

Research & Innovation Platform for Electric Road Systems

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Preface

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The Swedish government has prioritized achieving a fossil fuel-independent vehicle fleet by 2030 which will require radical transformation of the transport industry. Electrifying the vehicle fleet forms an important part of this transformation. For light vehicles, electrification using batteries and charging during parking is already well advanced. For city buses, charging at bus stops and bus depots is being developed, but for heavy, long-distance road transport, batteries with enough capacity to provide sufficient range would be too cumbersome and too much time would have to be spent stationary for charging.

One solution might be the introduction of electric roads, supplying the moving vehicle with electricity both to power running and for charging. In the longer term, this approach could also be used for light vehicles and buses.

The objective of the Research and Innovation Platform for Electric Roads was to enhance Swedish and Nordic research and innovation in this field, this has been done by developing a joint knowledge base through collaboration with research institutions, universities, public authorities, regions, and industries.

The work of the Research and Innovation Platform was intended to create clarity concerning the socioeconomic conditions, benefits, and other effects associated with electric roads. We have investigated the benefits from the perspectives of various actors, implementation strategies, operation and maintenance standards, proposed regulatory systems, and factors conducive of the acceptance and development of international collaborative activities.

The project commenced in the autumn of 2016 and the main research continued until December 2019, the work during year 2020 has been focused on knowledge spread and coordination with the Swedish-Germany research collaboration on ERS (CollERS). The results of the Research and Innovation Platform have been disseminated through information meetings, seminars, and four annual international conferences. Reports have been published in the participating partners' ordinary publication series and on www.electricroads.org. The project was funded by Strategic Vehicle Research and Innovation (FFI) and the Swedish Transport Administration.

The work previously titled "Laws, regulatory system, and standardization" was revised in January 2019 on request from the Swedish Transport Administration at a reference group meeting.

Martin Gustavsson, project manager and report editor

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Partners

RISE Research Institutes of Sweden, Swedish National Road and Transport Research Institute – VTI, KTH Royal Institute of Technology, Norwegian Institute of Transport Economics – TØI, Scania CV, Volvo Group, Vattenfall, AB PROFU, Region Gävleborg, Chalmers University of Technology, Airport City Stockholm, Region Kalmar, Fortum, Trafikverket – Swedish Transport Administration, Faculty of Engineering Lund and Swedish Electromobility Centre.

Reference Group

The reference group for the project has played a crucial advisory role, and have consisted of representatives from Alstom, Bombardier, Elonroad, National Electrical Safety Board, Elways, Energiforsk, E.ON, Ericsson, Ernst Express, FKG, NCC, NEVS, Postnord, Siemens, SSAB, Swedish Energy Agency, TRB and Volvo Cars.

Key words: electric road system, energy, electricity supply, environment, construction, operations, maintenance, architecture, business ecosystem, society, implementation strategy, business case, access, payment, standardisation

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Summary

Electric Road Systems (ERS) include all technologies that enable the transfer of power to electric vehicles on the move. While increasing energy efficiency in the transport sector, ERS is a technology area with the potential to reduce fossil fuel dependency, reduce greenhouse gas emissions, reduce air pollution as well as reduce noise in urban environments.

A comprehensive analysis of ERS in an electricity supply context has been carried out, applying vehicle simulations and energy systems modelling as well as estimating distribution and costs of substations for powering ERS along a road stretch.

The power requirements of a single truck with a total payload of 60 tonnes, have been simulated for two different roads (E6 and E4). It is found that for a case of 100 % electrification, a truck can have a 40 kWh battery and travel the entire E6 road without a negative impact on the SOC, despite the ERS only providing a constant 140 kWh of power.

Modelling the hourly electricity demand related to implementing an ERS on five Swedish roads with the highest traffic flows shows that those roads can reduce the CO₂ emissions from using fossil fuels in combustion engines by approximately 20 % from the road transport sector, while increasing the electricity demand on the peak dimensioning hour with 4 % . Installation of ERS on all the European and National roads would cover more than 60 % of the CO₂ emissions from all heavy traffic. From the modelling it can be concluded that with a full electrification of the road transport sector, including dynamic power transfer for trucks and buses, the new electricity demand can, in Sweden as well as in neighbouring countries, be met by an increase in generation from mainly wind and solar power.

The results of this work reveal that for roads with an ADT of at least 1 200 vehicles using an ERS, total cost per kilometre for a truck using ERS is in the range between 0.35 and 0.55 €₂₀₁₆/vkm, which does not appear to be excessive, as compared to the current most-cost-efficient alternatives diesel, of approximately 0.7 €₂₀₁₆/vkm.

The basic concept of ERS is to supply energy to vehicles. In doing so there will be need for good conductors as well as good isolators and shields. The materials that are used in various ERS concepts will hence need to have the same characteristics and possibly consist of the same kind of material.

When comparing environmental impact between different concepts it will instead be the amount of materials used as well as how often parts need to be replaced, i.e. the wear and tear of the components of the system, that will be of importance. The wear of the conductive techniques might also contribute to emissions of PM10 particles from the contact between the electric current collector and the conductor.

Generally, when discussing noise issues and electrical vehicles the noises are reduced at velocities up to 30 km/h. Hence, as ERS will be implemented on high-speed roads noise will not be significantly reduced. There might however be different kinds of added noise from arcing or when the pick-up slides along the current conductor.

When preparing for implementing ERS it will be necessary to consider the effects of electromagnetic fields and different kinds of shielding for other electrical devices and for people living close to the electric road should be investigated.

When it comes to road construction it seems as if both the inductive as well as the conductive imbedded or on road rail concepts will need transverse power supply at regular intervals. It is common to put such cables or ducts in transvers trenches. This will however cause damage to the road construction. Regulations regarding electrical wiring in the road area indicates however that it is not allowed to install wires in such ways that it will damage road construction. This will be a challenge for the embedded ERS techniques.

It has furthermore been shown from Finite Element Model analyses that loading on top of embedded techniques might cause deformation and cracking, which might lead to water ingress. It will therefore be very important to keep bonds intact at joints between ERS apparatus and the road materials.

When it comes to the overhead catenary concept, it is not only maintenance operations affected by safety barriers which will complicate operations such as side verge cutting and snow ploughing that will be affected. Road construction will also be affected as the poles might cause unstable slope conditions if placed in too steep slopes or too close to the road.

A detailed the system architecture of ERS is presented and highlights its different subsystems, components, actors and communication pathways. The characteristics of the Electric Road System Operator (ERSO) are defined, a system actor which will probably play a central role in future ERS implementations. Furthermore, critical communication and technical interfaces are identified, and possible solutions depending on various ERS actor constellations and responsibilities are presented.

Various business models are extensively discussed from three central ERS actor perspectives: road operator, transport operator and energy company. The possibilities of managing an ERS as a Public-Private Partnership (PPP) is examined, along with an analysis of possible ownership models and their subsequent consequences for both the public and private sector. Finally, the question of how to finance electric road systems is examined through several capital investment appraisal models that are broken down into separate cost and revenue elements for different ERS actors.

The business ecosystem around ERS has been studied, both on a socio-economic level and implications for specific actors in the system. Interviews with members from the Riksdag and further analysis identifies the main priorities for large-scale deployment of ERS in Sweden, and a method for socio-economic analysis of ERS has been developed, including what parameters and other prerequisites to consider.

Interviews with the transport & electricity industries have been conducted to find out what is required for electric roads to be desired and used by respective actor. The transport industry mainly emphasises the importance of good economics, loading capacities and higher customer demand for sustainable transports. The electricity industry highlights the importance of knowing where connection to the power grid occurs and by who, to make good investments in parts of the electric road network that is closest to the existing grid as well as having dialogue with the Energy Market

Inspectorate and to investigate law permits. Moreover, they point out that ERS can result in better utilization of existing networks, people and equipment as well as generate new businesses.

Implementation strategies are discussed based on ownership models and for two different future use-cases, mining operations and highway operations, and the future role of ERSO (Electric Road System Operator) is discussed for small- and large-scale deployment.

Lastly, we look further into specific roll-out scenarios and ERS business cases based on real road traffic data and measurements. One study examines the possibility of using GPS data from heavy trucks to develop better basis for identifying road stretches suitable for ERS. Another study investigates a business ecosystem likely to be built up alongside an electrified road stretch of 120 km between Gävle and Borlänge, Sweden. A computational model has been developed to be able to analyse the influence of various parameters.

A study on how both access and payment systems may possibly look in the context of ERS has been carried out. The study has focused on the vital functions, components and critical interfaces of such systems should they be part of the ERS.

Access control is seen as a crucial part of the interaction between the ERS and the vehicles travelling upon it, mainly to control that every vehicle on an ERS is authorized to use it and has the right technical capabilities to do so safely. One major challenge for an ERS access system will probably be to switch on the right ERS-segments depending on each vehicle's speed and geographical position, especially for short segment ERS-designs. A possible way forward is to integrate or base upcoming ERS access system solutions with existing fleet management control systems present in many heavy-duty vehicles.

An ERS payment system needs to be highly flexible and possible to adapt to different business models and with a scalable architecture, at least in the current ERS development phase. Research done shows that there are such systems available on the market in the telecom sector, and that they would likely be a good fit for ERS as well with some modifications. There are also electric metering components available on the market that can be used for ERS as well, although where these meters should optimally be placed (in the vehicle or the road) is not yet determined and will probably depend on other design aspects of the ERS. The fee for use of the ERS may consist of several parts, some fixed and some variable depending on how, where and when the vehicle uses the ERS.

Electric road systems (ERS) is a relatively recent field of emerging technologies. At present, the field is neither subject of specific regulation, nor dedicated standardisation.

For ERS to take off successfully, matters such as security, safety, environmental, and technical requirements must be properly considered. However, it is still not known to what extent it is possible to use present legal frameworks and standards for already existing related transport solutions, or if entirely new legislation and standardisation needs to be created. An inventory of standards is one step towards getting a clearer picture of the needs in the field of electric road systems.

The work on regulations focussed on examining standards with the purpose and goal to identify, analyse and recommend areas where standards are missing, or where there is need of adaptation of existing standards to ERS. A preliminary mapping and analysis of applicable standards to ERS was followed by a stakeholder reference group enquiry, especially with a view to get input on the applicability of standards to ERS, or to add any missing standards in the mapping.

This report includes a first mapping and analysis of standards directly or indirectly relevant for ERS. The results are presented in a separate report accompanied with a simplified Excel “database” with commentary. The main findings show that a number of published standards and standards under development within the three different categories (vehicle, infrastructure, electric power supply) and with four different applications (general, conductive transmission by rail in road, conductive transmission overhead, inductive power transmission) can be considered useful in the context of ERS. 96 standards (out of a total of 244) have preliminarily been classified as “applicable”.

Information from the standard “database” is expected to have high relevance for recommendations of new important areas for standardisation, and for setting priorities in future standardisation work within the developing field of ERS.

Sammanfattning

Elvägar innefattar teknik som möjliggör energiöverföring till eldrivna fordon i rörelse. Benämningen på engelska är Electric Road Systems (ERS). Elvägar är ett teknikområde med potential att minska beroendet av fossila bränslen, minska utsläppen av växthusgaser, minska luftföroreningar och minska buller i stadsmiljöer, och samtidigt öka energieffektiviteten i transportsektorn.

En omfattande analys av ERS i ett elförsörjningssammanhang har genomförts, med hjälp av fordonssimuleringar och energisystemmodellering, inkluderande även en uppskattning av en lämplig fördelning av, och kostnaderna för, de omkopplingsstationerna som behövs för att driva ERS längs en vägsträcka.

Effektbehovet för en enskild lastbil, med en total nyttolast på 60 ton, har simulerats för två olika vägar (E6 och E4). Resultaten visar att även om en 100 % elektrifiering antas, kan en lastbil klara sig med ett 40 kWh batteri och ändå kunna köra hela E6:an utan negativ påverkan på SOC, trots att ERS maximalt erbjuder 140 kWh.

Modellering av elförbrukningen, timme för timme, som en implementering av ERS på de fem svenska vägarna med de högsta trafikflödena ger upphov till, visar att dessa vägar kan minska koldioxidutsläppen med ungefär 20 % från vägtransportsektorn, samtidigt som efterfrågan av elektricitet maximalt ökar med 4 % under den dimensionerande toppförbrukningstimmen. Installation av ERS på alla europa- och riksvägar i landet skulle täcka mer än 60 % av alla koldioxidutsläpp från all tung trafik. Från modelleringen kan man dra slutsatsen att även med en fullständig elektrifiering av vägtransportsektorn, inklusive dynamisk kraftöverföring för lastbilar och bussar, kan det ökade elbehovet, både i Sverige och i grannländerna, tillgodoses av en ökning av främst vind- och solkraft.

Resultaten av detta arbete visar att för vägar med en ADT på minst 1 200 fordon som använder en ERS ligger den totala kostnaden per kilometer för en lastbil i intervallet mellan 0,35 och 0,55 €₂₀₁₆ per fordonskilometer, vilket torde vara ett rimligt kostnadsläge, i jämförelse med dagens mest kostnadseffektiva dieseldrivna lastbilar som ligger på cirka 0,7 €₂₀₁₆ per fordonskilometer.

Det grundläggande konceptet med ERS är att leverera energi till fordon. Därmed kommer det att finnas behov av goda ledare såväl som goda isolatorer och avskärmningar. Materialen som används i olika ERS-koncept bör därför ha liknande egenskaper och möjligen bestå av samma material. Vid en jämförelse av miljöpåverkan mellan olika koncept kommer det istället att vara mängden material som används såväl som hur ofta delar måste bytas ut, dvs slitage på systemets komponenter, vilket kommer att vara av betydelse. Slitaget av ledande tekniker kan också bidra till utsläpp av PM10-partiklar från kontakten mellan den elektriska strömkollektorn och ledaren.

Generellt kan sägas elfordon är tystare än fordon med förbränningsmotor, i hastigheter upp till 30 km/h. Eftersom ERS kommer att implementeras på vägar med höga hastigheter kommer troligtvis inte ljudbilden att ändras särskilt mycket. Det kan emellertid finnas olika typer av extra brus från ljusbågar eller när pickupen glider längs strömledaren.

Vid förberedelser för implementering av ERS kommer det att vara nödvändigt att undersöka effekterna av elektromagnetiska fält och olika typer av avskärmning för andra elektriska apparater och för människor som bor nära den elektriska vägen.

När det gäller vägbyggnad verkar det som om både de induktiva och de konduktiva ERS som ligger i eller på vägen kommer att behöva tvärgående strömförsörjning med jämna mellanrum. Det är vanligt att placera sådana kablar i tvärgående kanaler eller diken. Detta kommer dock att orsaka skador på vägkonstruktionen. Föreskrifter om elektriska ledningar i vägområdet indikerar dock att det inte är tillåtet att installera ledningar på sådant sätt att de kan skada konstruktionen. Detta kommer att vara en utmaning för dessa typer av ERS-tekniker.

Det har vidare visats från finita elementmetod-analyser att trafikbelastning ovanpå de inbäddade teknikerna kan orsaka deformation och sprickbildning, vilket till slut kan leda till vatteninträngning. Det kommer därför att vara mycket viktigt att underhålla förslutningar vid skarvarna mellan ERS-apparater och vägmateriäl.

När det gäller konceptet med luftledningarna är det inte bara de underhållsåtgärder som påverkas av vägräcken som kommer att komplicera åtgärder så som slätter och snöplogning. Vägkonstruktionen kommer också att påverkas eftersom pelarna som håller upp luftledningarna kan orsaka instabila sluttningsförhållanden om de placeras i för branta sluttningar eller för nära vägen.

En detaljerad systemarkitekturen för elvägar är presenterad och belyser dess olika delsystem, komponenter, aktörer och kommunikationsvägar har beskrivits. Egenskaperna för elvägsoperatören, Electric Road System Operator (ERSO) definieras, en systemaktör som troligen kommer att spela en central roll i framtida implementeringar av ERS. Vidare identifieras kritiska gränssnitt avseende kommunikation mellan systemaktörer och tekniska problem, och möjliga lösningar beroende på elvägsystemets aktörkonstellation och ansvarsområden presenteras.

