DWPT scheme, before it becomes a business as usual enterprise, which would be in line with a Smart Motorway infrastructure project; a government top 40 infrastructure priority.

### **H.3 National Policy Statements for Electricity Networks**

The National Policy Statement for Electricity Networks (NPS-EN) provides the primary basis for decisions taken by the Infrastructure Planning Commission (IPC) on applications it receives for electricity network infrastructure. It is intended to be used in conjunction with the NPS for energy (EN-1). EN-1 covers:

- The high level objectives, policy and regulatory framework for new nationally significant infrastructure projects. These are covered by the suite of energy NPSs (referred to as energy NSIPs) and any associated development
- The need and urgency for new energy infrastructure to be consented and built with the objective of contributing to a secure, diverse and affordable energy supply and supporting the Government's policies on sustainable development in particular by mitigating and adapting to climate change
- The need for specific technologies, including the types of infrastructure covered by this NPS

- Key principles to be followed in the examination and determination of applications
- The role of the Appraisals of Sustainability (AoS) in relation to the suite of energy NPSs
- Policy on good design, climate change adaptation and other matters relevant to more than one technology-specific NPS
- The assessment and handling of generic impacts that are not specific to particular technologies

As discussed in the Planning Act 2008 section, the IPC decides to provide consent for an infrastructure project. However, the localism bill, which received Royal Assent on 15 November 2011, abolishes the IPC and passes the function of granting planning applications to the Secretary of State for Energy and Climate change. The Major Infrastructure Planning Unit (MIPU) passes reports and recommendations to the Secretary of State for Energy and Climate change, for a decision on consent.

The NPSEN and EN-1 covers England and Wales and will remain in force until withdrawn by the Secretary of State. Like the Planning Act, the NPSEN covers Above Ground Electricity Lines (AGELs), whose nominal voltage is 132kV and above. NPSEN emphasises requirements for overhead lines to be resilient to the effects of climate change and have a good design approach. NPSEN also sets additional technology-specific considerations and associated mitigation options on the following generic impacts considered in EN-1:

- Biodiversity and Geological Conservation – This involves not siting AGELs across flight paths, making AGELs more visible to birds and reducing electrocution risk to wildlife
- Landscape and Visual – Considering reinforcement alternatives, visual screening and the most suitable AGELs support structures
- Noise and Vibration – Involving positioning of lines to lower noise levels experienced and ensuring the appropriate size conductor is used to minimise potential noise

Electromagnetic Field (EMF) effects are also described in NPSEN; however, it does not repeat the detail of the ICNIRP 1998 guidelines on restrictions or reference levels nor the 1999 EU Recommendation. NPSEN states that before granting consent to an overhead line application, the IPC should satisfy itself that the proposal is in accordance with the guidelines in Power Lines: Demonstrating compliance with EMF public exposure (DECC, 2011). There is no statutory provision in the planning system relating to the protection from EMFs, however, NPSEN states the following mitigation should have been considered:

- The height, position, insulation and protection (electrical or mechanical as appropriate) measures subject to ensuring compliance with the Electricity Safety, Quality and Continuity Regulations 2002
- That optimal phasing of high voltage overhead power lines is introduced wherever possible and practicable in accordance with the Code of Practice to minimise effects of EMFs

- Any new advice emerging from the Department of Health relating to Government policy for EMF exposure guidelines

Where it can be shown that the new line has to comply with the current public exposure guidelines and the policy on phasing, no further mitigation should be necessary.

#### **H.4 Transport National Policy Statements for Roads & Rail Networks**

The Transport National Policy Statements for Roads & Rail Networks (TNPSRR) outlines the coalition government's vision and strategic objectives for the national road network as:

- Networks with the capacity and connectivity and resilience to support national and local economic activity and facilitate growth and create jobs
- Networks which support and improve journey quality, reliability and safety
- Networks which support the delivery of environmental goals and the move to a low carbon economy
- Networks which join up our communities and link effectively to each other

A DWPT project improves journey quality, readability and safety for EV users and supports increased penetrations levels of EVs, which can assist in the decarbonisation of the transport sector. As DWPT SRN is independent of, but may coincide with, motorway widening and expansion, much of the requirement of the directives and regulations in TNPSRRN will not apply specifically to the DWPT aspect of SRNs. In summary, a DWPT project should not influence the following, as they are defined in TNPSRRNs:

- Habitat isolation and severance
- Changes to hydrology
- Changes to erosion or sedimentation regimes
- Pollution to water, air or soil
- Light disturbance
- Human activity

A DWPT SRN site may affect noise levels by increasing level from an AGELS installation (covered by NPSEN) or reducing it through the use of EVs as opposed to ICEVs. Therefore noise levels, as a detracting factor, should not come under TNPSRRNs unless traffic flows are expected to increase as a direct result.

