Transportation Research Part D 122 (2023) 103870

Contents lists available at ScienceDirect

Transportation Research Part D

journal homepage: www.elsevier.com/locate/trd

A breakeven cost analysis framework for electric road systems

Parth Deshpande [a,*], Christopher de Saxe [a,b], Daniel Ainalis [a], John Miles [a], David Cebon [a]

[a] *Department of Engineering, University of Cambridge, Trumpington Street, Cambridge, CB2 1PZ, United Kingdom*
[b] *School of Mechanical, Industrial and Aeronautical Engineering, University of the Witwatersrand, Johannesburg 2000, South Africa*

ARTICLE INFO

Keywords:
Electric road systems
Electric heavy goods vehicles
Road freight decarbonisation

ABSTRACT

Road freight emissions form a significant part of a country's total emissions. Thus, one of the key steps for achieving net zero is to decarbonise road freight. Battery electric heavy goods vehicles (HGVs) require large batteries that are heavier and more expensive. This paper investigates the feasibility and impact of electrifying HGVs using electric road systems (ERS), thus reducing the need for large batteries. It is established that using the ERS reduces well-to-wheel (WTW) emissions by approximately 10%. A cost breakeven analysis was formulated to identify the locations where an ERS is economically viable in England, France, India and South Africa. The differences in these countries are observed in terms of their road freight distribution. This analysis reveals that up to 47% of the total road freight in England, 72% in France, 38% in India and 57% in South Africa could be electrified using ERS with a 20-year breakeven period.

1. Introduction

Heavy goods vehicles (HGVs) account for 18% of the emissions by road transport in the UK (Ainalis et al., 2020), 29% in India (IEA, 2017) and 27% in South Africa (DoT, 2018). Furthermore, in South Africa, the logistics sector contributes to around 9.3% of all emissions (Goedhals-Gerber et al., 2018), while in India, road transport itself contributes to around 13% of the total CO_2 emissions. These numbers make it clear that it is critical to rapidly decarbonise road freight. At the same time, decarbonisation of road freight is a difficult problem to solve because of there being a wide variety of alternate fuels, electrification strategies and vehicle types to choose from, along with a lack of infrastructure for refuelling or charging. Currently, the trucking industry only uses diesel HGVs, worldwide. Because diesel vehicles everywhere use standardised technology, it gives benefits of scale and international harmonisation in manufacturing HGV powertrains. It is not obvious how this entire world-wide industry will transition into a new paradigm. This study is attempting to address this issue by investigating decarbonisation options in various geographies using a common assessment methodology.

Different countries have different resources, geographies and infrastructure, and hence, require different strategies for the decarbonisation of road freight. Thus, it is important to analyse use case scenarios and formulate solutions for decarbonising road freight across the globe. The need to consider developing countries is also motivated by the rapid growth of road freight and their more sparse geographies which make electrification more difficult.

Fig. 1 shows the road freight movement in several countries from 1998 to 2017 (OECD, 2022). The road freight movement in the USA, China and India is much higher than in the UK and EU. Hence, it is important to consider how solutions being considered for the UK and EU could be adapted to work in high-emitting countries.

---

[*] Corresponding author.
E-mail address: prd41@cam.ac.uk (P. Deshpande).

https://doi.org/10.1016/j.trd.2023.103870
Received 3 March 2023; Received in revised form 21 June 2023; Accepted 31 July 2023

Nomenclature

Symbols

α	Proportion of vehicles on the ERS with a fully charged battery
C_+	Net income from electricity profit up to the year n_{y} (£/km)
C_-	Net expenditure up to the year n_{y} (£/km)
C_{ERS}	Cost of constructing ERS per km (£/km)
$C_{\mathrm{ERS,a}}$	Annual instalment of constructing ERS per km with a loan (£/km)
$C_{\mathrm{ERS,m}}$	Cost of maintenance of the ERS per year (£/km)
$C_{\mathrm{V,ERS}}$	Cost charged to the vehicle for using the ERS (£/km)
Δr_{e}	Electricity profit margin (pence/kWh)
e_{tr}	Energy transferred from the ERS to the vehicle per km (kWh/km)
f	Fraction of annual maintenance cost of ERS with respect to infrastructure cost
n_{c}	Time required for ERS construction (years)
n_{d}	Number of days the ERS is in use, per year
n_{i}	Duration of the loan (years)
n_{r}	Time required for 98% ERS usage ramp-up (years)
n_{T}	Number of HGVs per day using the ERS
n_{Tmax}	Number of HGVs per day using a road section averaged annually
n_{y}	Time required for ERS cost breakeven (years)
P_{ERS}	Power rating of the ERS per vehicle (kW)
Q_{T}	Average payload per truck (tonnes)
Q_{Tmax}	Annual freight flow on a road section (tonnes)
r_{i}	Loan interest rate for constructing ERS
r_{z}	Average rate of inflation, year-on-year
v_{V}	Cruising speed of the vehicle (km/h) = average traffic speed of the section (km/h)

Abbreviations

AADT	Average annual daily traffic
ERS	Electric road system
HGV	Heavy goods vehicle
SRN	Strategic Road Network
TCO	Total cost of ownership
WTW	Well-to-wheel

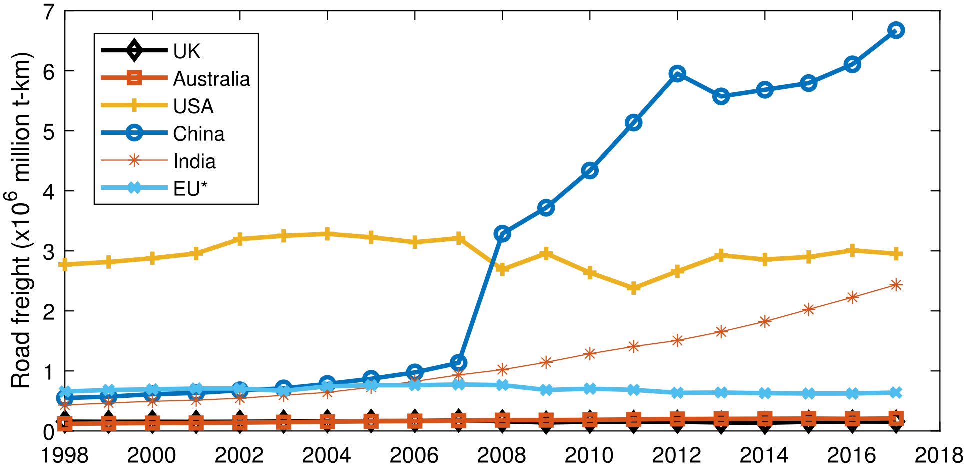

Fig. 1. Road freight data (OECD, 2022). *EU includes data from major countries, i.e., France, Germany, Italy and the Netherlands.

Several methods exist for decarbonising road freight transport that can be classified as short-term and long-term. The short-term methods include efficiency improvements of HGVs such as improved tyres, aerodynamics and light-weighting (Madhusudhanan et al., 2021). Some of these methods such as driver training for eco-driving (Kumar Dadsena et al., 2019; Subel et al., 2021), using higher capacity vehicles (Odhams et al., 2010) and proper fleet maintenance (Liu et al., 2019) result in significant efficiency improvements, and can and should be implemented immediately (Mulholland et al., 2018). Most of these can also be carried into a net zero future to minimise energy use. Another improvement that can be implemented soon is the modal shift of freight transport to rail given the higher efficiencies, for example, in the United States (Liu et al., 2019). This can be particularly effective in countries with wide electric rail coverage, such as India, where over 67% of the rail freight network is electrified (Indian Railways, 2020). However, this is only attractive where there is a high level of spare capacity in the existing rail network. This paper focuses on methods for the decarbonisation of road freight transport in the long term.

One of the most effective approaches to decarbonise road freight in the long term is a shift in powertrain technology. Some popular alternative powertrain options are biofuel HGVs, hydrogen fuel cell battery electric HGVs, and battery electric HGVs. Biofuel HGVs are cleaner in terms of emissions than diesel HGVs but are let down by inadequacies in biofuel supply (Panoutsou et al., 2021). Biofuel-driven powertrains can also be used as range extenders in electric HGVs. HGVs that run on green hydrogen[1] fuel cells are much less efficient in 'well-to-wheel' (WTW) terms than HGVs that run directly on electricity (Haugen et al., 2021), and are therefore not the best option to decarbonise road freight in the long run. On the other hand, battery electric HGVs require large batteries for sufficient range. These are heavy, expensive and take longer to charge (WEF, 2021).

To tackle these shortcomings, one approach is to construct 'electric road systems' (ERS) on major highways and freight routes (Grünjes and Birkner, 2012). ERS implementations can use wireless power transfer, on-ground power supply, or overhead catenary cables (Gustavsson and Hacker, 2019; Nicolaides et al., 2018).

Wireless ERS consists of inductive circuits in the road and vehicle that transfer power from the road to the vehicle in a contactless way (Nicolaides, 2018). This type of system is more convenient as it could be used by all types of vehicles, does not involve any intervention from the driver and is not prone to interference from weather conditions. However, it is limited by issues such as misalignment and could be difficult to construct as it requires digging up the road. Maintenance of many systems buried in the road is also likely to be a significant issue.

On-ground power supply systems use live rails on the road to supply power to the vehicle (RGRA, 2022). This type of system is similar to the 'third rail' used in some railway systems, particularly the underground. However, such a type of system has major safety concerns due to live wires on the ground, along with other issues such as being prone to blockages from rain, snow or debris on the road.

The overhead catenary implementation, shown in Fig. 2, consists of overhead power lines in the outermost lane that supply power to the HGV via a pantograph. The active pantograph aligns itself with the cables to be connected at all times and can automatically retract if the driver changes lanes. It is also easier to add to existing roads, safer, and not affected as much by weather conditions. It is, therefore, more efficient, mature and simpler than the others, and is best suited for HGVs (Gustavsson and Hacker, 2019; Navidi et al., 2016). This paper focuses on such an implementation of the ERS.

