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Vehicle and charging requirements for an electrified road freight system demonstrator in the UK

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Abstract

The UK has set into law a target reduction of greenhouse houses of 78% by 2035 and 100% by 2050. Heavy Goods Vehicles (HGVs) represent 16% of UK road transport emissions are one of the 'difficult-to-decarbonise' sectors owing to their large mass and range requirements. An Electric Road System (ERS) with overhead charging wires presents an attractive solution to rapidly decarbonise HGVs at minimal cost and without the need for megawatt-scale batteries. In this work, we investigate some of the technical requirements for a proposed UK ERS demonstrator comprising 25 km of ERS on the M180 motorway in North Lincolnshire, including battery sizes and static charging infrastructure. A range of theoretical journey scenarios were considered, using simulated journeys and a detailed dynamic model of a 44 t ERS electric lorry. The results indicate the need for three vehicle types: a 150 kWh 'small-battery' ERS vehicle, a 500 kWh 'medium-battery' ERS vehicle, and a 300 kWh battery variant with a range extender for journeys with significant off-ERS driving requirements during the demonstrator.

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Keywords: Electric Road System; Road Freight Transport; Decarbonisation; Greening Freight Transport

1. Introduction

In its sixth Carbon Budget, the UK set into law a target reduction of greenhouse gas (GHG) emissions of 78% by 2035 relative to 1990 levels (CCC, 2020), and reaffirmed its dedication to net zero emissions by 2050 (HM Government, 2019). By sector, transport is the largest contributor to GHG emissions in the UK, accounting for 27% of emissions in 2019, and of this road transport carries the biggest share of 91% (DfT, 2021). Heavy Goods Vehicles (HGVs) are particularly over-represented, responsible for 16% of road transport emissions while contributing 5% of vehicle kilometres travelled (DfT, 2021). While full battery electric vehicles (BEVs) seem set to become the *de facto*

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solution to decarbonise passenger and light to medium-duty goods vehicles, long-haul heavy-duty road freight transport remains a difficult-to-decarbonise sector and there are numerous solutions under investigation.

Several studies in Europe have demonstrated the economic and practical feasibility of an 'Electric Road System' (ERS) for decarbonising road freight transport, and trials in Germany and Sweden are underway (Singh, 2016; Bateman *et al.*, 2018; Boltze, 2020; Taljegard *et al.*, 2020; Aronietis and Vanelslander, 2021). A UK study has shown that an overhead catenary ERS may be the lowest cost, lowest energy, and lowest carbon solution to achieving net zero HGVs in the UK by 2050 (Ainalis, Thorne and Cebon, 2020). A consortium of university and industry partners has obtained funding from the UK government via UKRI to carry out a feasibility study for a potential ERS demonstrator in the UK based on the Siemens 'eHighway' system (UKRI, 2021). The eHighway system, shown in Figure 1, comprises roadside infrastructure of overhead electric cables and compatible electric lorries with deployable pantograph systems ('ERS-BEVs') (Siemens Mobility Solutions, no date). The ERS can power the lorries directly while also charging relatively small on-board battery packs that provide sufficient operating range off the ERS network.

The proposed location of the UK ERS demonstrator is the M180 motorway between Immingham and Doncaster in North Lincolnshire as shown in Figure 2. The M180 has a high density of lorry traffic owing to its strategic location between the ports of Immingham and Grimsby, several major warehouses in the Doncaster and Armthorpe region, and good connections to the major centres of Manchester, Liverpool and Sheffield. The UKRI feasibility study requires that a minimum of 30 lane-km of ERS be considered for the demonstrator.

In this work, we set out to determine preliminary specifications for the proposed M180 ERS demonstrator, including the required vehicle battery sizes, and the need for additional static charging facilities at drop-off or rest stops for participating demonstrator vehicles travelling significant distances off the ERS test site. This was achieved by simulating several representative journey scenarios using artificial drive cycles and a detailed model of a 44 t ERS battery electric lorry.

