RoadRail

An economically viable infrastructure which facilitates the transition from oil to electricity for all forms of road transport

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16 November 2012

Abstract

In recent decades, economic renewable energy technologies have been developed for the electricity and heat sectors. Although there has been some development in the transport sector, there is still no well-establish sustainable alternatives to oil. In this study, a new alternative is proposed to convert road transport from oil to electricity. This involves the electrification of major roads so that electric cars, vans, busses, and trucks can use electricity as their primary fuel over long distance, which in this study is referred to as 'RoadRail'. This is a new and radical alternative for the transport sector in the future, so no specific technological design is promoted here. Instead, the aim in this study is to carry out a socio-economic feasibility study of the RoadRail infrastructure by using indicative costs relating to similar technologies. Using assumptions for vehicle costs and electricity/oil costs, Denmark is presented as a case study for the installation of RoadRail. The results indicate that based on 2020 cost assumptions, RoadRail is a more socio-economic alternative than a business-as-usual using oil. This is primarily due to decreasing electric vehicle costs, decreasing electricity production costs, and increasing oil prices. Furthermore, the additional costs of the RoadRail infrastructure is less than 5% of the total transport costs in all scenarios considered here. This indicates that if the RoadRail infrastructure can be developed for similar costs to those assumed here, then the technology offers an economically viable alternative to oil for road transport while also using the most sustainable form of fuel in the future, electricity.

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1. Introduction

Typical convention is to consider the energy system as three separate sectors: electricity, heat, and transport. In recent decades major changes have begun to transform each of these sectors from fossil-fuel based technologies to more sustainable solutions by reducing demands, increasing conversion efficiencies, and utilising more renewable energy sources. Both the electricity and heat sectors have made significant progress, but the transport sector is proving more difficult. Historical Danish energy statistics epitomise this [1]: Figure 1 outlines how the sectors based on electricity and heat have either stabilised or reduced their energy demands between 1980 and 2010, while simultaneously the demand for energy in the transport sector has grown by almost 50%. Furthermore, the Danish transport sector is still almost completely dependent on oil for its transport needs: since 1980 to 2010, oil has accounted for ~98% of the fuel in the Danish transport sector. These are the same trends which are occurring globally [2].

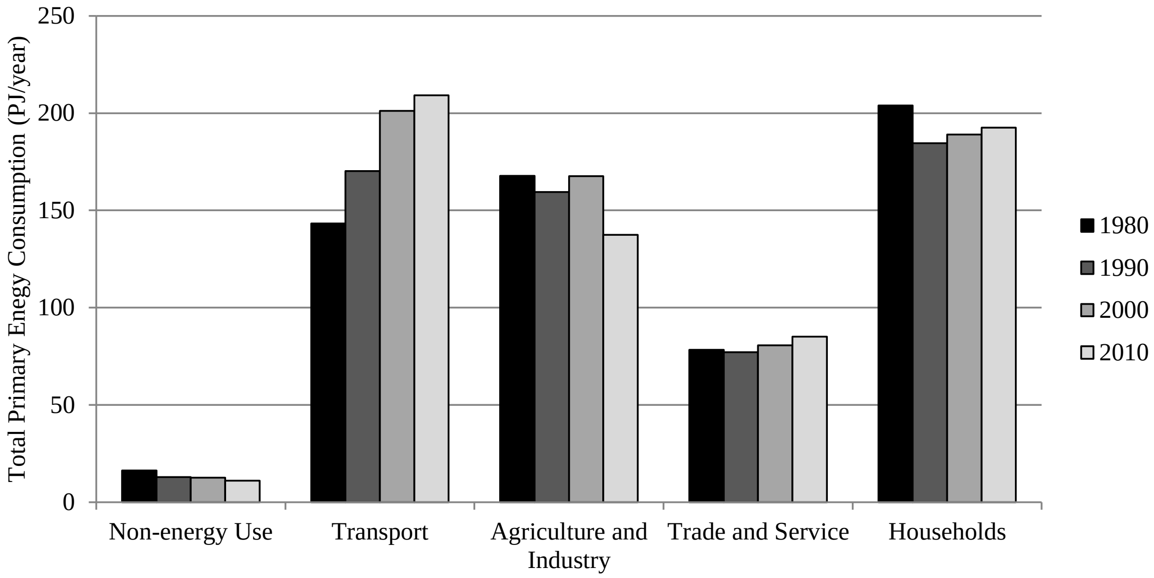

Figure 1: Total primary energy consumption in Denmark divided by sector from 1980 to 2010 [1].

To overcome these trends, there are many existing studies which have focused on sustainable alternatives for the transport sector. Some of these have focused on the potential for new policy [3] or modal shift [4] to reduce the demand for energy in the transport sector. However, it seems that most research is focused on the feasibility of alternative fuels such as electric vehicles [5], hydrogen [6], biogas [7], bioenergy hydrogenation [8], ethanol fermentation [9], and synthetic fuels [10]. A recent comparison by Mathiesen *et al.* between a wide range of these different fuels concluded that electricity is the most sustainable form of transport fuel currently available, in terms of energy efficiency and the resources required [11].

Electricity for transport currently comes in two main forms: *direct electrification* such as electric rail where electricity is delivered to the vehicles, and *battery electrification* such as electric vehicles where electricity is stored in the vehicle. The comparison by Mathiesen *et al.* indicated that direct electrification and battery electrification have very similar efficiencies, but both forms are limited to a specific set of applications. Direct electrification can only be utilised where vehicles can be connected to overhead electric lines, while battery electrification is limited to light vehicles due to the low energy densities of batteries (see Figure 2). In this study, an amalgamation of these two concepts is proposed to increase the number of vehicles which can be converted from oil to electricity. The concept is called RoadRail, which in basic terms involves the electrification of roads so that battery electric vehicles can also use direct electrification for long-range journeys and for larger vehicles.