En omfattande diskussion kring olika affärsmodeller för tre centrala ERS-aktörsperspektiv presenteras: vägoperatör, transportoperatör och energiföretag. Möjligheterna att hantera ERS som ett offentlig-privat partnerskap (PPP) undersöks, tillsammans med en analys av möjliga ägarmodeller och dess påföljande konsekvenser för både den offentliga och privata sektorn. Slutligen undersöks frågan om hur man finansierar elvägsystem genom olika utvärderingsmodeller för kapitalinvesteringar som delas upp i separata kostnads- och intäktselement för olika elvägsaktörer.

Affärsekosystemet runt ERS har studerats, både på en socioekonomisk nivå och konsekvenser för specifika aktörer i systemet. Intervjuer med medlemmar från Riksdagen och vidare analys identifierar de viktigaste prioriteringarna för storskalig implementering av ERS i Sverige, och en metod för socioekonomisk analys av ERS har utvecklats, inklusive vilka parametrar och andra förutsättningar som bör beaktas.

Intervjuer med transport- och elindustrin har genomförts för att ta reda på vad som krävs för att elvägar ska önskas och användas av respektive aktör. Transportbranschen betonar främst vikten av god ekonomi, lastkapacitet och incitament till högre efterfrågan på hållbara transporter. Elindustrin belyser vikten av att veta var anslutning till elnätet inträffar och av vem, för att göra bra investeringar i delar av elvägsnätet som är närmast det befintliga elnätet samt att ha en dialog med

Energimarknadsinspektionen och att undersöka lagliga aspekter. Dessutom påpekar de att ERS kan resultera i bättre utnyttjande av befintliga nätverk, personer och utrustning samt generera nya tjänster.

Implementeringsstrategier diskuteras baserat på ägandemodeller och för två olika framtida användningsfall, gruvdrift och motorvägsdrift, och den framtida rollen för ERSO (Electric Road System Operator) diskuteras för små och stora utbyggnader.

Slutligen tittar vi vidare på specifika utrullningsscenarioer och ERS-affärsfall baserade på verkliga vägtrafikdata och mätningar. En studie undersöker möjligheten att använda GPS-data från tunga lastbilar för att utveckla en bättre bas för att identifiera vägsträckor som är lämpliga för ERS. En annan studie undersöker ett potentiellt affärsekosystem längs en elektrifierad vägsträcka på 120 km mellan Gävle och Borlänge, Sverige. En beräkningsmodell har utvecklats för att kunna analysera påverkan av olika parametrar.

En studie kring hur tillträdes och betalssystem kan komma att se ut i en elvägscontext har utförts. Studien fokuserade på viktiga funktioner, komponenter och kritiska gränssnitt för sådana system då de skall vara en del i ett elvägssystem.

Tillträdeskontroll ses som en kritisk del av interaktionen mellan elväg och vägfordonen som utnyttjar elvägen, främst för att kontrollera att de har giltigt tillstånd och de rätta tekniska förutsättningarna för att använda elvägen på ett säkert sätt. En stor utmaning för ett tillträdesystem för elvägar kommer förmodligen vara att sätta på rätt elvägssegment i kombination med varje fordons fart och geografiska position, speciellt i de fall elvägen designats med korta segment. En möjlig väg framåt är att försöka integrera eller basera kommande tillträdeslösningar för elvägar med nuvarande hanteringssystem för fordonsflottor som finns närvarande i många av dagens tunga lastbilar.

Ett betalssystem för elvägar bör vara mycket flexibelt med möjligheter för anpassning enligt olika affärsmodeller och med en skalbar arkitektur. Forskning visar att sådana lösningar finns tillgängliga på dagens marknad i telekom-branschen och att dessa lösningar bör kunna passa bra även för elvägar med viss modifikation. Det finns också elmätningsskomponenter tillgängliga idag som kan användas i elvägssammanhang, dock är det inte helt klart än var dessa optimalt bör placeras (i fordonen eller i vägen), dock är det troligt att detta kommer bero på andra designaspekter i elvägssystemet. Avgiften för att använda elvägen kan vara uppdelad i både fasta och rörliga kostnader beroende på hur, vart och när ett fordon använder elvägen och dess tjänster.

Elvägssystem (ERS) är ett relativt nytt fält med framväxande tekniker. För närvarande är fältet varken föremål för specifik reglering eller särskild standardisering.

För att ERS ska bli framgångsrika måste frågor om skyddaspekter, säkerhet, miljö och tekniska krav övervägas ordentligt. Det är emellertid fortfarande okänt i vilken utsträckning det är möjligt att använda nuvarande rättsliga ramverk och standarder för redan befintliga relaterade transportlösningar, eller om helt ny reglering och standardisering behöver skapas. En inventering av standarder är ett steg mot att få en tydligare bild av behoven inom området elvägssystem.

Arbetet med att studera regelverk fokuserade på att undersöka standarder med syfte och mål att identifiera, analysera och rekommendera områden där standarder saknas

eller där det finns behov av anpassning av befintliga standarder till ERS. En preliminär kartläggning och analys av tillämpliga standarder för ERS, följdes av en referensgruppsundersökning med intressenter, särskilt i syfte att få kommentarer om tillämpligheten av standarder på ERS, eller för att lägga till eventuella saknade standarder i kartläggningen.

Denna rapport innehåller en första kartläggning och analys av standarder som är direkt eller indirekt relevanta för ERS. Resultaten presenteras i en separat rapport åtföljd av en förenklad Excel-"databas" med kommentarer. De viktigaste slutsatserna visar att ett antal publicerade standarder och standarder under utveckling inom de tre olika kategorierna (fordon, infrastruktur, elförsörjning) och med fyra olika applikationer (allmän, konduktiv överföring via vägskena, konduktiv överföring via luftledning, induktiv kraftöverföring) kan anses vara användbara i samband med ERS. 96 standarder (av totalt 244) har preliminärt klassificerats som "tillämpliga".

Information från standard-"databasen" förväntas ha hög relevans för rekommendationer av nya viktiga områden för standardisering och för att göra prioriteringar i framtida standardiseringsarbete inom utvecklingsområdet ERS.

1 Electricity supply

The research presented in this chapter has been performed by Chalmers University of Technology and Swedish National Road and Transport Research Institute. Chalmers University of Technology has been the research leader.

1.1 Aim and scope

The overall aim of the work presented in this chapter is to assess how Electric Road Systems (ERS) influence and interact with the electricity supply system in terms of the use and distribution of electricity and to evaluate the potential for CO₂ emission reduction from ERS. The analysis in this chapter is done at different levels, from dedicated analyses of the electricity demand of specific roads to the impacts of ERS at the national and multi-national levels. Thus, this chapter describes:

- I) The yearly and hourly electricity and power demand for a single truck using a road, as well, as for all vehicles using the five roads with most traffic in Sweden.
- II) The types of roads, how much of the road network and which vehicle types that are beneficial to electrify based on an analysis of current road traffic volumes, CO₂ emissions mitigation potential, and infrastructure investment costs.
- III) The impact of ERS on the electricity system in terms of investments in new power capacity and the dispatch of the system, assuming different future scenarios of the electricity system.
- IV) The impacts on the regional grid from ERS.
- V) The potential climate impacts of large-scale deployment of ERS.

The emission reduction is evaluated with respect to reduced CO₂ emissions from avoiding burning fossil fuels in the vehicles, as well as the reduction in CO₂ emissions from the electricity system when assuming a development of the electricity generation system under different scenarios. The emissions are obtained by means of analysing the road transportation work for the National (N) and European (E) roads in Sweden for different degrees of electrification of the traffic volumes. In addition, this chapter explores the possibilities to determine the required electricity and energy supply along selected roads (European Highway E6 and E4) as basis for dimensioning the electricity supply system of the road.

It should be stressed that *the aim is not to try to predict the future* but to test key assumptions with respect to how these will influence the conditions for ERS so as to understand the possible role of ERS in shaping tomorrow's transportation system. In order to formulate credible scenarios also other forms of electrification of the transportation sector has to be considered, in particular various degrees of electrification of the passenger car fleet, applying different strategies for charging of batteries. Important aspects which are investigated by means of scenario analysis are technology choices and the effect of different types of policy measures such as targets

on reduction in carbon (CO₂) emissions, renewable energy and renewable transportation fuels.

Considering that a successful ramp-up of ERS most likely will take several decades to reach a large penetration, its associated emissions will be strongly linked to the future electricity system which will also have to be transformed over the same period. The required electricity and energy supply for a truck driving on chosen roads have been calculated using a vehicle energy consumption model. The model calculates the power requirements of a single truck with a total payload of 60 tonnes, taking into account only the air resistance (drag), rolling friction and the gravitational work due to the road topology (elevation) and the speed limit.

The emissions from the electricity system when using ERS are calculated from electricity systems modelling of the development of the European and Nordic electricity system, assuming one or more scenarios for the future development of policies and CO₂ emission reduction targets. This allows to calculate the development of the CO₂ emissions from European as well as Nordic electricity system applying the ELIN/EPOD modelling package [1], [2], and [3], which considers import and export of electricity between countries, considering limitations in transmission capacity. If the electricity system is assumed to develop in accordance with the EU roadmap it is clear that the CO₂ emissions from electricity will decrease with time, in particular if the European electricity generation mix is chosen as base for the emission (but then starting from higher CO₂ levels than if a Nordic mix would have been chosen).

1.2 Activities

As indicated above, this chapter has focussed on three main tasks; simulation of the energy demand for a truck using a road; electricity systems modelling for different scenarios of electrification and analysis of road transportation work on Swedish National and European roads. The latter also includes a detailed analysis on hourly electricity demand related to implementing an ERS on five Swedish roads with the highest traffic flows. The energy systems modelling has been carried out partly in cooperation with similar activities in the Norwegian project Ferry Free E39.

1.3 Results

Below is a brief summary of the main results obtained related to the ERS and the electricity system.

1.3.1 Electricity and power demand for Swedish roads

1.3.1.1 Power demand for a single truck

The power requirements of a single truck with a total payload of 60 tonnes, have been simulated for two different roads, E6 from Trelleborg to Svinesund, and E4 from Helsingborg to Stockholm. The simulation takes into account the air resistance (drag), rolling friction and the gravitational work due to the road topology (elevation) and the speed limit. As the truck is assumed to be a heavy truck, its maximum speed is assumed to be 80 km/h. As a base for the road topology we used the database PMSV₃ from Trafikverket (Swedish Road Administration). The three-dimensional data was filtered

using a second order Butterworth filter with a cut-off-frequency of 0.01 in combination with a zero-phase digital filtering algorithm in order to smooth out measurement noise. The filtered road elevation of the road E6 from Trelleborg to Svinesund and E4 from Helsingborg to Stockholm can be found in Appendix A. Figure 1 shows the mechanical power required to drive the 60 tonne truck along the road E6 from Trelleborg to Svinesund (orange) and road E4 from Helsingborg to Stockholm (blue) while maintaining the speed limit. The main contribution to the power requirement is the road inclination. A negative power corresponds to the truck being able to generate power through regenerative braking due to travelling downhill. The maximum power that can be supplied to the vehicles using the ERS is assumed to be 130 kW. The time averaged power that the ERS needs to supply the truck using E4 and E6 are 135 kW and 140 kW, respectively.

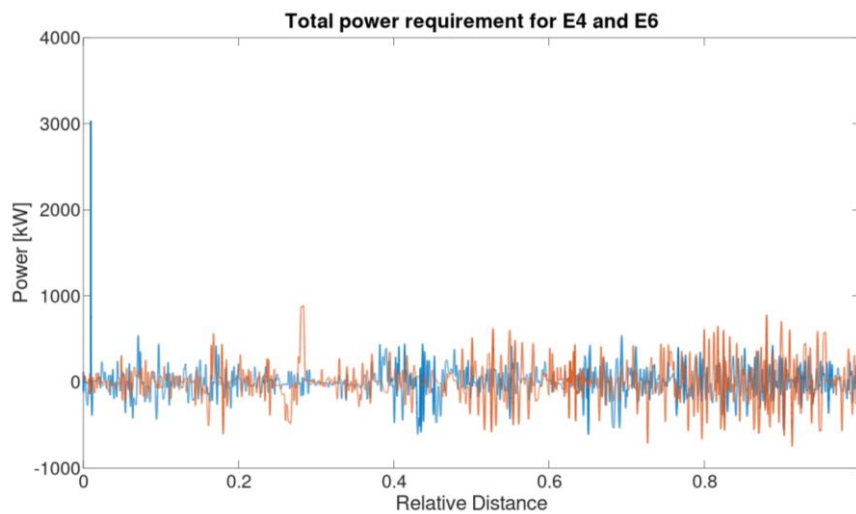


Figure 1: The mechanical power required to propel a single 60 tonne truck along the E6 (orange) from Trelleborg to Svinesund and E4 (blue) from Helsingborg to Stockholm, maintaining the speed limit.

When the truck is connected to the ERS, we have assumed there is an onboard DC/DC converter on the truck that regulates the charging current. If the power provided by the ERS is greater than the power required to maintain the speed limit, the battery is charged, while if the power provided by the ERS is less than the power required to maintain the speed limit, the battery is discharged to supply electricity to the wheels. If the ERS supplies a constant power greater or equal to the time averaged power along the entire road, any truck travelling the entire road will end up with a higher state of charge than when first connecting to the ERS. At the same time, any truck connecting even for a short distance will have a higher SOC if it uses the ERS than if it would not. Without knowing the exact routes of the trucks along the road (i.e. where they would connect and disconnect to the ERS), it will be difficult to cater to the exact needs of the trucks. Using a truck travelling the entire road with the target of having at least the same SOC when it leaves as when it started will at least give some quantifying number for the minimum battery capacity needed.

Figure 2 shows the energy flowing into the battery for a 60 tonne truck travelling along the road E6 from Trelleborg to Svinesund and E4 from Helsingborg to Stockholm assuming 100% of the road being electrified with ERS. The power supplied by the ERS is equal to the time averaged power needed for the truck to maintain the speed limit, in

this case 133 kW. A negative value corresponds to the battery having been discharged relative to the starting SOC. The difference between the maximum and the minimum levels gives the minimum useable battery energy content in order for this strategy to be possible. In this case, for the E6 road, this minimum usable battery capacity is 40 kWh. Thus, if the truck is supplied with a 40 kWh battery, the truck can travel the entire E6 road without a negative impact on the SOC, despite the ERS only providing a constant 140 kWh of power along the entire E6 road. For the road E4 the minimum usable battery capacity is 56 kWh. The reason for this is that the E4 has higher elevation difference. While the start point and end point are close to the same height, the larger battery is needed to be able to handle the longer climb uphill in between.

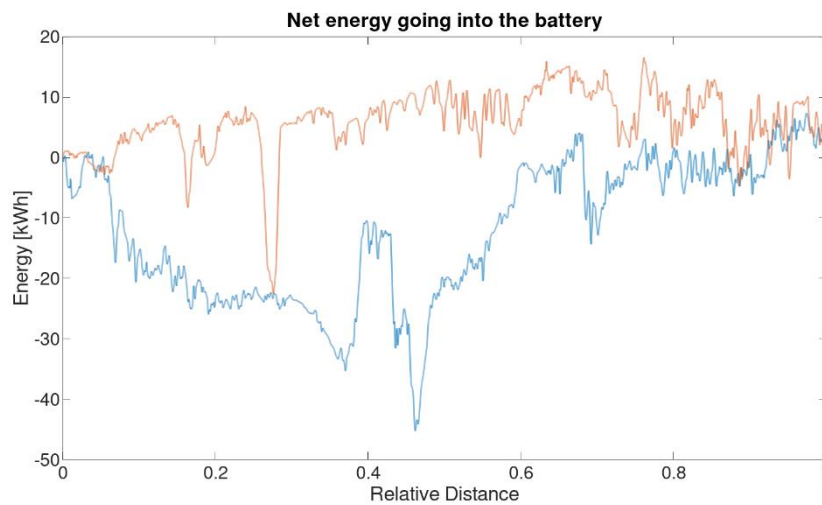


Figure 2: Net energy going into the battery for a 60 tonne truck travelling in the northwards direction along E6 (orange) and E4 (blue). The power supplied by the ERS is equal to the time averaged power needed for the truck to maintain the speed limit. 100 % of the road was electrified. Note that the constant power provided by the ERS is slightly different between the two roads in order for the net energy to end up at the starting point, as this allows for the estimation of the minimum usable battery capacity.