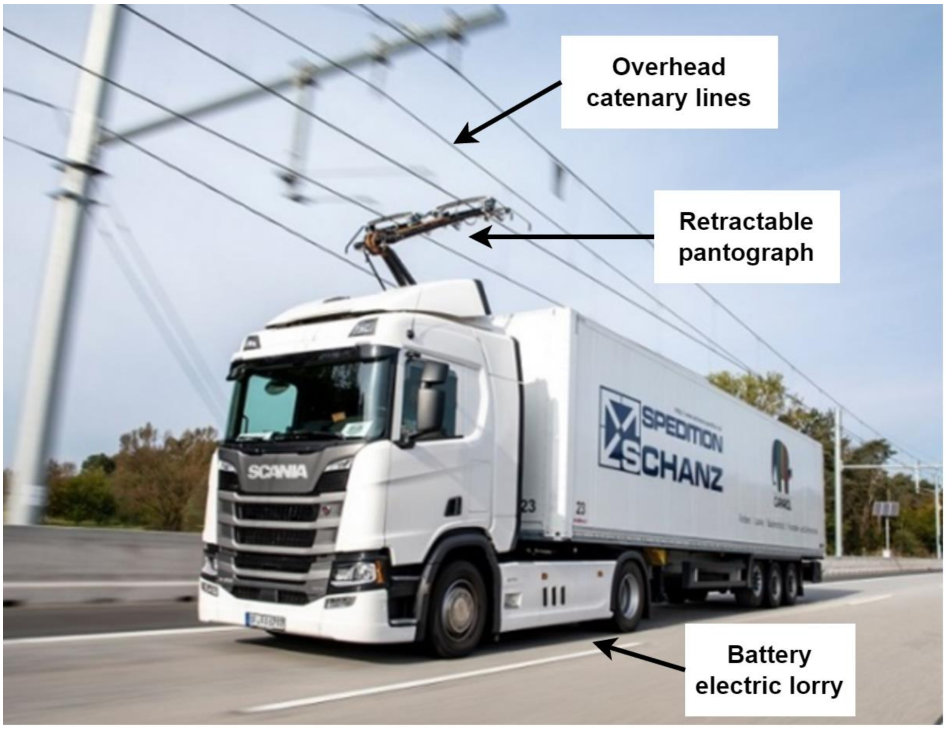


Figure 1: The Siemens eHighway system (Siemens Mobility GmbH, 2021)