#### **H.5 GB Electricity Distribution Licence Agreements**

Some commercial aspects of the standard conditions of the Electricity Distribution Licence (EDL) have been discussed in 7.2. In this subsection, the licence agreements in the EDL, and how this affects the DWPT provider are discussed. The Distribution Network Licensee (DNL) must comply with the following agreements:

- The Distribution Connection and Use of System Agreement (DUSCA)
- The Master Registration Agreement (MRA)

The DUSCA is a 995 page document, which provides DNOs and Independent DNOs (IDNOs) with the following general aims which are relevant to a DWPT system connecting at the distribution level:

- The development, maintenance and operation of an efficient, co-ordinated, and economical Distribution System
- The facilitation of effective competition in the generation and supply of electricity and (so far as is consistent with that) the promotion of such competition in the sale, distribution and purchase of electricity
- The efficient discharge imposed upon them by their Distribution Licences

Other aims contained in DUSCA, specific to charging methodologies, have been discussed in 7.2. The DUSCA also contains the conditions of commercial arrangements and relationships between the electricity distributor and:

- A supplier or generator
- An offshore transmission operator
- A gas supplier

The DUSCA document outlines the conditions that follow connection to the distribution network. The DWPT operator will have a commercial relationship with their supplier and the supplier will be responsible for the energisation and de-energisation of the DWPT system at the point of meter installation(s). The DWPT operator will need to provide the DNO with:

- The relevant Connectee's name
- The Metering Point or Metering System address
- In respect of an Exit Point, the Customer's Maximum Import Capacity
- if:
  - The Customer is not a Domestic Customer (as defined in the Supply Licences)
  - The Customer has a maximum power requirement of not less than 20kVA
  - The Customer is a new owner or occupier of the site; and in respect of an Entry Point, the Maximum Export Capacity

The MRA provides a governance mechanism to manage the processes established between electricity suppliers and distribution companies to enable electricity suppliers to transfer customers. It includes terms for the provision of Metering Point Administration Services (MPAS) Registrations.

The MRA document provides guidance to the supplier on connecting new customers, new metering points and registration of new supply numbers as well as other billing administration procedures. This will not be of direct interest to the DWPT operator, as the relevant information for supply and connection to the electricity network will be provided by their DWPT electricity supplier.

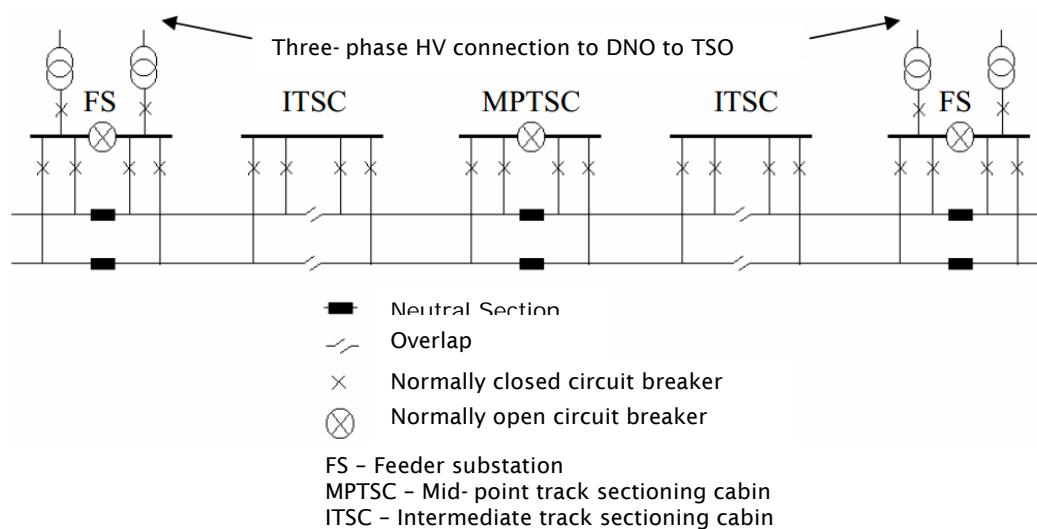
## **H.6 DNO and rail industry cooperation**

Rail networks in the UK can either be DC or AC, with the railway (network rail) electrified infrastructure feeding the traction motors of electric trains. Electrical configurations of AC systems are the most similar to the likely electrical layout of a DWPT charging scheme and will be discussed in this subsection.