An alternative to electrifying 100 % of the road as seen in Figure 2, is to electrify only parts of the road and instead increasing the power available from the ERS. This might be viable if for instance there are locations that are impossible to electrify, such as crossing overhead bridges in the case of applying overhead lines (pantograph) system, or due to too high ERS infrastructure costs. The increased electricity supply cost due to transformer stations with higher output might be smaller than a higher ERS road infrastructure cost when electrifying 100 % of the road.

Figure 3 shows the net energy going into the battery of a vehicle travelling along the E6 in northwards direction with 50 % of the road being electrified. The electrified road stretches are here 10 km long, regularly spaced with corresponding 10 km of non-electrified road sections in between. In order to compensate the loss of power from the ERS on half the road, the power the ERS provides is double compared to Figure 2 (280 kW). The usable battery capacity is increased to 50 kWh due to the charge/discharge cycles occurring as the power from the ERS is not continuously available. Note that the exact placements of the ERS segments can have a large impact on the minimum battery capacity required. This is because for some road geometries the end of a road segment happens exactly when a high, sufficiently steep, hill begins, leading to additional discharging of the battery.

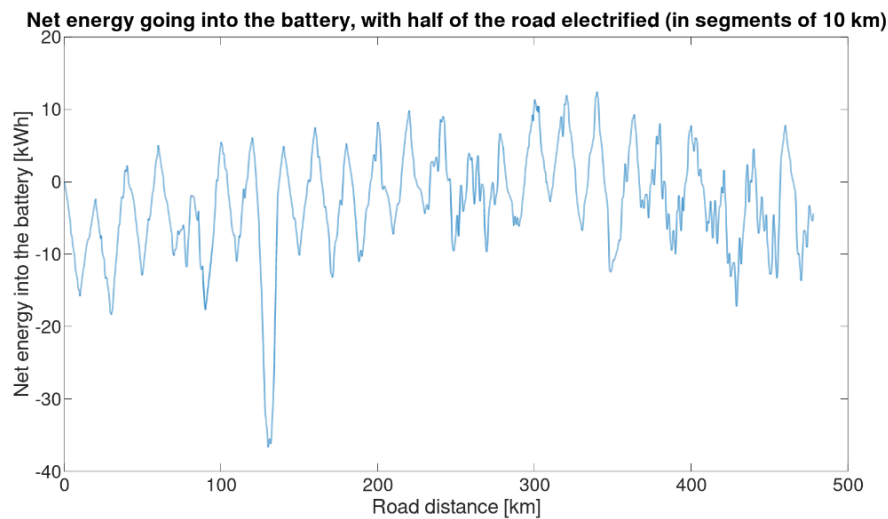


Figure 3: Net energy going into the battery for a 60 tonne truck travelling in the northwards direction along the road E6 when only 50 % of the road is electrified. The electrified road stretches are here 10 km long, regularly space with corresponding 10 km of non-electrified road sections in between. In order for the average power to be the same, the power supplied in the electrified road stretches is here doubled.

1.3.1.2 Yearly and hourly electricity demand

Figure 4 shows the energy requirement per year and kilometre for the E6 simulated with the vehicle energy consumption model in the northward's direction. As seen in Figure 4, the geographical distribution of the electricity demand for a single road depends to a large extent on the traffic flow along the road, with a higher demand seen in the vicinity of urban areas. The geographical peaks around the densely populated areas, mainly caused by light vehicles that are used for shorter commutes, could instead of daytime charging with ERS or fast chargers, be met by larger vehicle batteries that are charged during night-time or during a period of high-power output from VRE.

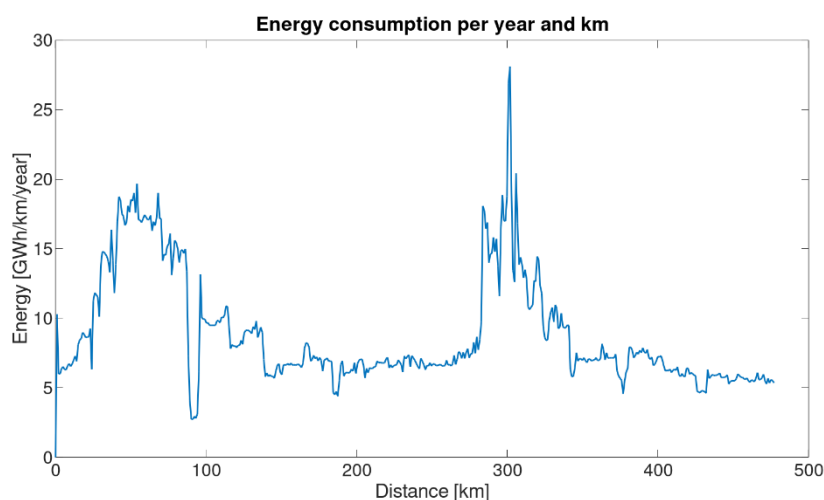


Figure 4: Energy requirement per year and kilometre for the E6 in the northwards direction. This is based on the ERS providing constant power along the road, given by the required time averaged power. For this road this is 140 kW.

An additional work by Jelica et al. [4] investigated the hourly electricity demand related to implementing an ERS on five Swedish roads with the highest traffic flows. These five

ERS to night-time to avoid a correlation with other loads will obviously be difficult. Passenger cars are using the ERS for example between home and work-place. A change of the goods traffic on the roads to night-time might be possible with autonomous trucks. However, this would require new logistics patterns.

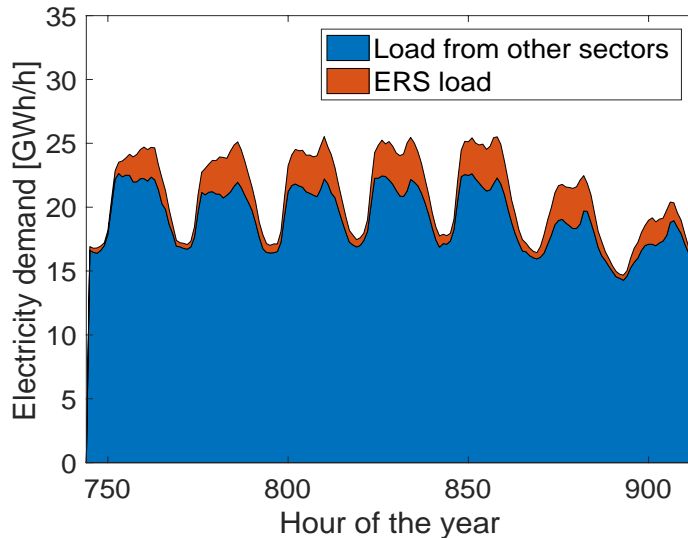


Figure 6: Hourly electricity demand in Sweden during the first week of February, shown as the load from ERS on all Swedish E- and N-roads and other sectors. The starting hour 745 is 12 AM on a Monday night. From Jelica et al. [4].

1.3.2 Electrify part of the road-network and associated costs

In Taljegard et al. [5], we have investigated the costs and impact of road CO₂ emissions from large-scale implementation of electric road system (ERS) Sweden (and Norway) by identifying: (i) which roads; (ii) how much of the road network; and (iii) which vehicle types are beneficial to electrify based on an analysis of current road traffic volumes, CO₂ emissions mitigation potential, and infrastructure investment costs. All the European (E) and National (N) roads in Sweden and Norway were included, while assuming different degrees of electrification in terms of the fraction of the road length with an ERS, prioritising roads with high-traffic loads.

The results from [5] show that implementing an ERS already for 25 % of the E- and N-road lengths would result in electrification of 70 % of the traffic on these roads (Figure 7), as well as 35 % of the total vehicle kilometres in Norway and Sweden. It will then connect some of the larger cities in Norway and Sweden with ERS. The results reveal that an ambitious plan to electrify more than 50 % of light vehicles with ERS must include also county roads and private roads. While full implementation of ERS is unlikely, these data are provided solely to demonstrate the future potential of ERS for the electrification of road transportation of people and goods.

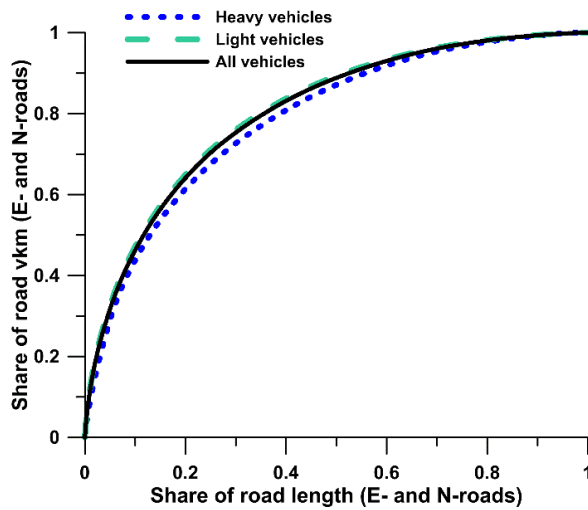


Figure 7: The shares of E- and N-road length with ERS and the corresponding shares of vehicle kilometres on the E- and N-roads, aggregated for Norway and Sweden (from [5]).

Large-scale implementation of ERS on 25 % of the E- and N-road lengths in Norway and Sweden (i.e. about 6,800 km) would require a total investment of between 2.7 and 7.5 billion €₂₀₁₆, assuming an investment cost of between 0.4 and 1.1 M€₂₀₁₆ per kilometre [5]. For roads with an average daily traffic of >6 800 and >1 200 vehicles per day (corresponding to 25 % and 75 % of the E- and N-road length assuming all vehicles use the ERS) the costs of infrastructure investment are about 0.03 €₂₀₁₆ per vkm and 0.15 €₂₀₁₆ per vkm. The infrastructure investment cost per vehicle kilometre increases dramatically, as expected, for roads with an ADT of less than approximately 500 if assuming all vehicle types. Thus, electrifying roads with an ERS that only applies to heavy vehicles will increase the cost per vehicle kilometre for a road, as compared to using an ERS for both heavy and light vehicles.

As shown in Figure 8, approximately 90 % (all vehicles) and 40 % (heavy vehicles) of the total E- and N-road lengths have a traffic volume of at least 500 vehicles per day. The extent to which ERS is a cost competitive strategy for reducing CO₂ emissions from road traffic depends, of course, on the cost of alternative drive-trains and fuels. The vehicle cost per kilometre (vkm) for ERS, i.e., cost for pick-up system and use of electricity, is in the range between 0.2 and 0.4 €₂₀₁₆/vkm and between 0.03 and 0.13 €₂₀₁₆/vkm for a truck and passenger car, respectively. The total cost per vkm is the vehicle cost plus the ERS infrastructure cost. The ERS infrastructure cost per vkm varies depending on the number of vehicles using the ERS, as seen in Figure 8.

The results reveal that for roads with an ADT of at least 1 200 vehicles using an ERS, total cost per kilometre for a truck using ERS (between 0.35 and 0.55 €₂₀₁₆/vkm) does not appear to be excessive, as compared to the current most-cost-efficient alternatives diesel, of approximately 0.7 €₂₀₁₆/vkm. Approximately, 15 % and 75 % of the total length of the E- and N-roads has a traffic volume of heavy and light vehicles, respectively, that exceeds 1 200 vehicles per day, as shown in Figure 8.

We conclude that for roads with high traffic volumes using an ERS, the total driving cost per km does not seem to be an issue although also light vehicles can bring down cost per vehicle kilometre further. The results are presented in detail by [5] and [6].

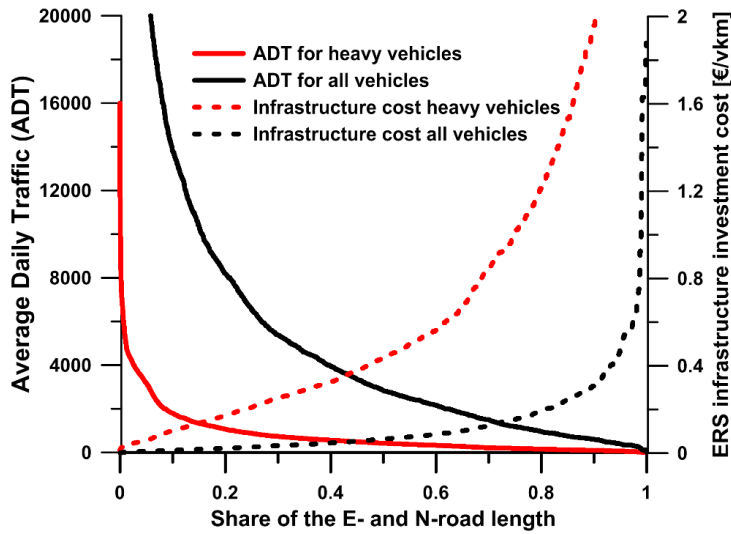


Figure 8: Electric road system (ERS) infrastructure investment costs per vehicle kilometre (right y-axis) and the present average daily traffic (left y-axis) as a function of the shares of the European (E) and National (N) road length in Norway and Sweden. The cost for the ERS infrastructure is assumed to be 1.1 M€2016/km (i.e., cost level 2 as defined in [5]).

1.3.3 Interaction with the electricity supply system

In order to investigate the impact of ERS on the electricity supply system, the modelling work in this study applies a cost-optimisation investment model (ELIN) and an electricity dispatch model (EPOD) of the European electricity systems including an electricity demand from EVs. The two models have previously been used to study the transformation of the European electricity system to meet European policy targets on CO₂ emissions, see [3] for a description of the model package. To include electrified transportation systems, the two electricity models are expanded with an add-on module to include also an electrified road transport sector in the form of static and dynamic charging of passenger vehicles, trucks and buses. Thus, a new demand for electric transportation has been added to both the investment model and the dispatch model. Figure 9 shows a schematic picture of the modelling-package, including ELIN, EPOD and the transportation module.

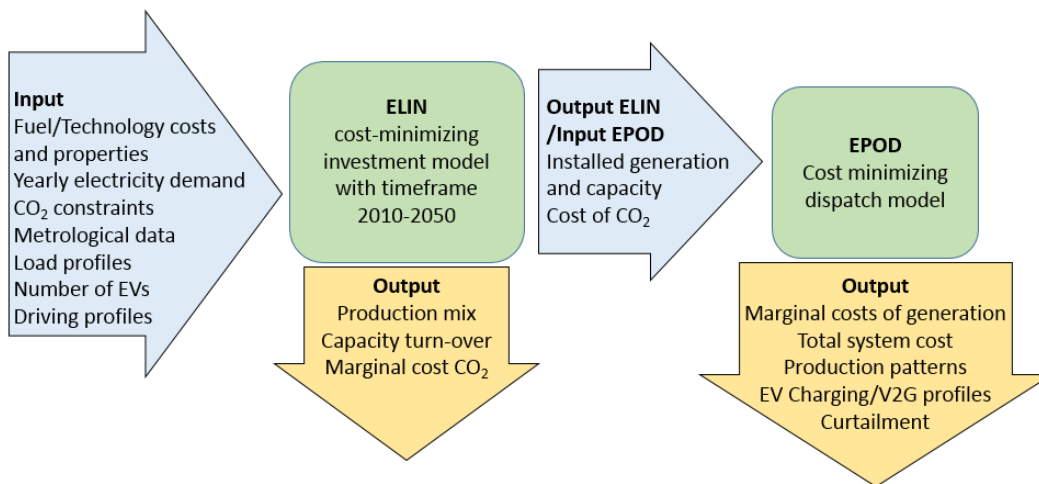


Figure 9: A schematic picture of the modelling-package applied in for the electricity modelling (and related projects [7]).

Although the focus is on ERS an assessment of the future of ERS and how it interacts and influence investments in the electricity supply system require ERS to be analysed as part of an assumed electrification of also the passenger cars (light EVs). It is hardly likely that there will be a large-scale roll-out of ERS without electrification of light EVs. As pointed out above, it is obviously not possible to predict the future of electrification of the transportation sector and, thus, the aim is here to investigate the impact of ERS assuming different scenarios of electrification of road transportation applying different charging strategies.

Figure 10 exemplifies modelling results for Sweden, Germany, Great Britain and Spain (although the neighbouring countries are also modelled to account for import/export of electricity). All countries are sub-divided into smaller regions based on the current bottlenecks in transmission capacity. Yet there is a possibility to invest in transmission capacity between regions. A cap on CO₂ corresponding to 99 % emission reduction by 2050 relative 1990 emissions is assumed. It should be stressed that Europe has an integrated electricity market and, thus, in order to provide a meaningful analysis, it is important to model and analyse results not only for individual countries in isolation. There are indeed different bottlenecks in electricity transfer regions throughout Europe which is included in the modelling (as well as that the model can invest in new transmission capacity).