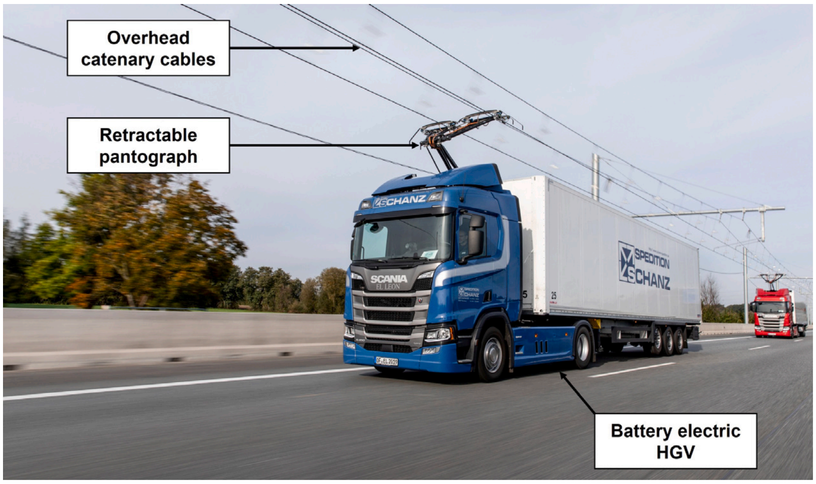

Fig. 2. An overhead catenary implementation of ERS (Siemens Mobility GmbH, 2021).

Studies on the environmental benefits of ERS show that the ERS is effective in significantly reducing emissions from road freight. Tasnim (2014) showed that electrification of high-volume freight corridors such as the I-170 in the US can reduce emissions by

---

[1] Green hydrogen is generated by electrolysis of water using electricity from the grid.

44%–94%. Gnann et al. (2017) showed that the high efficiency due to direct electricity usage in the ERS requires less installation of additional renewable power compared to fuel cell HGVs. A life cycle emissions analysis of ERS showed that emissions payback times are within 5 years on roads with traffic flows of at least 400 HGVs per day (Schulte and Ny, 2018). It was also shown by Sundelin et al. (2016) that critical components of ERS have reached maturity. The infrastructure itself has several use cases, such as mining and long-haul freight (Tongur and Sundelin, 2017), and this paper focuses on the latter.

There are still some unanswered questions about financial models for the construction of ERS infrastructure (Tongur and Sundelin, 2017). One step towards answering this is to establish that the ERS is both effective and financially feasible with an achievable breakeven period, which forms the basis of this paper. The following section summarises some existing literature on the economics of the ERS and the objectives of this paper.

2. Literature review and objectives

There have been several studies about the impacts and feasibility of the ERS in specific countries, for example, using vehicle counts to obtain suitable ERS locations (Teixeira Sebastiani, 2020; Taljegard et al., 2019; Ainalis et al., 2020) and selecting the most suitable countries to install the ERS based on economic feasibility (Singh, 2016; Bateman et al., 2018). There have also been studies on estimating the increase in energy demand arising from the ERS (Jelica, 2017).

The methodologies, outcomes and gaps in these studies have been summarised in Table 1. While some of the studies analyse the economic aspects of the ERS, they do not highlight specific locations where cost feasibility can be achieved. The other studies

Table 1
Review of literature on the economic feasibility of the ERS.

Study	Methodology and gaps	Location analysis approach	Case studies
Singh (2016)	Performed a cost breakeven analysis by equating fuel cost savings to infrastructure investment. However, fuel cost savings were assumed to be invested in purchasing the vehicle and not installing the ERS.	Estimated the road length electrified and the number of countries where ERS is feasible. Specific locations were not highlighted.	All roads in Sweden.
Bateman et al. (2018)	Compared economic feasibility for different types of ERS. Found that breakeven can be achieved with an investment of capital cost and sufficient electricity profit margin. No road network analysis was done.	Not done.	None.
Sundelin et al. (2018)	Analysed truck routes on the ERS to identify traffic flow required for economic feasibility. This was only done for one type of journey utilising one ERS road section.	Specified upper and lower limits on the number of trucks that should be using the ERS.	One road in Sweden.
Taljegard et al. (2019)	Obtained infrastructure cost as a function of traffic counts and ERS length. Depicted roads with the highest emissions on a map.	Did not highlight specific roads but estimated the road length share of ERS.	European and National roads in Sweden.
Ainalis et al. (2020, 2022)	Studied the effect of rolling out ERS on vehicle ownership costs. Assumed a fixed traffic flow threshold to define high-usage scenarios for ERS rollout.	Locations filtered based on assumed traffic flow thresholds.	United Kingdom.
Ngo et al. (2020)	Determined locations of in-road ERS by minimising societal cost, total travel time and energy consumption. Only studied a small region and did not account for detailed costs to the infrastructure provider.	Suggested major highways for ERS based on demand for origin–destination pairs.	Montgomery County, Maryland USA.
Sun et al. (2020)	Used a network equilibrium model to identify optimal locations for static chargers and ERS. Considered small road networks as graphs and optimised the societal cost of the network based on routes and electricity prices.	Analysed origin–destination pairs by switching between charging lanes (i.e., ERS) and charging stations and finding the optimal configuration.	Nguyen-Dupuis, Sioux Falls and South Florida networks.
Teixeira Sebastiani (2020)	Presented an ERS location analysis based on traffic counts along with a method for freight flow estimation. Did not account for costs to the infrastructure provider.	Highlighted locations based on assumed thresholds on vehicle miles travelled.	California state roads.
Börjesson et al. (2021)	Analysed ERS usage scenarios based on the electricity profit margin for two vehicle classes. Highlighted the uncertainty in costs and recommended public ownership for the ERS.	No specific location analysis.	Roads in Sweden.
This study	Formulates the cost breakeven period of ERS infrastructure by considering costs and income for the infrastructure provider. Uses freight movement data to present specific locations at a national level where ERS infrastructure could pay for itself.	Highlights roads in a national road network using real data on traffic counts and annual freight flows.	Road networks in England, France, India and South Africa.

propose ERS locations based on assumed thresholds on road freight flows, which may not be economically feasible. Based on these gaps, there is a need for a framework to perform a *quantified* cost breakeven analysis for the ERS and highlight the locations where it is feasible to install it as a part of an overall system for electrifying road freight world-wide.

Based on this motivation, this paper aims to analyse the effectiveness and feasibility of ERS in decarbonising road freight across selected countries. This is achieved by enlisting the following objectives:

1. To analyse the emissions in operating HGVs with different powertrains in different countries.
2. To understand the feasibility of ERS by formulating the cost breakeven period of the infrastructure.
3. To identify feasible locations for the ERS in different countries based on the economic analysis.

The scope of this paper is restricted to analysing implementations of the ERS with overhead catenary cables and the feasibility is illustrated for countries with readily available traffic data.

The rest of this paper is structured as follows. Section 3 compares emissions across different powertrains for different countries. Section 4 then focuses on ERS cost feasibility by deriving a cost breakeven formulation. The results of this formulation are showcased in Section 5 with plots of parameters and maps of calculated ERS configurations in the selected countries. This is followed by a discussion of the results, and then by concluding remarks in Section 6.

3. Energy usage and emissions

This section compares net CO_2 emissions for different powertrains. Here, it is critical to consider WTW emissions, i.e., the emissions involved in the process from producing the 'fuel' to using it in the vehicle. At this stage, emissions involved in manufacturing the powertrains and charging infrastructure are not considered as they are not significant when considered over the lifetime of a vehicle. It is worth noting that using the ERS would result in significantly smaller batteries, as shown by de Saxe et al. (2022), which would essentially reduce embodied emissions (Hall and Lutsey, 2018). This analysis is performed for countries with varying grid carbon factors, ranging from Sweden with one of the lowest grid factors, the UK, USA, China, India, Australia and South Africa, in increasing order of their grid factors for the year 2020 (Carbon Footprint, 2020).

For this simplified analysis, it is assumed that the net energy required at the wheels is 100 kWh for all powertrain types. The energy required at various locations in the powertrain is shown in Fig. 3. This is traced to the energy required at the source 'well' by factoring-in the efficiencies at every stage of energy conversion as done by Haugen et al. (2021). These efficiencies are assumed to be the same in every country. The difference in the efficiencies of using an electric HGV on and off the ERS is the energy lost in charging the batteries. It may be noted that an ERS vehicle would have to make parts of its journey on battery power, and hence, its real efficiency would be a mix of the battery electric and HGV efficiencies. It can be seen that for every 100 kWh of propulsion energy, an ERS HGV requires 130 kWh of electricity, a battery electric HGV requires 144 kWh of electricity, whereas a hydrogen fuel cell HGV running on green hydrogen requires 434 kWh of electricity. The diesel vehicle requires 263 kWh of diesel fuel, but note that this number cannot be compared directly with the electrical powers because diesel fuel is considered to be thermodynamic 'heat' whereas electricity is thermodynamic 'work'.

For the electric powertrains, the net WTW emissions are obtained using the energy required from the grid for each country, where the grid emissions factors are obtained from the Carbon Footprint report for the year 2020 which has a compilation of grid emissions data from government sources (Carbon Footprint, 2020). These grid factors are shown in Fig. 4. For a diesel vehicle, the energy required from Fig. 3 is translated to the emissions using the ratio of the net energy density of diesel, $36.0\ \mathrm{MJ/l} \approx 10.0\ \mathrm{kWh/l}$, and the WTW emissions factor, $2.62\ \mathrm{kg\text{-}CO_2/l}$ (SFC, 2018). This gives the emissions as $0.26\ \mathrm{kg\text{-}CO_2/kWh}$. The net emissions for all powertrain types are shown in Fig. 4.

