A National Power Infrastructure for Charge-on-the-move: An appraisal for Great Britain

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***Abstract*— The electrification of road transportation is a necessary step for coping with climate change. Charge-on-the-move is considered to be a key enabling factor in moving towards electric vehicles. The development of individual charging devices for implementing in-motion charging has been rapid but their integration with the road infrastructure at national scale is still in need of more comprehensive consideration. This work aims to outline the performance requirements of a national power infrastructure suitable for implementing charge-on-the-move. From an estimation of electric vehicles' power requirements in conjunction with Great Britain's road traffic data the anticipated power demand is expected to be augmented by 16 GW. Furthermore, a simulation tool is proposed to investigate the application of dynamic charging and the effects of system design variables. Based on that, a possible charging layout is suggested. Such infrastructure involves 30 kW chargers, 1.5 m length apiece, installed every 2.1 m and 4.3 m on motorways and rural sections of road respectively. Finally, a strategic overview for Great Britain suggests that the installation of a nationwide charging infrastructure of this type could be economically viable. Indeed, the cost to develop the infrastructure to enable the electrification of 86% of car-miles in Great Britain is around £76 billion at present prices.**

***Index Terms*— charge-on-the-move, dynamic charging, electric vehicles, economics, infrastructure, power demand**

I. Introduction

IT has been generally accepted that decarbonisation of the transport sector is a necessary step towards alleviating climate change. The shift towards electric vehicles (EVs) has been identified as one of the most beneficial approaches for achieving this target since significant reduction of CO_2 emissions in comparison with conventional vehicles can be achieved. In addition, EVs offer zero tailpipe emissions, eliminating the release of noxious pollutants. Aspirations for better air quality coupled with low operational noise make EVs an attractive solution particularly for urban areas.

Charge-on-the-move (CoM), also known as dynamic charging, is considered to be a key enabling factor in moving towards the widespread use of EVs for long distance travel. It is an idea whereby the road infrastructure will be capable of transferring energy to EVs whilst they are on move. The technology offers the opportunity for substantially reducing the installed battery capacity of EVs, thereby eliminating 'range anxiety' and reducing the vehicle purchase price and mass, which are some of the major barriers to increasing use of EVs [1], [2].

This would be particularly advantageous for the electrification of long-haul freight transport. It would be impractical and too expensive to convert existing long-haul road freight vehicles to battery-powered electric vehicles, because of the high-power consumption, long distances travelled and the large amounts of energy required. The only way to overcome this barrier would be to provide electricity to the vehicles while they are in motion [3].

Previous work showed that a nationwide charging infrastructure of this type in Great Britain (GB) could be a key enabling factor in moving towards EVs and a significant driver for substantial CO_2 emissions reductions in the near future [4], [5]. Additionally, a feasibility study conducted by the Transport Research Laboratory (TRL) for Highways England highlights that shifting towards EVs will critically depend on the wide availability of CoM at national scale [6].

The development of inductive power transfer (IPT) charging devices for implementing a CoM infrastructure has advanced significantly over the last few years. A typical IPT system comprises two major subsystems: the road charging unit and the vehicle charging unit. Energy is transferred wirelessly between the two parts of the system when they are in proximity to each other. High efficiencies, over 90%, can be obtained for static charging applications [7], [8], [9] and similar efficiencies are expected to be achieved for dynamic charging as well [10], [11].

However, the integration of IPT road charging units with the road infrastructure on a national scale needs more comprehensive consideration. The report 'preparing the strategic road network for increased use by electric vehicles' is a first of its kind comprehensive analysis for introducing CoM on the roads of GB [6]. The study covers topics of stakeholder engagement; functional requirements (such as review of IPT systems and identification of other services provided using IPT technology); performance requirements (such as installation of CoM equipment on vehicles and construction methods of installing CoM); and process requirements of a CoM infrastructure (such as power demand requirements of vehicles and charging layouts). The report also makes recommendations on future trials and identifies potential economic, social, and

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environmental impacts (costs and benefits) of the technology. Additional system level studies include a cost effectiveness analysis of electric transit buses in Minneapolis, Minnesota [12] and a feasibility analysis on a dynamic charging system for electric buses in California [13].

It was generally shown that the exact requirements, costs and benefits of a CoM infrastructure will depend on the specific application of dynamic charging and the final specifications of the IPT technology, which is advancing drastically. Additional significant factors include market acceptance, EVs uptake, future policies, possible funding schemes, business models, etc.

This paper provides an overall understanding of the challenges of the CoM technology at the level of the system. It should be considered as a preliminary study towards the implementation of CoM at national scale. It is based on current traffic data and current/ expected technical specifications of IPT systems to outline the requirements of a national power infrastructure for deployment of CoM. More detailed studies focusing on different regions of the country, local traffic and driving patterns, environmental and social factors and different economic cost models should be conducted in the future.

In particular, from an estimation of EVs' power requirements in conjunction with GB road traffic data, a baseline for the anticipated power demand was established. Furthermore, a simulation tool was used to investigate the application of dynamic charging and the effects of system design variables on important performance parameters of travelling EVs. Then, a possible charging layout is proposed to minimise the range of real-time power demand per mile of road. In the end, a GB strategic overview suggested that the installation of a nationwide charging infrastructure based on the IPT technology for electrified (i) cars, (ii) road freight and (iii) both cars and road freight transportation could be economically viable.

The work is focused on the case of GB which has been legally obliged to reduce substantially its CO_2 emissions by 2050; and therefore, has been keen to adopt innovative strategies for achieving this target. Nevertheless, the methodology presented in the paper could be considered as a framework to assess the prospects of CoM in other countries as well. Alternative national traffic statistics, road length data, drive cycle profiles, etc. could be processed by the simulation tools and methods developed.

II. System Characterisation

Initially, the study aims to outline the system performance requirements of a CoM national power infrastructure. Tools and procedures are proposed to calculate the power requirements of EVs and set the baseline of the anticipated power demand on the roads of GB.

The 'Advanced Vehicle Simulator' (Advisor) was used to estimate the power requirements of EVs. Advisor is an open source software tool that was developed at the National Renewable Energy Laboratory for the US Department of Energy [14]. Its accuracy has been validated by several authors and international laboratories [15], [16]. The user models the vehicle of interest and investigates the characteristics of the journey over specific drive cycles, such as the required power from the electric motor, the state of charge (SOC) of the on-board battery, etc.