The results in Figure 10 are given as the difference in investments for the period 2020-2050 between a scenario without EVs and under different EV scenarios, including those with ERS. The additional investments due to an electrification of the transport sector is somewhat different depending on the country. See [7] for details on the modelled cases.

As seen in in Figure 10, by 2050 a large part of the new demand is met by electricity generation consists of renewable electricity to meet the climate target of 99 % reduction in emissions compared to 1990. The results show that with an uncontrolled static charging (called direct charging) and ERS, the composition of the electricity system and the share of VRE in year 2050 are similar to those in the scenario without EVs. In Germany, the share of wind power is decreasing with a few percent points when introducing direct charging of EVs and ERS compared to without an electrification of road transport. This is due to that the sites with the most favourable wind conditions in Germany have already been deployed and there is instead an investment in more thermal power to cover the additional EV demand.

In all regions investigated, controlled (i.e., optimised) static charging of passenger EVs leads to reduced investments in peak power units, as well as, nuclear and/or thermal power (in the form of natural gas with carbon capture and storage (CCS), biogas, and CCS coal co-fired with biomass), as compared to uncontrolled (direct) static charging.

The share of solar power increases with at least ten percentage points with the possibility to optimise the charging and to perform V2G in all the regions investigated (except for Sweden).

A scenario with full electrification of road transport, including also dynamic power transfer for heavy vehicles, still decreases the need for investments in peak power compared to the scenario without EVs, provided that V2G is applied for the passenger vehicles. However, if all trucks and buses uses dynamic power transfer and V2G is

applied for the passenger vehicles, both the total investment and the investments in peak power will decrease to a larger extent than with just optimising the charging [7].

In summary, it can be concluded from the modelling that with a full electrification of the road transport sector, including dynamic power transfer for trucks and buses, the need for investments in peak power and curtailment of wind power decrease compared to a scenario without EVs, provided that an optimal charging strategy and vehicle-to-grid is applied for the passenger vehicles. Flexibility from EVs can facilitate an increase of investments in renewable electricity, especially solar PVs in sunny regions. Other ways of balancing the grid, with a new demand from ERS, could be not to use the EV batteries but stationary batteries. However, large amount of stationary batteries (with only the purpose of balancing the grid) will be costly. See [7] for a more extensive description of the results.

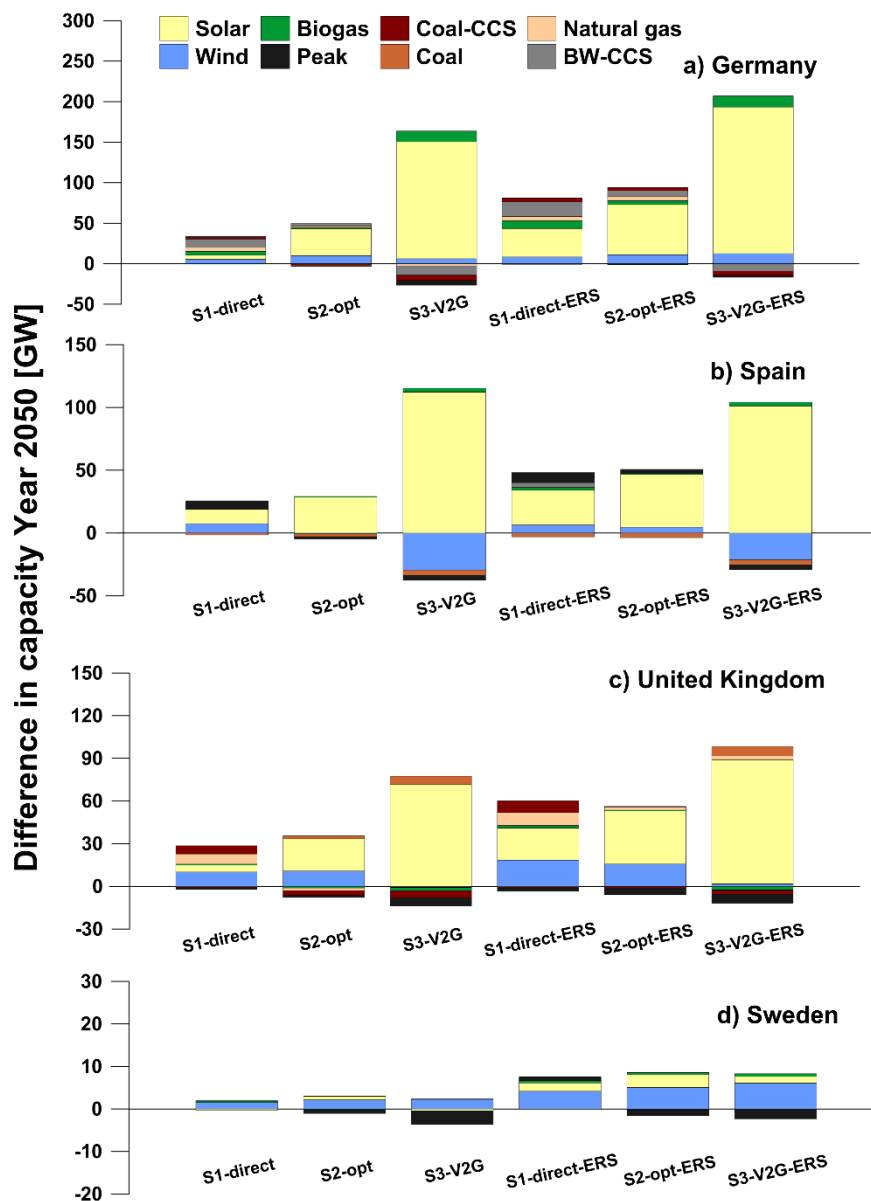


Figure 10: The difference in capacity investments between a scenario without EVs and the different EVs scenarios investigated for (a) Germany, (b) Spain, (c) Great Britain and (d) Sweden. Opt= optimisation; CCS=carbon capture and storage; V2G=vehicle-to-grid; ERS =electric road system; BW= lignite co-fired with biomass. From [7].

The main output from the work on the link between the electricity supply system and an electrified transport sector are scientific publications, which are listed in section 1.5 (some of which are co-funded by other projects, such as the project Coastal Highway Route E39 funded by the Norwegian Public Roads Administration).

1.3.4 Local grid implications

1.3.4.1 Placement and sizing of substations

The electricity and power demand for a road, as well as, a road network is presented in section 1.3.1. As concluded in section 1.3.1, the electricity demand varies a lot both geographically and between hours of the day. For example, for E6, the largest hourly peak identified was 3.86 times more compared to the average demand. Some of the municipalities will see a significant increase in electricity demand along E6. This will of course also be important when analysing the impacts on the current electricity grid and for the dimension of a reinforcement of the grid. Since information on the capacity and load of the current regional and local grid are classified data such data could not be obtained along the E6 road. However, we have made some estimates of possible ways to place transformer stations along E6 in order to supply an ERS.

Three different cases of placing substations along E6 have been investigated and the cost of these three have been compared. The three cases are:

1. A substation is placed every 40 km as proposed by Vattenfall AB in Olsson et al. [8]
2. Use existing grid as much as possible to reduce costs
3. Cost optimized according to the geographical load of the road

Figure 11 shows the placement of the substations using the three cases presented assuming a 100 % electrification of the heavy traffic on E6.



Figure 11: The placement of substations along E6 assuming a substation every 40 km (left), optimization according to load (center) and using existing grid to as large extent as possible (right). All cases assume 100 % electrification of the heavy vehicles using E6.

The suggested substation placement based on Vattenfall's proposition of a substation every 40 km gives 12 substations in total (see Figure 11 left) with a peak demand per substations between 15 and 52 MW. The total cost is then 1 100 MSEK (273, 251 and 588 for substations, transformers and cables, respectively).

If instead using the existing grid of 23 substations (see Figure 11 center), the maximum peak power demand per substation will be between 4 and 33 MW. If existing substations and transformers are assumed to be used, only the cost of the cables (about 589 MSEK) would be applicable to this case, making it considerably cheaper than the other two ways. However, if new substations and transformers are being built the total cost far exceeds the costs of the other cases. Most likely not all of the current substations along the E6 are fully occupied, but there was no information on the capacity and load of the current substations.

A cost optimization of the placement and size of the substations gives instead only 9 substations with a maximum capacity of 48 MW per substation (Figure 11 right). The total cost for cables, transformers and substations ends up at 1 000 MSEK as seen in Figure 12. It should, however, be noted that this work does not take into account the losses along the cables along the road, i.e. once the electricity has been transformed down to the voltage level of the ERS. This may be an important limitation since losses increases with a reduction in voltage level. See below (section 1.4.1 for a discussion on this).

Figure 13 shows the cost for substations, cables and transformers for the three cases, as well as, for three different electrification rates of the heavy traffic (40 %, 70 % and 100 %).

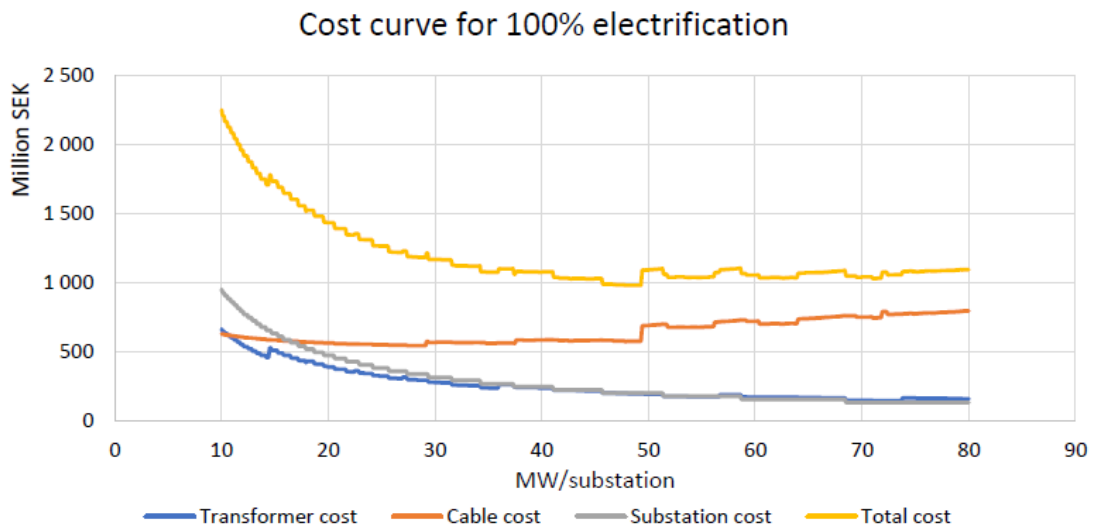


Figure 12: Cost curve of substations, cables and transformers based on substation size for 100% electrification of heavy vehicles on E6.

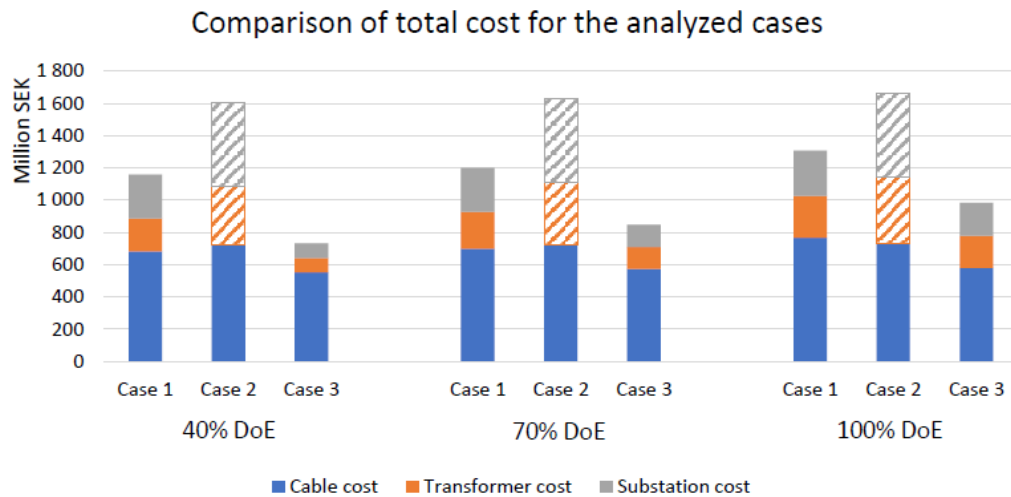


Figure 13: Total cost (substations, cables and transformers) for the three cases analysed and for three electrification rates (DoE) 40 %, 70 % and 100 % of the heavy traffic. The patterned part of the bars represents the potential savings that can be made from using existing infrastructure.

The main conclusions are that if a new electricity grid has to be invested in (i.e., not connect to the local grid), it should be economically better to place the substations based on the geographical load distribution of the road. The reason for this is that the substation dimensions as well as cable length and size is then optimized. Another conclusion from the work is that the peak demands of the ERS are very high compared to the average. As the dimensions of the required equipment needs to be dimensioned for the peak demands in order to supply electricity at all times, the peaks in traffic demand is an important factor when calculating the investment costs of the electricity supply system to the road. The development of the traffic over time, as well as new electricity demands on the grid, needs to be accounted for already in the planning phase of an ERS.

The costs for ERS obviously need to be distributed on the vehicles that traffic such road. It should be kept in mind that the infrastructural costs are a mix of costs dependent on the length of the road as well as discrete costs, for example costs for standardized substations. Thus, Figure 14 illustrates a schematic cost model describing expected cost per vehicle as a function of ADT. The costs for substations in discrete steps when the increase in ADT requires an additional substation to be added. The cost for every new substation per vehicle drops as the ADT increase until a new substation is required.

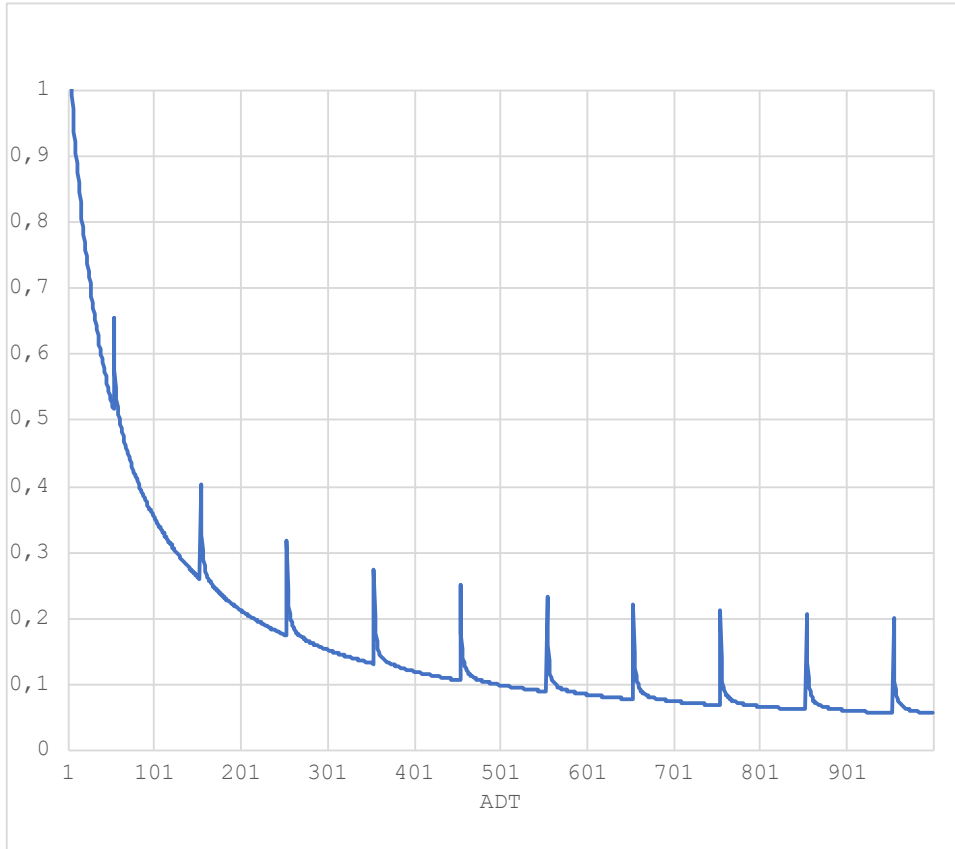


Figure 14: Cost distribution (in MSEK/AADT) for ERS along a road stretch.