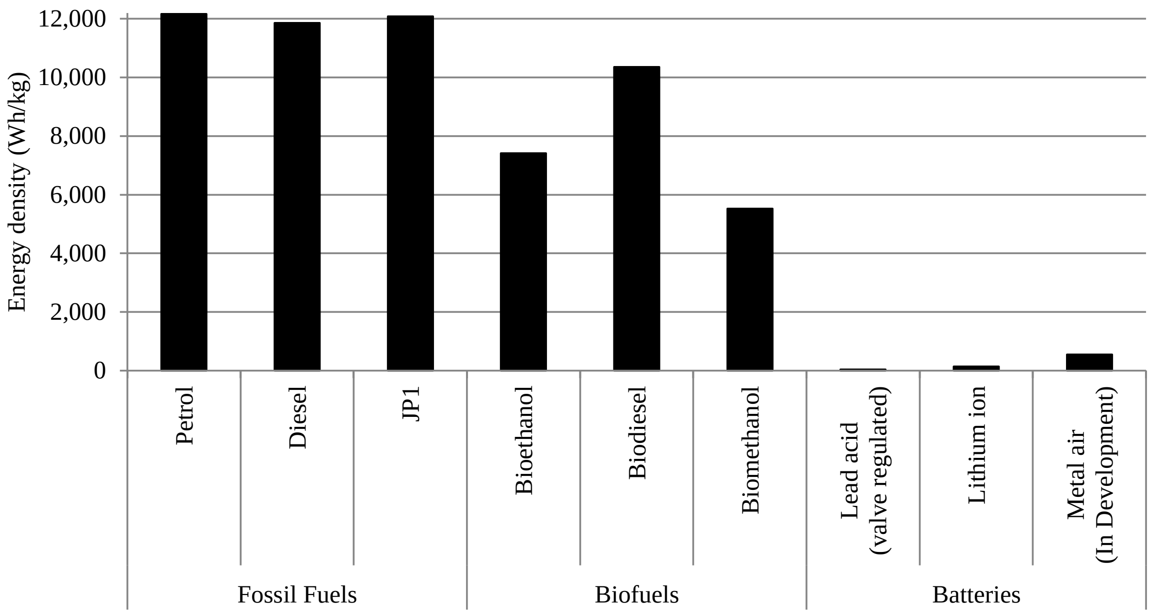

Figure 2: Energy density for a selection of fossil fuels, biofuels, and batteries [12, 13].

The purpose of RoadRail is to enable the use of electric vehicles for applications which are currently not viable due to the low energy densities of batteries. This includes long-distance journeys for cars and freight transport (such as vans and trucks). By doing so, vehicles will not only use the most sustainable form of transport fuel (i.e. electricity) [11], but the RoadRail infrastructure could introduce numerous other advantages. These include driverless cars, intelligent vehicles, and faster journeys which are discussed in more detail in section 4.

There is no specific design proposed for RoadRail in this study. A number of different electric road concepts are currently being investigated worldwide. In South Korea [14] and the USA [15], two research projects are investigating how inductive charging can be used to charge cars while they drive along the road. Hence, there is no direct connection to the vehicle, but instead the energy is transferred to the moving vehicle. Bombardier has developed a similar inductive charging technology for trams that cannot use overhead power lines called PRIMOVE [16]. An electric road technology developed by Siemens called 'eHighways' utilises a direct connection between overhead power lines and trucks [17]. This is being promoted in Sweden [18], but since it uses overhead lines it is unlikely to be suitable for cars. Instead of using overhead lines, Alstom have already demonstrated a ground-based connection to an electric tram in Bordeaux, France using a technology called Innorail [19]. This proves that direct electrification to the road is technically possible, although it is not clear how transferrable this technology is to road vehicles and no economic data for Innorail has been obtained. Researchers at Toyohashi University of Technology in Japan are currently developing a new technology which could provide a direct connection between the road and the wheel of a moving road vehicle [20, 21]. To date, Hanazawa *et al.* [20, 21] has proven that electricity can be transferred from metal plates on the road to the wheel of a road vehicle in the laboratory, while the next step is to test it on a full-scale car [21]. A concept called RUF has been proposed in Denmark to electrify roads, but this requires the construction of a monorail for the vehicles: the infrastructure costs would most likely be higher than the concept proposed by Hanazawa *et al.* [20, 21] if it can be developed. One significant assumption in this study is that the RoadRail infrastructure can be utilised for cars, vans, and trucks, so the concepts developed by Alstom [19] and Hanazawa *et al.* [20, 21], are the closest representation of what RoadRail was initially imagined to be in this study: that is a direct connection between the road the moving vehicle. However, depending on technological developments and final costs, any concept which connects a vehicle to electricity along a road could potentially be used for the RoadRail concept (such as those outlined in Figure 3).

