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Wireless Electric Charge-On-The-Move: An Economic Appraisal of the Potential for the UK Transport Application

Doros Nicolaides[1], and John Miles[2]

[1]PhD Candidate with the Department of Engineering, University of Cambridge, dn314@cam.ac.uk

[2] Professor with the Department of Engineering, University of Cambridge, jcm91@eng.cam.ac.uk

Abstract: *This paper presents an economic appraisal of the wireless charge-on-the-move technology of the potential for the UK transport application based on the inductive power transfer system. The critical review of statistical governmental data had led to the development of potential solution schemes and subsequently, a computerised economic model was constructed to examine the economic affordability of the proposal. Sensitivity analysis of the outputs was studied taking into consider major key cost drivers and technical characteristics of the proposed technology. Indeed, the estimated expenditure required for introducing inductive power transfer systems on the roads of UK based on the basic scenario ranges from £2m to £3m per mile and the total expenditure of £80bn is adequate to cover over 85% of all available car-miles.*

Keywords: *charge-on-the-move, dynamic charging, economic appraisal, electric vehicles (EVs), inductive power transfer, online EVs, solution schemes, wireless power transfe*r

1. Introduction

Based predominantly on fossil fuels the transport sector not only does it stimulate issues in relevance with climate change, but it also severely affects human and ecosystem health. Carbon dioxide (CO_2) emissions from the transport sector in 2013 accounted 25% of all CO_2 emissions in the UK [1], and literature indicates that human effects range from breathing difficulties, asthma, skin irritation, to increase risk of developing cancer [2]. Similarly, as a major source of air pollution it deteriorates visibility, damages plants, and degrades biodiversity [3]. This coupled with the inevitable growth of population and number of vehicles in the future, the necessity to strive for a more sustainable transport sector is at the forefront as it has never been before.

A variety of scenarios have been developed to reduce CO_2 emissions in transportation and all of them highlight the obligation to decarbonise the road transport. More specifically, passenger cars amount around 52.5% of all transport CO_2 emissions in the UK and if substantial progress has to be made, an adequate penetration of electric cars is prerequisite to achieve the specified targets [4]. However, the successful uptake of electric cars on the roads of UK is constrained by significant diachronic product barriers. Initially, the major consideration is the high purchase and maintenance cost due batteries. According to a survey [5], 76% of British car buyers have or would consider buying an electric car but they are not willing to pay more than the price of a conventional car. Moreover, limited mileage range and high recharging time [6] are the next two undesirable product attributes which have negative influence on consumer choice and acceptance.

Wireless electric charge-on-the-move technology can reject the adverse characteristics of electric cars and facilitate their dominance on the roads of UK. It is about an idea whereby wireless power chargers will be installed along the transport grid of UK with the purpose to provide energy to moving electric cars. The owners of electric cars will not have to worry about the mileage range since their cars will be charged dynamically but more importantly, batteries with considerably lower capacity can be exploited instead of the bulky, heavy and expensive ones used for current applications. This means that not only will the cars' performance be improved significantly due to lower weight and smaller volume but also the cost will be reduced dramatically. Consequently, wireless electric charge-on-the-move technology will establish the consumer preference for electric cars over combustion engine vehicles and drive the shifting towards a more efficient and lower-carbon transport sector in the future.

It was revealed in other work [7] that the adoption of inductive power transfer systems at the magnitude of a country is technically feasible, socially responsible, and environmentally liable. However, the scalability of the technology is challenged by economic concerns and therefore, this paper presents an economic appraisal of the potential for the UK transport application. The critical review of statistical governmental data had led to the development of potential solution schemes and subsequently, a computerised economic model was constructed to examine the economic affordability of the proposal. Sensitivity analysis of the outputs was studied taking into consider major key cost drivers and technical characteristics of the proposed technology. Indeed, the estimated expenditure required to introduce dynamic charging on the roads of UK based on the basic scenario ranges from £2m to £3m per mile and the total expenditure of £80bn is adequate to cover over 85% of all available car-miles.