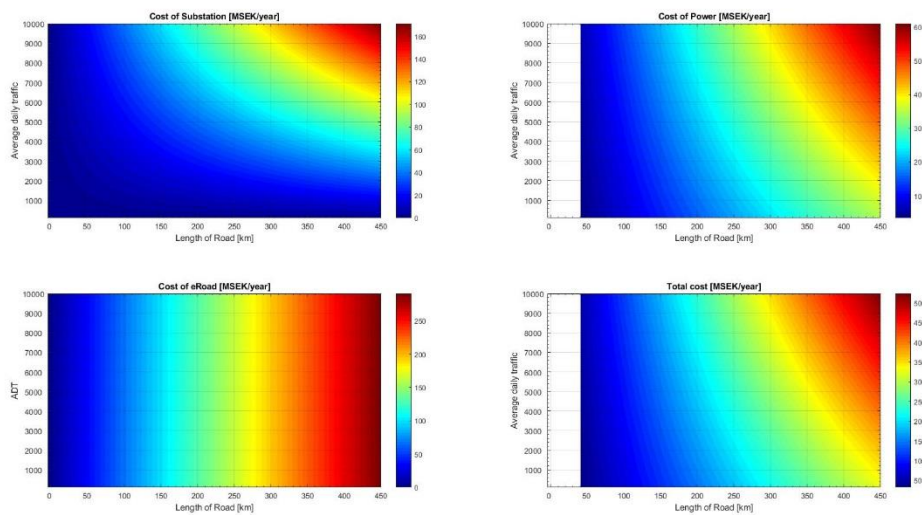


Figure 15: ERS cost co-dependency length of road and traffic volume.

Furthermore, costs arise both due to electrifying longer roads as well as due to larger traffic volumes. Figure 15 indicate how costs depend on both length of road and traffic volume.

1.3.4.2 Cable efficiency losses

Using an ERS with a DC-voltage of 700 V means that power losses in the cables themselves can be substantial due to the high current required, as long as the cable is

long enough. For instance, if the ERS is to provide all the power required to drive a truck with a 300 kW engine, the peak current would be $300 \cdot 10^3 \cdot 700 \approx 430$ A. With a resistance of 0.2 Ohm per kilometre, this would mean that when the truck is 500 m away from the power station, the losses in the cable would amount to 36 kW which would be over 10 % of the power. As the ohmic losses are quadratic in the current, if the road is steep enough for a substantial amount of its length, by using the battery as a buffer, the peak power can be avoided and the overall energy required for transporting the truck along the road can be lowered by adding a DC/DC converter on the truck. Despite the fact that the DC/DC-converter would add additional power losses the overall energy consumption can be lowered due to the lowered peak current in the cables.

Figure 16 shows the power losses in the transmission cables and a more zoomed in view of Figure 16 is shown in Figure 17. The orange curve in Figure 16 shows when the ERS is used as a battery charger, providing constant power with the magnitude required for the truck to leave the E6 road at Svinesund with the same SOC as when it first started at Trelleborg. The blue curve in Figure 16 shows the same truck but where all the instantaneous power comes from the ERS. In this example, using the battery as a buffer leads to an energy saving of 4 % for the transportation between Trelleborg and Svinesund, while also allowing for smaller power stations along the road. It should also be noted that we have assumed that when only the ERS is used to provide the power to actively drive the truck forward the truck is not allowed to use regenerative braking.

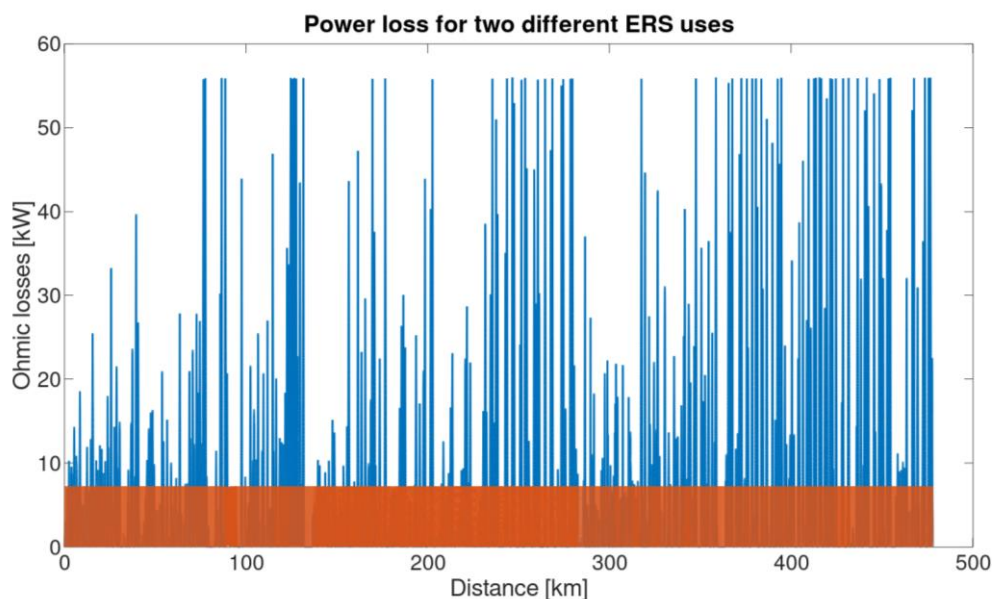


Figure 16: Power losses in the transmission cables of the ERS for a truck travelling along the E6. The blue curve shows the power losses for when the ERS is used as the sole power provider of the motor of the truck, and the orange curve shows the case where the ERS only provide the constant, time averaged power, required for the truck to leave the end of the road with the same SOC as when it started, and the battery is used as a buffer to handle the slopes. The power lines of the ERS are here assumed to have a voltage of 700 V, with a resistance of 0.2 Ohm/km and extend symmetrically (the same in both directions) 500 m from the transformer stations. Furthermore, regenerative braking has been disallowed unless the battery is connected.

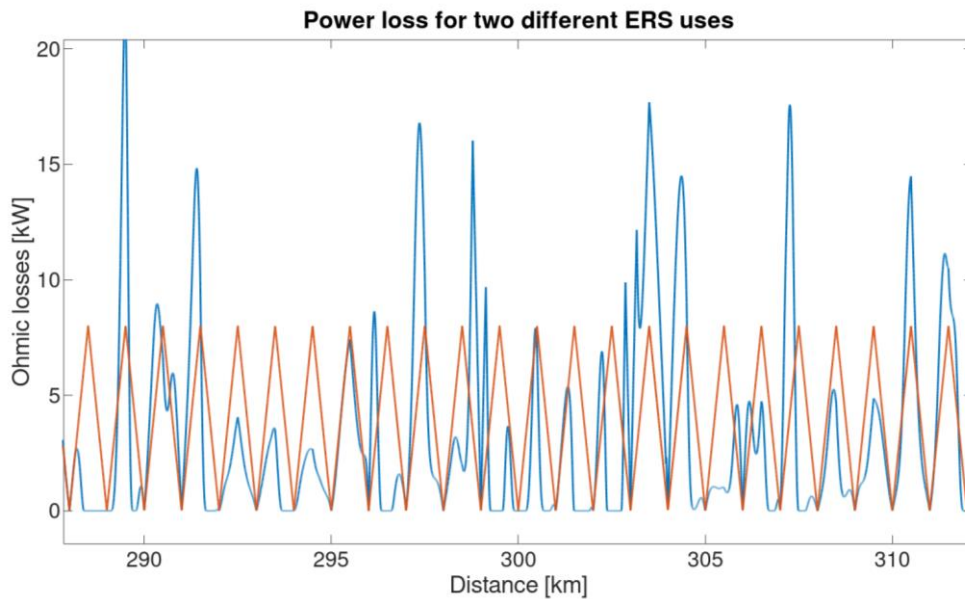


Figure 17: The power losses along the E6 in the northwards direction. The blue curve shows the power losses for when the ERS is used as the sole power provider of the motor of the truck, and the orange curve shows the case where the ERS only provide the constant, time averaged power, required for the truck to leave the end of the road with the same SOC as when it started, and the battery is used as a buffer to handle the slopes. The triangular shape of the red curve is due to the distance to the transformers growing linearly, then decreasing linearly as the truck changes to a different road segment and starts to close in on the following transformer.

1.4 Reduced CO₂ emissions

The reduction in CO₂ emissions from burning less fossil fuels depends on the amount of the transport work that is covered by the ERS, the emissions from the electricity system, as well as, from building the ERS. Emissions from construction of the ERS and materials are not included in this study. However, the environmental impact of ERS will depend to a large extent on the technology mix used to generate the electricity required to power an ERS.

Assuming no emissions from the electricity supply, Figure 18 shows the shares of E- and N-road lengths with ERS and the corresponding road traffic CO₂ emissions from E- and N-roads, as well as, the corresponding share of the national road traffic CO₂ emissions. It is clear that there is a step reduction in CO₂ emissions with road share until approximately between 20 % and 40% of the road length is covered by ERS, for both light and heavy vehicles. An ERS on all E- and N-roads covers would save 40 % and 70 % of the total emissions from light vehicles and heavy vehicles in Sweden, respectively [5].

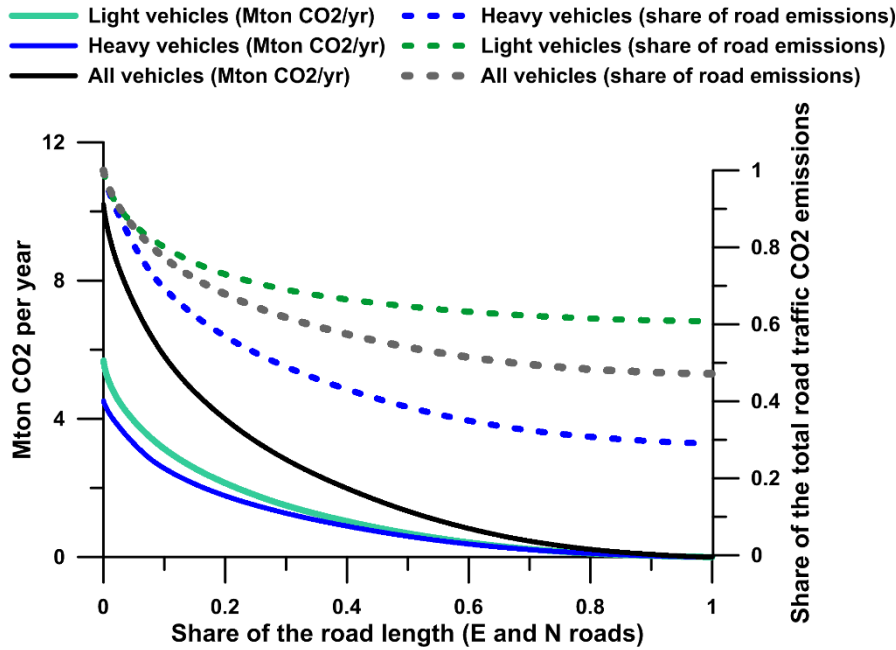


Figure 18: Shares of the European and National road (E- and N-road) lengths with ERS and the corresponding road traffic CO₂ emissions from E- and N-roads, as well as, the corresponding shares of the total national road traffic CO₂ emissions for all, light and heavy vehicles. The reference level on emissions were obtained from today's emission levels [5].

As mentioned above, the amount of emissions that can be reduced depends on the electricity mix. There has been an ongoing debate in recent years about the climate impacts from EVs, some arguing that the real carbon footprint of EVs can be as high as conventional vehicles. This may be the case if assuming coal power on the margin, .i.e. that any additional electricity demand (such as from ERS) will be produced by coal-fired power. However, this is hardly relevant since the electricity system must be transformed to meet climate targets and is typically considered the sector which is the least challenging to transform. Thus, in order to determine the climate impact of EVs and ERS on the long-term, it is not sufficient to use statistics for the average CO₂ emissions, or the marginal electricity production, of the current electricity system. As described earlier, we have modelled the electricity systems of several European countries (e.g., Germany, Sweden, Norway, Spain, UK, Ireland, France), starting with today's electricity system and reaching close-to-zero emissions in year 2050. The modelling in Taljegard [6] takes into consideration the changes in electricity production that are due to electrification of the road transport sector (i.e., charging of EVs and ERS). Figure 19 shows the total CO₂ emissions (Figure 19 a) and the CO₂ emissions per unit of electricity generated (Figure 19 b) from the electricity system between 2020 and 2050. The results in Figure 19 are obtained from the investments model ELIN assuming close-to-zero CO₂ emissions in year 2050 [6].

The results obtained from the modelling show that the total CO₂ emissions from the electricity system, as well as the CO₂ emissions related to the charging of EVs and ERS are, of course, expected to decline in all regions over the coming decades when meeting the climate targets. However, some regions with already low levels of emissions, such as Sweden, Ireland and Norway, will reach the target of CO₂ emissions in the electricity system prior to the target dates. It is reasonable to suppose that the electricity generation system must be decarbonised if the world is developing in line with the Paris

Agreement and, thus, the carbon intensity of the future electricity generation should be in line with the use of EVs to reduce emissions from the transport. Thus, assuming that the successful ramping up of both EVs and ERS will likely take several decades to reach a significant penetration level, its associated emissions will be strongly linked to the future electricity system, which, as pointed out above, will also have to be transformed over the same period.

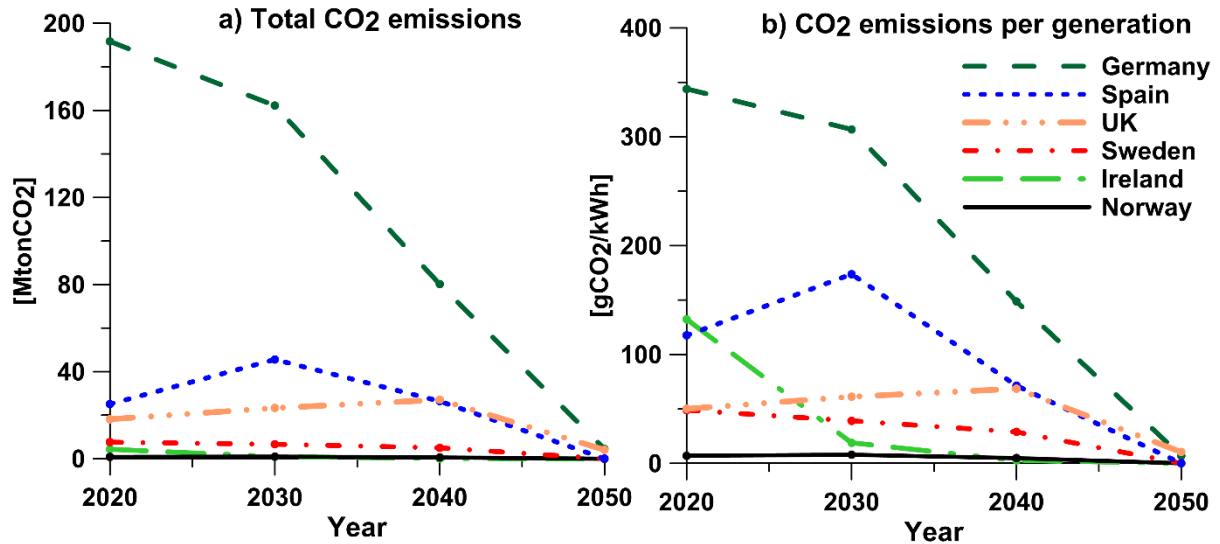


Figure 19: Total CO₂ emissions per year (a) and the average CO₂ emissions per generation unit from the electricity systems in different countries, as obtained from the runs with the ELIN model, assuming a target of 99% reduction of CO₂ emissions by year 2050, as compared to year 1990. The model run is without EVs, and the target for CO₂ emissions is constrained as one goal for all regions (i.e., not country-specific targets) [6].