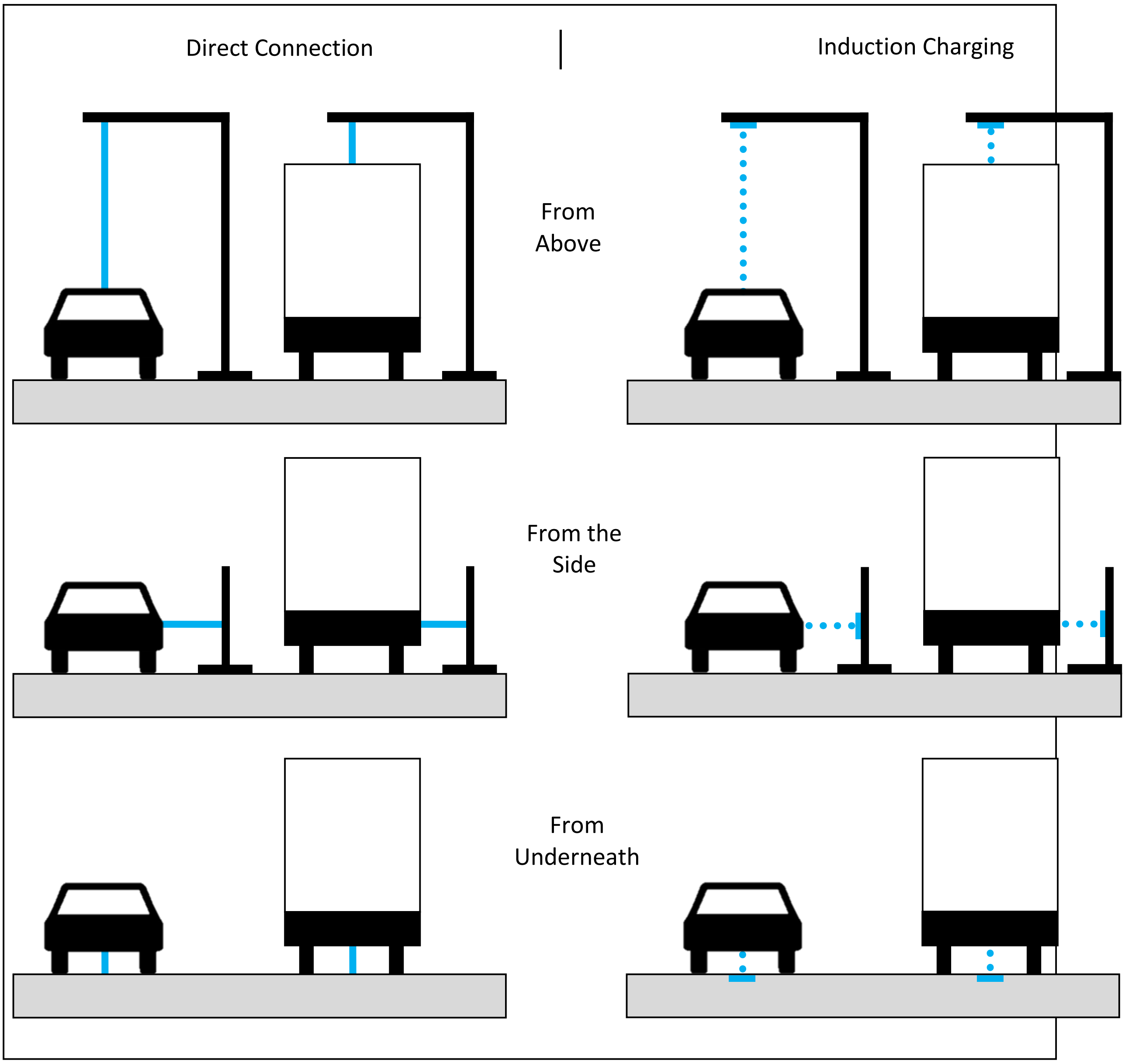

Figure 3: Different concepts currently being investigated to electrify roads (inspired by the illustrations in [22]).

In theory, RoadRail could eventually be implemented as any one of these designs currently under investigation, depending on technological development and cost. The purpose of this study is not to focus on the technology required to implement RoadRail, but instead it is to analyse the socio-economic consequences of implementing such a technology. No previous research relating to the socio-economic costs of electric roads has been identified. It is necessary to contextualise the economic viability of electric roads, to determine their credibility as a major alternative to oil in transport for the future. Intuitively, the cost of constructing electric roads on major road networks seems extremely expensive. However, the results in this study indicate that it is actually a relatively small cost, particularly when it is compared to the cost of the vehicles on the road. The methodology and assumptions used for the analyses in this study is outlined in section 2, while the corresponding results are displayed in section 3. The context and additional benefits of a RoadRail network are discussed in section 4 and the primary conclusions from this study are summarised in section 5. If electric roads can be constructed at the costs assumed in this study, then the results suggest that the most sustainable form of fuel for the transport sector (i.e. electricity) is also a more socio-economic alternative than the business-as-usual scenario with oil.

2.Methodology

In this study, the socio-economic implications of RoadRail are assessed using Denmark as a case study. Denmark has been chosen for two specific reasons: the energy, cost, and transport data required to complete the analysis is readily available from previous research [23, 24] and the geographical location of Denmark's cities makes it very suitable as a test case for RoadRail. To be specific, the four major cities of Denmark are all connected along one primary route from Copenhagen to Aalborg (i.e. route E20/E45 connects Copenhagen, Odense, Aarhus, and Aalborg as displayed in Figure 4). This suggests that a very large proportion of long-distance travel can be met by installing RoadRail on this single route in Denmark.

To assess the economic impact of RoadRail in Denmark, the following costs need to be considered:

1. Cost of installing RoadRail and where to put it.
2. Cost of using electric vehicles instead of petrol and diesel vehicles.
3. Cost of producing electricity for transport instead of using oil.

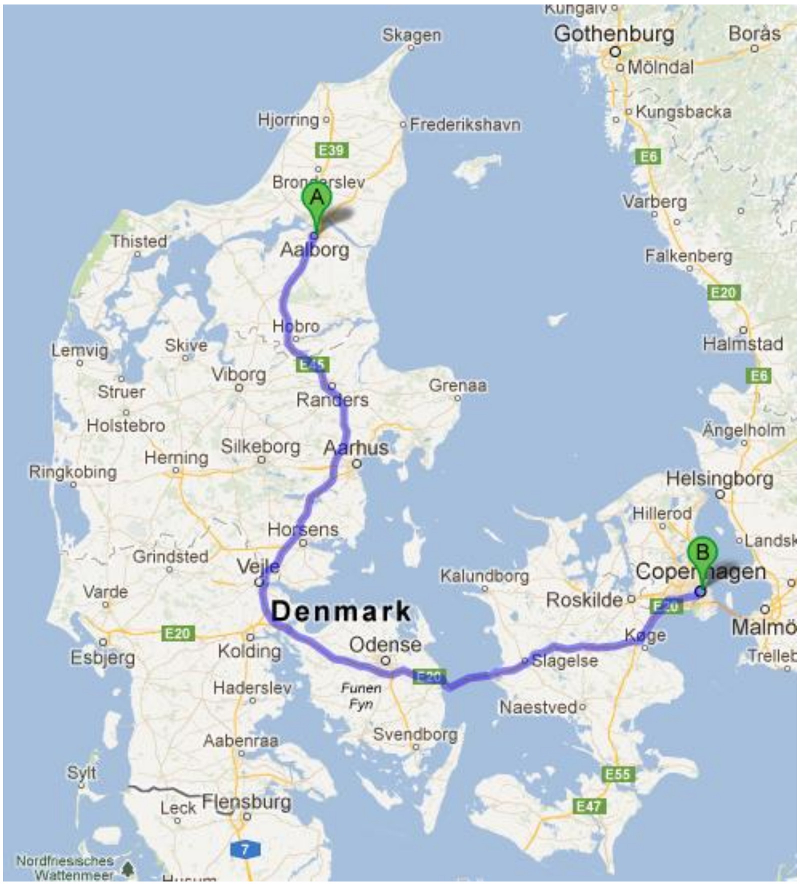

Figure 4: Route E20/E45 which connects the four largest cities in Denmark: Copenhagen, Odense, Aarhus, and Aalborg [25].

2.1. Cost of RoadRail

Estimating the cost of the RoadRail infrastructure is extremely difficult since no costs were identified from existing designs or demonstration projects. To overcome this, the cost of projects which are similar to the direct connection proposed by Alstom [19] and Hanazawa *et al.* [20, 21] were identified. These costs are then used as indicative costs for the socio-economic assessment in this study. After reviewing a wide range of different sources, two unique examples were deemed adequately similar to the direct connection RoadRail concept to be used as a proxy in this study:

1. The cost of doubling the width and electrifying 26 km of railway in Spain in 2011 was M€2.125/km [26]. RoadRail should have similar material and construction costs to the electrification of the rail network, since it involves the laying of electric cable to power vehicles using electricity. It obviously differs as the cables will be on the ground for RoadRail, whereas the electric wires are typically overhead on railway lines. However, there is a buffer in this cost since it also includes the price of adding an additional track.
2. The cost of installing 251 km of 1440 MW (2 x 720 MW) HVDC cable in Sweden, which had approximately 189 km of it buried along the roadside is estimated to cost M€570 [27]. This is approximately M€2/km. As RoadRail is a cable on the ground, it is assumed that it is similar to the costs of undergrounding HVDC cables along the road. For example, this includes the costs of burying an electric cable, handling a cable, and working on major highways.