As seen in Fig. 4, the WTW emissions from electric HGVs, either on or off the ERS, are lower than diesel vehicles in Sweden,[2] UK and USA. However, this is not the case in other countries, because of their higher grid factors in the year 2020. These are expected to drop rapidly in the future as these countries decarbonise their electricity grids, thus reducing WTW emissions of electric HGVs. According to this analysis, the cutoff grid factor for the emissions from an electric HGV on the ERS to be lower than that of a diesel HGV is $0.53\ \mathrm{kg\text{-}CO_2/kWh}$, which could be achieved soon by most of these countries. At the same time, powering electric HGVs via the ERS results in 10.5% lower CO_2 emissions as compared to battery-powered electric HGVs, because no energy is lost in charging the batteries when operating on the ERS. Hydrogen is the worst performer in every country because of the inefficiencies associated with the energy conversions shown in Fig. 3.

From these observations, it can be said that the ERS reduces emissions while reducing charging time and resulting in smaller batteries. This also results in additional benefits due to smaller batteries, such as lower cost, lower emissions and less use of materials in battery manufacturing, reduced mass and hence, increased energy efficiency of the vehicles. Therefore, in parallel to decarbonising grids, it is vital to also focus on developing ERS infrastructure to support the introduction of electric HGVs. What remains to be seen here is if the ERS is economically viable, which is addressed in the following section.

---

[2] Sweden has a particularly 'clean' electricity grid generated mainly by hydro and nuclear power with some wind.

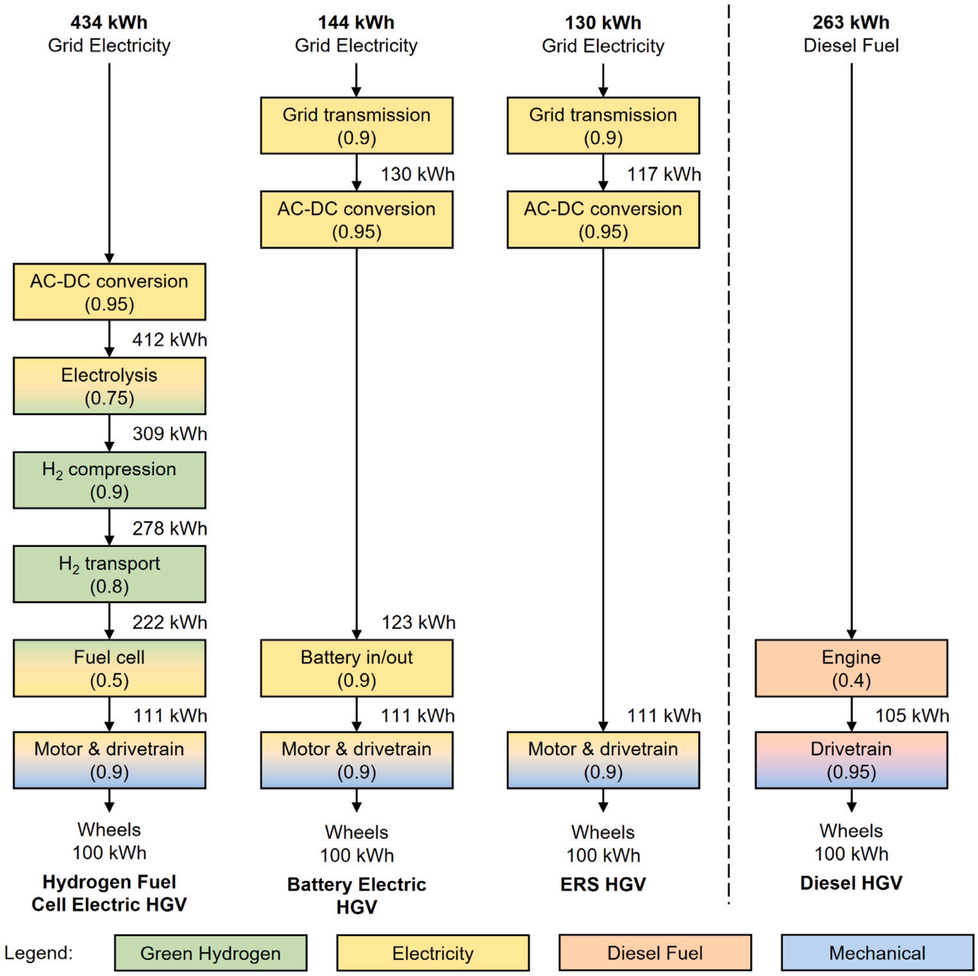

Fig. 3. Energy requirements from different power sources.

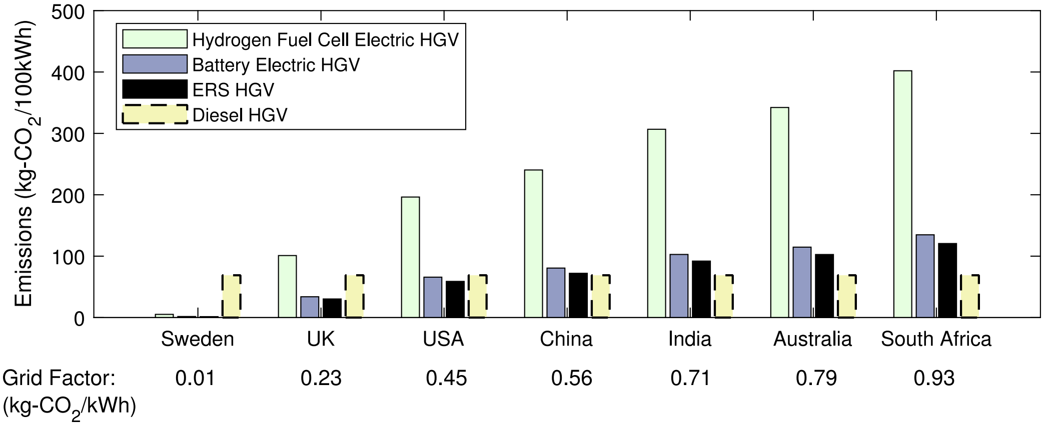

Fig. 4. Comparison of WTW emissions for various powertrains across different countries using grid carbon factors for the year 2020 (Carbon Footprint, 2020).

4. Cost breakeven for ERS

From the previous section, it is evident that along with a transition to clean electricity, technologies such as the ERS can help in reducing road freight emissions in most countries. At the same time, it is important to evaluate the economic feasibility of the ERS for it to be a viable solution. This section derives a formulation that highlights the roads in a country's network that are suitable for installing an ERS with an economically attractive cost breakeven period. It is assumed that the ERS requires an initial construction period of n_c years when there is no income and no maintenance cost, while the loan repayments start on day one. This construction period is assumed to be 5 years for this analysis (Ainalis et al., 2022).

4.1. Infrastructure cost analysis

The first step in this formulation is to estimate the total cost incurred by an ERS provider in constructing and running 1 km of an ERS section (Deshpande et al., 2022). This includes the cost of the infrastructure itself, its maintenance, and the purchase of electricity from the grid. No assumption is made regarding whether the ERS is funded directly by the government or by a private concession.

4.1.1. ERS income

For the preliminary assessment, it is assumed that when a vehicle uses the ERS, it will do so when moving at its cruising speed and drawing traction power of 150 kW, while charging its batteries at 150 kW, giving a total ERS power draw of $P_{\text{ERS}} = 300$ kW (de Saxe et al., 2022). It is also assumed that a proportion, α, of all vehicles would have charged up their battery completely and would only draw 150 kW of power. For this analysis, the number of such vehicles with a fully charged battery is assumed to be 25% of all vehicles using the ERS, thus equating α to 0.25.

Thus, the average energy transferred to a vehicle when it uses the ERS per km, e_{tr}, is given by dividing the power rating, P_{ERS}, by the speed of the vehicle, v_{V}, assumed to be 90 km/h, as

$$e_{\text{tr}} = \frac{P_{\text{ERS}}}{v_{\text{V}}}\left(1 - \frac{\alpha}{2}\right), \tag{1}$$

where the parameters are defined in the Nomenclature section.

Consequently, the profit from the cost charged to a vehicle per km of the ERS, $C_{\text{V,ERS}}$, is proportional to the energy drawn and the electricity profit margin, Δr_{e}, converted from pence/kWh to £/kWh, given by

$$C_{\text{V,ERS}} = \frac{\Delta r_{\text{e}}}{100} e_{\text{tr}}. \tag{2}$$

This number would change every year with inflation. Hence, the total profit up to the breakeven year, n_{y}, would depend on inflation. Assuming r_{z} to be the rate of inflation, the profit would increase by $\left(1 + r_{\text{z}}\right)$ times every year. The profit also depends on the number of HGVs using the ERS per day, n_{T}, and the number of days it is in use per year, n_{d}. Hence, the total profit up to the year, n_{y}, is given by

$$C_{+} = C_{\text{V,ERS}} n_{\text{T}} n_{\text{d}} \left(1 + \left(1 + r_{\text{z}}\right) + \left(1 + r_{\text{z}}\right)^2 + \cdots + \left(1 + r_{\text{z}}\right)^{\left(n_{\text{y}} - n_{\text{c}}\right)}\right) \tag{3}$$

$$= \frac{\Delta r_{\text{e}}}{100} e_{\text{tr}} n_{\text{T}} n_{\text{d}} \left(1 + \left(1 + r_{\text{z}}\right) + \left(1 + r_{\text{z}}\right)^2 + \cdots + \left(1 + r_{\text{z}}\right)^{\left(n_{\text{y}} - n_{\text{c}}\right)}\right), \tag{4}$$

where $\frac{\Delta r_{\text{e}}}{100} e_{\text{tr}} n_{\text{T}} n_{\text{d}}$ is the total annual profit in the first year. The progression is only considered for $\left(n_{\text{y}} - n_{\text{c}}\right)$ years to exclude the construction period at the start.