1.4.1 Outlook for further studies

The chapter has explored important aspects of ERS, including the power demand, which roads are beneficial to electrify and the corresponding CO₂ mitigation potential, required investments in new electricity generation capacity for different ERS and EV charging strategies and the ERS impact on the regional grid. There are, of course, a number of other aspects of the electrification of the road transport sector through ERS and its implications for the electricity system that need to be studied further. In particular the following should be of interest for further studies:

- A more detailed analysis of the ERS impact on regional and local electricity grids. Such a study could include a cost analysis of the whole grid network comparing different charging strategies of passenger vehicles and ERS.
- A study of the factors determining the willingness of the vehicle owners (cars, trucks and buses) to use an electric road system in the future.
- It would be interesting to analyse the outcomes from ERS being used as a variable in the model for passenger cars (i.e., the model can choose if it is more cost efficient to use static charging or the ERS). This combined with a study from the passenger car perspective to answer when it is most beneficial to use the ERS.

1.5 Publications

Taljegard, M., Thorson, L., Odenberger, M., & Johnsson, F. (2019) Large-scale implementation of electric road systems: Associated costs and the impact on CO₂ emissions. *International Journal of Sustainable Transportation*, pp.1-14. [1]

Taljegard, M., Göransson, L., Odenberger, M., & Johnsson, F. (2019) Impacts of electric vehicles on the electricity generation portfolio - A Scandinavian-German case study. *Applied Energy*, 235, 1637-1650. [2]

Taljegard, M., Göransson, L., Odenberger, M., & Johnsson, F. (2019) Electric vehicles as flexibility management strategy for the electricity system - A comparison between different regions of Europe. *Energies*, 12(13), 2597. [3]

Jelica, D., Taljegard, M., Thorson, L., & Johnsson, F. (2018) Hourly electricity demand from an electric road system – A Swedish case study. *Applied Energy*, 228, 141-148. [4]

Taljegard, M., Göransson, L., Odenberger, M., & Johnsson, F. (2017) Spatial and dynamic energy demand of the E39 highway – Implications on electrification options. *Applied Energy*, 195, 681-692.[5]

Taljegard, M. (2019) The impact of an Electrification of Road Transportation on the Electricity system in Scandinavia. Doctoral thesis. Chalmers. [6]

Grahn, M., Taljegard, M., & Brynolf, S. (2018) Electricity as an energy carrier in transport – Cost and efficiency comparison of different pathways. Electric Vehicle Symposium 31. Kobe. Japan. [7]

Thorson, L., Taljegard, M., Odenberger, M. and Johnsson, F. (2017) Electric road systems in Norway and Sweden – impact on CO₂ emissions and infrastructure cost. 1st Electric Road Systems Conference 2017. Gävle. Sweden. [8]

Taljegard, M., Goransson, L. and Odenberger, M. (2018) Impact of electric road systems on the Swedish-German electricity mix. 2nd Electric Road Systems Conference 2017. Stockholm, Sweden. [9]

Jelica, D., Taljegard, M., Thorson, L. & Johnsson, F. (2018) What is the hourly electricity demand for an ERS? – Swedish case study. 2nd Electric Road Systems Conference 2017. Stockholm, Sweden. [10]

Taljegard, M., von Bonin, M., Olovsson, J., Ernst, B., Gerhardt, N. and Johnsson, F. (2019) Impact of implementation of ERS on the German and Swedish electricity system. 2nd E-Mobility Power System Integration Symposium 2019. Stockholm. Sweden. [11]

Jelica, D. (2017) The effect of electric roads on future energy demand for transportation- A case study of a Swedish highway. Master Thesis. [12]

Taljegard, M., Goransson, L., Odenberger, M. and Johnsson F. (2018) Elbilars klimatnytta – Kan vi nå klimatmålen med elbilen? Transportforum 2018. Linköping, Sweden. [13]

Taljegard, M. and Johnsson, F. (2019) Behöver personbilar elvägen eller behöver elvägen personbilar? Transportforum 2019. Linköping, Sweden. [14]

2 Environmental impact

The work in this work package is a review of possible environmental effects resulting from the introduction of electric roads. The review has considered factors such as air quality and noise. The main findings from the literature review are presented below. Further elaboration is found in the full report Environmental Impacts of Electric Roads – A Literature Review. This part of the literature review has been done in cooperation between Yvonne Andersson-Sköld, Fredrik Hellman, Anders Genell Mats Gustafsson, Lina Nordin and Georg Tschan at VTI. The authors are also grateful to Mikael Carlson at Elsäkerhetsverket for constructive input on the work.

2.1 Scope

The major environmental benefit of electric roads, and electrical vehicles in general, are that the exhaust emissions of both carbon dioxide and other air pollutants such as nitrogen oxides, particulate matter, carbon monoxide and volatile hydrocarbons are reduced. This implies that despite how electricity is produced, there are no exhaust emissions to the environment during operation. Therefore, electricity is always preferable in urban environments. The overall impact of electricity on carbon dioxide depends, however, on how the energy is produced as well as on used raw materials.

A disadvantage of ordinary electric vehicles is that the batteries are large and heavy which not only requires more space but also other, and more rare natural resources, for its production, and more energy when in use. The heavier batteries, and thereby heavier vehicles, also contribute to increased surface wear in comparison to conventional vehicles. Electric road systems are, therefore, an option to reduce these negative effects by being able to charge the vehicles during operation. Since charging and power transfer can occur during operation, the size of the batteries can be reduced, which makes vehicles lighter and less expensive. This also reduces the impact on the environment due to the less need of rare metals and other raw materials in the production of batteries.

Potential new environmental impacts are related to the need of new road constructions and the electromagnetic fields that might be generated. The main environmental impacts studied are the effects of electromagnetic fields, differences in particle formation and noise between conventional roads and electric roads.

2.2 Activities

- Presentation of WP 2 and WP3 at Transportforum, Linköping, January 2018.
- Presentation of WP 2 and WP3 at Transportforum, Linköping, January 2019.
- Change of working group from Sara Janhäll and Anna Flodin to Yvonne Andersson-Sköld, Fredrik Hellman, Georg Tschan and Mats Gustafsson 2018-03-01.
- Change of working group to Lina Nordin, Fredrik Hellman and Anders Genell 2018-10-01

- Literature review
- Literature review of LCA studies related to ERS or similar concepts.

The results presented below were achieved through a literature review that focused on the following tasks related to environmental potential effects of electrical roads:

- Potential differences in material use between different ERS concepts
- Potential effects caused by the electromagnetic field with special emphasis on human effects and hypersensitivity
- Potential differences in particle formation between conventional roads and electric roads in the road environment
- Potential difference on noise between conventional roads and electric roads in the road environment

2.3 Results

The environmental impact of ERS depend on different aspects such as materials used, the robustness of the technique, how much and how fast the material will wear down.

The obvious improvement an ERS would have, when comparing to conventional roads with combustion driven vehicles, are the local reduction of greenhouse gas emissions. With no combustion engines there will be no emissions of greenhouse gases or particles from the combustion of fossil fuel. But how about other environmental impacts? This section of the report will describe material usage and particles, noise emissions and electromagnetic fields.

2.3.1 Material use

Each of the ERS techniques considered in Sweden are under development, and to understand how much material that in the end will be needed is difficult. Questions have been asked to both test sites eHighway and eRoadArlanda since they have already installed their techniques. The eRoadArlanda project was helpful and let us know about what materials that was used but they also mentioned to keep in mind that the technique is under constant development.

Their rail is made from steel with the dimensions of about 0.148 m × 0.144 m, and apart from that, drainpipes are used as well as different sizes of aggregates and asphalt mixtures. The pick-up consists of plastic, and metals, such as copper, steel and aluminum.

When it comes to eHighway the answers come from reports written during the startup phase of the demonstration site. The overhead cable carrier was made of bronze; copper and magnesium, the contact wire also seems to be made from copper and magnesium, while the pantograph is made from steel and fiberglass plastics. The poles are made of galvanized steel and have foundations of concrete. The poles are 12,5 meters high with a cantilever reaching out eight to ten meters, over the road. The diameter of the poles used in the Swedish test site are 0.57 m. One pole is used every 50 – 60 meters. Depending on where the ERS is to be installed, there might be needs for

extra safety rails to protect road users from running into the poles if driving off road for some reason.

The materials used in the different ERS techniques are mainly the same and if comparing between two or more different concepts, it is the amount of materials used that will be of greatest importance.

A quick calculation can be made using the cases of the catenary solution of E16, eHighway and eRoad Arlanda in Sweden. The poles of the catenary solution are estimated to be 12.5 m tall and 0,57 m in diameter giving a total volume of 3.2 m³ not counting the cantilever or safety rails. One pole is used every 50 meters. The dimensions of the rail solution on eRoad Arlanda are about 0.148 m × 0.144 m, giving a total volume of about 1 m² over a road stretch of 50 meters, which would be comparable to the one pole of the catenary solution every 50 m. The rail concept will possibly not need extra safety rails.

This simplified calculation has left out several parts but still illustrates the large difference in material use between the two different techniques. Hence the question regarding amount of materials used will be important when it comes to environmental issues.

2.3.2 Inhalable wear particle emissions from electric roads and vehicles

Airborne inhalable particulates is a general health problem that has been highlighted in recent years [15]–[20]. Primarily, cars and other road traffic are major sources to these particles but emissions also origin from trains and other rail bound traffic. Particularly high concentrations from trains can be achieved at station areas in connection with braking and in enclosed spaces such as tunnels. On roads, it is the suspension of dust and gravel from winter road maintenance that causes the highest emissions. Also, exhaust particles, mainly from diesel engines, contribute. On a local level, there may be high concentrations during certain days with heavy traffic, strong particle sources and bad ventilation.

This literature survey focuses on highlighting information about how the ERS-Electric Road System and its vehicles contribute to particle emissions. Electric road systems where the vehicles are operated, or charged, through direct transmission of electricity via conductive transmission through physical contact with wires or through wireless induction. Conductive transmission is well-established technology for trains and tramways. Therefore, knowledge from particle emissions from rail and tramway combined with road traffic knowledge can be applied to the ERS roads. The literature review has focused on conductive transmission that is very similar to train traffic and other electrical rail bound traffic.

2.3.3 Airborne particles - a background

In principle, all human activity creates air pollution of various kinds. During the last century the concentrations of harmful air pollutants increased dramatically in comparison to pre-industrial concentrations. Air quality has generally improved in Europe by reducing emissions of hazardous substances such as NO_x, NMVOCs, and

SO₂ the last decades and also in comparison to the 2010 levels [21]. Although, the decrease is not at a needed and desirable rate due to an increased traffic. The trend of reduced emissions does, however, not apply to inhalable small particles which instead in general increase, and today are considered a major health problem [21]. High concentrations of small particles are often found in many large urban areas along busy roads but also in metros and train stations [22]. The particles consist of exhaust particles and non-exhaust particles from brakes, surface, tires and dust from large urban areas by the side of the roads.

The vehicle emissions of exhaust particles has, as with other vehicle exhaust emissions, been significantly reduced since the introduction of particulate filters in diesel cars [23, pp. 270–282] in contrast to the non-exhaust sources. One estimate is that non-exhaust related particles account for more than 90% of the road and traffic related particles less than 10 µm [24]. Trains and rail bound traffic and other activities contribute as well as natural sources (e.g. airborne dust from deserts, dry soils and construction sites). In Sweden, the suspension of dust from winter maintenance activities and wear from studded tires is an important source of dusting during the winter season [25], [26].

The particles are often denoted as PM (particulate matter) and usually mentioned as PM₁₀ and PM_{2.5}. PM₁₀ consists of solid or liquid particles less than 10 µm and PM_{2.5} of particles less than 2.5 µm. As a result of the awareness of the dangers of these particles, the EU has set out directives on how high concentrations are accepted [27], [28]. Under these directives, outdoor concentrations of PM₁₀ may exceed 50 µg/m³ for 35 days in a year and the mean value may not exceed 40 µg/m³. For PM_{2.5} the concentration must be lower than 25 µg/m³.

Airborne particles are identified with several serious health risks. Many epidemic studies show several different types of adverse health effects such as early death, heart and lung diseases, negative effect on infant's lung development, increased asthma, chronic obstructive pulmonary disease [29]–[33]. The properties of the particles may vary and depend on its source and on chemical and physical processes that interact during the suspension time. The hazardousness of the particles depends not only on mass concentration in the air but also on its size, chemical composition morphology and surface properties. Particles from combustion are generally very small (a few 100 nm or less) and consists of different kind of organic compound whereas non-combustion particles generally are larger and consist of minerals and metals. The health aspects can therefore be different.

The particles dealt with here are non-combustion in origin. The effect of particles in sizes 2,5-10 µm have in epidemical studies been shown to have negative effects on humans with airway deceases, but also increased acute mortality in connection to high pollution levels [34]–[37]. In toxicological studies (e.g. [38]) it has been shown that non-exhaust particles from subway traffic often are dominated by metals, mainly Fe (iron). In cell studies these particles induce more DNA damage than mineral dominated wear particles from road pavements. On the other hand, wear particles from road pavements have been found to induce higher inflammatory response [38]–[40]. There are also studies in the underground metro environment that indicate that negative health problems caused by particles emitted in there are not large at the observed concentrations [41].

Another aspect that is important with regard to exposure and consequent health impacts is the nature of the site. If the source is in a closed room such as a subway, this means that the concentrations may be higher than in an open space since the existing air volume is more limited. Similarly, buildings, ceilings and trees can limit the available air volume, and dispersion, and aggravate the situation near the source that generates the particles. Also, humidity, rain and wind can affect the amount both negatively and positively. Dry environment allows the recirculation and dusting of particles to increase, while moist road paving reduces emissions [42]. The speed and size of vehicles also affect the amount of particles that recirculate [42]. The smaller particles can stay suspended while larger and heavier particles fall down to the ground. An example is African desert dust that is carried by the wind and provides elevated PM10 values around the Mediterranean [43]. In addition, the particles are recirculated and transported.



Figure 20: An eHighways truck with current collector on pentagraph and overhead lines.

2.3.3.1 Possible sources of airborne particles related to electric road systems and vehicles

Electric road systems (ERS) can contribute to emissions of PM10 particles. The identified places are 1) the contact between the current collector (pantograph) and the overhead lines (or tracks), 2) brakes and other moving parts, 3) tires and road surface.

Vehicles operating on ERS roads are like regular trucks but have engine and powertrain systems more similar to rail bound electric traffic. The vehicles will be charged either through a current collector on the roof (Pantograph) connected to overhead lines (Figure 20) or a current collector under the vehicle to take the power from a ERS track in the road [44], [45].

Current collectors and overhead lines degrade with time because of the physical contact between them. The wear is both mechanical and electrically induced. These are

inversely correlated to the contact pressure to the overhead line. Small particles are emitted when wear occurs but can be lowered by using optimized contact pressure. ERS systems using a current collector (pick up) under the vehicle in a track have similar wear of both track and pickup.

It is probable that the wear will be faster on a busy ERS road as these systems (fully developed) will have a higher vehicle density that collect electricity than a corresponding train system with one locomotive carrying many cars. In practice, the number of particles emitted from overhead lines, ERS tracks and current collectors will therefore probably be higher. The emitted particles will also consist of metals that correspond to the materials in the used conductor materials. The current collectors (pantographs) are made of graphite (C) and overhead lines are in copper (Cu) (eHighway, 2018).

When it comes to wear from the electric current collector in the road, it is even more uncertain as these systems are in the experimental stage. The ERS tracks in the road are made of steel and the current collector consists of plastic, and metals, such as copper, steel and aluminum [44], [45]. It is also uncertain how the dispersion will occur as the vehicle creates turbulence when it runs, and the particles swirl around. However, it is a big difference between train traffic and planned ERS roads for freight traffic.

Particle measurements made on train traffic e.g. [22] in tunnel or station environment are relatively closed spaces with limited air volume whereas road freight traffic is planned along the major motorways, preferably in rural areas. Therefore, particle dispersion will be over a reasonably large area and at lower concentrations. If the systems will be used for example by buses in the urban area, there may be greater risks but the number of buses that operate these routes will still be limited.