A medium-sized car was firstly modelled and its main vehicle components include a 75 kW electric motor, a 30 kWh on-board battery and 1,500 kg overall mass. Although various size passenger cars are available, including small and large SUVs, this study assumes that all cars have a medium size.

The simulation was performed over a variety of drive cycles including standard and real drive cycles. An electronic logging device, developed in Cambridge University Engineering Department for the Centre for Sustainable Road Freight, was used to define real drive cycles whilst driving around in private cars. It is based on a mobile phone which is connected to the vehicle using one of the vehicle's standardised ports to collect real time operational data about speed, latitude, longitude and time. The elevation profile was determined for each drive cycle and included in the analysis as well. The aim was to record drive cycles in different regions and times of the day to identify any potential discrepancies on power requirement and energy consumption. The outputs of the simulation showed that the average power requirements are 20.3 kW, 11.2 kW and 4.3 kW for travelling on motorways, rural sections and urban sections of road respectively. Any differences on power requirements across the regions of GB are insignificant and therefore, were not considered further in this study.

TABLE 1
EVs POWER REQUIREMENTS FOR VARIOUS DRIVE CYCLES

Name/Region	Max speed (mph)	Aver. speed (mph)	Max grade (%)	Aver. Power (kW)	Energy (kWh/ mile)
Motorway					
Artemis Motor. [17]	81.9	60.2	0	19.8	0.33
M11 pm hours, UK	77.2	64.0	18	19.4	0.30
M11 am hours, UK	76.5	69.2	18	21.6	0.31
			Average	*20.3*	*0.3*
Rural					
Artemis Rural [17]	69.3	35.7	0	9.4	0.26
Rural A1 pm, UK	71.1	44.6	6	12.9	0.29
			Average	*11.2*	*0.28*
Urban					
Artemis Urban [17]	35.9	11.0	0	4.1	0.37
Cambridge A, UK	31.6	10.9	4	3.7	0.34
Cambridge B, UK	30.2	12.8	5	4.4	0.34
Cambridge C, UK	34.8	16.1	4	4.8	0.30
			Average	*4.3*	*0.3*

Relative short journeys are undertaken in urban roads and therefore, CoM would not be necessary on urban roads. According to national statistics, the average length of a journey in urban roads is less than 7 miles [18]. This corresponds to 2.1 kWh assuming the average energy consumption of 0.3 kWh/mile as shown in TABLE 1. The on-board battery capacity would be sufficient to satisfy the needs of EVs on urban roadways. Besides, charging of EVs in urban environments might be facilitated by a well-developed home and/or public infrastructure without the need of a CoM infrastructure. Even if drivers have some stretch of urban roadway to reach a motorway or a rural section of road, the CoM infrastructure over there would allow a constant or

increasing state of charge.

The figures derived were combined with GB traffic data in order to estimate the power demands from the power infrastructure. Average daily traffic flow statistics for cars travelling on various roads were obtained from the Department for Transport (DfT) in GB [19]. The base data give the number of vehicles per day that will drive on a specific stretch of road on an average day of the year. The number of vehicles per day is divided by 24 to obtain vehicles per hour. Then, the computed figure is divided by the speed limit of each section of road (which is assumed to be the same as the average speed) to calculate the average number of vehicles per mile of road. A speed limit of 70 mph and 60 mph applies for cars travelling on motorways and rural sections of road respectively [20]. A conservative safety margin of 30% was included in the calculations. The results for each region of GB are stated in TABLE 2 and classified into trunk (TR) and principal (PR) sections[1].

TABLE 2
AVERAGE NUMBER OF PASSENGER CARS PER MILE OF ROAD FOR BOTH DIRECTIONS IN GB BY REGION IN 2014

		Motorway		Rural 'A'	
		TR	PR	TR	PR
England	North East	33	49	19	7
	North West	46	29	13	6
	Yorkshire & the Humber	36	37	20	7
	East Midlands	53	0	23	7
	West Midlands	46	54	17	6
	East of England	53	0	24	9
	London	59	0	0	19
	South East	56	48	29	9
	South West	44	0	16	6
Wales		40	0	8	4
Scotland		25	0	6	2

The average number of vehicles per mile of road across a day was shaped with daily traffic distribution data obtained from DfT [19]. The daily profiles derived were combined with the power requirements of EVs to calculate the power demand per mile of road across GB throughout a typical day. The analysis takes into account current traffic statistics and 100% uptake of EVs for sizing the infrastructure for a potential CoM system.

It is true that some EVs might not support CoM and charging will be performed while stopped from static chargers along the road infrastructure (e.g. at motorway services). However, we can still calculate the additional power demand based on the number of vehicles per mile of road. The required energy to be supplied to the EVs on the roads of GB, given by TABLE 2, i) from a CoM infrastructure or ii) from static charging points along the road infrastructure must be the same. The power demand is calculated in hourly steps. Hence, the average power within a 1 h time slot is the same for both situations, regardless the proportion of EVs that charge statically or on the move. Although the actual power demand varies within the 1 h time slot, the study does not consider higher time resolution. This means that a CoM infrastructure will distribute the natural increase of power demand (due to the penetration of EVs) along the road infrastructure of the country but will not add an extra significant load.

As an illustration, the average density of cars per mile of motorway in London is depicted with the dashed line in Fig. 1. During the peak hours of commuting there are around 110 passenger cars per mile of road and the peak power required to propel this number of EVs is approximately 2.2 MW per mile. In a similar way, the number of EVs and power required on trunk rural sections of 'A' roads in South East during peak hours are 54 cars and 0.6 MW respectively. Indeed, trunk sections of motorways of London and rural 'A' sections of South East have the highest density of EVs per mile of road. The selection of alternative regions leads to lower power demand per mile for both road types.

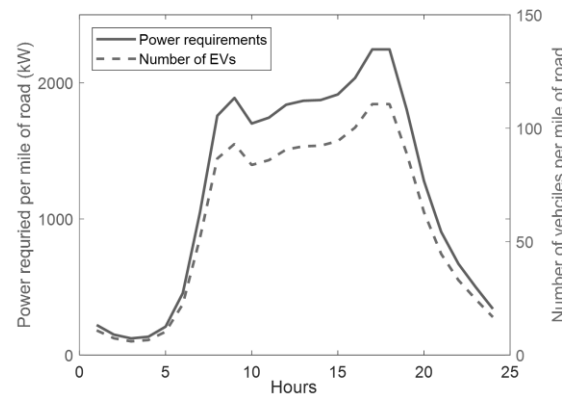


Fig. 1. Power required and density of EVs on motorways of London by hour

The analysis was conducted for all areas of GB. The figures were combined with road length data [21] and the overall power demand for a CoM infrastructure for EVs was estimated. The results are summarised in TABLE 3. A similar analysis was followed by the same authors for estimating the power demands from a possible electrified road freight transport network in GB [3]. The results of that study are presented in TABLE 4.