By adding the terms of the geometric progression, the total profit is given by

$$C_{+} = \frac{\Delta r_{\text{e}}}{100} e_{\text{tr}} n_{\text{T}} n_{\text{d}} \frac{\left(1 + r_{\text{z}}\right)^{\left(n_{\text{y}} - n_{\text{c}}\right)} - 1}{r_{\text{z}}}. \tag{5}$$

Here, the electricity profit margin, Δr_{e}, is assumed to be between 8 pence/kWh and 18 pence/kWh, explained further in Section 5.1. The number of days, n_{d}, is considered to be 365, and the average annual rate of inflation, r_{z}, is assumed to be 3% for developed economies (England, France) and 7% for developing economies (India, South Africa), based on averaged historical inflation data. However, it is observed that the analysis is not very sensitive to this variable.

In Eq. (5), the number of trucks (n_{T}) would gradually increase as more HGVs start using the ERS every year during the 'adoption' phase. Ideally, the ramp-up would be best depicted by an S-curve, but because the ERS is an 'add-on' charging method for battery electric trucks and because of the construction time at the start, an inverse exponential ramp-up is assumed here. This adoption phase accounts for the transition period required for remaining diesel HGVs to be replaced by battery electric HGVs and for any existing battery electric HGVs to add support for the ERS using a pantograph kit. Hence, the number of trucks is given by

$$n_{\text{T}} = n_{\text{Tmax}} \left(1 - e^{\frac{-4\left(n_{\text{y}} - n_{\text{c}}\right)}{n_{\text{r}}}}\right), \tag{6}$$

where, n_{Tmax} is the final expected number of ERS vehicles using the road, which is equal to the current number of diesel HGVs, n_{r} is the number of years required for a ramp-up to around 98% of the final value. Here, n_{r} is assumed to be 10 years, which is

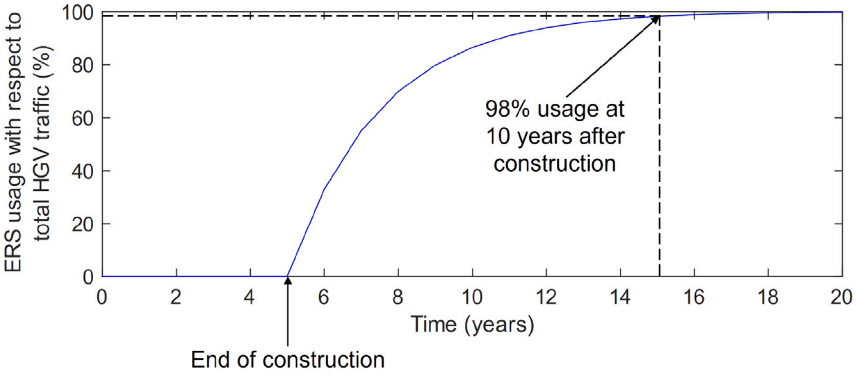

Fig. 5. ERS usage ramp-up curve.

the average lifespan of HGVs based on inputs from fleet operators. A plot of this function with time is shown in Fig. 5. There is no usage for the first 5 years which is the construction period, followed by a ramp-up over the next 10 years.

Hence, the total profit from Eqs. (5) and (6) is

$$C_{+} = \frac{\Delta r_{\mathrm{e}}}{100} e_{\mathrm{tr}} n_{\mathrm{d}} n_{\mathrm{Tmax}} \left(1 - e^{\frac{-4(n_{\mathrm{y}}-n_{\mathrm{c}})}{n_{\mathrm{r}}}}\right) \left[\frac{(1+r_{\mathrm{z}})^{(n_{\mathrm{y}}-n_{\mathrm{c}})} - 1}{r_{\mathrm{z}}}\right]. \tag{7}$$

4.1.2. ERS cost

The cost incurred by the infrastructure provider consists of the capital cost and an annual cost of maintenance. The capital cost is assumed to be proportional to the length of the ERS section and is represented in terms of the installation cost per km, C_{ERS}. The installation cost per km is assumed to vary between £1.2 million/km and £2 million/km (Ainalis et al., 2022; den Boer et al., 2013), and it depends on the country due to varying labour costs. Hence, it is assumed to be lower in countries with lower labour costs.

The ERS prices derived from previous studies are estimated to be the full cost to build the infrastructure, without government subsidies. These numbers may change in the future because of several factors. Economies of scale for the final implementation would reduce the prices. The system will have more traffic in the future, thus increasing the price of the infrastructure due to larger substations. At the same time, due to an increase in traffic, the starting income for the infrastructure provider will also be higher. Therefore, while it cannot be estimated whether the cost of the infrastructure may increase in the future, it can be assumed that the above factors will be counteracting, and their combined effect can be neglected.

It is assumed that an ERS operator would obtain a commercial loan to meet the initial cost of construction, with an interest structure similar to a mortgage. For large infrastructure projects, the cost might alternatively be financed by a bond, where the interest payments per annum are fixed and the capital sum is repaid at completion. For a commercial loan assumed here, the total cost paid would include the interest paid on the loan amount. Assuming that the entire amount is loaned and the interest is compounded annually, the annual instalment, $C_{\mathrm{ERS,a}}$, is given by

$$C_{\mathrm{ERS,a}} = C_{\mathrm{ERS}} \left(\frac{r_{\mathrm{i}} (1+r_{\mathrm{i}})^{n_{\mathrm{i}}}}{(1+r_{\mathrm{i}})^{n_{\mathrm{i}}} - 1}\right). \tag{8}$$

Here, the interest rate, r_{i}, is assumed to be 6% for developed economies and 9% for developing economies based on historical data, and the loan duration, n_{i}, is varied between 30 and 40 years.

The annual cost of maintenance of the ERS, $C_{\mathrm{ERS,m}}$ is considered as a fraction of the infrastructure cost, C_{ERS}, inclusive of taxes. The maintenance fraction is assumed to be more conservative, and hence, $f = 5\%$ in this study (den Boer et al., 2013). Inflation is accounted for in the maintenance cost similar to the profit in Eq. (7), and the maintenance is assumed to only start after the end of the construction period. Thus, the total maintenance cost from the year n_{c} to the year n_{y} is given as

$$C_{\mathrm{ERS,m}} = f C_{\mathrm{ERS}} \frac{(1+r_{\mathrm{z}})^{(n_{\mathrm{y}}-n_{\mathrm{c}})} - 1}{r_{\mathrm{z}}}. \tag{9}$$

Thus, the total expenditure on the ERS, C_{-}, per km up to the year n_{y} ($< n_{\mathrm{i}}$) is given by the sum of the loan repayments and the total maintenance cost as

$$C_{-} = C_{\mathrm{ERS,a}} + C_{\mathrm{ERS,m}} \tag{10}$$

$$= C_{\mathrm{ERS}} \left[n_{\mathrm{y}} \frac{r_{\mathrm{i}} (1+r_{\mathrm{i}})^{n_{\mathrm{i}}}}{(1+r_{\mathrm{i}})^{n_{\mathrm{i}}} - 1} + f \frac{(1+r_{\mathrm{z}})^{(n_{\mathrm{y}}-n_{\mathrm{c}})} - 1}{r_{\mathrm{z}}}\right]. \tag{11}$$

4.2. ERS cost breakeven calculations

The breakeven period for the ERS can be calculated by equating the expenditure and the profit equations. The income for an ERS depends on the number of vehicles per day which can be expressed either in terms of the number of HGVs using the road per day, i.e., the traffic counts, or in terms of its annual freight flow, depending on the type of traffic data available. Here, the expressions are obtained for both types of data.

4.2.1. Traffic counts

The objective here is to obtain the number of vehicles required to use the ERS per day, in order to achieve breakeven within n_{y} years. At the breakeven point, the profit equals the expenditure, i.e.,

$$C_{+} = C_{-}. \tag{12}$$

Substituting the expressions for C_{+} and C_{-} from Eqs. (7) and (11), respectively,

$$\frac{\Delta r_{\mathrm{e}}}{100} e_{\mathrm{tr}} n_{\mathrm{d}} n_{\mathrm{Tmax}} \left(1 - e^{\frac{-4\left(n_{\mathrm{y}}-n_{\mathrm{c}}\right)}{n_{\mathrm{r}}}}\right)\left[\frac{\left(1+r_{\mathrm{z}}\right)^{\left(n_{\mathrm{y}}-n_{\mathrm{c}}\right)}-1}{r_{\mathrm{z}}}\right] = C_{\mathrm{ERS}}\left[n_{\mathrm{y}} \frac{r_{\mathrm{i}}\left(1+r_{\mathrm{i}}\right)^{n_{\mathrm{i}}}}{\left(1+r_{\mathrm{i}}\right)^{n_{\mathrm{i}}}-1} + f \frac{\left(1+r_{\mathrm{z}}\right)^{\left(n_{\mathrm{y}}-n_{\mathrm{c}}\right)}-1}{r_{\mathrm{z}}}\right]. \tag{13}$$

Rearranging the terms, the number of HGVs is given by

$$n_{\mathrm{Tmax}} = \frac{C_{\mathrm{ERS}}\left[n_{\mathrm{y}} \frac{r_{\mathrm{i}}\left(1+r_{\mathrm{i}}\right)^{n_{\mathrm{i}}}}{\left(1+r_{\mathrm{i}}\right)^{n_{\mathrm{i}}}-1} + f \frac{\left(1+r_{\mathrm{z}}\right)^{\left(n_{\mathrm{y}}-n_{\mathrm{c}}\right)}-1}{r_{\mathrm{z}}}\right]}{\frac{\Delta r_{\mathrm{e}}}{100} e_{\mathrm{tr}} n_{\mathrm{d}} \left(1 - e^{\frac{-4\left(n_{\mathrm{y}}-n_{\mathrm{c}}\right)}{n_{\mathrm{r}}}}\right)\left[\frac{\left(1+r_{\mathrm{z}}\right)^{\left(n_{\mathrm{y}}-n_{\mathrm{c}}\right)}-1}{r_{\mathrm{z}}}\right]}. \tag{14}$$

This expression for n_{Tmax} gives the peak number of HGVs per day required to use a 1 km long ERS section, for it to break even within n_{y} years.