Based on these proxies, it is assumed here that the RoadRail infrastructure will cost approximately M€2.5/km. Like other transmission infrastructure, it is assumed that RoadRail has a lifetime of 25 years which is typical for many new renewable energy technologies [28]: it should be noted that this is lower than the 40 year lifetime assumed for electric grids [29, 30] since RoadRail is likely to undergo more wear and tear. The annual operation and maintenance (O&M) costs are assumed to be 3% of the total investment. No concrete comparisons have yet been identified to confirm this, so for now this is simply a proxy based on the typical O&M required for renewable energy infrastructure (i.e. wind, wave, and PV) [28].

After defining a cost per kilometre of RoadRail, the next step is to define where it should be installed for the concept to work. Table 1 and Figure 5 outline the list of potential routes which have been considered here for RoadRail. If the first four routes outlined in Table 1 are installed, then everywhere in Denmark except a strip of land approximately 30 km wide on the west of Jutland would be within 50 km of a road with RoadRail. Furthermore, all major cities (i.e. Copenhagen, Aarhus, Aalborg, Odense, and Esbjerg) and routes (i.e. the main road to Sweden and Germany) would have RoadRail. To convert all of these routes, approximately 755 km of road will need to be fitted with RoadRail.

However, two additional 'branches' are also included here: one around Jutland to ensure that nowhere in Denmark is further than 50 km from a RoadRail and one where even more 'branches' are added around the capital city of Copenhagen. The number of routes with RoadRail is linked to the proportion of cars, busses, and trucks that will convert from oil to electricity, so these additional branches have been added to ensure that even a small electric vehicle could utilise the RoadRail infrastructure. This makes a relatively high conversion rate from fossil-fuel to electric vehicles more realistic. The total costs of the RoadRail infrastructure are annualised based on a fixed-rate repayment over its lifetime and a 3% interest rate.

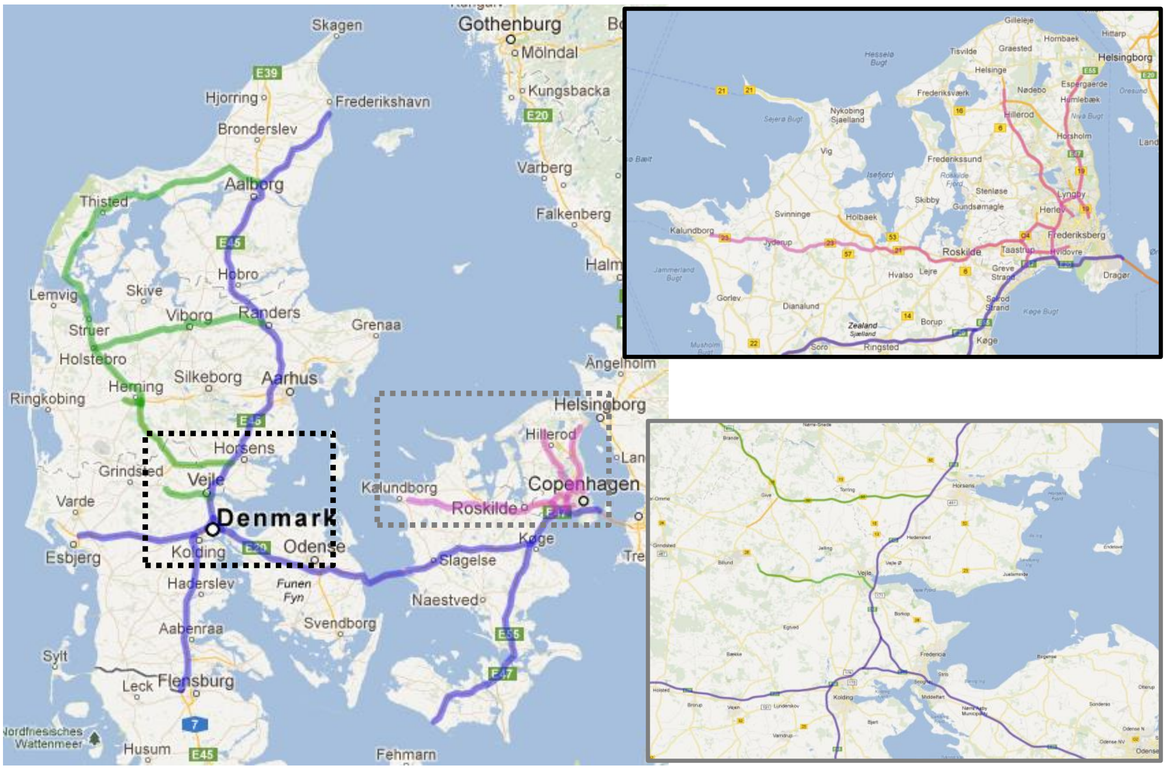

Figure 5: Map of potential routes to install RoadRail in Denmark (see Table 1 also).

Table 1: Distance of potential routes with RoadRail installed in Denmark (see Figure 5 also).

Route		Distance (km)		RoadRail Required (km)	
Start	**End**	**Absolute**	**Cumulative**	**Absolute**	**Cumulative**
Copenhagen	Frederikshavn	475	475	950	950
Fredericia	Esbjerg	85	560	170	1,120
Kolding	Flensburg	85	645	170	1,290
Køge	Fehmarn Bridge (Lolland)	120	765	240	1,530
Jutland Branches		*410*	*1,175*	*820*	*2,350*
Zealand Branches		*175*	*1,350*	*350*	*2,700*
Total		**1,350**		**2,700**	
Jutland Branches					
Horsens	Herning	70	70	140	140
Herning	Aalborg (via Holstebro)	215	285	430	570
Holstebro	Randers	90	375	180	750
Vejle	Billund	25	400	50	800
Herning East	Herning West	10	410	20	820
Subtotal		*410*		*820*	
Zealand Branches					
Copenhagen	Kalundborg	90	90	180	180
Copenhagen	Hillerod	35	125	70	250
Copenhagen	Helsingborg	35	160	70	320
Copenhagen	Ring/Connections	15	175	30	350
Subtotal		*175*		*350*	

2.2. Cost of electric vehicles instead of oil vehicles

The cost of converting the vehicles in Denmark to 'RoadRail' vehicles is once again very difficult to estimate, particularly for busses and trucks. For cars, if RoadRail is installed, then it should reduce the size of the battery required for electric vehicles, which should also significantly reduce the cost of the electric car. However, some modifications will be necessary to connect the car to the road. Here, it is assumed that RoadRail electric cars will be the same as the current price forecast for existing battery electric vehicles. In other words, it is assumed that the additional costs for the device that connects the car to RoadRail will be cancelled out by the cost savings due to a small battery. Since the battery is the most expensive component of an electric vehicle, it is conservative to assume that the average 'RoadRail' scenario electric car is the same price as an electric car with today's road networks.