TABLE 3
PEAK POWER DEMAND IN GW OF ELECTRIFIED PASSENGER CAR TRANSPORTATION

	Motorway	Rural 'A'	Total
England	3.7	2.8	6.5
Wales	0.1	0.3	0.4
Scotland	0.3	0.4	0.7
Total	*4.1*	*3.5*	*7.6*

TABLE 4
PEAK POWER DEMAND IN GW OF ELECTRIFIED ROAD FREIGHT TRANSPORTATION

	Motorway	Rural 'A'	Total
England	4.8	2.8	7.6
Wales	0.1	0.2	0.3
Scotland	0.4	0.4	0.8
Total	*5.3*	*3.4*	*8.7*

[1] A trunk road in GB is a major road between places of traffic importance. The entire trunk road network (Primary Route Network) has the aim to provide easily identifiable routes to access the whole of the country [47]. The remaining sections of major roads in GB (A-Roads) are classified as Principal roads

A potential CoM infrastructure of electrified passenger car and road freight transportation would add an additional peak power load of 7.6 GW and 8.7 GW respectively. The new peak power demand of 16.3 GW represents an additional load of 31% based on the 2016/2017 winter peak demand (53 GW) [22] and goes significantly beyond the capacity margin of the electricity system (around 5 GW) in GB [23].

However, various authorities have already embarked on plans to upgrade the electricity supply network mainly due to the shift to EVs and electric heating. The anticipated installed generating capacity in GB is estimated to be around 130 GW by 2050 [24] thus allowing a considerable capacity margin for CoM. Furthermore, the Electricity Networks Strategy Group has defined pathways to reinforce the transmission network of GB [25] and finally, various distribution companies have already embarked on upgrade projects to deal with the increased future demand [26], [27].The figures outline the power demand requirements of a CoM infrastructure in GB. A more detailed analysis focusing on different regions of the country including local traffic conditions and driving patterns it is worth exploring. However, it is expected that the results would lie in the same order of magnitude without altering substantially the outcome of this study.

Another factor influencing the power demand of a CoM infrastructure is the power transfer efficiency of the chosen IPT charging devices. Again, this does not change the main outcome of the study. Assuming a 90% efficiency for dynamic charging the additional power demand increases from 16.3 GW to 18.1 GW. The new additional peak power demand corresponds to 34% based on the 2016/2017 peak power demand in GB. The minor increase from the initial calculated figure of 31% shows that the final efficiency of the system is a second order effect.

It is also worth mentioning that some drivers might choose to charge at home or at work if they have adequate on-board capacity. However, this study assumes that all vehicles charge on the go without considering the initial value of the state of charge of the battery (SOC). This is not an unrealistic scenario as the CoM infrastructure delivers the energy needed to the vehicle for balancing out the energy consumed in real-time. This means that a steady-state SOC is possible throughout the entire journey regardless the initial SOC.

III. Charging Simulation Tool

A simulation tool has been developed on top of Advisor to investigate the application of dynamic charging and the effects of system design variables on important performance parameters, such as the mileage range and SOC. The tool was also used for exploring the prospects of road freight electrification in [3].

The charging simulation tool produces a variety of outputs. Among others the user has access to i) the battery capacity of the vehicle under investigation, (ii) the final SOC without any charging facilities, (iii) the final SOC with CoM infrastructure, (iv) the total energy requested (used by the electric motor) in the simulation run, (v) the energy received from the CoM system, (vi) the energy consumed during the whole journey, (vii) the average speed of the vehicle, (viii) the average consumption of the vehicle, and finally (ix) the 'Mean Effective Charging Rate' (MECR), denoted Ψ, which is the average energy delivered by the charging system per mile along the road.

Fig. 2 shows the motorway SOC of the modelled 'compact car' for various MECRs based on the 'Artemis Motorway' drive cycle which is repeated five times. It can be noticed that the car would have a fully depleted battery on battery power alone solution after 85 miles on motorways. The actual mileage range of EVs will depend on the capacity of the on-board battery. Yet, with a dynamic charging system capable of delivering Ψ equals 0.36 kWh/mile they could run indefinitely with an even increasing SOC. Although charging is continuous, it can be noticed that the SOC varies throughout the journey. This is due to the fact that the 'compact car' does not have a constant speed over the modelled drive cycle. The energy received from the CoM infrastructure is not sufficient to balance out the energy consumed when the car travels relatively fast (faster than the average speed) thus decreasing SOC. In contrast, an increasing SOC is possible when the speed is relatively slow. Overall, a steady an even an increasing SOC is achieved over the entire cycle.

A similar analysis was conducted for the rural sections of roads. The required MECR for this type of journeys is 0.29 kWh/mile.

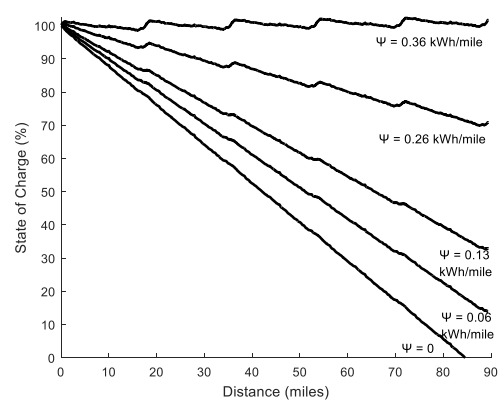


Fig. 2. Motorway SOC of 'compact car' for various levels of MECRs

IV. Charging Layout

Multiple combinations between (i) charging segment length, l, (ii) nominal power rating, P, and (iii) number of charging segments, n, might be decided to meet the needed MECR, as shown in Fig. 3. The energy received, E_r, from a single charging segment is proportional to the power transfer rate of the charger, P, and the charging time, t_c. The charging time, t_c, is equivalent to the ratio of the charging segment length, l, and the average speed of the vehicle, u, as shown in the following expression, $E_r = P.t_c = P.{}^{l}/_{u}$.