4.2.2. Freight flows

When the annual freight flow of a road section is known instead of the number of vehicles using it, the cost breakeven period can be obtained in terms of the tonnes of freight moved. In this case, the total annual freight flow on a road is represented in terms of the number of HGVs by multiplying it by the average payload per HGV. Thus, the peak annual freight flow required is given by

$$Q_{\mathrm{Tmax}} = Q_{\mathrm{T}} n_{\mathrm{Tmax}} n_{\mathrm{d}}, \tag{15}$$

where Q_{T} is the average payload per truck in tonnes and $n_{\mathrm{Tmax}} n_{\mathrm{d}}$ gives the total number of HGVs on a road over one year.

Replacing n_{Tmax} in Eq. (15) using Eq. (14),

$$Q_{\mathrm{Tmax}} = \frac{C_{\mathrm{ERS}}\left[n_{\mathrm{y}} \frac{r_{\mathrm{i}}\left(1+r_{\mathrm{i}}\right)^{n_{\mathrm{i}}}}{\left(1+r_{\mathrm{i}}\right)^{n_{\mathrm{i}}}-1} + f \frac{\left(1+r_{\mathrm{z}}\right)^{\left(n_{\mathrm{y}}-n_{\mathrm{c}}\right)}-1}{r_{\mathrm{z}}}\right]}{\frac{\Delta r_{\mathrm{e}}}{100} \frac{e_{\mathrm{tr}}}{Q_{\mathrm{T}}} \left(1 - e^{\frac{-4\left(n_{\mathrm{y}}-n_{\mathrm{c}}\right)}{n_{\mathrm{r}}}}\right)\left[\frac{\left(1+r_{\mathrm{z}}\right)^{\left(n_{\mathrm{y}}-n_{\mathrm{c}}\right)}-1}{r_{\mathrm{z}}}\right]}. \tag{16}$$

This expression for Q_{Tmax} gives the annual freight flow in tonnes required on an ERS section of 1 km for it to break even within n_{y} years. In this case, Q_{T} for a 44-tonne battery electric HGV is calculated by assuming a maximum payload capacity of 25 tonnes and that the proportion of unladen journeys is 30%. Thus, the average payload per HGV, Q_{T}, is estimated to be 17.5 tonnes.

4.3. Data processing

When the number of HGVs or flow of road freight in a country's road network is known, this formulation can be used to highlight roads where it is feasible to install ERS infrastructure with the desired cost breakeven period. The feasibility is illustrated for countries with readily available traffic data, including developing and developed countries, and countries with diverse geographies and logistics. The countries chosen to obtain feasible locations for the ERS are England, France, India and South Africa. This also demonstrates both methods of calculating the breakeven period — using traffic counts and using freight flows.

4.3.1. Traffic counts

The roads that are a part of the 'Strategic Road Network' (SRN) in England were considered to determine the best locations for constructing the ERS. Using Eq. (14), the number of HGVs required to use the ERS per day was obtained for breakeven durations of 20 and 30 years. The data for traffic counts of HGVs in England was obtained from the Department for Transport (DfT, 2020), and in France from the Ministry of Ecological Transition (MTE, 2018). These counts are available in terms of the average annual daily traffic (AADT)[3] for both traffic directions combined. Hence, the number of HGVs obtained from Eq. (14) was doubled, and the roads were filtered accordingly. The roads were then plotted on a map in QGIS (QGIS.org, 2022), by filtering the roads using their name.

---

[3] AADT: The number of vehicles using a road per day, averaged annually.

4.3.2. Freight flows

For India and South Africa, annual freight flows were used to determine the best locations to install ERS infrastructure. The annual freight flows corresponding to breakeven periods of 20 and 30 years were obtained using Eq. (16). The data for annual road freight flows in India and South Africa were obtained from a freight demand model by Simpson et al. (2021). The datasets were directly imported to QGIS as network shapefiles, and the roads were filtered by their annual freight flows corresponding to the calculated breakeven period.

5. Results

This section provides a visual representation and sensitivity analysis of the parameters in the cost breakeven analysis along with plots of their sensitivity. The analysis is used to identify roads in a country that can achieve breakeven within a short duration, and are thus feasible locations to install ERS infrastructure.

5.1. Parameter analysis

The values of the parameters considered for the base case are summarised in Table 2. Doing the calculations with an example breakeven period of 20 years for England, the number of HGVs to achieve breakeven is obtained as around 3000 per day. When installing the ERS for traffic moving in both directions along the road, the number of HGVs that are needed on the road on average is twice of n_{Tmax}, i.e., around 6000.

Table 2
Values of ERS parameters for the base case scenario.

Parameter	Description	Value (England, France)	Value (India, South Africa)
α	Proportion of vehicles on the ERS with a fully charged battery	25%	25%
C_{ERS}	Cost of constructing ERS per km	£2 million/km	£1.8 million/km
f	Fraction of annual maintenance cost of ERS to infrastructure cost	5% pa	5% pa
n_{d}	Number of days the ERS is in use, per year	365	365
n_{i}	Duration of the loan in years	30	30
P_{ERS}	Maximum power rating of the ERS per vehicle	300 kW	300 kW
Q_{T}	Average payload per truck	N/R	17.5 tonnes
Δr_{e}	Electricity profit margin	8 pence/kWh	11 pence/kWh
r_{i}	Loan interest rate for constructing ERS	6%	9%
r_{z}	Average rate of inflation, year-on-year	3%	7%
v_V	Average motorway cruising speed of the vehicle	90 km/h	60 km/h

N/R: not required in this calculation.

A visual representation of the income and expenditure of the infrastructure provider can be seen in Fig. 6. Here, a sample case of $n_{\mathrm{Tmax}} = 3000$ is considered. There is no income for the first 5 years which is the construction period. This is followed by the time required to ramp-up the usage to 98% of the current number of diesel HGVs. The loan ends at 30 years here, which is why the expenditure drops after this time. The point at which the income curve crosses the expenditure curve denotes the breakeven duration, which is approximately 20 years in this example.

Fig. 7 shows the effect of the electricity profit margin on the number of HGV trips per day required to breakeven in a specified period. The figure shows that it is beneficial to keep the profit margin at least 8 pence/kWh for a favourable breakeven period. It is also seen that decreasing the breakeven duration from 20 years to 10 years requires significantly more ERS usage than from 30 years to 20 years. Thus, this analysis aids in selecting the parameters for the feasibility checks, as discussed in the following subsection.

5.2. ERS location analysis

This study considers several countries as outlined in Section 4.3. The following subsections present maps of these countries for different economic cases, with roads where the ERS can achieve breakeven within a certain duration highlighted. It should be noted that the highlighted locations are only based on economic feasibility and would need to be rationalised based on logistic requirements and resources. The cases considered are chosen such that the sensitivity to changing critical economic parameters can be visualised. These cases are generated by varying one of the following three parameters each time: the electricity profit margin, the installation cost and the duration of the loan.

While the installation cost per km (C_{ERS}) is linearly related to the number of HGVs (n_{Tmax}) or freight flow (Q_{Tmax}) as seen in Eqs. (14) and (16), the electricity profit margin is related exponentially, as seen in Fig. 7. Hence, it is increased to always be more than 8 pence/kWh. It may be noted that the upper limit on this profit margin is also constrained by the total cost of ownership (TCO) of the vehicle, and cannot be increased much in order for the TCO to be lower than a diesel HGV (Ainalis et al., 2022). The loan duration is increased by 10 years to check its effect on the breakeven. A summary of the scenarios considered is shown in Table 3.

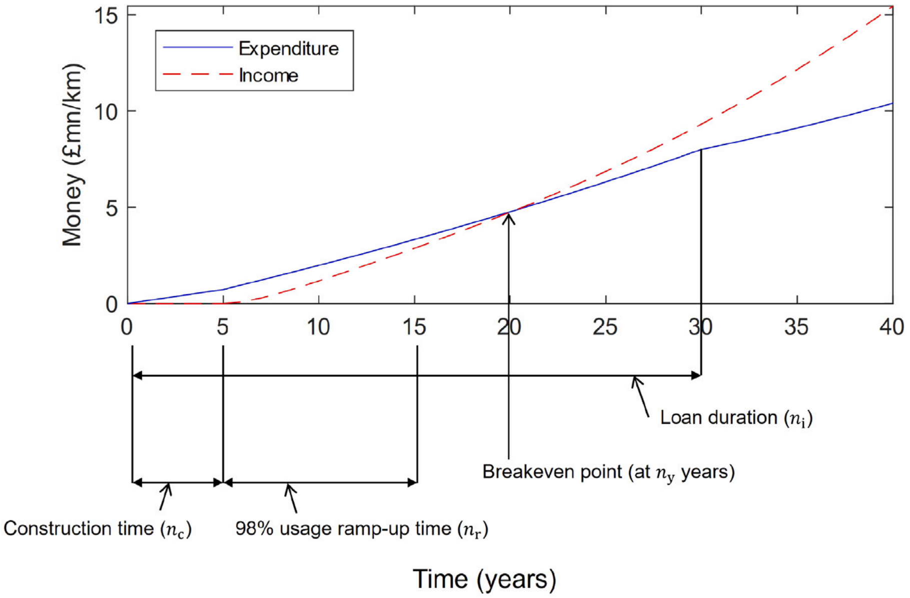

Fig. 6. Sample income and expenditure plots for an ERS section with a daily single-directional traffic flow of 3000 HGVs.