2. Solution Schemes

The development of potential solution schemes for connecting the charging devices with the electricity supply grid [7] was a mandatory step in order to perceive the general picture of the economic resources required. Initially, the upcoming 20kW system of Qualcomm Company for stationary and dynamic charging applications was chosen since it had been considered as the most promising product up to that time. Then, the required number of units per mile was investigated taking into consider 0.14kWh/mile average energy consumption of electric cars at constant speed and ±250mm fore-aft misalignment tolerance. Afterwards, statistical data from the Department for Transport in the UK were exploited to provide an accurate indication about the typical congestion of the roads [8] with the purpose to derive the power requirements per mile of road. The results are summarised in TABLE **I** by road type and by region of UK.

TABLE I: Number of Units and Power Requirements kW per Mile

	Major Roads			Minor Roads
	Motorways	Rural ‘A’ roads		Rural
		Trunk	Principal	
England	1,000	200	60	5
Wales	1,000	60	500	5
Scotland	500	60	200	5
No units	1,750	1,500	1,500	1,500

It is worth to say that our investigation excluded all urban roads of UK. The average trip distance within a city is below 7 miles according statistical data and therefore, it is not required to intervene for recharging. Besides, an adequate charging infrastructure will be available in the cities of the UK by 2030 which will include stationary charging points at designated slots regardless contact or contactless technologies [9].

Based on these assumptions, a variety of power distribution configurations have been examined wherein the general principal is to take power from the transmission network and supply the units on the roads. New feeder stations have to be established with additional sub-stations to provide flexibility and circuit protection, wherein their distance apart is mainly influenced on operational requirements. Those include AC designs at 11kV and 3.3kV, a DC set up at 750VDC as it is illustrated in Fig. I as well as solutions to adopt inductive joints instead of physical joints between the feeder cables and the road chargers. For every type of configuration, five more sub-categories are distinguished based on power requirements. In particular, separate power distribution diagrams were deployed for England and Wales motorways; Scotland motorways and Wales principal ‘A’ roads; England trunk ‘A’ roads and Scotland principal ‘A’ roads; England principal ‘A’ roads plus Wales/Scotland trunk ‘A’ roads; and minor roads for all regions.

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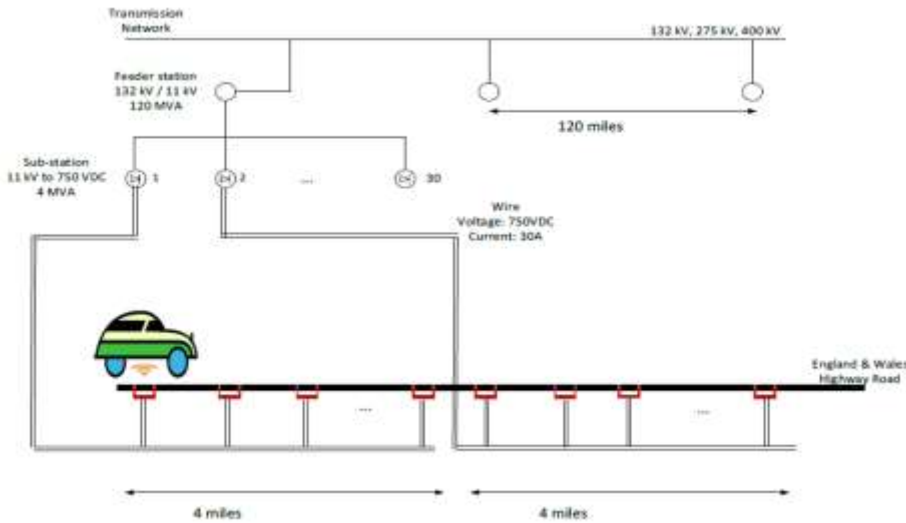

Fig. I: 750VDC power infrastructure for England and Wales Motorways

3. Cost model deployment

The variety of possible solution schemes, which are based on alternative power distribution configurations, emerges a plethora of economic trade-offs among materials, electrical equipment, and civil constructions solutions. Consequently, a computerised cost model was developed to conduct an economic oriented comparison of the possible implementation strategies.