For busses and trucks it is assumed that the new 'RoadRail' versions will be the same as the costs currently projected for electric hybrid vehicles. Trolley busses are already widely utilised around the world and a demonstration truck has also been established to use electricity by Siemens (see Figure 6), but it uses overhead cables instead of a cable on the ground. No costs were identified for these busses and trucks, but the design is very similar to a hybrid vehicle so this is deemed an adequate proxy. The vehicle costs used in this study are outlined in Table 2 and they are based on projections by the Danish Energy Agency (DEA) for the years 2010, 2020, and 2030 [31].

Figure 6: Siemens trolley bus [32] and eHighway hybrid truck which can both be powered by electricity delivered via overhead lines [33]: © Siemens press picture (reused with permission).

Table 2: Vehicle costs assumed for cars, busses, and trucks in 2010, 2020, and 2030 [31].

Vehicle		Investment (€/vehicle)[2]	Annual O&M (% of Invest)	Lifetime (Years)
2010				
Cars	ICE Diesel	21,560	3.92%	16.3
	ICE Petrol	19,560	4.32%	16.3
	Battery electric vehicles	20,490	10.16%	16.3
	ICE Bio-methanol	19,560	4.32%	16.3
Busses	ICE Diesel	129,781	7.14%	8
	Electric Hybrid	196,895	4.47%	8
Trucks	ICE Diesel	80,537	9.17%	8
	Electric Hybrid[1]	122,185	5.74%	8
2020				
Cars	ICE Diesel	21,560	4.05%	16.3
	ICE Petrol	19,560	4.32%	16.3
	Battery electric vehicles	18,055	7.14%	16.3
	ICE Bio-methanol	19,560	4.32%	16.3
Busses	ICE Diesel	129,781	7.14%	8
	Electric Hybrid	196,895	4.47%	8
Trucks	ICE Diesel	80,537	9.17%	8
	Electric Hybrid[1]	122,185	5.74%	8
2030				
Cars	ICE Diesel	21,560	4.05%	16.3
	ICE Petrol	19,560	4.32%	16.3
	Battery electric vehicles	18,055	5.51%	16.3
	ICE Bio-methanol	19,560	4.32%	16.3
Busses	ICE Diesel	129,781	4.28%	8
	Electric Hybrid	196,895	4.47%	8
Trucks	ICE Diesel	80,537	9.17%	8
	Electric Hybrid[1]	122,185	9.58%	8

[1]No electric hybrid truck costs were reports so this cost is estimated using the cost of an ICE diesel truck and the relationship between an ICE bus and electric hybrid bus.
[2]Assuming €1 equals DKK7.45.

Now that the individual vehicle costs are defined, the next step is to estimate how many vehicles can be converted based on the potential routes that could have RoadRail installed (see Table 1). A study on transport habits in Denmark indicated that 90% of trips in cars are for journeys below 100 km [34], while existing electric vehicles have a range of approximately 160 km [35]. Since RoadRail will reduce the battery capacity required for electric vehicles and make them more accessible to the end-user, it is assumed that 75% of electric vehicles can be converted to electricity if RoadRail is implemented. Furthermore, it is assumed that if 75% of vehicles are converted to electricity, then 75% of the petrol and diesel is also replaced by electricity. In other words, it is assumed that energy is proportional to the number of cars.

For busses, vans, and trucks, statistics from a previous study on the Danish transport sector and its energy demands are used [11]. In this study, which is called CEESA, a detailed breakdown of the Danish transport sector was created along with the corresponding energy demands. Data from the 2010 reference model in this study, which was constructed using historical data, is used to estimate the amount of busses, vans, and trucks that could be converted if a RoadRail system is available. As outlined in Table 3 for busses and in Table 4 for vans and trucks, the amount of energy is based on the distance that these vehicles typically travel. Once again, the proportion of diesel converted to electricity is assumed to be the same as the proportion of vehicles converted to electricity.

Table 3: Breakdown of the transport demand, traffic work, and energy demand for passenger busses in Denmark in 2010 [11].

Vehicle and Trip	Transport Demand (Mpkm)	Traffic work (Mkm)	Energy Demand (TJ)	Conversion Assumed
Bus	9,105	616	8,960	16%: energy for national busses with trips above 50 km and for international busses.
National bus	7,250	563	7,871	
< 5km	744	58	841	
5-25 km	4,875	379	5,508	
25-50km	1,064	83	1,202	
>50 km	566	44	320	
International bus	1,855	53	1,089	

Table 4: Breakdown of the transport demand, traffic work, and energy demand for freight vans and trucks in Denmark in 2010 [11].

Vehicle and Trip	Transport Demand (Mpkm)	Traffic work (Mkm)	Energy Demand (TJ)	Conversion Assumed
Vans (2-6 t)	4,057	8,451	40,565	66%: energy for vans with trips above 50 km.
<50km	1,374	2,862	13,739	
National truck	10,002	1,186	23,967	34%: energy for national trucks with trips above 50 km.
<50km	1,212	161	8,125	
International truck	9,748	626	16,358	82%: energy for international trucks with trips above 250 km.
<250km	486	41	2,963	

2.3. Cost of electricity instead of oil

A summary of the conversions assumed in the RoadRail scenario are outlined in Table 5 along with the corresponding oil that is converted to electricity. The efficiency of electric vehicles is higher than oil vehicles so the total fossil fuel replaced in Table 5 will not equal the total electricity required to drive the vehicles. To estimate what the electricity demand will be, typical electric vehicle efficiencies were obtained from the detailed breakdown of the Danish transport sector in the CEESA project [11]. As outlined in Table 6, the specific energy consumption of electric cars, vans, and busses is typically 3.5 times less than its petrol or diesel equivalents. Therefore, it is assumed here that 3.5 times less electricity will be required to meet the same transport demands than the total fossil fuel that needs to be replaced. The losses in the direct connection between the road and the vehicle are thus assumed to be the same as the losses that occur in the battery of an existing electric vehicle. This seems reasonable since Hanazawa *et al.* have demonstrated efficiencies of approximately 80% for their direct connection concept, which they conclude "may be comparable to the usual charge-discharge efficiency of current batteries" [21]. For the RoadRail scenario outlined in Table 5, this means that 33,750 TJ (i.e. 9.4 TWh) of electricity will be required. It is important to note that the transport demand, and therefore the transport energy consumption, is not changed in any of the scenarios proposed here. In other words, the 2010 scenario is used in all years (i.e. 2010, 2020, and 2030). This is to avoid creating another variable in the assessment in this study. Forecasts in the CEESA study indicate that the transport demand is likely to increase in the future so by maintaining 2010 statistics, the amount of fossil fuels replaced by electricity is most likely underestimated.