The single-phase 25kV rail electricity network is now the UK's standard overhead catenary feeding system. An AC railway power supply system has several notable configuration features:

- A typical AC railway feeder substation is directly connected to the three-phase high-voltage supply grid
- The high-voltage side is connected to the utility's three phase busbar, with the low-voltage side connected to a single-phase busbar as shown in Figure 64
- The feeding arrangement of the single-phase AC railway power supply requires neutral sections to separate two adjacent feeding networks supplied at the feeder substation

Each feeder substation in the UK typically consists of two power transformers at either 132/25kV, 275/25kV and 400/25kV. This indicates that for an electrified rail system supporting large trains, the DNO may not always be involved and the TSO may be the grid connecting party.



**Figure 64: Typical feeding diagram of a double-track railway in the UK (Kulworawanichpong, 2003)**

There are some basic feeding configurations that are widely used for feeding electric energy to electric trains in mainline AC railways. These are:

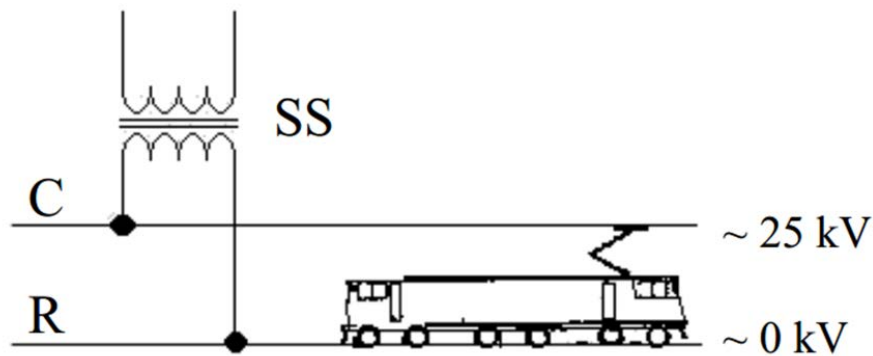
- Direct connection
- Booster transformer feeding configuration
- Autotransformer feeding configuration

Direct connection of the feeding transformer to the overhead catenary and the rails at each substation is relatively straight forward and low cost. However, there are some disadvantages to this scheme which are:



- High impedances of feeders resulting in large power losses
- High rail-to-earth voltage
- The interference to neighbouring communication circuits

To reduce the associated disadvantages, the addition of Return Conductor (RC), paralleled and tied to the rails, at typically 5 or 6km intervals, is required. This has the advantage of reducing electromagnetic interference in parallel communication lines by ~30%. Figure 65 shows a diagram of the direct feeding configuration.

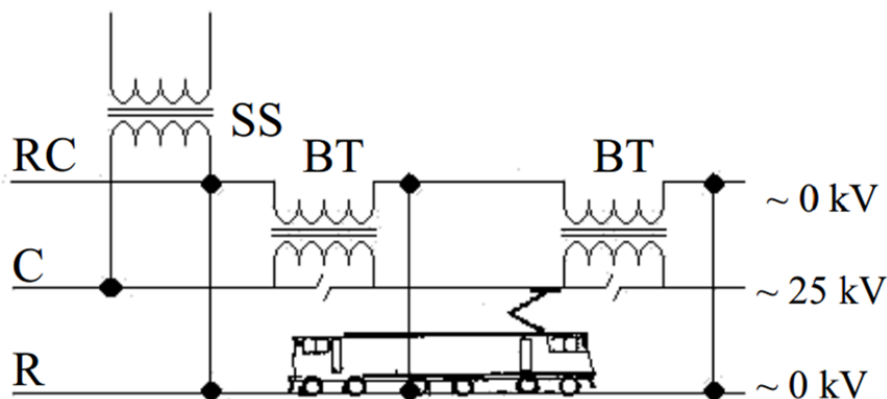


**Figure 65: Diagram of the direct feeding configuration. C is the catenary conductor, R is the rail conductor and SS is the grid connect substation (Kulworawanichpong, 2003)**