Particles from brake pads of train and rail traffic are an important source of particle emissions at station areas [22], [46]. Also, for heavy and lighter road vehicles, the brakes are a major source of particle formation. It has been found to constitute between 16- and 55 % by weight of the non-exhaust PM₁₀ particles and 11-21 % of the total PM₁₀ emissions [47]. In urban areas with frequent braking the contribution can be as much as 55 wt% of all PM₁₀ non-combustion particles [47]. However, this proportion is considerably smaller for rural roads and highways with steady speed and less braking. These are the kind of roads where electric roads primarily are going to be implemented. At road exits and other places where braking occurs, the emissions may also be high [42]. For trains with electromagnetic brakes, particle emissions are lower [46].

Another source of particles relevant to all road traffic, including electric roads is tire wear. Emissions of PM₁₀ from tires are estimated to 2.4-13 mg/km for cars [48]. These particles may contribute to both pollution of air and may also contribute as a source of microplastic [49]. It is not known if these emissions are affected by the introduction of electric roads. Electric vehicles (battery powered) are often heavier which make the emissions of wear particles higher [24]. With the introduction of ERS such wear could possibly be reduced as the batteries will be smaller and less heavy.

Resuspended dust is often identified as the main particle sources to PM₁₀ emissions [50], [51]. The dust consists mainly of wear particles from road surface, tires and brakes created from vehicles that traffic the road or dust from sources nearby the road (e.g. building activities, bare soils and gravel roads).

In Sweden and other northern countries, wear caused by studded tires and materials from winter road maintenance is found to be a significant source [22], [52], [53]. The direct emission from studded tires wear cannot be assumed to differ on an electric road compared to a normal road, unless special surfacing materials are used with other properties than conventional road materials.

A main difference between conventional roads and vehicles is that electric vehicles do not emit exhaust particles from internal combustion engines and in particular NO_x from diesel vehicles. During the last decades, however, the EURO vehicle emission standards have resulted in successively improved particle filters which have reduced the exhaust related particle emissions from both light and heavy-duty vehicles. To be able to provide information on particulate emissions from electrical roads and its vehicles, measurements must be made. These measurements should then be designed in a way so that it is possible to compare with combustion motor vehicles in the same road environment.

Particle emission – Electric road techniques contribute to emissions of PM₁₀ particles in three different ways 1) the contact between the electric current collector and the conductor, 2) brakes and other moving parts, 3) tires and road surface.

The pantograph and wire are worn from vehicles using the system and small particles mainly from iron are emitted. From studies on railway and in subways it is shown that largest concentrations of particulate matter are found in closed areas such as in subways or in train stations. This implicates that it might not have such large effect in open rural areas where the air is circulated.

Particulate matter coming from the contact between the current collector and the in-road rail is unknown and measurements are required.

An obvious difference from conventional roads and vehicles is that there are no exhaust particles from the combustion in electric vehicles. The effects on the particle emissions (PM₁₀ and PM_{2.5}) are however unclear as the successively improved particle filters used in cars in recent years have reduce the exhaust related particles from conventional vehicles. Measurements are needed to be able to compare particles from combustion motor vehicles and electric vehicles in the same road environment. Particulate mission from brakes, tires and road surface of ERS systems correlate with the weight of the vehicles and therefore thought to be similar to conventional combustion vehicles.

2.3.4 Electric roads and noise

Traditional ICE vehicles have essentially three sources of noise: the drive train, the tire-road contact and aerodynamic noise. Supplying electricity to the vehicle through the infrastructure may remove the drive train source, provided the propulsion is fully electric. There are, to our knowledge, no studies about electric roads and the impact on noise levels or how it affects the experience of noise, but the vehicles utilizing an electric road is in essence an electric vehicle, and there are a few studies on noise and electric cars. Within the European *Electromobility+* research framework, one work package of the COMPetitive Electric Town Transport (COMPETT) project lead by the Danish Road Directorate included both a literature review [54] as well as results from own measurements in urban environments [55]. The literature review points out that there may be great opportunities to reduce noise by replacing ordinary internal

combustion engines with electric power, but that there are still considerable uncertainties about the extent of this potential [54]. There are major differences in the outcome between different studies, and the outcome depends on how and where the study was conducted. This depends, for example, on speed, acceleration and braking, as well as the type of tire and road surface.

Often the conditions of the reported studies were not fully documented with regard to the type of vehicle, tires or road surface. Common for most studies however is that it is mainly at low speeds the noise reduction potential can be relatively large [55], which was also supported by calculations using the traffic noise prediction calculation model Nord 2000. Their own measurements was done at a parking space with dense graded asphalt concrete with soft binder, located so as not to be affected by noise from other traffic, with four different vehicles: Citroen Berlingo, conventional, fitted with Michelin Agilis 51 tires (71 dB); Citroen Berlingo, Electric, with Michelin Energy saver tires (69 dB); Nissan Leaf, Electric, with Michelin Energy saver tires (70 dB); and VW Golf conventional, with Michelin Energy saver tires (70 dB). In this study, it was found, in accordance with the predominant results in the literature review, that it is at low speeds the electric car contributes to lower noise than conventional vehicles.

The conclusion of the study is that at low speeds, up to about 30 km/h, the sound emission from electric vehicles is significantly lower than from conventional vehicles. At higher speeds, the road/tire sounds completely dominate [55], [56].

In general, it can be inferred from the literature review as well as from the measurements that the difference in noise level between ICE vehicles and fully electric vehicles is negligible at speeds above 30 km/h for most prevalent road surface conditions. At higher speeds, the tire-road interaction dominates the radiated sound. For an extensive description of tire-road noise mechanisms, see e.g. [57]. It should be noted that the conclusions from the literature review and the measurements mainly concern passenger vehicles and not heavy trucks or buses.

For higher speeds there would still be a possibility to reduce noise emissions from electric roads compared to conventional ICE traffic, by applying low noise road surface materials on the electric road. Since the dominating source of noise from traffic at the speed range relevant for electric roads is tire-road noise, the lack of drive train noise makes applying low noise road surface materials particularly efficient.

As for aerodynamic noise, it will mainly occur at higher speeds where turbulent flow starts appearing around edges of the vehicle body. For electric roads, there is a possibility that equipment such as a pantograph on a vehicle might cause increased aerodynamic noise. There are no studies for electric road use, but there are plenty of studies on aerodynamic noise from trains. In a study on potential noise issues in a future development of high-speed trains in Sweden, a simple model for aerodynamic noise from the pantograph was presented [58]. In short, the contribution from the pantograph was mainly valid at speeds above 150 km/h, and this is also corroborated in modern noise prediction calculation models where aerodynamic noise from trains is disregarded below 200 km/h. Hence, the contribution of aerodynamic noise is likely to be small for a vehicle on an electric road. Other technical solutions such as a pickup sliding on a rail in the road to supply electricity is an untested system but might be more related to the rolling noise of a train and may contribute also at lower speeds.

All vehicle types within European Union need to be approved according the UN-ECE Regulation No. 51 - *Uniform provisions concerning the approval of motor vehicles having at least four wheels with regard to their sound emissions*. The regulation specifies the noise levels to be met as well as under what conditions measurements are to be made regarding tires, road surface, vehicle load and driving conditions. The regulation does not take the existence of electric roads or the associated vehicle mounted equipment into account. It is very likely that with a wide adoption of electric roads the regulation will take these issues into account, which points to the need for developing measurement methods and driving conditions to capture noise from vehicles on electric roads. This is particularly important for heavy vehicles, as there are very few studies performed on noise from fully electric or hybrid electric heavy vehicles.

2.3.5 Electromagnetic fields

Electromagnetic fields (EMF) are a common source of interest when it comes to electric devices, techniques or solutions. The concerns regarding EMF in ERS is of course also of huge interest in a work package that should consider all environmental aspects of ERS.

EMF consists of two components, the electric fields that are induced from electrical power, and the magnetic fields that are generated when the electric fields are moving, creating a current. Electric fields exist whenever there is an electric voltage present even though there is no electrical current flowing in the cable, while the magnetic fields are only induced when electrical current is flowing, such as when the lamp is switched on.

2.3.6 EMF effects on human health

The European Commission have produced a guide for good practice concerning electromagnetic fields and workplaces, to help implementing the Electromagnetic field directive 2013/35/EU [59]. They have differentiated between direct and indirect effects of EMF. The direct effects mentioned are vertigo and nausea, effects on sense organs, nerves and muscles, heating of nearby human bodies. Indirect effects are interferences with medical electronic equipment as well as implanted medical devices or medical devices worn on body such as insulin pumps. They also list risk for fires, explosions from ignition of flammable or explosive material, electric shock or burns if someone mistakenly touches a conductive part within an electromagnetic field, as well as risks of initiation of detonators. The International commission on Non-Ionizing Radiation Protection (ICNIRP) did also mention such effects on human bodies in their guidelines for occupational and general public exposure to EMF [60].

In terms of electromagnetic fields generated from powerlines and electric vehicles the frequencies ranges in the extremely low frequency fields from 0 – 300 Hz. Bi et al. [61] mentioned several studies made on the effects on humans from EMF below 100 Hz. Such effects are annoyance, surface electric-charge effects and stimulation of central and peripheral nervous tissues. Another possible effect is where electromagnetic fields induces waves that are experienced as a sensation of a flickering light in the corner of the eye. This disorder is called retinal phosphene visualization [62].

The World's Health Organization (WHO) have initiated an international electromagnetic field (EMF) project which aims at coordinating all international research regarding EMF and health effects. The research includes studies on cells, animals and human health [63]. 25 000 scientific papers over a time span of 30 years have been examined and according to WHO there is no evidence that exposure to low levels of electromagnetic fields are harmful to human health. However, long-term effects are not satisfactorily studied and further research is needed.

The project also aims at facilitating development of international standards for EMF exposure. The guidelines that are used today differ between different countries and a common view is preferable. The guidelines set by ICNIRP are according to WHO set in regard to when behavioral disturbances are detected on tested animals. The limitation values for the general public are set to 50 times lower than the limits when the disturbances in animals are detected. It is mentioned that exposure to EMF below the limits is safe to a scientific knowledge, not meaning that values above are harmful.

This is, however, still not enough according to the International EMF Scientist Appeal, a group of scientists from 43 different nations engaged in the study of biological and health effects of non-ionizing electromagnetic fields (EMF). In July 2019 they renewed the appeal which they sent to the Environmental Program of UN, UNEP, in 2015 where they ask for an independent multidisciplinary committee to further investigate alternatives to current practices with the potential of lower human exposures to RF (radiofrequency) and ELF fields. They further demand that children and pregnant women should be protected and that standards and guidelines should be strengthened [64]. They mean that several recent publications show that EMF is affecting living organisms at much lower levels than what is set in most existing national and international guidelines ([65]).

It is interesting to compare between the limits set by different organization. For instance, the ICNIRP and the Swedish Radiation Safety Authority have set a limit of 61 V/m or 0.20 μT (magnetic flux density) for mobile phone and WiFi, while the Bioinitiative.org (consisting of a group of 29 researchers from ten different nations, including three former presidents and five full members of the Bioelectromagnetics Society, BEMS) have set the same limit at 0.033 V/m (3 $\mu\text{W}/\text{m}^2$) [60], [66], [67].

The Bioinitiative have summarized a comprehensive report on how humans are affected by EMF [66]. They strongly suggest that the limits set by ICNIRP are outdated. Instead new limits should be developed and implemented. They furthermore suggest that meanwhile setting a planning limit of 0.1 μT for new or upgraded power lines, such as, for instance, will be used for ERS, and 0.2 μT for all other new construction.

In the home environment there are other aspects to consider, and people with cardiac implants are for instance to keep a safe distance from induction furnace [59]. This would further imply safety precautions when it comes to inductive ERS.

2.3.6.1 Electromagnetic hypersensitivity

Electromagnetic hypersensitivity has been reported since the 1980's and since then several studies have been performed. Rubin [68] investigated 31 experiments, including 725 patients with electromagnetic hypersensitivity. They concluded that even though the patients experienced symptoms that can be severe and disabling, the studies could

not prove that exposure to EMF can trigger these symptoms under blind conditions. Nevertheless, the symptoms remain and are experienced by the patients. Introducing an obvious and visually overwhelming sight of overhead lines will possibly trigger such symptoms on hypersensitive people.

The Resolution 1815 set by the Parliamentary Assembly of the Council of Europe, European Union [69] on “*The potential dangers of electromagnetic fields and their effect on the environment*” recommends that the member states should take measures to reduce the exposure to EMF. This should be done by reconsidering the limits set by ICNIRP, as they consider those limits having “serious limitations”. The limits should include both thermal and athermic or biological effects of EM emissions and radiation. The resolution, furthermore, emphasizes to put particular attention to electrosensitive people. People suffering from such syndromes should get special measures for protection including wave-free zones where no wireless networks are allowed.

When it comes to planning for electrical power lines, as such that could be expected with the introduction of ERS, it is important to plan such lines at safe distances from dwellings. The limits for relay antennae should be reduced and follow the ALARA principles (as low as reasonably achievable) and all antennae should be continuously and comprehensively monitored [69].

2.3.7 EMC

Electromagnetic compatibility, EMC is the concept that makes sure that electronics or electrical devices can operate in close proximity to each other without interfering. Basically, the EMC makes sure that the electromagnetic environment is not affected in such a way that it would impact the functionality of other devices. There are EMC standards and methods to make sure that all electronic devices are within limits [70]. It is important to understand that the emission limits in the EMC standards in CISPR (International Committee on Radio Frequency Interference) are foremost set to protect radio frequencies but other electromagnetic interferences are also discussed in subcommittees of CISPR. The impact on radiofrequency fields are further elaborated in the full report of this work [71]

There are so called EMC emissions which is the generation of unwanted electromagnetic energy. The emission levels need to be kept low and might have to be reduced if they interfere with other devices. It is also necessary to have some sort of immunity inbuilt within a device to make the radio transmitters less vulnerable to EMC-emissions. Other means of protection from unwanted electromagnetic signals such as EMI (electromagnetic interference) is to use EMI-shields, often composed from carbon materials such as carbon composites or colloidal graphite, to either reflect or adsorb radiation [72]. It is however important to mention that such shields are often the last way out and often tend to be a very costly solution. The most cost-efficient way is to consider EMC emissions in the development stage and thereby produce products with good circuit designs.

2.3.7.1 EMC in ERS

Each type of ERS technique would of course also need to follow the EMC standards but there might be unforeseen signals from the use of such a large-scale system. the size of the railway system. When it comes to standards, it is important to analyze the standard

in terms of what it originally was intended to be used for. Take for instance the example of optimizers for solar panels. They use the generic EMC standard for CE-marking but since the standard does not include DC (Direct Current) the optimizers might not fulfill the requirements in the standard. Other examples come from the use of several devices in a module where one device would reach the requirement but when put together, the emissions would exceed the limits of the standard requirements.

In the railway systems there have been reports of disturbances when trains for some reason might have to put in extra effort, in for instance up a hillslope [73], along rails that are damaged etc. Studies on trains have shown that such interference might cause the signalling system to malfunction and in worst case cause collision.

Unforeseen signals might occur during arcing or possibly in the on or off connection with the conductive solutions. There is, however, a lack of knowledge in these aspects of the ERS since it is such a new type of concept and since no technique have been tested in full scale. Further research is needed to understand where and how unwanted signals might appear as well as how they might interfere with other vehicles or equipment along the roads.

According to [73], electromagnetic disturbance stands for about 70% of all failures in the railway system. There might hence be an increased risk of malfunctioning information systems also within ERS, hence inventories regarding crucial information services along ERS potential roads are needed to understand how and what effect EMC emissions might have on the road safety.

2.3.7.2 EMI tests of ERS

Lindgren [74] tested EMI on one conductive ERS technique and found that EMI emissions would fulfil the requirements of EN 50121-2, but are just on the limits for fulfilling the CISPR 12. They could not find any concerning EMI levels below 10 MHz.

They also tested ERS short circuit through a tire and found that short circuit would only damage the tire locally unless it generated a fire inside of the pressurized tire. They, furthermore, suggested that if the tire was filled with flammable substances from canned tire inflators there could be risks for hazardous situations. Such effects could not be safely tested in their laboratory but should be further investigated in terms of large-scale implementations of ERS.

Kanz et al. [75] found that some of the advisory system models of automated external defibrillators (AED) often found in public places, such as for instance train stations, are vulnerable to EMI, especially that generated from electric cables with 15 kV and 16 2/3 Hz AC. These advisory systems are crucial as they give simple audio and visual commands to help the person that uses it. The interference is however, minimized if the person in need of defibrillator is positioned parallel to the overhead line, and the electrode cables are perpendicular to the overhead line.