Table 5: Percentage of cars, busses, vans, and trucks converted under the RoadRail scenario along with the corresponding amount of oil (petrol and diesel) that is replaced.

Service	Vehicle	Fuel	2010 Energy Consumption[1] (TJ)	Conversions	Fossil Fuels Replaced with Electricity (TJ)
Passenger Transport	Cars	Diesel	26,207	75%	19,655
		Petrol	65,127	75%	48,846
	Busses	Diesel	8,960	16%	1,434
Freight Transport	Vans	Diesel	34,683	66%	22,891
		Petrol	5,679	66%	3,748
	Truck (Diesel)	National	23,967	34%	8,149
		International	16,358	82%	13,413
	Total		180,982		**118,136**

[1]The 2010 energy consumption is used in all years (i.e. 2010, 2020, and 2030).

Table 6: Specific energy consumption of electric and oil powered cars, vans, and trucks in the 2010 Danish transport sector [11].

Vehicle	Fuel	2010 Vehicle Efficiency (MJ/km)	Proportion of Electric Option
Cars	Electric	0.48	100%
	Diesel	1.73	467%
	Petrol	2.24	360%
Vans	Electric	0.82	100%
	Diesel	3.09	377%
	Petrol	4.07	496%
Busses	Electric	2.5	100%
	Diesel	9.76	390%

This new electricity demand also has a cost. In a sustainable energy system, wind energy will be used. However, due to its intermittent nature there will be times when supply doesn't meet the demand. In other articles, this is overcome by completing an energy systems analysis [5]. Since the RoadRail concept proposed in this study is already based on a number of assumptions, an energy systems analysis is not used here. Instead a sensitivity analysis assuming that coal power plants provide all of the electricity for the RoadRail vehicles is also carried out. Hence, there are two different fuel prices used in this study for the new electricity demand to the electric vehicles: one where the electricity is provided by onshore wind farms and one where the electricity is provided by baseload coal plants. Based on data for the years 2015, 2020, and 2030 the cost of producing electricity from these plants has been estimated based on future cost projections by the Danish Energy Agency [28] (see Table 7).

The petrol and diesel prices in Table 7 have also been obtained from projections by the Danish Energy Agency [36].

Table 7: Unit costs assumed for the electricity produced and the diesel/petrol replaced in the RoadRail scenario [28, 36]. The electricity costs have been estimated using a fixed-rate repayment over the technical lifetime of the infrastructure and a 3% interest rate.

Electricity Costs (M€/TWh)	2015[1]	2020	2030
Wind Costs	46.9	42.2	39.7
Coal Costs	63.2	62.4	59.5
Oil Costs (€/GJ)	2010	2020	2030
Oil Price[2] ($/bbl)	75	98	109
Diesel	11.7	15.0	16.6
Petrol	11.7	15.0	16.6

[1]The year 2015 is used for 2010 prices.
[2]These fuel prices can be considered conservative since the average oil price in 2011 was $107/bbl [37].

3. Results

The first results presented in Figure 7 indicate that the RoadRail alternative is more expensive than the business-as-usual Reference scenario based on 2010 assumptions, but by 2020 the two scenarios are the same price. After 2020 the costs in the Reference scenario continue to increase while the RoadRail alternative continues to decrease. By 2030, the RoadRail scenario is approximately 6% less than the Reference indicating that, it is not only a comparable alternative to a business-as-usual scenario, but could potentially be a cheaper socio-economical alternative (based on the methodology outlined in section 2). There is no notable difference in the results when coal is used instead of wind to provide the electricity required: overall the cost of the RoadRail scenario increases by almost 2% in each year (150-190 M€/year). Overall, the key conclusion is that by 2020 and 2030, there is negligible difference between the costs of the Reference and RoadRail scenarios.

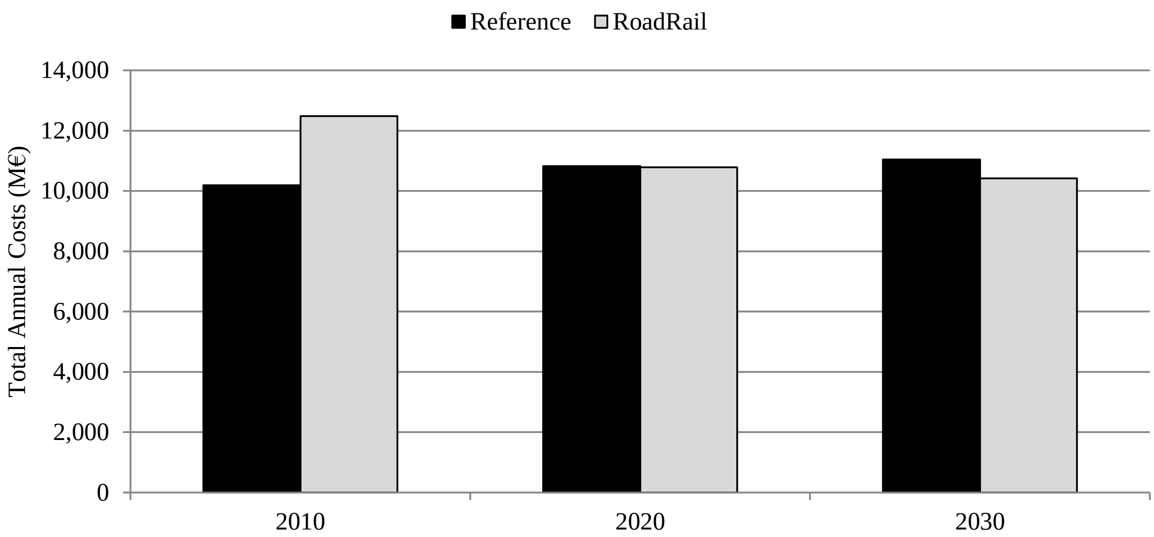

Figure 7: Total annual costs of the business-as-usual reference scenario and the RoadRail scenario with all routes converted (see Figure 5) and using wind power to provide the electricity for the electric vehicles.

Figure 8 and Figure 9 outline the costs of the different components in the Reference and RoadRail scenarios respectively over the period 2010-2030. These results indicate that the vehicle costs are the primary component in the transport sector, accounting for approximately 80% of the total costs. The results are thus very sensitive to the vehicle cost assumptions in Table 2. The reducing costs for electric cars over the 2010-2030 period considered here are thus the primary reason for the reduction in costs in the RoadRail scenario. Over the same period, the cost of petrol and diesel vehicles is almost the same in each year (see Figure 8).