The booster transformer feeding configuration employs booster transformers (BTs) added along the catenary conductor at every 3-4km. The BT turn ratio is unity to force the return current to flow in the return conductor, rather than in the rails. This suppresses the magneto-motive force resulting from the catenary current. This feeding arrangement has the following advantages and disadvantages:

- Reduction of electromagnetic interference
- Increase in the total feeding impedance by approximately 50% compared with the direct feeding
- Reduction in the separation distance of feeder substations because of the voltage drop along the contact wire
- Can cause severe arching at conductor overlap points with large electric trains, resulting in damage to the catenary conductor and pantograph

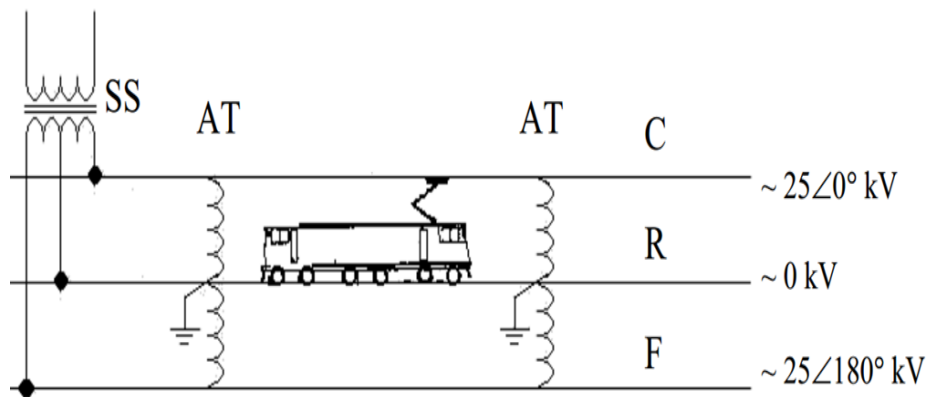
Figure 66 shows the configuration of the BT feeding system.



**Figure 66: Diagram of the BT feeding configuration. C is the catenary conductor, R is the rail conductor, RC is the return conductor and SS is the grid connect substation**

For the autotransformer (AT) configuration, the AT has two equal-turn windings, whose middle tap is connected to the rails to provide earth potential for balancing a voltage between the contact wire and the return conductor. Figure 67 shows the configuration of the AT feeding system, which has the following advantages and disadvantages:

- The electromagnetic interference in an AT system is normally lower than that in the BT system
- Adding 50kV AT, instead of BTs, every 8-15km can increase substation distance up to 50-100km
- The size and MVA rating of the AT configuration are much larger and more expensive respectively than the BTs in the BT configuration
- The protection equipment is more complicated and it needs more installation space



**Figure 67: Diagram of the AT feeding configuration. C is the catenary conductor, R is the rail conductor, RC is the return conductor and SS is the grid connect substation (Kulworawanichpong, 2003)**

Because the DWPT segment circuits are isolated and relatively short, compared with the conductors used in private rail electricity networks, the configurations and features discussed here are unlikely to be applicable.

It is recommended that learning from the rail electrical network development, over the past century, be used at the design stage of the DWPT demonstration and commercial systems.

## Appendix I Gordon Growth Model

Future earnings (terminal year value) can be estimated using the Constant Gordon Growth Model (Ultimate Calculators - Constant Gordon Growth Model, 2010), according to which the terminal value is defined as

$$T_v = \frac{CF_{fy}(1+\%CF_{LT})}{(r-\%CF_{LT})}$$

where  $T_v$ ,  $CF_{fy}$ ,  $r$  and  $\%CF_{LT}$  the terminal value, final projected year cash flow, discount rate and the long term cash flow growth rate respectively. The discount rate can be found by applying the concept of the weighted cost of capital which is a mixture of the cost of equity and the after-tax cost of debt.