The total energy received from n charging segments per mile of road must meet the needed MECR. Hence, for a given charging segment length and power rating, the number of required charging segments is calculated using the following expression,

$$MECR = n.E_r = n.P.{}^{l}/_{u} \rightarrow n = \frac{MECR.u}{P.l} = \frac{34870}{P.l}$$

where MECR equals 0.36 kWh and average speed 60.2 mph. It should be noted that a conversion coefficient between miles and metres equal to 1609 is applied.

It is worth mentioning that each charging segment might consist of multiple individual charging devices. Their number within one charging segment will depend on i) the length of the charging segment and ii) the length of individual devices. This technique, also used by TRL [6], allows the deployment of long charging segments that would have not been possible to deploy with the utilisation of a single individual device; since the length of current IPT systems is usually around 0.75 m [6], [9].

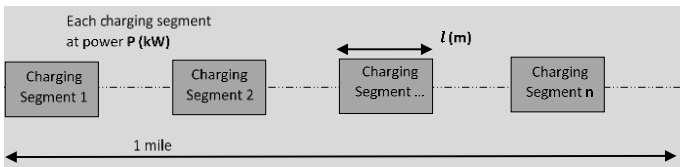


Fig. 3. CoM infrastructure design variables - length (m), power (kW), number of charging segments (n)

The required MECR of 0.36 kWh/mile translates into 21.7 kW mean power transfer[2]. However, the power drawn from the grid as function of time is a rectangular wave. This is because power is drawn periodically while EVs travel over the charging segments. For more than one EV, the power demand over time fluctuates around the mean power demand in a random way depending on the number of active charging segments at each time.

All feasible combinations between charging segment length, power transfer and number of segments were investigated to explore the range of power demand. The length of segments was assumed to vary from 0.75 m to 30 m. The lower value was chosen based on the average length of individual IPT units, whereas the upper value based on the 30 m minimum length occupied by a vehicle on motorways under normal conditions [10]. This assures that a charging segment is coupled with only one vehicle under normal flow conditions. Power transfer rates were assumed to range between 30 kW and 100 kW. The former value was selected by rounding up the mean power demand of 21.7 kW, whereas the latter value is an expected power transfer rate to be offered by individual IPT devices in the near future. It was assumed that the installation interval is the same between any two charging segments.

Three flow conditions are considered in this study which are the 'free', 'high density' and 'near capacity' scenarios [28]. Each scenario assumes 12, 46 and 67 EVs per mile of road (67 is the maximum density of vehicles per mile of motorway before a breakdown situation). Assuming an average vehicle length of 5 m, the gap between vehicles is 130 m, 30 m and 20 m for each case [10]. The range of power for all possible charging layouts is calculated and the average fluctuation around the mean power demand is computed for each examined scenario. The results showed that some charging layouts lead up to ± 170% variance per mile whereas the smallest average fluctuation was found to be ± 11% around the mean power demand.

A charging layout was identified as the most suitable solution among the explored options. Such a CoM layout is shown conceptually in Fig. 4 and involves:

i. 1.5 m charging segments (two IPT units)
ii. 30 kW power transfer
iii. 775 charging segments per mile of motorway (installed every 2.1 m – 1,609 m divided by 775 segments. This ensures that the minimum number of charging segments are installed to guarantee the needed MECR.)
iv. 371 charging segments per mile of rural section of road (installed every 4.3 m)[3]

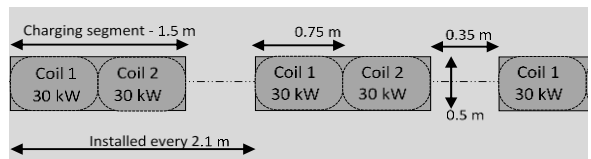


Fig. 4. Chosen CoM infrastructure for motorways

The criteria for choosing this particular charging layout are the following. Firstly, the range of power demand for this charging layout is low at ± 14% per mile of motorway; a figure close to the optimal margin of ± 11% between all investigated options. Secondly, the length of each charging segment is shorter than 5 m which is the average length of a vehicle [10]. This is particular advantageous in motorway queues with stop-start driving because no charging device would transmit energy to multiple EVs at the same time. This eliminates any technical and practical considerations such as dealing with multiple driver accounts simultaneously.

Although the charging layout is a combination of two individual IPT units, the receiver system on the vehicle's side consists only by one IPT unit, as shown in Fig. 5. This increases the charging time from each segment but not the power transfer rate between the charging infrastructure and the vehicle.

The same charging layout could be exploited for road freight transport as well. It was shown in [3] that 4.1 kWh/mile MECR has to be delivered dynamically to long-haul road freight vehicles on motorways, which is about eleven times higher than then the mean power needed for passenger cars. Nevertheless, it would be possible to have multiple pick-up devices underneath each truck. Each receiving device could receive power from a single 30 kW charging segment for reaching the required power transfer levels. This concept is shown in Fig. 5 where eleven receiving pads, 30 kW apiece, are used to meet the needed MECR for long-haul operations.

It is worth mentioning that the proposed CoM infrastructure should be perceived only as a recommendation rather than a fixed statement. The aim is to suggest a CoM infrastructure as a reference solution for identifying any technical and economic limitations. The study was based on current data and robust

[2] The average speed of the vehicle following the 'Artemis motorway' drive cycle, used for the simulation is 60.2 mph. The power required is calculated as P=0.36 kWh/mile (Ψ) X 60.2 mph (average speed) = 21.7 kW

[3] Based on the 35.8 mph average speed of 'Artemis Rural' drive cycle and the needed MECR of 0.29 kWh/mile

assumptions. The process should be adjusted to include up-to date information as this becomes available; including development of technology, business models, local traffic conditions, etc.