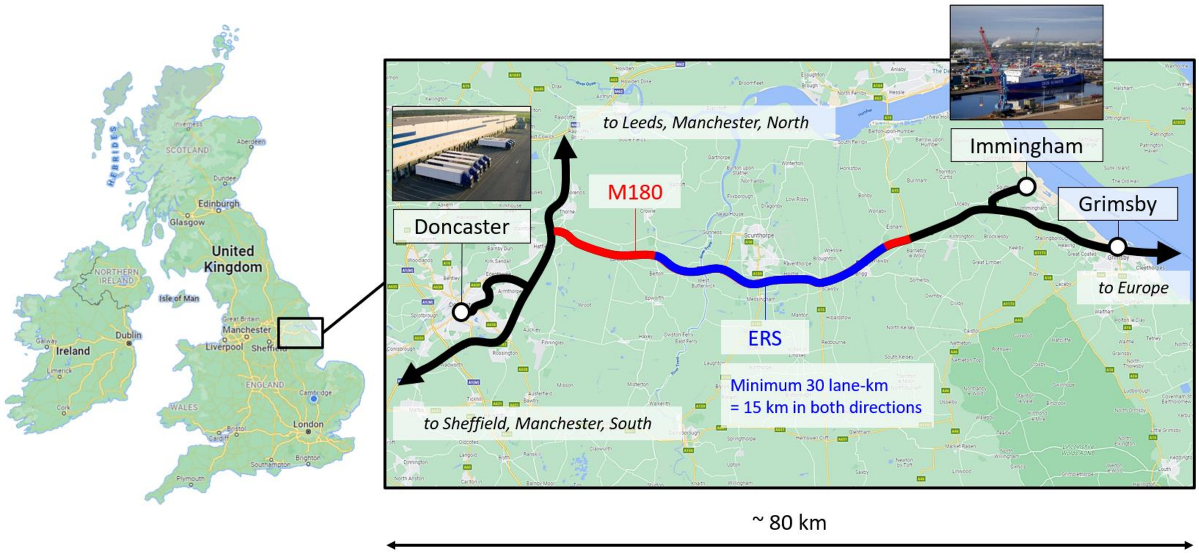


Figure 2: Proposed M180 demonstrator site between Immingham and Doncaster

2. Methodology

2.1. Journey selection

Four journey scenarios were identified for this initial study which would make use of the M180 demonstrator site, as summarised in Table 1. These include warehouse-to-warehouse journeys along the M180 with and without static charging at the assumed depot in Doncaster, as well as more difficult multi-drop scenarios. The 'transitional phase' scenario represents a difficult multi-drop journey taking place during the build-out phase of future charging infrastructure, where it is possible that no static charging sites are available. It was assumed that each drop-off would entail a 20-minute stop. Driver rest stops of 45 minutes after 4h30m of driving were added where necessary in accordance with UK/EU driver hour regulations. Although it is possible for drivers to rest during drop-off stops, it was assumed for these simulations that the driver was still 'working' during these stops (i.e., helping to unload etc.) and so rest time was only accumulated at the dedicated rest stops. Any static charging at drop-off and rest stops were initially assumed to be rated at 600 kW.

Table 1: Journey scenarios

Scenario	Journey description	Origin, stops, destination	Battery charging
1	Journeys without intermediate charging at off-ERS locations (Warehouse-to-Warehouse)	Immingham – Doncaster – Immingham (x 3 trips)	ERS only
2	Journeys with intermediate charging at off-ERS locations (Warehouse-to-Warehouse)	Immingham – Doncaster – Immingham (x 3 trips)	ERS, Doncaster
3	Journeys with intermediate charging at off-ERS locations (Multi-Drop/Tramping)	Immingham Leeds – Manchester – Rest – Immingham	ERS, Leeds, Manchester, Rest
4	'Transitional Phase – Minimal Infrastructure'	Immingham –- Leeds –- Manchester – Rest – Liverpool – Sheffield – Immingham	ERS only

2.2. Drive cycle simulation model

The drive cycle simulation model is summarised in Figure 3 and comprises two sub-models: the drive cycle generator and the detailed vehicle model. The drive cycle generator was implemented in Python and takes as inputs the locations of origin, stops and destination, as well as the ERS locations and available static charging capacity in kilowatts at each stop (which can be zero). Utilising the HERE Maps routing API, the programme generates a GPS-defined route using the fastest time condition, a target speed profile based on posted speed limits and assumed acceleration and deceleration rates, an elevation profile, and two charging profiles (binary signals indicating the existence of ERS or static charger sections along the route.) Stop-start manoeuvres were included at any intersections and roundabouts. An overriding speed limit of 90 km/h was enforced. Traffic effects were neglected. A fixed ERS length of 50 lane-km was assumed based on preliminary costing assessments (25 km in both directions).

The detailed vehicle model was implemented in MATLAB/Simulink, building on an existing battery electric bus model (Madhusudhanan and Na, 2020). The bus model was previously validated against in-service drive cycle data from a 'Metrocity' electric bus operated by Stagecoach in London (Madhusudhanan, Na and Cebon, 2021) showing good agreement of the battery state of charge (SOC) as well as the overall energy consumption. The bus model was then scaled up and modified for suitability to a prospective 44 t electric lorry, also incorporating ERS and depot charging functionality. Although it is not possible to fully validate the 44 t lorry model at this stage, all model modifications and parameter updates were validated with project partners Siemens and Scania to ensure reliability. Future validation work may be carried out once the ERS vehicle and infrastructure are available for testing.