The cost of equity can be interpreted as the costs a company to maintain a share price that is satisfactory to investors. The cost of equity,  $E_C$  is given commonly given by

$$E_C = R_f \cdot \beta(R_m - R_f)$$

where  $R_f$ ,  $\beta$  and  $(R_m - R_f)$  are the 'risk-free' rate, the market stability factor and the Equity Market Risk Premium (EMRP) respectively. The risk free rate is usual the return on investment when investing in government bonds.  $\beta$  is a factor applied show how stable a company is in the market, i.e.  $\beta < 1$  the company is more stable than the market and  $\beta > 1$  less stable than the market. The EMRP represents the returns investors expect, over and above the risk-free rate.

The net cost of the debt is the interest paid less the tax savings resulting from the tax-deductible interest payment.

The weighted average cost of capital is the weighted average of  $E_C$  and the cost of debt based on the proportion of debt and equity in the company's capital structure.

## Appendix J **Applicable standards**

Standards are in place covering conductive and radiated disturbances. Among these the key ones of relevance to WPT have been reviewed.

### **BS 7671 Requirements for electrical installations**

This British Standard gives general guidance for the design and installation of electrical systems. It covers the safety aspects including protection of electrical circuits, adequacy of rating and earthing requirements (IET, 2015). It is addressed to electrical contractors who design and install wiring installations and provides assurance that installations carried out to this standard will be safe.

To enable the electrical contractor to design any installation, detailed specifications of all equipment to be installed will be required, in particular the voltage and current rating and any special protection requirements.

This standard will affect the installers of WPT, and Highways England to the extent that they will need to be assured that the installation complies with the British Standard. For the installer to adequately design the installation, the manufacturer will need to provide the full technical specification as set out above.

### **IEC 50160 Characteristics of electricity systems**

This International Electrotechnical Commission (IEC) standard is implemented through BS EN 50160:2010 – Voltage characteristics of electricity supplied by public electricity networks (IEC, 2010). It sets out the characteristic of electricity systems, including the permissible variation in the system voltage. It also covers such characteristics as transient fluctuations caused by switching or lightning as well as variations to frequency and phase imbalances.

Equipment designers need to ensure that any equipment to be connected to these electricity systems is resilient to the variations in these key parameters likely to be encountered on electricity systems.

Electricity systems themselves are prone to faults and interruptions in supply and, again, the manufacturers need to take into account how their equipment will perform when the supply is interrupted and restored. The key parameters are summarised in Table 52 below.

**Table 52: Characteristics of electricity systems IEC 50160**

No	Parameter	Supply voltage characteristics according to EN 50160
1	Power frequency	LV, MV: mean value of fundamental measured over 10s $\pm 1\%$ (49.5-50.5Hz) for 99.5% of week -6%/+4% (47-52Hz) for 100% of week

<b>2</b>	Voltage magnitude variations	LV, MV: $\pm 10\%$ for 95% of week, mean 10 minutes rms values
<b>3</b>	Rapid voltage changes	LV: 5% normal 10% infrequently $Plt \leq 1$ for 95% of week MV: 4% normal 6% infrequently $Plt \leq 1$ for 95% of week
<b>4</b>	Supply voltage dips	Majority: duration $< 1s$ , depth $< 60\%$ . Locally limited dips caused by load switching on: LV: 10-50%, MV: 10-15%
<b>5</b>	Short interruptions of supply voltage	LV, MV: (up to 3 minutes) few tens – few hundreds/year Duration 70% of them $< 1s$
<b>6</b>	Long interruption of supply voltage	LV, MV: (longer than 3 minutes) $< 10-50/year$
<b>7</b>	Temporary, power frequency overvoltages	LV: $< 1.5kV$ rms MV: $1.7 U_c$ (solid or impedance earth) $2.0 U_c$ (unearthed or resonant earth)
<b>8</b>	Transient overvoltages	LV: generally $< 6kV$ , Occasionally higher; rise time: ms- $\mu s$ . MV: not defined
<b>9</b>	Supply voltage unbalance	LV, MV: up to 2% for 95% of week, mean 10 minutes rms values, up to 3% in some locations

## J.1 Engineering recommendations

Engineering Recommendations (ERs) are produced by the Energy Networks Association covering a wide range of topics on the design, operation and maintenance of public electricity distribution networks. The key ERs of relevance to WPT manufacturers are G5/4 and P28 covering harmonics and voltage fluctuations respectively.