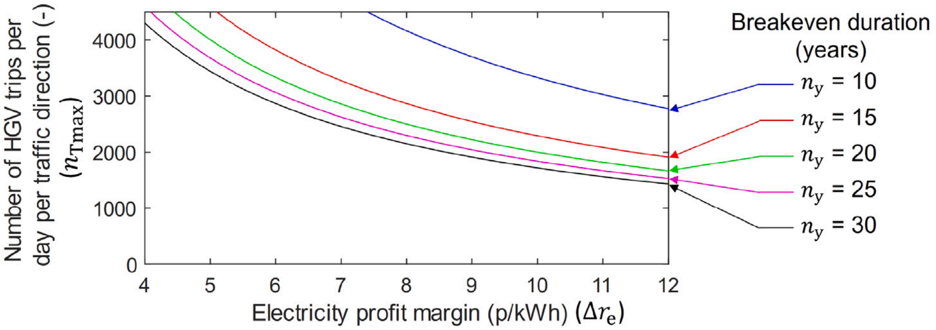

Fig. 7. Change in the number of HGV trips required per day to achieve breakeven with a change in the electricity profit margin.

Table 3
Considered cases for ERS feasibility check.

Scenario		(a)	(b)	(c)	(d)
Country	Parameter	Base case	Increased profit margin	Lower infrastructure costs	Longer duration of loan
England, France	Δr_e	8 pence/kWh	14 pence/kWh	8 pence/kWh	8 pence/kWh
	C_{ERS}	£2 million/km	£2 million/km	£1.5 million/km	£2 million/km
	n_i	30 years	30 years	30 years	40 years
India, South Africa	Δr_e	11 pence/kWh	18 pence/kWh	11 pence/kWh	11 pence/kWh
	C_{ERS}	£1.8 million/km	£1.8 million/km	£1.2 million/km	£1.8 million/km
	n_i	30 years	30 years	30 years	40 years

5.2.1. England

The results for suitable roads in England are shown in Fig. 8. As seen in the figure, many of the major highways in the SRN can be covered by ERS with breakeven within 20 years. This includes highly populated motorways such as the M1, M5, M6, M20, M25 and M40. This also includes the M180 linking Immingham with Doncaster, which is the proposed location for a pilot test of the ERS in the UK (de Saxe et al., 2022; Siemens, 2021).

Comparing the different cases in the figure, it can be seen that increasing the profit margin in case (b) or decreasing the cost of installation in case (c) both result in a significant increase in the number of roads that breakeven early, i.e., make the ERS more feasible economically. Increasing the duration of the loan from 30 to 40 years in case (d) results in a slight improvement over case (a). Hence, since cases (a) and (d), and cases (b) and (c) are found to produce similar results, respectively, only maps for cases (a) and (b) are shown for the next two countries.

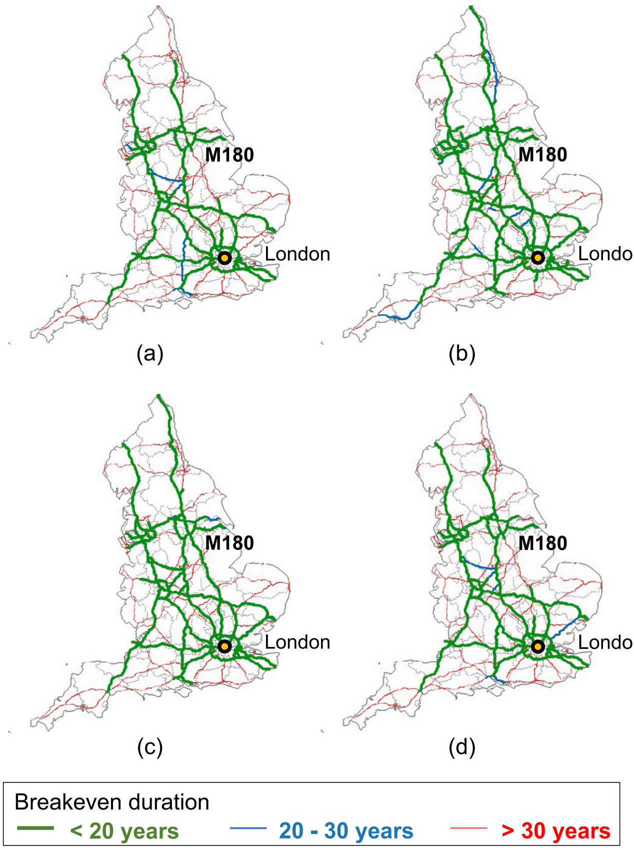

Fig. 8. Road network maps of England according to ERS infrastructure cost breakeven period for cases (a) Base case, (b) Higher profit margin, (c) Lower infrastructure costs, (d) Longer loan duration.

5.2.2. France

The roads in France best suited for installing the ERS based on this analysis are shown in Fig. 9. In the base case (a), the roads with a breakeven period lower than 20 years consist of major freight routes connecting Belgium in the northeast to Spain in the southwest via Paris, from Germany in the east to Spain in the south via Lyon, and from Italy in the southeast to Spain in the South. When the electricity profit margin is increased from 8 pence/kWh to 14 pence/kWh in case (b), the additional roads feasible for ERS include connections from Paris to ports in the north and west; from Paris to Lyon, and from Lyon to Switzerland and other interior parts of the country. The road network in case (b) matches the ERS locations proposed to be completed by the year 2030 (RGRA, 2022). It may be noted that this proposal focuses on the on-ground power supply implementation of ERS with the overhead catenary implementation as a fall-back option.

5.2.3. India

The resulting feasible roadways in India based on the breakeven period are shown in Fig. 10. As seen in the figure, only the most populated highways are seen to be feasible locations for the ERS in case (a). These include a major section of the Delhi–Kolkata highway, which is itself a part of the Asian Highway 1 and the Golden Quadrilateral.[4] It also includes the Mumbai–Ahmedabad and Nagpur–Hyderabad stretches. Increasing the electricity profit margin in case (b) results in the addition of more parts of the Delhi–Bengaluru route and most of the Golden Quadrilateral, including the Mumbai–Delhi route on which the Indian government is looking at constructing ERS infrastructure (Times Now, 2022).

5.2.4. South Africa

The results for feasible roads in South Africa are shown in Fig. 11. It can be seen that in both cases (a) and (b), the two major freight routes in South Africa, the N1 section from Johannesburg to Cape Town and the N3 section from Johannesburg to Durban can be electrified with economic feasibility. Increasing the electricity profit margin in case (b) only adds a small set of roads, including

---

[4] Golden Quadrilateral: A national highway network in India connecting the major metro cities of Delhi (north), Kolkata (east), Mumbai (west) and Chennai (south).

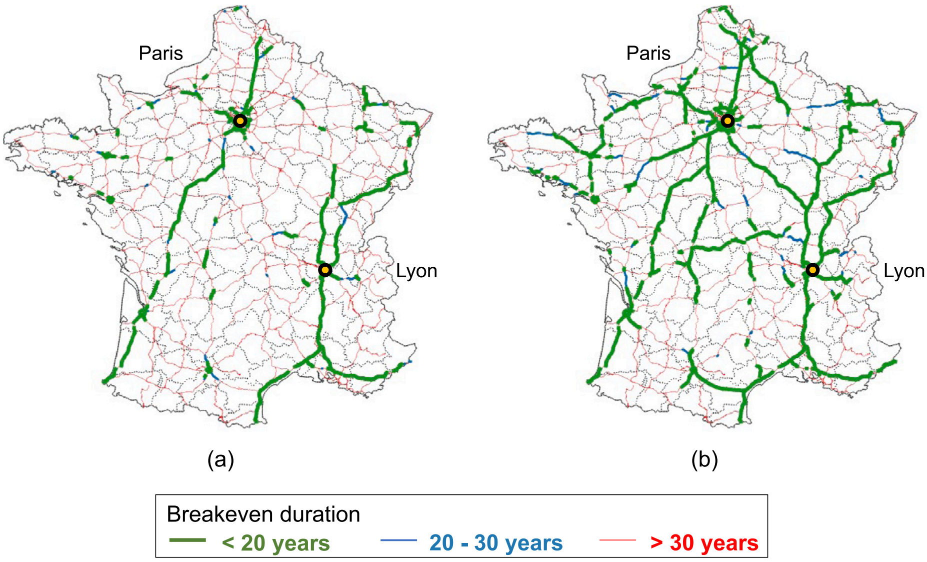

Fig. 9. Road network maps of France according to ERS infrastructure cost breakeven period for cases (a) Base case, (b) Higher profit margin.

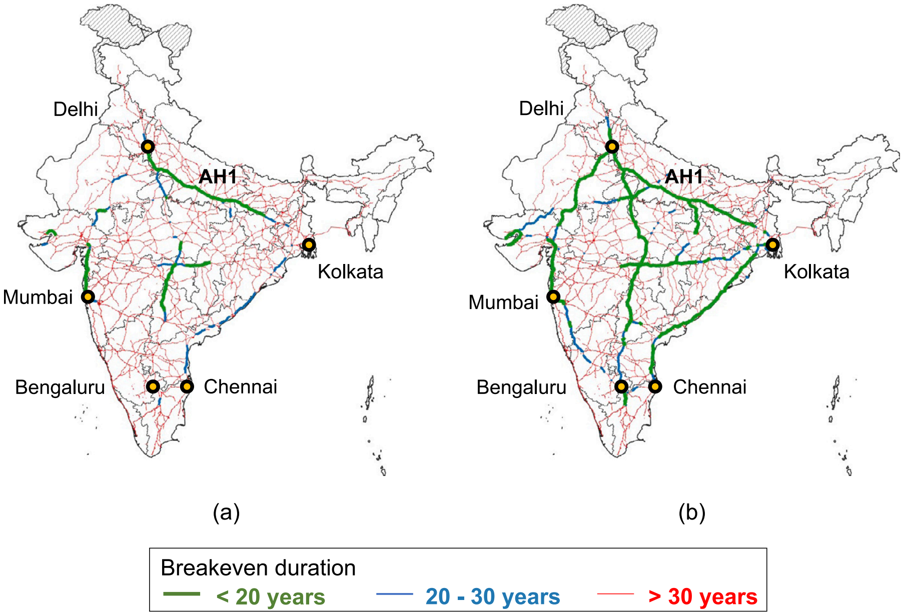

Fig. 10. Road network maps of India according to ERS infrastructure cost breakeven period for cases (a) Base case, (b) Higher profit margin.

a section from Johannesburg to Polokwane via Pretoria. While the South African government has not yet expressed any interest in the ERS publicly, this analysis shows that it is an economically feasible option to be looked at for decarbonising road freight there. The N1 and N3 highways are good locations for this, given that they are major freight routes in the country.