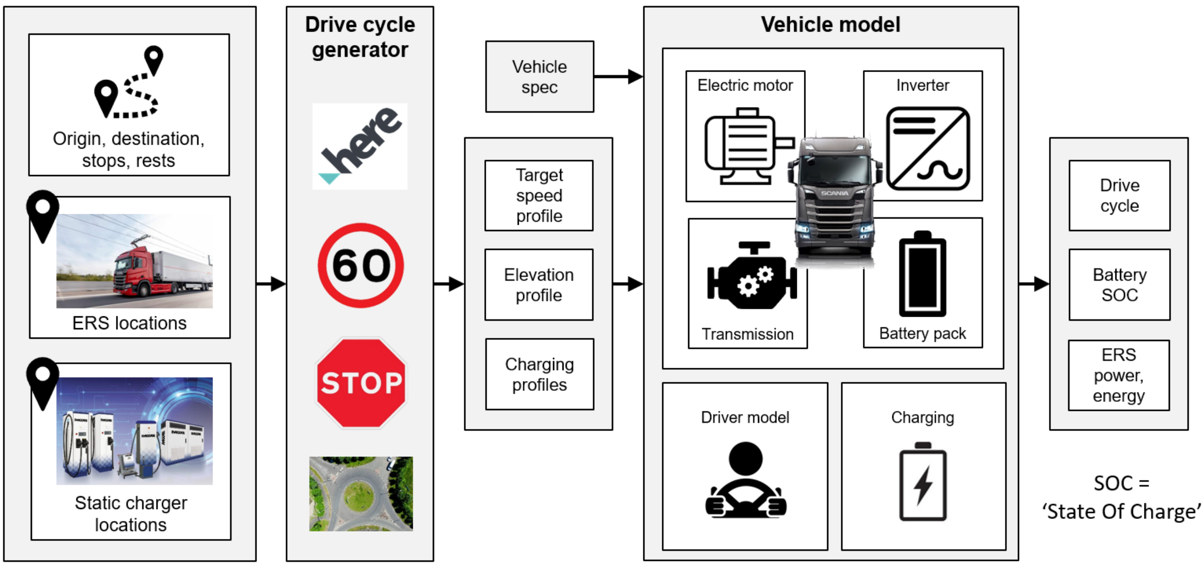


Figure 3: Simulation model, comprising the drive cycle generator (left) and vehicle model (right)

A vehicle mass of 44 t, the heaviest permissible by regulation, was assumed throughout the journey. Auxiliary loads were added for trailer refrigeration and cabin heating, assuming an efficient heat pump heating system, and typical refrigeration cycle loads as published by Zemo (Robinson and Fraser, 2021). It was assumed that the ERS supplies the full vehicle traction demand (typically ~150 kW for a 44 t lorry at steady motorway speeds), and simultaneously charges the battery at an assumed rate of 150 kW (supplying a total of 300 kW).

The model outputs a time history of the drive cycle. An example is given in Figure 4 showing a repeated warehouse-to-warehouse journey along an electrified section of motorway. The top plot shows the speed, elevation profile and regions of ERS. The bottom plot shows the resultant battery 'dip' or state of charge and any charging opportunities via ERS (blue) or static charging (red). The availability of the charging is shown as a dashed line; the line is solid where the battery draws charge. A useable state of charge of 80% was assumed. I.e., a maximum battery dip of 300 kWh and a useable state of charge of 80% would suggest a required battery capacity of 300/80% = 375 kWh.

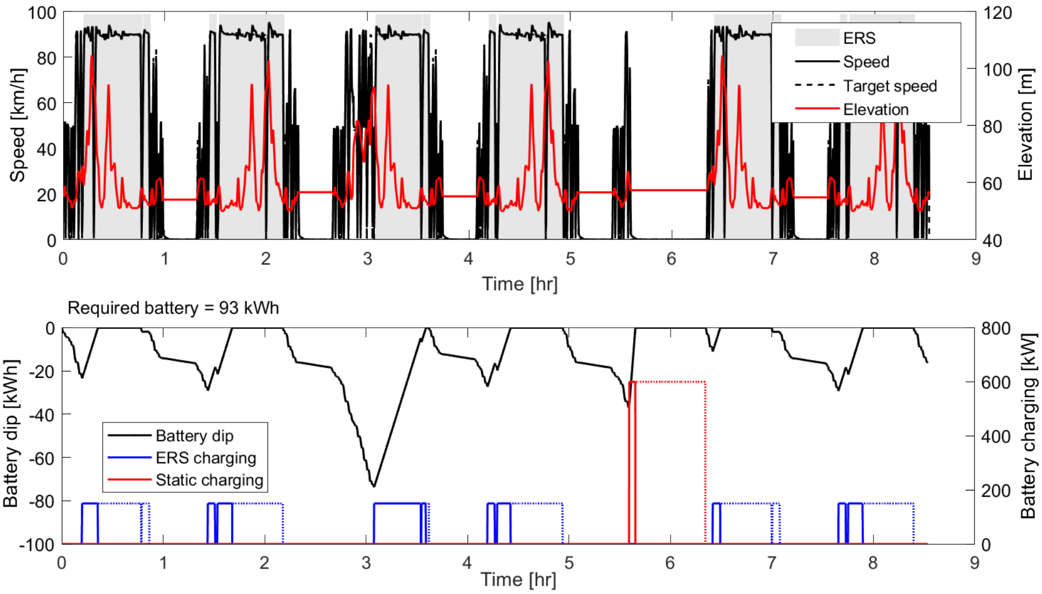


Figure 4: Sample drive cycle and battery state of charge output from the simulation model