### ***J.1.1 ER G5/4 - Harmonics***

The ER G5/4 standard (Harmonic Standard G5/4 ER, 2001) sets out permissible levels of harmonics on the electricity distribution system. Equipment with non-linear characteristics (such as WPT installations) is known to generate harmonics and therefore its harmonic performance is of great importance to the network operator in designing the connection. Depending on the level of harmonics generated by the equipment and the voltage level of the connection, filtration or isolation transformers may need to be considered for the installation to prevent disturbances to other equipment. Such equipment can be retrofitted at the point of supply so that the installation as a whole is compliant, and the costs would have to be part of the installation costs.

### ***J.1.2 ER P28 – Planning limits for voltage fluctuations***

ER P28 set out the limits of voltage fluctuations or “flicker” on the distribution system caused by loads with rapidly varying demands. It is important that the suppliers of the WPT provide information on the likely demand variations and timescales so that the network can be designed so as to prevent disturbances to other customers.

### ***J.1.3 IEC 61000 Electromagnetic Compatibility (EMC)***

#### Structure

IEC 61000 contains a number of parts as described below (Electromagnetic compatibility (EMC). (n.d.). IEC 61000).

Part 1: General: General considerations (introduction, fundamental principles) Definitions, terminology (Electromagnetic compatibility - General considerations IEC 61000).

Part 2: Environment: Description of the environment, Classification of the environment, Compatibility levels (Electromagnetic compatibility - Generic standards. IEC 61000).

Part 3: Limits: Emission limits, Immunity limits (in so far as they do not fall under the responsibility of the product committees) (Electromagnetic compatibility - Testing and measurement techniques. IEC 61000).

Part 4: Testing and measurement techniques: Measurement techniques testing techniques fast transients/bursts. It additionally defines ranges of test levels and establishes test procedures (Electromagnetic compatibility - Testing and measurement techniques. IEC 61000).

Part 5: Installation and mitigation guidelines: Installation guidelines mitigation methods and devices (Electromagnetic compatibility - Generic standards).

Part 6: Generic standards (Electromagnetic compatibility - Generic standards. IEC 61000).

The IEC standard is transposed into UK standards in the BS EN 61000 series of documents and the key ones relate to Part 3 which describes the emission limits for equipment connected to the public electricity supply network. Part 4 is also relevant as it describes testing methodologies and part 6 contains some generic standards.

### Part 3 – Limits

Several British standards exist setting limits to harmonic current emissions and voltage fluctuations as set out below.

#### **BS EN 61000-3-2:2014**

Electromagnetic compatibility (EMC). Limits. Limits for harmonic current emissions (equipment input current  $\leq 16\text{A}$  per phase) (Electromagnetic compatibility (EMC). Testing and measurement techniques. Surge immunity test. BS EN 61000-3-2).

This Standard deals with the limitation of harmonic currents injected into the public low-voltage mains electricity supply system by electrical and electronic equipment.

#### **BS EN 61000-3-3:2008**

Electromagnetic compatibility (EMC). Limits. Limitation of voltage changes, voltage fluctuations and flicker in public low-voltage supply systems, for equipment with rated current  $\leq 16\text{A}$  per phase and not subject to conditional connection (Electromagnetic compatibility (EMC). Limits. Limitation of voltage changes, voltage fluctuations and flicker in public low-voltage supply systems, for equipment with rated current  $\leq 16\text{A}$  per phase and not subject to conditional connection BS EN 6, 2008).

#### **BS EN 61000-3-11:2001, IEC 61000-3-11:2000**

Electromagnetic compatibility (EMC). Limits. Limitation of voltage changes, voltage fluctuations and flicker in public low-voltage supply systems. Equipment with rated voltage current  $\leq 75\text{A}$  and subject to conditional connection (Electromagnetic compatibility (EMC). Testing and measurement techniques. Immunity to conducted disturbances, induced by radio-frequency fields. BS EN 61000-3-12:2001, IEC 61000-3-12:2000, 2001).

#### **BS EN 61000-3-12:2011**

Electromagnetic compatibility (EMC). Limits. Limits for harmonic currents produced by equipment connected to public low-voltage systems with input current  $>16\text{A}$  and  $\leq 75\text{A}$  per phase (Electromagnetic compatibility (EMC). Limits. Limits for harmonic currents produced by equipment connected to public low-voltage systems with input current  $>16\text{A}$  and  $\leq 75\text{A}$  per phase. BS EN 61000-3-12, 2011).