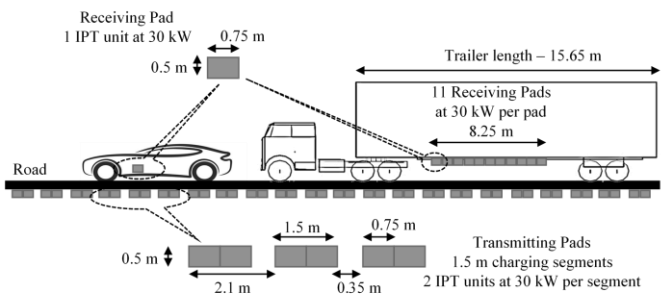


Fig. 5. CoM infrastructure for motorways for electrified car and freight transportation

V. GB Strategic Overview

In this section, a GB Strategic Overview is presented. The analysis starts with the development of solution schemes for implementing a potential CoM infrastructure. Conceptual AC and DC power distribution configurations were developed for establishing the required connections between the charging transmitting devices and the electricity supply network (Fig. 6). 1.5 m long charging segments at 30 kW installed every 2.1 m and 4.3 m on motorways and rural sections of road respectively were considered according to the analysis presented in the previous section. Furthermore, new feeder stations and substations are introduced to provide flexibility and circuit protection. The size of stations is influenced by operational conditions and based on the calculated peak power demand per mile. In particular, 3 MW sub-stations were assumed to meet the peak power demand of 2.2 MW per mile of motorway, as shown in Fig. 1. It should be noted that this demand refers only to passenger cars. A CoM infrastructure suitable for passenger cars and freight vehicles is explored in later sections.

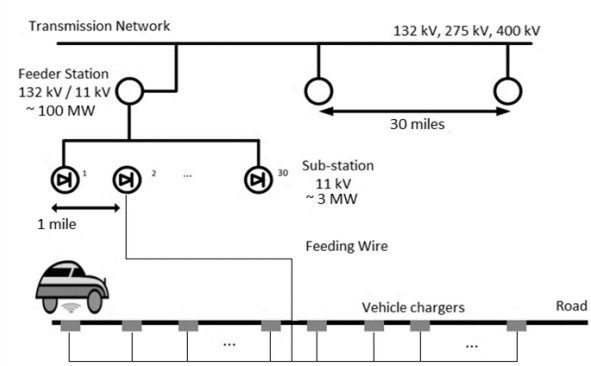


Fig. 6. Conceptual power distribution configuration for CoM (not to scale)

Subsequently, an economic model was developed to examine the financial viability of the proposed scheme. The aim was to examine whether the deployment of a CoM infrastructure at national scale could be financially reasonable rather than developing an accurate business model.

The key cost drivers of the model include the price of charging devices and cables and for the cost of cable trenching. Moreover, the cost of feeder stations and sub-stations was considered in the study, including expenditure for necessary equipment such as circuit breakers, transformers, connection switchgear and protection/metering. In addition, fees for system design and civil engineering were considered. The study does not provide any insight on topics such as operational costs, environmental benefits (such as reductions in emissions of CO_2), tax revenues, government funding, etc.

The technology involved with CoM is still in the early stages and market data are not available. Some real projects have been built and demonstrated around the world, such as the Milton Keynes Electric Bus project [29]; the OLEV system in Gumi City, South Korea [30]; the dynamic charging testing of Primove Bombardier in Mannhein [31]; and the testing projects of the European project Fabric in France, Italy and Sweden [32]. However, cost data have not yet been disclosed. Even if data were available, they might not be representative as the costs involved with a demonstration project do not always reflect the actual costs of a real system at national scale. Nevertheless, we have made some assumptions based on available data and personal judgments to assess the financial viability of such a large infrastructure project. The assumptions of the cost model are summarised in TABLE 5.

The price of the charging segments, 1.5 m long at 30 kW was calculated at £3.6 k. This was based on the approach followed by the authors of [33] who estimated the cost of a charging device from the design point of view. In particular, the total copper mass required for an individual 30 kW IPT system - about 15 kg [34] - was combined with the cost of Litz wire[4] of £30 per kg [33], [35]. An additional cost of £45 per kW was added for the cost of the power electronics [33], [36]. The overall cost of a 30 kW individual IPT system was calculated at £1.8 k which corresponds to £60 per kW.

It is should be noted that this approach does not include any costs related with the receiving system on the vehicle side and the overall development costs of the system. Some IPT systems have been commercially available including the 30 kW INTIS system [37], the 7.2 kW Plugless system [38] and the 3.2 kW BMW system [39]. Cost figures for these systems range from £50-400 per kW, including costs for equipment, installation costs and vehicle upgrade. The actual cost of IPT charging devices cannot get estimated precisely. Mainly because the market is largely immature and prices would change greatly with volume [37]. Besides, the cost would depend on the final specifications of the CoM infrastructure. These can be high in case the CoM infrastructure is compatible with different EV's dynamic charging systems or can be relative low when a shared standard is achieved between EV manufactures.

Prices for the remaining equipment, (cables, feeder stations, sub-stations, connections, civil engineering fees and additional fees) have been mainly obtained from reports on the

[4] This type of wire is usually adopted for IPT systems that operate between 20-150 kHz to minimise skin effect losses [48].

electrification of Britain's railway network [40], [41]. Additional sources of cost data were reports from distribution network operators in GB like [42], [43] and the engineering teams of the Milton Keynes Electric Bus project [29]. Again, the actual figures will depend on the local power requirements and on-site available capacity.

TABLE 5
COST DRIVERS

Cost Variable	Price (£k)	Comments
Charging Devices		
Charging segments	3.6	2 IPT unit, 0.75 cm long and 30 kW
Cables		
Cables 132 kV	200	Per mile rated at around 100 MW
Cables 11 kV	50	
Cables 3.3 kV	27	Per mile rated at around 3 MW
Cables 1 kV-DC	8	
Feeder Stations		
Circuit breaker	0.8	
Switchgear/metering	0.8	Per MW
Transformer 132 kV/11 kV	6.6	
Sub-stations		
11 kV circuit breaker	0.1	
Rectifier 11 kV/1 kV-DC	6	Per MW
Transformer 11kV/3.3kV	4	
Booster 11kV/11kV	1	
Connections		
11 kV	0.5	
3.3 kV	0.3	2 joints for each charging segment
1 kV-DC	0.1	
Civil Engineering		
Cable Trenching	100	Per mile
Construction works	20%	On equipment cost
Additional Fees		
DNO design fees	3%	On equipment cost

A. CoM for electrified Cars transportation

The model produces the cost per mile relative to the class of road and distribution approach. Three distribution approaches were considered which are (i) 1 kV-DC (ii) 3.3 kV-AC and (iii) 11 kV-AC. The expenditure figures include installation of IPT on one lane of road. It is also assumed that sub-stations are spaced every mile as shown in Fig. 6. TABLE 6 summarises the results of the cost per mile for a CoM infrastructure suitable for EVs based on the 11 kV-AC power distribution configuration.