3. Results and discussion

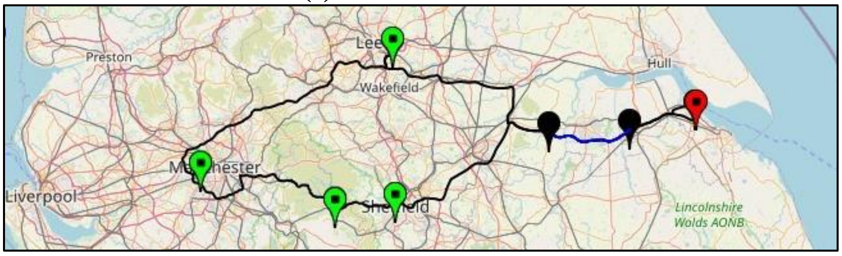
The calculated theoretical battery sizes required for each journey scenario are given in Table 2. The simulated journey routes are shown in Figure 5, where the blue (delimited with black markers) indicates the 25 km ERS section of the M180, the green markers indicate drop-off and erst stop locations, and the red marker indicates the origin and destination location at Immingham.

Three successive warehouse-to-warehouse trips in a day (Scenario 1) would require a 450 kWh battery pack with only ERS charging, but this could be reduced to 150 kWh if static charging is available at the warehouse in Doncaster. Likewise, a single return trip journey with only ERS charging (Scenario 2) would also require only 150 kWh. We can consider the 150 kWh option to be the ‘small-battery’ (‘Type 1’) variant of demonstrator vehicle. The longer multi-drop journey to Leeds, Manchester and Sheffield with drop-off charging (Scenario 3) would require a battery pack of at least 300 kWh, due to most of the journey being off the ERS demonstrator and larger distances between stops. Journeys like scenarios 1 and 3 would in practise likely be serviced by a single ‘medium-battery’ vehicle of around 500 kWh (the ‘Type 2’ variant), giving the operators some flexibility in vehicle allocation due to variations in routes and availability of static charging facilities. The two ERS-BEV vehicle types are summarised in Figure 6.

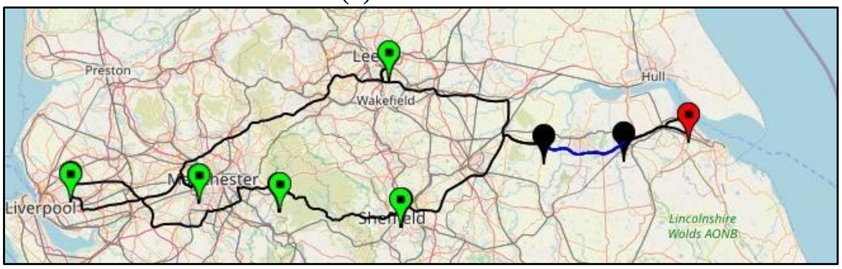
Table 2: Summarised battery capacity observations

Journey type	**Required battery size (kWh)**
Scenario 1: Journeys without intermediate charging at off-ERS locations (Warehouse-to-Warehouse)	450
Scenario 2: Journeys with intermediate charging at off-ERS locations (Warehouse-to-Warehouse)	150
Scenario 3: Journeys with intermediate charging at off-ERS locations (Multi-Drop/Tramping)	300
Scenario 4: ‘Transitional Phase – Minimal Infrastructure’	1100