All the above standards may be relevant for WPT systems depending on the rating of the individual modules. 16Amps per phase equates to approximately 11kVA and 75Amps to 52kVA. It is the responsibility of the WPT manufacturer to ensure that the equipment does not cause harmonics or fluctuations in excess of the stated limits. In the event that the disturbances exceed these limits, the DNO may refuse connection or require remedial action to be taken. For higher ratings, these standards do not apply, and in the procedure set out in G5/4 would be used by the DNO before permitting connection to the public network.

### Part 4 – Measurement

Again, there are several standards in existence and the objective of these standards is to describe the measurement techniques to be applied when assessing the performance of

equipment and its compliance with the emission limits. Two examples of relevant standards are given below, but this is not an exhaustive list as there are some 50 individual standards published under part 4.

#### **BS EN 61000-4-5:2014**

Electromagnetic compatibility (EMC). Testing and measurement techniques. Surge immunity test (Electromagnetic compatibility (EMC). Testing and measurement techniques. Surge immunity test. BS EN 61000-3-2, 2014).

Its aim is to define test methods and equipment to determine the immunity of electrical and electronic equipment from electromagnetic disturbances caused by lightning or switching transients.

#### **BS EN 61000-4-6:2014**

Electromagnetic compatibility (EMC). Testing and measurement techniques. Immunity to conducted disturbances, induced by radio-frequency fields (Electromagnetic compatibility (EMC). Testing and measurement techniques. Immunity to conducted disturbances, induced by radio-frequency fields. BS EN 61000-4-6, 2014).

#### Part 6 – Generic Standards

Again there are several generic standards applicable to electrical equipment but the following are of particular relevance:

#### **BS EN 61000-6-4:2007+A1:2011**

Electromagnetic compatibility (EMC). Generic standards. Emission standard for industrial environments (Electromagnetic compatibility (EMC). Generic standards. Emission standard for industrial environments. BS EN 61000-6-4:2007+A1:2011, 2011).

BS EN 61000 specifies the electromagnetic compatibility emission requirements for electrical and electronic equipment and components designed for industrial environments. It covers the frequency range 0Hz to 400GHz. This standard concerns electrical equipment that has to be connected to a power network, or uses battery power in an industrial environment – whether it's indoors or outdoors. For a location to be classified as industrial, it has to have industrial, scientific and medical apparatus; heavy inductive or capacitive loads; and high currents associated with electromagnetic fields.

This may therefore apply to WPT equipment as there are high currents associated with magnetic fields.

#### **PD IEC/TR 61000-3-6:2008**

Electromagnetic compatibility (EMC). Limits. Assessment of emission limits for the connection of distorting installations to MV, HV and EHV power system (Electromagnetic compatibility (EMC) – Part 3-6: Limits – Assessment of emission limits for the connection of distorting installations to MV, HV and EHV power systems. PD IEC/TR 61000-3-6:2008, 2008).



#### ***J.1.4 ETSI standards 300220, 302228, and 300330***

These standards refer to the testing of devices that generate EMFs for communication or power transfer purposes. Each is described below.

##### ETSI EN 300220 EMC 25 to 1,000MHz devices

This standard covers devices in the range 25 to 1,000MHz, and covers the following Short Range Device major equipment types:

1. Non-specific Short Range Devices
2. Alarms, identification systems, radio-determination, telecomm, telemetry, etc.
3. Radio Frequency Identification (RFID)
4. Detection, movement and alert applications

If any of the ancillary equipment of the WPT uses communications in this frequency range then the standard is applicable and the manufacturer would be responsible for compliance (EMC 25 to 1,000MHz devices).

##### ETSI EN 302288 EMC 24GHz Short range Radar

This standard covers devices in the 24 GHz spectrum and applies to:

- a) Transmitters in the range from 22,000GHz to 26,625GHz operating as broadband devices over the specific bandwidth defined for the individual devices
- b) Receivers operating in the range from 22,000GHz to 26,625GHz
- c) Integrated transceivers

If any of the ancillary equipment of the WPT uses communications in this frequency range then the standard is applicable and the manufacturer would be responsible for compliance (Electromagnetic compatibility and Radio spectrum Matters (ERM); Short Range Devices. ETSI EN 302 288-1, 2006).