3.1. Model structure

The development of cost model was based on key cost drivers which come under the headings of equipment, construction fees, and designing fees. In particular, the section of equipment consists purchase and installation price for wireless transmitters, cost for different types of cables, the expenditure required for feeder stations and sub-stations with the necessary equipment, such as circuit breakers, transformers, and metering, plus the expense for excavation, cable laying, and joints between cables and chargers. Then, civil engineering construction expenses and immunisation of signalling and telecommunication equipment come under the construction fees and in the end, designing fees for the distribution company have also been considered. Finally, the cost model does not include any costs for associate traffic management or lane rental fees payable to the Highways Authority. A list of variables with their associated values is listed in TABLE II.

TABLE II: Key cost drivers

	Cost variable	Price (£k)	Low-Price (£k)	Comments
1	Wireless Transmitters			
	Chargers	2	2	Purchase and installation
	Inductive Joints	1	0.5	Purchase and installation
2	Cables			
	132kV	200	150	Per mile
	11kV	50	25	Per mile
	3.3kV	27	13	Per mile
	750VDC	3	3	Per mile
3	Feeder stations			
	DNO Circuit breaker	100	100	
	Connection switchgear and protection/metering	100	60	at 11kV
	Transformer 132kV/11kV	6.6	6.6	per MVA

4	Sub-stations			
	11kV incoming isolator/circuit breaker	4	4	up to 4000A
	Rectifier 11kv/750VDC	6	4.5	per MVA
	Transformer 11kV/3.3kV	4	4	per MVA
	Booster Voltage station	25	25	all inclusive
5	Joints			
	Inverters	3	3	20kW
	11kV	0.5	0.1	2 joints for each separate cable length
	3.3kV	0.3	0.1	2 joints for each separate cable length
	750VDC	0.1	0.05	2 joints for each separate cable length
6	Civil Engineering			
	Cable Trenching	100	100	per mile
	Immunisation of signalling and telecommunications	1	1	per mile
	Construction works	20%	20%	of total cost
7	Additional fees			
	DNO designing fees	3%	3%	of total cost

3.2. Sources of data

Cost data with regard electrical equipment, cables, excavation, and designing fees have been obtained from recent projects submitted for endorsement to the Office of Gas and Electricity Markets in the UK. Moreover, the majority of distribution companies have published design manuals where they explain some of the factors and design principles used for designing networks, but also our collection of data was enriched through the identification of parallels with railway electrification projects. Lastly, direct contacts with key suppliers and personal interviews with associate experts in energy projects of ARUP Company were valuable feedback mechanisms for our cost model.

3.3. Outputs

The outputs of the cost model are summarised in TABLE III which presents the expenditure required to introduce inductive power transfer chargers per mile for different types of roads. There is separation by region and power distribution configuration. The results disclose that the maximum expenditure to adopt this technology is £6.7m but we have to bear in mind that this figure refers to motorways with the adoption of inductive joints between feeder cables and road units. Certainly, for other types of roads, which require less power demands, the installation expenditure per mile is significantly lower. For instance, the installation of chargers on minor roads using again inductive joints is only £5.8m instead of £6.7m required for motorways. Besides, alternative power distribution setups provide dissimilar results. As evidence, take the case of 3.3kV with inductive and physical joints on motorways where the estimate expenditure per mile for the former solution is £6.7m whereas for the latter is just £5.2m.