TABLE 6
COST PER MILE OF ROAD IN £m BASED ON THE 11 kV-AC CONFIGURATION OF ELECTRIFIED CARS TRANSPORTATION

		Motorway		Rural 'A'		Minor
		Tr	Pr	Tr	Pr	Rural
England	North East	4.53	4.55	2.38	2.38	2.38
	North West	4.55	4.53	2.38	2.38	2.38
	York.-Humber	4.53	4.53	2.38	2.38	2.38
	East Midlands	4.55	4.53	2.38	2.38	2.38
	West Midlands	4.55	4.55	2.38	2.38	2.38
	East of England	4.55	4.53	2.38	2.38	2.38
	London	4.55	4.53	2.37	2.38	2.38
	South East	4.55	4.55	2.38	2.38	2.38
	South West	4.55	4.53	2.38	2.38	2.38
Wales		4.55	4.53	2.38	2.38	2.38
Scotland		4.53	4.53	2.38	2.38	2.38

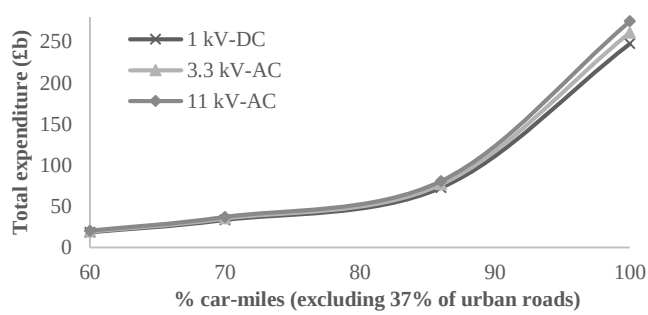
It is noticeable that the cost per mile is similar between regions. This is because the same charging layout was considered for all regions, which is 1.5 m length charging segments every 2.1 m on motorways and 4.3 m on rural sections of road. Any minor differences in TABLE 6 are due to different power requirements between regions. Hence, the price of charging segments was identified as the most significant cost driver; which accounts up to 68% of the total expenditure to deploy a CoM infrastructure.

The average costs per mile of motorway and rural section of road are shown in **Error! Not a valid bookmark self-reference.** for the three power distribution configurations examined in this study.

TABLE 7
COST PER MILE OF ROAD IN £m FOR ELECTRIFIED CARS TRANSPORTATION

Power Distribution Configuration	Motorway	Rural
1 kV-DC	4.1	2.1
3.3 kV-AC	4.3	2.3
11 kV-AC	4.6	2.4

The outcomes of the cost model were then combined with road length data [21] and traffic statistics [19] of GB. The results of the analysis are depicted in Fig. 7. The figure shows the total expenditure to install IPT devices relative to the percentage of electrified car-miles covered in GB excluding miles driven on urban roads.



	60%	70%	86%	100%
1 kV-DC	18	33	73	248
3.3 kV-AC	19	35	76	261
11 kV-AC	20	37	80	275
Average	*19*	*35*	*76*	*261*

Fig. 7. Total expenditure (£ billion) to install IPT devices relative to the percentage of electrified car-miles covered in GB

A CoM infrastructure for electrifying 60% of car-miles in GB (excluding miles travelled on urban roads) would cost around £19 billion (the average cost of the three distribution configurations). Such a charging infrastructure involves installation of IPT devices on the motorways of the country which account less than 2% of the total road length of the country [21]. The expenditure to cover 70% of car-miles is £35 billion and IPT devices should be introduced to motorways and trunk rural sections of 'A' roads (5% of the total road length). A CoM infrastructure on motorways and both on trunk and principal rural sections of 'A' roads would electrify up to 86% of car-miles reaching the cost of £76 billion (12% of the total road length). Finally, including IPT devices additionally on rural sections of minor roads, would cover essentially 100% of car-miles with a national cost without exceeding the level of

£261 billion in average (65% of the total road length).

It is highlighted in Fig. 7 that the results have similar trends for all power distribution concepts considered in the study; and therefore, the type of power distribution is not a critical factor to be addressed at this stage. Indeed, the cost required to electrify the greater part of all car-miles in the country is only a minor fraction of the total cost required to electrify the whole nation for all the power distribution configurations examined. In particular, the cost for 86% electrification is similar to the cost of other national large infrastructure projects such as the High Speed 2 (HS2) scheme in GB [44].

The impact of a widespread adoption of the CoM technology would be to reduce the total GB passenger vehicle emissions from approximately 62 $MtCO_2$ per year at today's emission rates to 35 $MtCO_2$ per year[5]. Making allowances for the estimated rate of population increase and changes in travel demand patterns, this would result in GB savings of around 45 $MtCO_2$ per year at 2050[6] and an estimated aggregate saving of 1,230 $MtCO_2$ over the intervening period[7]. Placing these figures in context, it should be noted that the HS2 scheme is expected to result around 3 $MtCO_2e$ savings during the first 60 years of operation [45].

In the long term, CoM will be applicable to most countries of the world and, as a result, these figures could be scaled-up to a global level that would lie in the order of 62,000 $MtCO_2$ per year by 2050[8]. In reality, the real savings are likely to be less than these figures, because the adoption of new low-energy transport systems at scale is unlikely to progress either uniformly or quickly. Nevertheless, simply because road-vehicle related emissions are such a large fraction of the emissions footprint of most countries, the potential for global impact is unquestionably enormous.

B. *CoM for electrified Freight transportation*

The financial viability of a CoM infrastructure for road freight is now considered. TABLE 8 presents the cost per mile of road of an electrified road freight system. The results are identical with the cost per mile of road of an electrified cars transportation system (It is noticeable that the cost per mile is similar between regions. This is because the same charging layout was considered for all regions, which is 1.5 m length charging segments every 2.1 m on motorways and 4.3 m on rural sections of road. Any minor differences in TABLE 6 are due to different power requirements between regions. Hence, the price of charging segments was identified as the most significant cost driver; which accounts up to 68% of the total expenditure to deploy a CoM infrastructure.

The average costs per mile of motorway and rural section of road are shown in **Error! Not a valid bookmark self-reference.** for the three power distribution configurations examined in this study.

TABLE 7). This is mainly because the same charging layout (number of charging segments) was considered for both systems, which is the most significant cost driver. Additionally, the two systems involve similar power requirements as shown in TABLE 3 and TABLE 4.