The fuel costs in the Reference scenario also increase faster than those in the RoadRail scenario. Oil prices are expected to increase in the future while electricity production costs (see Table 7) are expected to reduce in the future. Since the RoadRail scenario has less oil than the Reference, the fuel prices in the RoadRail scenario do not increase as much between now and 2030. As already mentioned in Table 7, the fuel prices assumed here are conservative estimates since the average oil price in 2011 was $107/bbl, which was not forecasted to occur until close to 2030. In this context, the cost savings relating to fuel in the RoadRail scenario can thus be considered conservative.

Figure 9 also reveals that the RoadRail infrastructure does not represent a very large proportion of the total costs i.e. it is approximately 5% of the total costs and approximately 6% of the total vehicle costs. Therefore, if the indicative costs assumed for RoadRail in this study are correct (see section 2), then the RoadRail infrastructure is a very minor part of the overall annual costs associated with the transport sector.

A number of sensitivity tests indicate that the cost of RoadRail can change significantly, but considering how small the costs are in comparison to the vehicle costs, the RoadRail infrastructure investments seem relatively robust. If the cost of RoadRail is doubled to 5 M€/km, it is still only 10% of the total transport sector costs in all years considered. Similarly, if the Jutland and Zealand branches are removed (see Table 1) under the assumption that they are not necessary to achieve the conversion rates proposed (see Table 5), then the annual cost of RoadRail is reduced to approximately 3% of the total costs. Although the cost of the RoadRail infrastructure is reduced by almost half when the Jutland and Zealand branches are removed (i.e. 43%), the change is relatively small in comparison to the total costs. Finally, if the lifetime of the RoadRail infrastructure is assumed to be 15 years instead of 25 years, the annual RoadRail costs increase by one-third, but once again this only increases the total costs by approximately 7%.

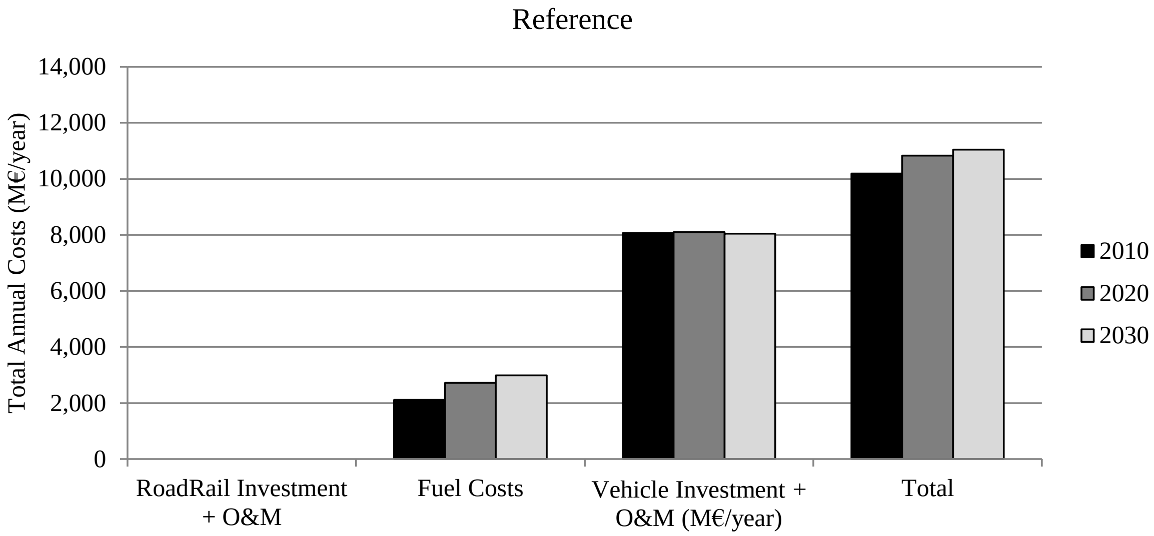

Figure 8: Breakdown of the annual costs by component in the Reference scenario.

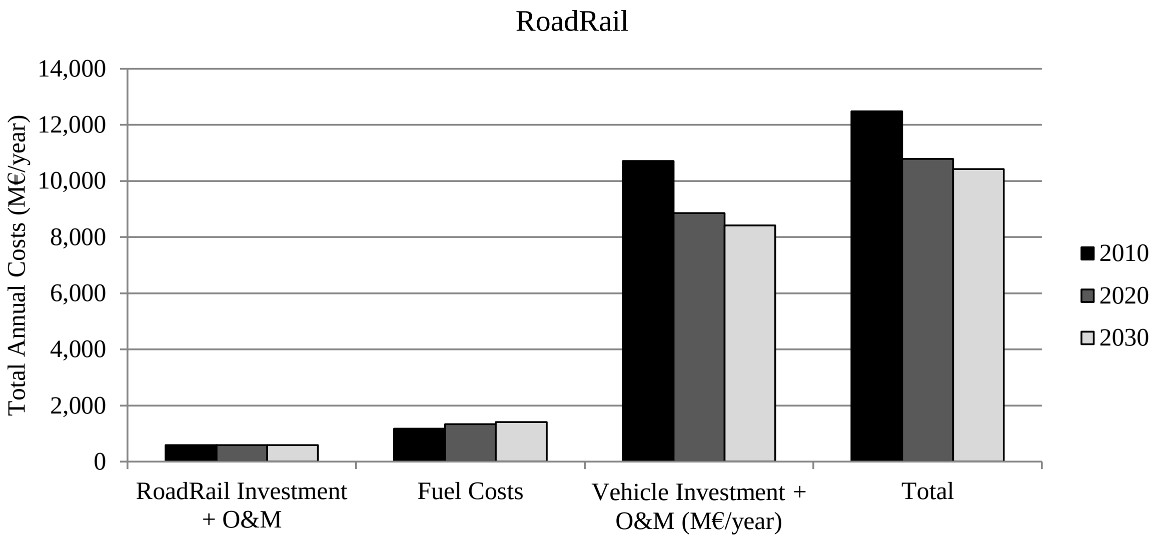

Figure 9: Breakdown of the annual costs by component in the RoadRail (wind) scenario.

4. Discussion

The aim in this study is to evaluate the socio-economic viability of RoadRail. The results displayed in section 3 indicate that a RoadRail scenario could be a cheaper alternative than a business-as-usual Reference scenario by 2030: however, this is under numerous assumptions which have been outlined in section 2. Since this is the first study to do such an analysis, the results clearly indicate that this area demands further research in the future. For example, more information is required in relation to the accuracy of the assumptions used, particularly in relation to the costs of RoadRail and the vehicles as well as the conversion assumptions assumed in Table 5. Overall, considering the minor cost of RoadRail (i.e. ~10% of the total transport costs), it is probable that a future electric road will eventually be a cheaper alternative than oil in the future.