TABLE III: £m per mile by road by region – conservative scenario

		Motorway	**Rural 'A' roads**		**Rural**
			Trunk	**Principal**	
750VDC	*England*	4.7	4.1	4.1	4.1
	Wales	4.7	4.1	4.1	4.1
	Scotland	4.7	4.1	4.1	4.1
11kV	*England*	5.6	4.9	4.9	4.9
	Wales	5.6	4.9	4.9	4.9
	Scotland	5.6	4.9	4.9	4.9

11kV-inductive	*England*	6.7	5.8	5.8	5.8
	Wales	6.7	5.8	5.8	5.8
	Scotland	6.7	5.8	5.8	5.8
3.3kV	*England*	5.2	4.6	4.5	4.5
	Wales	5.2	4.5	4.5	4.5
	Scotland	5.2	4.5	4.6	4.5
3.3kV-inductive	*England*	6.7	5.9	5.7	5.8
	Wales	6.7	5.7	5.8	5.8
	Scotland	6.7	5.7	5.9	5.8

3.4. Sensitivity analysis

Current research efforts aim to increase the fore-aft misalignment tolerance of transmitters. According to personal interviews with experts on the field suggest that the tolerance will be categorically increased in a few years from 250mm to 600mm reducing the number of units required per mile as well the total expenditure - basic scenario. Indeed, the outcomes of that basic scenario are presented in TABLE IV, where the reader recognises that the estimate cost is reduced from £6.7m to £3.0m per mile of motorway compared with the conservative scenario (11kV inductive joints setup).

TABLE IV: £m per mile by road by region – basic scenario

		Motorway	**Rural 'A' roads**		**Rural**
			Trunk	**Principal**	
750VDC	*England*	2.1	1.8	1.8	1.8
	Wales	2.1	1.8	1.8	1.8
	Scotland	2.1	1.8	1.8	1.8
11kV	*England*	2.5	2.2	3.1	2.2
	Wales	2.5	2.2	2.2	2.2
	Scotland	2.5	2.2	2.2	2.2
11kV-inductive	*England*	3.0	2.6	2.6	2.6
	Wales	3.0	2.6	2.6	2.6
	Scotland	3.0	2.6	2.6	2.6
3.3kV	*England*	2.3	2.1	2.6	2.0
	Wales	2.3	2.0	2.0	2.0
	Scotland	2.3	2.0	2.0	2.0
3.3kV-inductive	*England*	3.0	2.7	2.5	2.6
	Wales	3.0	2.5	2.6	2.6
	Scotland	3.0	2.5	2.7	2.6

Furthermore, it is generally agreed, that standardised procedures and bulk purchases of materials offer better prices per unit. To this end, a rather amended cost model was developed to consider lower prices of equipment (TABLE II) – low cost scenario. Additionally, critics may say that the extra-urban average energy consumption is sensitive at high speeds, which means that the energy consumption can reach higher levels than the value used for the abovementioned calculations (0.14kWh/mile); hence, another scenario was conducted to examine 0.2kWh/mile energy consumption – basic high consumption scenario.

4. Possible scenarios

Subsequently, possible implementation solutions have been developed in an effort to illustrate the magnitude of the total cost required. The economic analysis of potential solutions was based on the maximum expenditure obtained from basic model (TABLE IV), which refers to the adoption of inductive joints at 11kV. This expense combined with UK road statistics, such as road length and traffic car-miles, have produced TABLE V which indicates the estimate cost to install wireless chargers by road type, by region and by traffic in the UK.

TABLE V: Estimated expenditure by road type, by region and by traffic

	Motorway	**Rural 'A' Roads**			**Minor Roads**	**Total roads**
		Trunk	**Principal**	**Total**		
England *(£bn)*	11.2	10.2	33.0	43.2	247.8	302.2
Wales *(£bn)*	0.5	3.0	3.6	6.6	36.6	43.8
Scotland *(£bn)*	1.7	5.1	10.9	16.0	59.6	77.3
GB *(£bn)*	***13.4***	***18.2***	***47.5***	***65.8***	***344.1***	***423.2***
Traffic car-miles *(%)*	19.6	11.4	16.9	28.3	13.5	100.0

It can be derived from the table that, the adoption of wireless chargers on the motorways of UK covers 58.2% of all traffic car-miles (including 38.6% of car-miles travelled on urban roads without the obligation to install charge-on-the-move devices) with a total expenditure of £13.4bn. Including rural 'A' trunk roads the total expenditure raises to £31.6bn but the owners of electric cars will reject the range anxiety of 69.6% of all available car-miles. Moreover, the introduction of wireless chargers on rural 'A' principal roads covers 86.5% of car-miles with a total expenditure of £79.1bn. On the whole, establishing charge-on-the-move technology across the national transport grid of UK (excluding urban roads), will deliver 100% of all available traffic car-miles at the total expenditure of £423.2bn.