##### ETSI EN 300330 EMC inductive loop systems 9kHz to 30MHz

This standard covers inductive loop systems in the 9kHz to 30MHz range and applies to the following Short Range Device major equipment types (Electromagnetic compatibility (EMC) – Part 3-6: Limits – Assessment of emission limits for the connection of distorting installations to MV, HV and EHV power systems. PD IEC/TR 61000-3-6:2008, 2008):

1. Generic Short range Devices including transmitters operating in the range from 9kHz to 25MHz
2. inductive loop transmitters operating from 9kHz to 30MHz including Radio Frequency Identification (RFID) and EAS operating in LF and HF ranges and for inductive wireless power transfer WPT equipment
3. receivers operating from 9kHz to 30MHz

WPT equipment operates in this frequency band, and the standard specifically covers wireless power transfer systems and so is particularly relevant. It describes the types of WPT systems covered, and the information required from the provider regarding the tests.

The ETSI EN 300330 document covers wireless power transfer systems which consist of:

1. A power transmitter, with additional communication capability to control the charge function in conjunction with the receiving part. The power transmitter could also be named as charger.
2. A receiver, which supplies the received energy to a battery and performs a control/supervision function for the battery status and charge operation.

Both parts in combination are able to transmit and receive data on a secondary frequency in addition to the power transfer mode e.g. to control the battery status and to optimize the transfer mode.

Because of the close interaction between charger and battery, the manufacturer shall provide all necessary parts for the presentation of equipment and for testing purposes. The description of the setup including the positioning and mechanical orientation of both parts shall be provided since this affects the radiated emissions. When using different batteries or power receiving parts with one charger, the manufacturer shall declare the typical and the worst case combinations with regard to radiated emissions and provide such combinations for testing.

In certain cases it may be not possible to provide the necessary samples of batteries due to unavailability. In these cases the manufacturer has to declare that the charger was developed based on certain batteries and such charger/battery combinations shall be provided for testing.

The provider shall declare for each possible operation or charging mode of the WPT system:

- a) charging mode/power transfer/system in resonance
- b) communication mode (data transmission from and to the battery)
- c) communication and determination of the charging action e.g. to find the resonance frequency of the system or optimal charging parameters of the WPT systems
- d) Additional declarations to establish the appropriate test conditions:
  - i. the mechanical setup
  - ii. the mechanical orientation
  - iii. the frequency ranges
  - iv. the range of operating conditions including the duty cycle or pulsing operational parameter
- e) power requirements

The measurements itself shall be done on these actual set-up and operating conditions for each mode.

***J.1.5 BS EN 50293:2012 Road traffic signal systems. Electromagnetic compatibility***

This standard applies to road traffic signalling systems. It would not apply to the WPT systems, but is relevant to the operation of other electrical devices on the SRN (Road traffic signal systems. Electromagnetic compatibility BS EN 50293:2012, 2012).

***J.1.6 BS EN 50556:2011 Road traffic signal systems***

This standard supersedes BS 7987 and applies to road traffic signalling systems. It would not apply to the WPT systems, but is relevant to the operation of other electrical devices on the SRN (Road traffic signal systems BS EN 50556:2011, 2011).

***J.1.7 TR 2130 – Environmental Tests for Motorway Communications Equipment and Portable and Permanent Road Traffic Control Equipment***

The specification produced by the Highways England applies to all traffic control equipment including portable traffic signal equipment and motorway communications equipment installed on site.

It may not be directly relevant to WPT equipment but might apply to any ancillary equipment used to communicate the status of the WPT itself. It is also relevant to the operation of other electrical devices on the SRN (Highways Agency, 2002).

***J.1.8 MCH 1540 – Specification for the Installation of Detector Loops on Motorways and All-Purpose Trunk Roads***

The specification produced by the Highways England applies to the installation of detector loops. Since the equipment ancillary to the main WPT primary coils is provided to detect and identify vehicles using the WPT system, this will be relevant to the installers of the WPT systems. It will also be important to understand if there is a potential conflict with detector loops already installed on the SRN for other purposes (Highways Agency, 2006).

If you need help accessing this or any other Highways England information, please call **0300 123 5000** and we will help you.

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