TABLE 8
COST PER MILE OF ROAD IN £m FOR ELECTRIFIED ROAD FREIGHT TRANSPORTATION

Power Distribution Configuration	Motorway	Rural
1 kV-DC	4.1	2.1
3.3 kV-AC	4.3	2.3
11 kV-AC	4.6	2.4

C. *CoM for electrified Cars and Road Freight transportation*

Next, the costs per mile of a CoM infrastructure suitable for both cars and long-haul road freight vehicles are calculated. The results, which are summarised in TABLE 9, have not changed significantly in comparison with the costs involved for EVs or road freight systems separately. A CoM infrastructure using IPT charging coils designed for (i) EVs, (ii) road freight vehicles or (iii) both type of vehicles would require similar financial resources; since the number of installed IPT charging segments would be the same for all options.

It is also worth mentioning that CoM for an electrified road freight transport system could be implemented using overhead catenary systems [46]. This approach would require different charging devices to be installed for cars and road freight vehicles separately.

TABLE 9
COST PER MILE OF ROAD IN £m FOR ELECTRIFIED CARS AND ROAD FREIGHT TRANSPORTATION

Power Distribution Configuration	Motorway	Rural
1 kV-DC	4.1	2.2
3.3 kV-AC	4.3	2.3
11 kV-AC	4.6	2.4

VI. Conclusions

The average power requirements of EVs have been combined with the number of vehicles on various roads, in order to estimate the total power demand needed from the power infrastructure, indicating a need for an additional 16 GW, of which 7.6 GW is due to passenger cars. The remaining load is due to road freight vehicles. Furthermore, a charging simulation tool was proposed to investigate the application of dynamic charging. It was shown that a charging infrastructure capable of transferring 0.36 kWh/mile and 0.29 kWh/mile would preserve 100% SOC of the on-board battery for electric passenger cars travelling on motorways and rural sections of 'A' roads. A possible CoM layout should include (i) charging segment length at 1.5 m, (ii) power rating at 30 kW and (iii) distance between consecutive chargers at 2.1 m and 4.3 m for motorways and rural sections of road respectively. This charging layout was suggested as it offers minimum power

[5] Assuming 30 million cars; 8,200 miles average annual mileage range; 157 gCO_2/km for a conventional car [49] and 90 gCO_2/km for an EV (0.36 kWh/mile X 400 gCO_2/kWh [50]).

[6] Assuming 35 million cars; 9,400 miles average mileage range per year; 95gCO_2/km for a conventional car [4]; 11 gCO_2/km for an EV (0.36 kWh/mile X 50 gCO_2/kWh [50])

[7] Based on a constant 1.5% increase in annualised savings between the numbers calculated for today's norms and those calculated for 2050.

[8] The GB global carbon footprint is 2% [51]

demand range per mile of road. Long-haul vehicles with multiple pick-up systems could exploit the same charging infrastructure on motorways for achieving the 4.1 kWh/mile MECR.

The strategic overview for the CoM proposal for GB has revealed a great potential for electrification of the passenger road transport system. The development of potential approaches coupled with the economic appraisal suggested that a nationwide infrastructure of this type is economically feasible. The total expenditure to electrify up to 86% of all car-miles in the country is around £76 billion which is a similar figure to the cost of other national large infrastructure projects. Finally, a national CoM infrastructure using IPT charging coils for both passenger cars and long-haul road freight vehicles is not signifficantly more expensive. Such a charging infrastructure could obtain revenue from both cars and lorries.

REFERENCES

[1] S. Beggs, S. Cardell, and J. Hausman, "Assessing the potential demand for electric cars," J. Econom., vol. 17, no. 1, pp. 1–19, Sep. 1981.

[2] J. Reed, "Buyers loath to pay more for electric cars," Financial Times, 2010. [Online]. Available: http://www.ft.com/cms/s/0/acc0a646-c405-11df-b827-00144feab49a.html#axzz4GmVVbS5T.

[3] D. Nicolaides, D. Cebon, and J. Miles, "Prospects for electrification of freight transportation," IEEE Syst. J., vol. PP, no. 99, pp. 1–12, 2017.

[4] D. Nicolaides and J. Miles, "Wireless Electric Charge-on-the-move: A sustainability appraisal of the potential for the UK transport application," J. Multidiscip. Eng. Sci. Technol., vol. 2, no. 8, pp. 2238–2246, 2015.

[5] D. Nicolaides, R. McMahon, D. Cebon, and J. Miles, "A national power infrastructure for Charge-on-the-Move," in IEEE PELS Workshop on Emerging Technologies: Wireless Power, 2016, pp. 180–185.

[6] Transport Research Laboratory, "Preparing the Strategic Road Network for increased use by electric vehicles," UK, 2015.

[7] J. M. Miller, P. T. Jones, J.-M. Li, and O. C. Onar, "ORNL Experience and Challenges Facing Dynamic Wireless Power Charging of EV's," IEEE Circuits Syst. Mag., vol. 15, no. 2, pp. 40–53, Jan. 2015.

[8] J. T. Boys and G. A. Covic, "The Inductive Power Transfer Story at the University of Auckland," IEEE Circuits Syst. Mag., vol. 15, no. 2, pp. 6–27, Jan. 2015.

[9] T. M. Fisher, K. B. Farley, Y. Gao, H. Bai, and Z. T. H. Tse, "Electric vehicle wireless charging technology: a state-of-the-art review of magnetic coupling systems," Wirel. Power Transf., pp. 1–10, Sep. 2014.

[10] D. Naberezhnykh, N. Reed, F. Ognissanto, T. Theodoropoulos, and H. Bludszuweit, "Operational requirements for dynamic wireless power transfer systems for electric vehicles," in 2014 IEEE International Electric Vehicle Conference (IEVC), 2014, pp. 1–8.

[11] X. Zhang, Z. Yuan, Q. Yang, Y. Li, J. Zhu, and Y. Li, "Coil Design and Efficiency Analysis for Dynamic Wireless Charging System for Electric Vehicles," IEEE Trans. Magn., vol. 52, no. 7, pp. 1–4, Jul. 2016.

[12] L. Wang, J. Gonder, E. Burton, A. Brooker, A. Meintz, and A. Konan, "A Cost Effectiveness Analysis of Quasi-Static Wireless Power Transfer for Plug-In Hybrid Electric Transit Buses," in 2015 IEEE Vehicle Power and Propulsion Conference (VPPC), 2015, pp. 1–7.

[13] T. Navidi, Yue Cao, and P. T. Krein, "Analysis of wireless and catenary power transfer systems for electric vehicle range extension on rural highways," in 2016 IEEE Power and Energy Conference at Illinois (PECI), 2016, pp. 1–6.