(a) Scenarios 1 and 2



(b) Scenario 3



(c) Scenario 4

Figure 5: Simulated journey scenarios

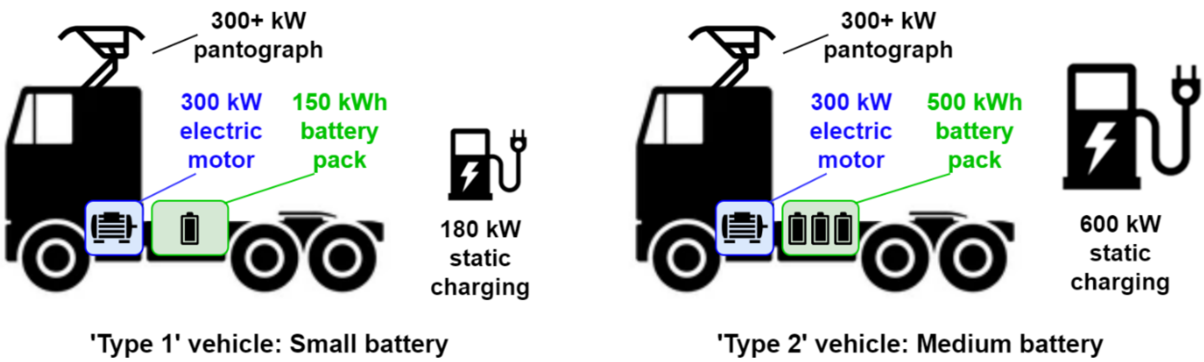


Figure 6: Proposed ERS-BEV vehicles, Type 1 and Type 2

The most challenging journey (Scenario 4) in which we consider a longer journey with additional stops with no static charging available *en route* would require a 1100 kWh battery pack. This is indicative of what a purely battery electric vehicle with no ERS would require for this journey (as the ERS forms a negligible proportion of the journey distance) and falls outside of the scope of ERS-type vehicles under consideration for the demonstrator. (There is a planned full battery electric lorry demonstrator planned in parallel with the ERS demonstrator, which will assess the feasibility of such 'big-battery' vehicles.) In the context of the ERS demonstrator, this indicates that a small- to medium- battery vehicle with a range extender would be required for any vehicles doing this type of journey. For example, a 300-kWh battery pack coupled with a diesel or biogas range extender could be suitable ('Type 3'). This is summarised in Figure 7.

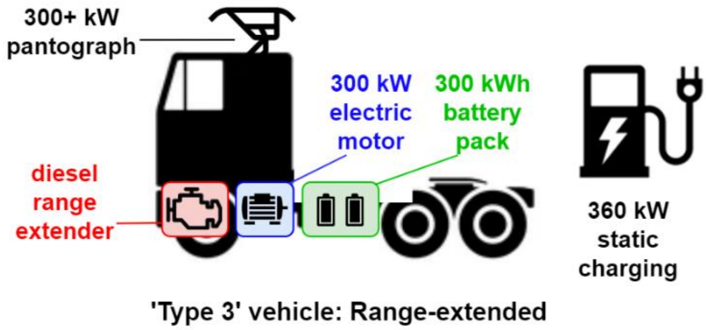


Figure 7: Proposed 'Type 3' vehicle, including a diesel/biogas range extender

Although a charge rate of 600 kW was assumed in all simulation scenarios, a realistic rate of 1.2C would likely suffice, which is better suited to battery longevity (*i.e.*, the charge rate in kW = 1.2 times the battery capacity in kWh). This is equivalent to the 500 kWh battery being charged at 600 kW, or the 150 kWh battery being charged at 180 kW. In each case this would allow close to a full charge during a 45 minute rest stop. The 300 kWh series hybrid would require a 360 kW charger. These charging specifications are included in the illustrations above. Note that, to the authors' knowledge, these vehicle configurations are in no way an indication of planned production vehicles by any Original Equipment Manufacturer.

4. Conclusions

From this preliminary study, we can propose expected specifications for the UK ERS demonstrator:

- An ERS length of 50 lane-km on the M180 (25 km on each direction) with a power supply capacity of at least 300 kW per vehicle should suffice for the proposed UK ERS demonstrator.

- Three pantograph battery electric vehicle types would likely be needed during the demonstration period: (Type 1) a 150 kWh ERS-BEV, (Type 2) a 500 kWh ERS-BEV, and (Type 3) a series hybrid ERS vehicle with a 300 kWh battery pack and diesel/biogas range-extender. Pantographs and on-board power electronics should be designed accordingly with power ratings of at least 300 kW.

- Static charging facilities at some warehouses, retailers and rest stops will likely be required during the demonstration to accommodate vehicle journeys with significant proportions off the 25 km ERS test site. A charging rate of 1.2C would allow for a close to full recharge of the batteries in a 45 minute rest stop, and about a 50% recharge during a 20-minute drop-off stop.

In future work, the study will be extended to examine proposed national-scale ERS topographies, using realistic journey data obtained from UK HGV operators and retailers. This will give further insights into the national system specifications and will enable the overall the cost and emissions impact of such a system to be calculated and compared with alternatives such as large-battery BEVs with no ERS (requiring megawatt static charging), and hydrogen fuel cell vehicles. Detailed economic and carbon emission models will be developed to fully benchmark the proposed national ERS system against the alternatives, including assessments of infrastructure cost, total cost of ownership, government subsidies, and carbon emissions from operation as well as from embodied carbon the vehicles and infrastructure.

Acknowledgements

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