5.3. ERS length and total freight electrified

The total road distance electrified by the ERS with a breakeven period within 20 years for all four cases is shown in Table 4. The table also shows the percentage of lane kilometres electrified for the 4 countries. It may be noted that for England, the percentage is with respect to the SRN shown in Fig. 8. For India and South Africa, it is with respect to the total length of roads with an annual freight flow of at least 0.5 million tonnes, which is the road network shown in Figs. 10 and 11. The table confirms that cases (a) and (d) give similar results, and cases (b) and (c) are similar too. It can also be seen that it is financially feasible to electrify up to 77% of the SRN in England, 28% of all roads in France and up to 10% of the significant freight routes in India and South Africa.

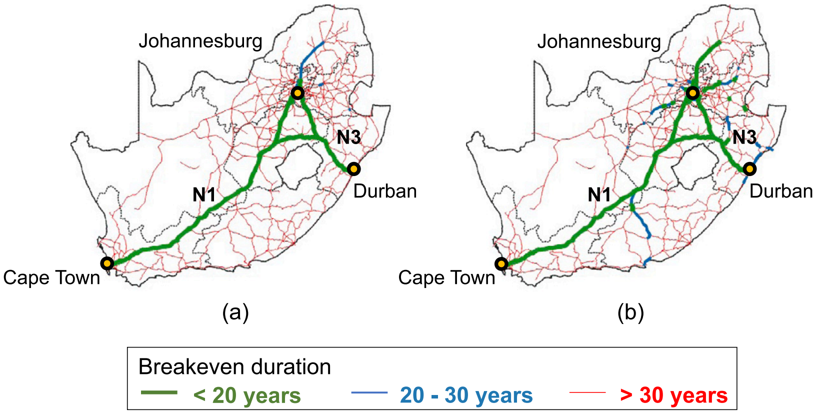

Fig. 11. Road network maps of South Africa according to ERS infrastructure cost breakeven period for cases (a) Base case, (b) Higher profit margin.

Table 4
Total lane-km and road freight electrified in the considered cases for England, France, India and South Africa.

	Case	Total lane-km electrified	% lane-km electrified[a]	% road freight electrified
In terms of traffic counts; with respect to total road freight:				
England	(a)	7,170	57	31
	(b)	9,711	77	47
	(c)	9,012	71	40
	(d)	7,478	59	33
France	(a)	5,804	14	51
	(b)	11,549	28	72
	(c)	9,251	22	65
	(d)	6,301	15	54
In terms of traffic flows; with respect to roads having an annual freight flow greater than 500 kilotonnes:				
India	(a)	4,321	3	16
	(b)	14,099	10	38
	(c)	11,202	8	32
	(d)	4,938	4	18
South Africa	(a)	4,319	8	47
	(b)	5,635	10	57
	(c)	5,297	9	55
	(d)	4,331	8	47

[a] Road length electrified is with respect to the SRN in England and with respect to major roads in other countries.

The proportion of road freight electrified by use of the ERS in all the considered cases is also shown in Table 4. The road freight electrified in England is calculated in terms of the number of HGVs, by using the ratio of the AADT of HGVs on the ERS sections to the total AADT of HGVs in the country. The total AADT of HGVs is estimated by dividing the total AADT of the SRN by 0.66, as the SRN carries approximately 66% of the country's HGVs (DfT, 2015). It can be seen that at least 31% of road freight is electrified in case (a), and the highest benefit is in increasing the electricity profit margin, as that can electrify up to 47% of road freight as seen in case (b). The lane kilometres electrified are very high because of road freight being spread across the SRN in England.

In France, the freight is concentrated on the international freight routes, thus leading to a larger amount of road freight electrification with a relatively smaller proportion of road length being electrified.

The proportion of road freight electrified in India and South Africa is with respect to the total road freight flow in the country (Simpson et al., 2021). It can be seen that while the proportion of road length electrified in India is not very high, the road freight electrified is higher, due to dense freight flows along the Golden Quadrilateral and geographically sparse elsewhere. It is also seen that India is a very price-sensitive market, as small changes in the economic parameters cause a large difference in the proportion of road freight electrified. It is also seen that while electrifying the N1 and N3 in South Africa does not cover significant road length, it does electrify a large proportion of road freight. This is because a very high proportion of road freight in South Africa is moved along these routes.

6. Conclusions

This paper investigated the economic feasibility of using ERS in different countries to decarbonise road freight by electrifying HGVs. It was established that the ERS can aid in the reduction of road freight emissions. Compared to battery electric HGVs, it can reduce WTW emissions by around 10%, while reducing battery sizes. A cost breakeven analysis of the ERS was formulated to identify the locations where it is viable. This was done by deriving the total income and expenditure for constructing the ERS on a 1 km section of road. The breakeven period was expressed in terms of both, the daily HGV traffic counts of a road section and its annual freight flow. The parameters in the formulation were varied to establish 4 different economic cases for ERS infrastructure in the countries considered.

The roads in England, France, India and South Africa were filtered based on their ERS cost breakeven period. It was seen that up to 9,700 lane-km in England, 11,500 lane-km in France, 14,000 lane-km in India and 5,600 lane-km in South Africa could be electrified economically using an ERS. It has the potential to be economically viable for most of the SRN in England, major European freight routes passing through Paris and Lyon in France, a significant part of the Golden Quadrilateral in India, and almost the entirety of the two major freight routes in South Africa, with a cost breakeven period that is less than 20 years. This can electrify at least 30% of the total road freight in the UK, 50%–70% of the total road freight in France, up to 38% of road freight in India and 50%–60% of the total road freight in South Africa. It was seen that the major differences between the 4 countries are in terms of the distribution of their road freight movement and price sensitivity. In England, road freight was seen to be more uniformly distributed on the SRN, while it was concentrated on the N1 and N3 motorways in South Africa. It was also seen that the price sensitivity was higher in India, and the majority of road freight was again seen only on the Golden Quadrilateral and Delhi–Bengaluru routes. It should be noted that this conclusion is sensitive to the capital cost of the ERS installation.

In summary, the contributions of this paper can be articulated as follows:

1. Compared WTW emissions for various powertrains in different countries and highlighted the benefits of using ERS.
2. Formulated the cost breakeven for ERS in terms of traffic and freight flow to identify suitable locations for ERS.
3. Conducted case studies for England, France, India and South Africa with varying economic parameters.
4. Demonstrated a 20-year breakeven period for ERS on major freight routes in these countries.

This study provides insight that supports the installation of ERS in both developed and developing countries, as well as countries with diverse geographies and freight types. It motivates the development of a universal solution for electrifying HGVs with a common modular platform that can serve different markets. In the future, it remains to be seen what the practicalities of such an implementation look like, such as studying the distribution of static charging infrastructure needed outside of the ERS network. It would also be interesting to study the impact of an ERS network on both logistics operations and vehicle manufacturers. Finally, data from more countries need to be studied to obtain feasible locations for constructing ERS sections.

CRediT authorship contribution statement

Parth Deshpande: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. **Christopher de Saxe:** Conceptualization, Data curation, Formal analysis, Methodology, Project administration, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. **Daniel Ainalis:** Conceptualization, Data curation, Formal analysis, Methodology, Project administration, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. **John Miles:** Conceptualization, Funding acquisition, Methodology, Project administration, Resources, Supervision, Validation, Writing – review & editing. **David Cebon:** Conceptualization, Funding acquisition, Methodology, Project administration, Resources, Supervision, Validation, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors acknowledge the support of the Centre for Sustainable Road Freight, which is funded by industry partners and UKRI under EPSRC Grant EP/R035199/1, and the Cambridge Commonwealth, European and International Trust. The authors thank GAIN South Africa, Imperial Logistics South Africa and Raman Roadways India for their support in this study.

References

Ainalis, D., Thorne, C., Cebon, D., 2020. White Paper: Decarbonising the UK's Long-Haul Road Freight at Minimum Economic Cost. Technical Report, The Centre for Sustainable Road Freight.

Ainalis, D., Thorne, C., Cebon, D., 2022. Technoeconomic comparison of an electric road system and hydrogen for decarbonising the UK's long-haul road freight. Res. Transp. Bus. Manag. 100914. http://dx.doi.org/10.1016/j.rtbm.2022.100914.

Bateman, D., Leal, D., Reeves, S., Emre, M., Stark, L., Ognissanto, F., Myers, R., Lamb, M., 2018. Electric Road Systems: A Solution for the Future? Technical Report, World Road Association (PIARC), p. 103, URL: http://www.piarc.org.

Börjesson, M., Johansson, M., Kågeson, P., 2021. The economics of electric roads. Transp. Res. C 125, http://dx.doi.org/10.1016/J.TRC.2021.102990.

Carbon Footprint, 2020. Country Specific Electricity Grid Greenhouse Gas Emission Factors. Technical Report, Carbon Footprint Ltd, URL: https://www.carbonfootprint.com/docs/2020_09_emissions_factors_sources_for_2020_electricity_v14.pdf.

de Saxe, C., Ainalis, D., Miles, J., Greening, P., Gripton, A., Thorne, C., Cebon, D., 2022. An Electric Road System or Big Batteries: Implications for UK Road Freight. Available at SSRN: http://dx.doi.org/10.2139/ssrn.4194379.

den Boer, E., Aarnink, S., Kleiner, F., Pagenkopf, J., 2013. Zero Emissions Trucks: An Overview of State-Of-The-Art Technologies and Their Potential. Technical Report, CE Delft.