[14] A. Brooker, K. Haraldsson, T. Hendricks, V. Johnson, K. Kenneth, B. Kramer, T. Markel, M. O'Keefe, S. Sprik, K. Wipke, and M. Zolot, "ADVISOR Advanced Vehicle Simulator," NREL, 2013. [Online]. Available: http://adv-vehicle-sim.sourceforge.net/.

[15] R. D. Senger, "Validation of ADVISOR as a Simulation Tool for a Series Hybrid Electric Vehicle Using the Virginia Tech FutureCar Lumina," Virginia Tech, 1997.

[16] K. B. Wipke, M. R. Cuddy, and S. D. Burch, "ADVISOR 2.1: a user-friendly advanced powertrain simulation using a combined backward/forward approach," IEEE Trans. Veh. Technol., vol. 48, no. 6, pp. 1751–1761, 1999.

[17] T. Barlow, S. Latham, I. McCrae, and P. Boulter, "A reference book of driving cycles for use in the measurement of road vehicle emissions," 2009.

[18] Department for Transport, "National Travel Survey: England," 2016.

[19] Department for Transport, "Traffic counts," 2015. [Online]. Available: http://www.dft.gov.uk/traffic-counts/index.php.

[20] GOV.UK, "Speed limits," 2016. [Online]. Available: https://www.gov.uk/speed-limits.

[21] Department for Transport, "Road length in Great Britain: 2014," National Statistics, 2015. [Online]. Available: https://www.gov.uk/government/statistics/road-lengths-in-great-britain-2014.

[22] National Grid, "Winter Consultation 2016," Warwick, UK, 2016.

[23] Royal Academy of Engineering, "GB electricity capacity margin," 2013.

[24] G. Ault, D. Frame, N. Hughes, and N. Strachan, "Electricity Network Scenarios for Great Britain in 2050," 2008.

[25] ENSG, "Our Electricity Transmission Network: A vision for 2020," 2012.

[26] Northwest Electricity, "Strategic Direction Statement," 2013.

[27] UK Power Networks, "Business plan (2015 to 2023)," 2012.

[28] J. Rihn, "Road Capacities," Indevelopment, 2004.

[29] Milton Keynes Council, "Electric Bus," 2012. [Online]. Available: https://www.milton-keynes.gov.uk/streets-transport-and-parking/bus-travel/bus-projects/electric-bus.

[30] S. Jeong, Y. J. Jang, and D. Kum, "Economic Analysis of the Dynamic Charging Electric Vehicle," IEEE Trans. Power Electron., vol. 30, no. 11, pp. 6368–6377, Nov. 2015.

[31] Primove, "Successful dynamic charging tests with PRIMOVE in Mannheim," 2016. [Online]. Available: http://primove.bombardier.com/media/news/news-detail-page/article////298.html.

[32] Fabric, "Feasibility analysis and development of on-road charging solutions for future electric vehicles," 2017. [Online]. Available: http://www.fabric-project.eu/.

[33] A. Shekhar, V. Prasanth, P. Bauer, and M. Bolech, "Economic Viability Study of an On-Road Wireless Charging System with a Generic Driving Range Estimation Method," Energies, vol. 9, no. 2, p. 76, Jan. 2016.

[34] J. Sallan, J. L. Villa, A. Llombart, and J. F. Sanz, "Optimal Design of ICPT Systems Applied to Electric Vehicle Battery Charge," IEEE Trans. Ind. Electron., vol. 56, no. 6, pp. 2140–2149, Jun. 2009.

[35] S. Chopra and P. Bauer, "Driving Range Extension of EV With On-Road Contactless Power Transfer—A Case Study," IEEE Trans. Ind. Electron., vol. 60, no. 1, pp. 329–338, Jan. 2013.

[36] R. W. De Doncker, "Power electronic technologies for flexible DC distribution grids," in 2014 International Power Electronics Conference (IPEC-Hiroshima 2014 - ECCE ASIA), 2014, pp. 736–743.

[37] INTIS, "EVs Unplugged," IHS-Automotive Hybrid-EV Anal., vol. 6, no. 5, pp. 8–11, 2015.

[38] Plugless, "Wireless electric vehicle charging," 2017. [Online]. Available: https://www.pluglesspower.com/.

[39] J. Brodie, "BMW previews wireless charging for 2018," AutoExpress, 2017. [Online]. Available: http://www.autoexpress.co.uk/bmw/5-series/101091/bmw-previews-wireless-charging-for-2018-on-530e-iperformance.

[40] Rail Safety & Standards Board, "Study on further electrification of Britain's railway network," 2007.

[41] Network Rail, "Network RUS Electrification," 2009.

[42] Parsons Brinckerhoff, "Review of Western Power Distribution Unit Costs," 2013.

[43] Scottish and Southern Energy, "Generation connections - case studies," 2012.

[44] M. Leftly, "HS2: Cost of London-to-Birmingham leg of proposed new railway a third higher than previously estimated," Independent, 2015. [Online]. Available: http://www.independent.co.uk/news/uk/politics/hs2-cost-of-london-to-birmingham-leg-of-proposed-new-railway-a-third-higher-than-previously-a6734746.html.

[45] UK Parliament, "HS2 and the environment," Environmental Audit, 2014. [Online]. Available: http://www.publications.parliament.uk/pa/cm201314/cmselect/cmenvaud/1076/107608.htm.

[46] H. G. Grunjes and M. Birkner, "Electro mobility for heavy duty vehicles (HDV): The Siemens eHighway System," 12th International Symposium on Heavy Vehicle Transportation Technology, Sweden, 2012.

[47] Department for Transport, “Guidance on Road Classification and the Primary Route network,” 2012.
[48] S. Li and C. Mi, “Wireless Power Transfer for Electric Vehicle Applications,” IEEE J. Emerg. Sel. Top. Power Electron., vol. PP, no. 99, pp. 1–1, 2014.
[49] Department for Transport, “Vehicle Licensing Statistics,” 2016.
[50] DECC, “Updated energy and emissions projections,” Department of Energy & Climate Change, 2015.
[51] Union of Concerned Scientists, “Each Country’s Share of CO2 Emissions,” Global Warming, 2014. [Online]. Available: http://www.ucsusa.org/global_warming/science_and_impacts/science/each-countrys-share-of-co2.html#.V73NF5grLIU