In a similar way, the total cost for the abovementioned solutions is estimated based on the conservative, low-cost, and basic-high consumption model. In Fig II, the percentage of car-miles travelled without the need for recharging batteries (excluding car-miles travelled on urban roads) are mentioned in relation with the required expenditure. Interestingly, the overwhelming majority of car-miles are covered by a minor fraction of the total expenditure required to cover 100% of all available car-miles for all scenarios.

5. Discussion - Conclusion

While it might be argued that the total expenditure for adopting wireless charge-on-the-move technology looks excessive high, the truth of matter is that this figure is not prohibitive compared with other large infrastructure projects in the UK. At the beginning, a study by the Institute of Economic Affairs estimated a total cost of £80bn for the development of HS2 and the erection of a new nuclear station with nominal capacity at 32MW demands £16bn. Moreover, the construction of a new motorway of 100km length requires on average £30bn, according to Highways Agency and finally, the cost required to electrify one mile of track is between £2m-£4m; an identical value with the charge-on-the-move expenditure. To this end, if it is essential to electrify our rail system which accounts 1.7% of transport emissions in UK [1], it is highly recommended to adopt charge-on-the-move technology to electrify our roads which amount 52.5% of transport emissions.

As a result, the big-picture review of the proposed system based on the aspects of economics has revealed a great potential for the UK transport application. It was shown that 86.5% of all available car-miles are covered with a total expenditure of £79.1bn according to the basic scenario and further development of technology will drive the cost to even lower levels. It is therefore expected that the economic possibility of the charge-on-the-move technology based on the inductive power transfer system will encourage academic and industrial R&D centres for pushing forward the development of the technology towards a more sustainable transport sector in the future.

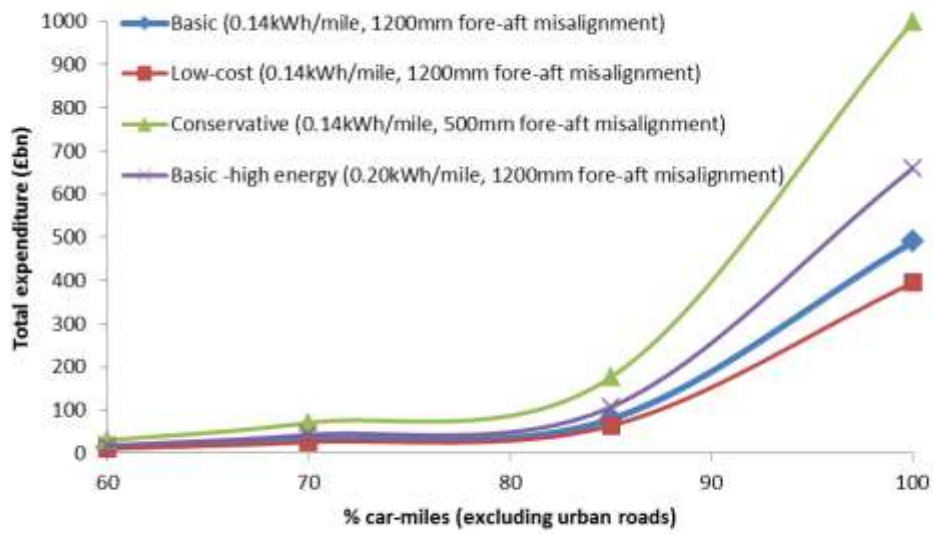

Fig II: Possible implementation scenarios

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