Deshpande, P., de Saxe, C., Ainalis, D., Miles, J., Cebon, D., 2022. Accelerating road freight electrification in various countries using electric road systems. In: 9th International Workshop on Sustainable Road Freight, Cambridge, UK. The Centre for Sustainable Road Freight, URL: https://www.csrf.ac.uk/9th-international-workshop-on-sustainable-road-freight/.

DfT, 2015. Strategic Road Network Statistics. Technical Report, Department for Transport, URL: https://www.gov.uk/government/statistics/strategic-road-network-statistics.

DfT, 2020. Road traffic statistics. Department for Transport, URL: https://roadtraffic.dft.gov.uk/downloads.

DoT, 2018. Green Transport Strategy for South Africa: (2018–2050). Technical Report, Department of Transport, pp. 1–58.

Gnann, T., Plötz, P., Kühn, A., Wietschel, M., 2017. How to decarbonise heavy road transport? In: ECEEE Summer Study Proceedings.

Goedhals-Gerber, L., Freiboth, H., Havenga, J., 2018. The decarbonisation of transport logistics: A South African case study. South. Afr. Bus. Rev. 22, http://dx.doi.org/10.25159/1998-8125/4362.

Grünjes, H.G., Birkner, M., 2012. Electro mobility for heavy duty vehicles (HDV): The Siemens eHighway System. In: 12th International Symposium on Heavy Vehicle Transport and Technology.

Gustavsson, M.G.H., Hacker, F., 2019. Overview of ERS Concepts and Complementary Technologies. Technical Report, CollERS: Swedish-German research collaboration on Electric Road Systems, URL: www.electricroads.org.

Hall, D., Lutsey, N., 2018. Effects of Battery Manufacturing on Electric Vehicle Life-Cycle Greenhouse Gas Emissions. Technical Report February, ICCT Briefing, p. 12.

Haugen, M.J., Paoli, L., Cullen, J., Cebon, D., Boies, A.M., 2021. A fork in the road: Which energy pathway offers the greatest energy efficiency and CO2 reduction potential for low-carbon vehicles? Appl. Energy 283, http://dx.doi.org/10.1016/J.APENERGY.2020.116295.

IEA, 2017. CO2 Emissions from Fuel Combustion. Technical Report, International Energy Agency, http://dx.doi.org/10.1787/co2_fuel-2007-en-fr.

Indian Railways, 2020. Year Book 2019-20. Technical Report, Indian Railways, Government of India, URL: https://indianrailways.gov.in/railwayboard/uploads/directorate/stat_econ/Annual-Reports-2019-2020/Year-Book-2019-20-English_Final_Web.pdf.

Jelica, D., 2017. The Effect of Electric Roads on Future Energy Demand for Transportation a Case Study of a Swedish Highway. Chalmers University of Technology.

Kumar Dadsena, K., Sarmah, S.P., Naikan, V.N., 2019. Risk evaluation and mitigation of sustainable road freight transport operation: A case of trucking industry. Int. J. Prod. Res. 57 (19), 6223–6245. http://dx.doi.org/10.1080/00207543.2019.1578429.

Liu, L., Hwang, T., Lee, S., Ouyang, Y., Lee, B., Smith, S.J., Tessum, C.W., Marshall, J.D., Yan, F., Daenzer, K., Bond, T.C., 2019. Health and climate impacts of future United States land freight modelled with global-to-urban models. Nat. Sustain. 2, http://dx.doi.org/10.1038/s41893-019-0224-3.

Madhusudhanan, A.K., Ainalis, D., Na, X., Garcia, I.V., Sutcliffe, M., Cebon, D., 2021. Effects of semi-trailer modifications on HGV fuel consumption. Transp. Res. D 92, 102717. http://dx.doi.org/10.1016/J.TRD.2021.102717.

MTE, 2018. Trafic moyen journalier annuel sur le réseau routier national. In: Ministère De La Transition Écologique. URL: https://www.data.gouv.fr/en/datasets/trafic-moyen-journalier-annuel-sur-le-reseau-routier-national/.

Mulholland, E., Teter, J., Cazzola, P., McDonald, Z., Ó Gallachóir, B.P., 2018. The long haul towards decarbonising road freight – A global assessment to 2050. Appl. Energy 216, 678–693. http://dx.doi.org/10.1016/J.APENERGY.2018.01.058.

Navidi, T., Cao, Y., Krein, P.T., 2016. 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, Institute of Electrical and Electronics Engineers Inc., http://dx.doi.org/10.1109/PECI.2016.7459224.

Ngo, H., Kumar, A., Mishra, S., 2020. Optimal positioning of dynamic wireless charging infrastructure in a road network for battery electric vehicles. Transp. Res. D 85, 102385. http://dx.doi.org/10.1016/J.TRD.2020.102385.

Nicolaides, D., 2018. Power Infrastructure Requirements for Road Transport Electrification (Ph.D. thesis). University of Cambridge, http://dx.doi.org/10.17863/CAM.28055.

Nicolaides, D., Cebon, D., Miles, J., 2018. Prospects for electrification of road freight. IEEE Syst. J. 12 (2), 1838–1849. http://dx.doi.org/10.1109/JSYST.2017.2691408.

Odhams, A.M., Roebuck, R.L., Lee, Y.J., Hunt, S.W., Cebon, D., 2010. Factors influencing the energy consumption of road freight transport. Proc. Inst. Mech. Eng. C 224 (9), 1995–2010. http://dx.doi.org/10.1243/09544062JMES2004.

OECD, 2022. Freight transport (indicator). http://dx.doi.org/10.1787/708eda32-en.

Panoutsou, C., Germer, S., Karka, P., Papadokostantakis, S., Kroyan, Y., Wojcieszyk, M., Maniatis, K., Marchand, P., Landalv, I., 2021. Advanced biofuels to decarbonise European transport by 2030: Markets, challenges, and policies that impact their successful market uptake. Energy Strategy Rev. 34, http://dx.doi.org/10.1016/J.ESR.2021.100633.

QGIS.org, 2022. QGIS Geographic Information System. URL: http://www.qgis.org. [Version 3.22].

RGRA, 2022. ERS to Decarbonize Road Transport. Technical Report, RGRA, URL: https://www.editions-rgra.com/dossier/ers-decarbonize-road-transport.

Schulte, J., Ny, H., 2018. Electric road systems: Strategic stepping stone on the way towards sustainable freight transport? Sustainability 2018, Vol. 10, Page 1148 10 (4), 1148. http://dx.doi.org/10.3390/SU10041148.

SFC, 2018. Global Logistics Emissions Council Framework. Technical Report., Smart Freight Centre.

Siemens, 2021. Green light for path to UK's first 'electric motorway'. URL: https://news.siemens.co.uk/news/green-light-for-path-to-uks-first-electric-motorway. (Accessed 20 July 2022).

Siemens Mobility GmbH, 2021. eHighway – Solutions for electrified road freight transport. URL: https://press.siemens.com/global/en/feature/ehighway-solutions-electrified-road-freight-transport. (Accessed 20 July 2022).

Simpson, Z.P., Havenga, J.H., Witthöft, I.E., Aritua, B., 2021. A methodology for disaggregated freight demand modeling in emerging economies. In: Freight Transport Modeling in Emerging Countries. Elsevier, pp. 55–84. http://dx.doi.org/10.1016/b978-0-12-821268-4.00004-6.

Singh, A., 2016. Electric Road Systems: A Feasibility Study Investigating a Possible Future of Road Transportation. KTH Royal Institute of Technology.

Subel, J., Ainalis, D., Lépine, J., Cebon, D., 2021. Impact of coasting on fuel consumption of heavy vehicles. In: 16th International Symposium on Heavy Vehicle Transport and Technology.

Sun, X., Chen, Z., Yin, Y., 2020. Integrated planning of static and dynamic charging infrastructure for electric vehicles. Transp. Res. D 83, 102331. http://dx.doi.org/10.1016/J.TRD.2020.102331.

Sundelin, H., Gustavsson, M.G., Tongur, S., 2016. The maturity of electric road systems. In: 2016 International Conference on Electrical Systems for Aircraft, Railway, Ship Propulsion and Road Vehicles and International Transportation Electrification Conference. ESARS-ITEC 2016, Institute of Electrical and Electronics Engineers Inc., http://dx.doi.org/10.1109/ESARS-ITEC.2016.7841380.

Sundelin, H., Linder, M., Mellquist, A.-C., Gustavsson, M., Börjesson, C., Pettersson, S., 2018. Business case for electric road. In: Proceedings of 7th Transport Research Arena.

Taljegard, M., Thorson, L., Odenberger, M., Johnsson, F., 2019. Large-scale implementation of electric road systems: Associated costs and the impact on CO2 emissions. Int. J. Sustain. Transp. 14 (8), 606–619. http://dx.doi.org/10.1080/15568318.2019.1595227.

Tasnim, S., 2014. Microscopic Simulation and Emissions Study of the Electrification of the I-710 Freight Corridor. UC Irvine, URL: https://escholarship.org/uc/item/4s788426.

Teixeira Sebastiani, M., 2020. Impacts of Electric Highways for Heavy-Duty Trucks (Ph.D. thesis). UC Irvine, URL: https://escholarship.org/uc/item/1vn3k6zt.

Times Now, 2022. E-highway connecting Mumbai and Delhi: All you need to know. URL: https://www.timesnownews.com/exclusive/e-highway-connecting-mumbai-and-delhi-all-you-need-to-know-article-92852032. (Accessed 20 July 2022).

Tongur, S., Sundelin, H., 2017. The electric road system transition from a system to a system-of-systems. In: 2016 Asian Conference on Energy, Power and Transportation Electrification. ACEPT 2016, Institute of Electrical and Electronics Engineers Inc., http://dx.doi.org/10.1109/ACEPT.2016.7811529.

WEF, 2021. Road Freight Zero: Pathways to Faster Adoption of Zero-Emission Trucks. Technical Report, World Economic Forum, URL: https://www3.weforum.org/docs/WEF_RFZ_Pathways_to_faster_adoption_of_zero_emission_trucks_2021.pdf.