4.1. Additional benefits

The advantage of RoadRail should not be seen from a purely economic perspective. As already discussed in the Introduction, electricity is the most sustainable form of fuel for transport. Furthermore, electricity is the highest quality of energy that is currently available, since it can be used in a ‘smart’ way in a range of electronic devices. Due to these characteristics, an electric road for vehicles will also enable a number of additional advantages, which include:

- Drivers will no longer need to refuel since the vehicle can be charged at home and while driving.
- Increased security of supply. Electricity from local renewable resources can be used for electric vehicles instead of importing large volumes of oil for the transport sector, which is currently the case for the majority of developed countries [37].
- Electric roads will create a new business for the first movers. New products will need to be developed and since road transport is required all over the world, there is a large potential for exports, new jobs, and patentable technologies.
- Road vehicles could communicate with one another while connected to the electric road. This should increase the utilisation of the road network and improve traffic flow. It could also facilitate more carpooling since it would be easier to track where vehicles are located on major road routes.
- Two additional benefits that could be the facilitated with RoadRail are:
    - Self-driving cars
    - Modal shifts from air to road

  Both of these are discussed in more details below.

Self-driving cars have already been developed and tested by many different organisations such as BMW [38], Google [39], and Victoria Tech University [40], while there is also a lot of research being carried out to facilitate them [41, 42]. In France, some self-driving public transport systems have even been tested on the residents of La Rochelle [43]. If RoadRail is installed on major routes, then vehicles could use RoadRail as a guide for the vehicle to follow, which would reduce the need for advanced radar and GPS systems on the self-driving vehicles currently being proposed. No cost data was identified for self-driving vehicles, so it is unclear how much additional investment would be required. However, with self-driving vehicles there would also be a significant number of additional benefits that could be possible with the RoadRail technology, including:

- Increased safety for road users, as the cars could communicate with one another.
- More free time for the driver, particularly those who travel long distances on a regular basis (for example, to work).
- Increased comfort for the driver, as it may be possible to engage in other activities behind the wheel such as reading, writing, or using a laptop.
- The speed of cars could be increased since all road users could be travelling at the same speed, particularly between junctions.

It is important to note that these benefits are associated with self-driving cars on the highways only. There is no evidence here to prove that self-driving vehicles are more likely to develop with RoadRail, but it is simply proposed as a proposition since it seems more likely with the availability of fixed piece of infrastructure in the road.

Finally, the last additional benefit that will be discussed is the reduction in long-distance travel costs when electricity can be utilised. As the efficiency of electric cars is relatively high and the cost of electricity is reducing while oil is increasing (see Table 7), it will be relatively cheap to travel long distances using electricity. For example, the distance between Paris and Berlin is approximately 1,000 km. Assuming the average domestic electricity cost including all taxes in the EU27 in 2011 of €182/MWh [44] and an electric vehicle efficiency of 0.5 MJ/km, the total cost of electricity for this journey is €25. The journey time is expected to be almost 10 hours. If the alternative is to use a plane, then the cheapest daily flight over the next month for a flight between Paris and Berlin is on average €61 per person. The flight time is approximately 2 hours. Hence, it would be possible to travel by electric car from Berlin to Paris for €25 over 10 hours or by plane for approximately €60/person over 2 hours plus the time it takes to go to/from the airport on each side. The car could potentially bring 4-5 people at very little extra cost, but the flight would be €60/person, so for a family of four it would be €240. If these costs are low enough to encourage people to use electric cars instead of aeroplanes to travel, then the RoadRail infrastructure could potential facilitate a shift from jet fuel to electricity. This would be a much more sustainable form of fuel since to date there is no obvious sustainable replacement for jet fuel. If RoadRail can also facilitate self-driving vehicles, then the 10 hour journey time may become immaterial as the driver could do other things such as work, relax, or sleep during the journey. The same story could also be applied to freight transport.

4.2. Challenges and disadvantages

Many challenges will need to be considered in relation to RoadRail if it is implemented in the futrue. Firstly, the technology has not yet been developed so a lot of research is still required to go from the concepts proposed to a final working solution. Since these technologies do not exist, it is unclear how these solutions will perform during road maintenance (i.e. roads need to be resurfaced) and after accidents: for example, if one section of RoadRail is damaged, will it shut down an entire section of the infrastructure and thus leave some traffic stranded? Also, the RoadRail infrastructure will need to safe for users and any wildlife that may come into contact with it, especially to avoid electrocutions. The infrastructure will also need to deal with the weather such as surface water, frost, and snow.

There are also many potential disadvantages that need to be considered in relation to RoadRail. For example, batteries may develop faster than expected and thus the infrastructure may not be necessary, although this is unlikely in relation to busses and trucks. Furthermore, cheaper alternatives may exist such as car-sharing and public transport (i.e. electric rail) and there may also be a significant rebound affect due to the increased comfort levels and cheaper fuel prices associated with RoadRail and electric vehicles. This could lead to congestion, especially in dense urban areas which are at the end of the roads with RoadRail installed. If RoadRail ever becomes a mainstream form of transport, these issues and many others will still need to be considered.

5. Conclusions

The primary objective in this study is to investigate the socio-economic feasibility of a radical technological change in the transport sector, RoadRail, which will facilitate the use of electricity in all modes of road transport instead of oil. In relation to this objective, the results indicate that based on the assumptions proposed and using Denmark as case study, RoadRail is a cheaper alternative than a business-as-usual scenario which utilises oil. Furthermore, the RoadRail infrastructure is a relatively small additional cost in the transport sector, particularly in comparison to the cost of vehicles. These conclusions are only as accurate as the data which they are supported by. From this perspective there are a number of assumptions in this study which are subject to further debate, since it is difficult to be accurate about a technology which is still only at the development stages. However, even based on the results obtained, it can be concluded that RoadRail is a realistic alternative for the future and should be developed further. There are also a significant number of additional benefits that RoadRail could facilitate such as self-driving cars, cheaper fuel costs, and less refuelling, but at present it is difficult to be concrete about their practical potential. In conclusion, if industry can produce a RoadRail solution at approximately M€2.5/km and the conversion rates proposed in this study can be reached with the RoadRail infrastructure proposed, then an electric road will be a more socio-economic alternative than a business-as-usual scenario by 2030, under existing forecasts for electricity and oil prices. This means that there is potentially a more sustainable alternative than oil for road transport in the future, which could be more cost-effective also.

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