For the case of ERS, the power in the overhead cables will not be more than 800V hence the interference might not be a question for concern. It is, however, important to consider and be aware of the risks. There might be a need for further investigations regarding such interference with other important electrical devices.

2.4 Summarizing Discussion

The basic concept of ERS is to supply energy to vehicles. In doing so there will be need for good conductors as well as good isolators and shields. The materials that are used in ERS will hence need to have the same characteristics and there will most possibly not be a particular difference between type of materials used in each of the ERS concepts.

It will instead be important to investigate and compare between amount of materials used as well as how often parts need to be replaced, i.e. the wear and tear of the components of the system will be important to consider.

When comparing between the catenary solution and the in-ground rail solution it seemed clear that the catenary solution, even though widely spaced, would use about 12 times more materials than the rail system,

This project set out to investigate environmental aspects of ERS but data on the amount and types of materials used for each ERS concept is needed to be able to come to a fair conclusion regarding differences between the concepts. It is common to use the life cycle assessment (LCA) methods in comparing between concepts. Such methods are very comprehensive and investigates the environmental impact that each product or concept will have from the production of the materials used in the concept to the use and maintenance of the concept and finally the end of life phase. There are a few LCA studies performed on ERS, but since the concepts are so new to the market it is difficult to get a good analysis regarding energy use of everyday maintenance as well as wear of the materials during a full deployment of the concept.

It was furthermore difficult to retrieve information from the demonstration projects as both are continuously developing and improving their respective techniques hence, the difficulty of getting a good comparison of the concepts.

2.4.1 Emissions

Electric road techniques contribute to emissions of PM₁₀ particles in three different ways 1) the contact between the electric current collector and the conductor, 2) brakes and other moving parts, 3) tires and road surface.

The pantograph and wire are worn from vehicles using the system and small particles mainly from iron are emitted. From studies on railway and in subways it is shown that the largest concentrations of particulate matter are found in closed areas such as in subways or in train stations. This implicates that the effects might not be substantial in open rural areas where the air is circulated.

Particulate matter coming from the contact between the current collector and the in-road rail is unknown and measurements are required.

An obvious difference from conventional roads and vehicles is that there are no exhaust particles from the combustion in electric vehicles. The effects on the particle emissions (PM₁₀ and PM_{2.5}) are however unclear as the successively improved particle filters used in cars in recent years have reduce the exhaust related particles from conventional vehicles. Measurements are needed to be able to compare particles from combustion motor vehicles and electric vehicles in the same road environment.

Particulate emission from brakes, tires and road surfaces of ERS correlates with the weight of the vehicles and are therefore thought to be similar to conventional combustion vehicles.

Emissions of particles will depend on the characteristics of the materials used. If materials are more prone to wear and tear more particles might form. It is difficult to compare between different ERS concepts when there is little information about the materials used. Measurements are needed to fully understand what type and how much particles are to be expected. This can be done on the test sites under similar test procedures.

One important part to consider when comparing different conductive techniques are the distribution of the particles to the ambient environment. Will particles from the catenary solution be more widespread due to wind dispersion? Or will turbulence from passing vehicles be the most crucial part in spreading particles to the environment?

Either way, all emissions from combustion engines, both greenhouse gases and particles will be reduced with the introduction of ERS. The inductive technique will however not create any airborne particles other than what comes from the regular wear and tear of tires and the road.

2.4.2 Noise

Generally, when discussing noise issues and electrical vehicles the noises are reduced at velocities up to 30 km/h. At higher speeds the noise from the interaction between tyres and the road will drown out the noise of the engine, hence there will be no difference between combustion engines and electrical engines at speeds over 30 km/h.

When it comes to conductive ERS, there will be occasions where arcing appears. Arcing is the lightening sensation when the contact between the current collector and the power supply cable or rail is interrupted. Such arcing will make a loud sound, depending on the strength of the electrical charge.

It is difficult to know about how often such arcing will occur and hence how often such noise will be apparent.

Noises from the interaction of the sliding contact between the current collector and the cable or rail is also difficult to estimate. Some measurements have been performed within each demonstration project, but the methods used are not comparable with each other and should be made by some independent party.

When it comes to the work environment of truck drivers it is also important to consider the noises within the cabin of their truck. It is however apparent from discussions with the test drivers of eHighway in Gävle that the noises are reduced within the cabin when the truck is connected to the ERS. The driver also mentioned that there is an apparent reduction in vibrations when driving on electricity as compared to when the combustion engine is used.

Again, the noise should be even more reduced if using the inductive concept of ERS, since there will be no sliding of current collectors.

2.4.3 EMF

The emissions of EMF will differ between the different concepts depending on how much power that is put into the system. However, each technique is constantly improving and the differences between these systems in terms of EMF emissions might in the end be insignificant. The risks of interfering with other equipment is however increased if there are unexpected emissions of EMF from the system. Such unexpected emissions could for instance be those from arcing. Arcing will apart from increasing the wear of the wire and carbon strips, also cause EMF that might reach much higher frequencies than what is expected during standard operation. Arcing will only occur in conductive techniques. Hence the risks of having unexpected EMF emissions are greater for the conductive techniques.

The distance from the source is furthermore important when discussing EMF. This will be different between the different concepts. The electrical fields are always present within the electric parts such as cables etc. Humans can be protected from such fields by shielding materials, such as walls, trees or soil. Cables that are put in the ground will hence not emit as strong fields as would overhead cables.

It is, however, unclear as to whether inductive techniques will be different since it depends on sending electrical charges from beneath the road surface. Further investigations are needed. Preferably done in the same manner between all different ERS test-sites, to be able to compare between different concepts.

When preparing for implementing ERS it is hence of importance to consider different kinds of shielding for people living close to the electric road or to plan for ERS at safe distances from dwellings. As described by the European Parliamentary Assembly, the present limits for relay antennae should be reduced and follow the ALARA principles (as low as reasonably achievable) and all antennae should be continuously and comprehensively monitored [69].

The vehicles themselves should be constructed in such a way that drivers are shielded from EMF. It is however difficult to shield magnetic fields as they will only diminish with distance from the source. When the vehicles are not connected to the road there will not be any magnetic fields, hence people living nearby will only be affected if someone is charging their vehicles from the ERS.

To be able to communicate with the vehicles and power systems as well as business models included in the ERS the need for WIFI or mobile communication will be evident. It seems, however, as if plants are more susceptible to EMF induced from WIFI. Migrating animals and insects, bats, birds and fish are furthermore affected by EMF and special investigations and precautions are therefore needed to understand and eliminate the risks of EMF from the whole Electric roads system including WIFI communication.

It will be important to investigate and analyze EMC standards which are to be used in ERS. There are risks when trying to use existing standards, without considering the original use of the standard and the system it was intended to standardize. There is furthermore a lack of standards optimized for the inductive ERS techniques. If standards that are intended for conductive transfer is used instead, the inductive ERS might uphold the standard but will not reach the requirements at system level. It is

furthermore important to consider such issues early in the development stage to limit the risks of increased costs later in the project, if it e.g. turns out that EMI shielding should be needed.

2.5 Publications and other dissemination

Literature study on environmental impact of ERS – VTI report - *work in progress*

Literature study on LCA concerning ERS and similar techniques – Impact of life cycle assessments for electrified road systems - Review and analysis of LCA studies

Presentation at Transportforum, 2017, Sara Janhäll

Presentation Transportforum, 2018 - TF19_6_1_Nordin_Hellman
Elvägar - nya utmaningar för vägkonstruktion, drift, underhåll och dess miljöeffekter

Meetings with Volvo busses – to discuss differences in vehicles service on ICE and EV

Bachelor thesis on GIS and Electric roads - Johansson, A. och Strömberg J.
ELEKTRIFIERA SVERIGES MOTORVÄGAR? - En GIS-analys över möjligheten att installera elvägssystem längs med två svenska motorvägar [76]

3 Construction, operations, and maintenance

The aim of the work package was to investigate how the installation of different types of electric road systems (ERS) would impact the construction, maintenance and operations of the roads. The work in this work package has been done in cooperation between Lina Nordin, Terence McGarvey, Ehsan Ghafoori, and Fredrik Hellman. The main findings of the work in work package 3 is found in this section. For further elaborations please read the full report [77].

3.1 Scope

ERS is basically a concept that provides the possibility for electric vehicles to charge while driving. When connected to the ERS the vehicle could either charge their batteries or use the electricity for propulsion. In Sweden there are basically three different concepts considered. The overhead conductive catenary concept is used in the demonstration project on E16 outside of Sandviken, while the conductive rail in the road technique is used in the demonstration project close to Arlanda. Two new demonstration projects include another type of rail technique in Lund as well as an inductive technique in Gotland which will be embedded beneath the road surface. These are all demonstration projects and the techniques and system solutions are constantly improving at a rapid speed. When considering the results presented in this report it is crucial to bear in mind that some issues that might be mentioned as a potential risk or impact on the construction or road maintenance might no longer be an issue of concern.

The aim of this work package of the Research and Innovation Platform for Electric Roads was to, at an early stage, reflect on such consequences that might have an impact on the construction, maintenance and operations of the roads with a so that such issues could be addressed and resolved before a large-scale deployment of ERS.

3.2 Activities

The activities within WP3 have mainly been focusing on reviewing how the construction, operation, and maintenance of electrified roads will work in comparison to the existing methods and road infrastructure. It is important to get an overview of the effects each system has on the road construction. This is relevant during the implementation phase and in terms of operations and maintenance.

- The work in WP3 was presented together with WP2 at Transportforum, Linköping, January 2018.
- Due to staff turnaround, the WP3 project group has changed since spring 2018. A new group has been working with WP3 since 2018-09-03 and consists of Terence McGarvey (VTI), Ehsan Ghafoori (VTI) and Lina Nordin (VTI).
- An assessment of the effects ERS might have on the road infrastructure has been carried out.

- Visits to the two demonstration sites have been done and discussions with the project leaders of each of them, have been very fruitful in understanding what will work as usual within road maintenance and what will need adjustment when introducing ERS.
- The developments and results were presented together with WP2 at Transportforum in January 2019.
- “Changes to road maintenance and operations on electric roads” was presented at the Electric roads conference in Frankfurt in May 2019.
- “Increased Road Surface Unevenness after the Installation of an Electric Road System” was presented as a poster at the Electric roads conference in Frankfurt in May 2019. This was based on a case study where longitudinal IRI profiles with surface irregularities at 100 m intervals were simulated.
- Two students from the University of Gothenburg performed a GIS study on how to develop a model to geographically analyze where different concepts of ERS would be best suited.
- Questions based on the assessment made in half time of the project was sent to the demonstration sites. Eroad Arlanda was the only one to answer. Hence comparisons between them have been based on the public reports as well as discussions with Stefan Hörnfeldt at NCC for the eRoad Arlanda project and with Magnus Ehrnström and Jan Nylander for the EHighway project in Sandviken. Jan Nylander has been very helpful in giving input to the project whenever asked.
- Meetings with personnel at Volvo busses to understand what differences in service that are suggested between combustion engine buses and electric powered buses.
- Compilation of possible changes or impact on road construction, maintenance and operations of the road

3.3 Results

Here follow the main findings from work package 3, concerning road construction, maintenance and operations.

3.3.1 Road construction challenges - Catenary

When it comes the overhead catenary ERS it is common to think that the road construction will not be affected since the technique in itself, is not intruding the road construction. The road is however consisting not only of the lanes but also of the side areas, the ditches and the infrastructure that is connected to it, such as safety rails or barriers. For the catenary solution, the installation will require drilling or piling in the roadside area. This might affect the road construction in such a way that the base or subbase layers might be affected. If the poles are installed in the ditch slope it is important to consider not placing them too close to the road, as this might affect the stability of the slope and furthermore the road foundation and sustainability. If the

ditch slope is inaccurately excavated it might result in settlements and other damage that are costly to repair [78]. It is hence important to always perform geotechnical investigations early in the planning phase of the project. This way the stability and underground conditions will be known before the excavation begins and it is possible to plan where to place the poles or other parts of the system, such as electrical cables, where they are best suited.

Geotechnical investigations are also needed when planning for other ERS concepts where the techniques will be installed into the road construction. If the underground conditions would be known before the installation of the ERS begins several time-consuming surprises can be avoided.

In Sweden, roadside barriers are only installed along road stretches that are bordering steep slopes or water, or where obstacles such as rocks or poles are within the safety zone of the road. Along highways in rural areas the safety zone is the area from the road to ten meters from the road. Safety barriers are needed if there are obstacles within this area that are more than ten centimetres above the ground. As for the overhead catenary concept where the poles are installed close to the road safety barriers are needed (see Figure 21).



Figure 21: Catenary poles and roadside safety barriers along E16, Sweden.

3.3.2 Road construction challenges - Conductive rail technique

The In-road rail concept

The conductive in-road electric rail that Elways have developed is installed into the road structure and transfers energy via a pick-up beneath the vehicle. The rail consists of conductive metal and isolating plastic with a top-cover of steel. It is articulated every metre, which according to Asplund [79] means that there will be no problem for the rails to follow the geometry of the road and still transfer energy. The segments are furthermore, only 12 m long to limit the risk for cracks [45]. The opening in the rail (see figure 2) is narrow to prevent cycle wheels or animals getting stuck. It is, however, broad enough for sand and dirt to sediment at the bottom and for small branches and leaves to get stuck in the rail.

The rail at the demonstration site, is 148 mm high and 144 mm wide and will be 3-5 mm underneath the driving lane [79]. The rails need to be placed within reach of each power distribution box which are located within 1500 m of each other [79], [80].

A 200 mm wide and 170-180 mm deep track was excavated into the road structure to be able to install the rails at the demonstration site. The bottom was filled with macadam.

The size is however easily customized as the steel rails are placed within a concrete body, making it possible to modify the outside dimensions of the rail. Further improvements are to use geotechnical investigations in the early planning process to be able to adjust the installation procedures according to how the sub-surface layers are constructed.



Figure 22: Rail in the road at Rosersberg, with narrow spacing, Sweden.

The on-road rail concept

This concept, developed by Elonroad, consists of a rail that is attached to steel plates which are glued on to the road surface every 1.5 m. The rail ends in a ramp that is glued or bolted on to the road surface. Since the rail is quite heavy, 100 m of the rail weigh 3.5 tonnes, it is in itself rather fixed to the surface. The rail is designed with 5 mm high rubber feet to allow water to flow under the rail. To provide power to the rails, power supply is required every kilometre. A transverse excavation track will be required to accommodate the power supply cable.

The rails used in this technique are mainly made of aluminium, isolators and copper. The rails have a life span of ten years [81] and can resist unevenness, roughness, and up to 4-5 cm deep potholes [81].

This concept is being tested in a new demonstration site in Lund in Sweden with start in 2020. The rail will from the beginning of the demonstration period be installed on-road but the plan is to develop a rail that can be submerged into the road surface to limit the risks of accidents for motorcyclists driving across the raised rail. That kind of solution will however, cause issues regarding road construction and sustainability of the road, similar to the in-road rail technique.

3.3.2.1 Rigid and flexible constructions

One obvious issue is the difficulty of combining rigid and flexible constructions. As the road is a flexible construction, the steel rail will, by being rigid, cause straining within the road construction during traffic loading on the rail. This is a common problem in areas where rails share the road with regular traffic, such as tramways in cities. Hedström [82] mentions settlements, which might cause cracks or elevated areas of the road surface. Such settlements might cause irregularities that might impair the effectiveness of winter road maintenance as well as increase the need for other maintenance operations such as resurfacing.

Bonding and good quality construction joints

The ERS apparatus is, furthermore, likely to be affected by thermal expansion and contraction. Differences in expansion properties will result in de-bonding between the ERS apparatus and the surrounding asphalt. The main issues are buckling at the joint between two units as well as rail lift. Expansion and contraction movement must be confined within the ERS unit. Figure 23 shows an early version of the joints. They were fixed and does now include a telescopic function making it possible for the joints to compensate for the thermal expansion during hot summers. This shows the importance of having demonstration sites on regular roads and the improvements that can be made from resulting issues.



Figure 23: Joint between ERS units (Photo by Terence McGarvey).

Bonding between the ERS apparatus and the surrounding asphalt is furthermore important when it comes to distributing traffic loading through the construction layers. If this fails it might result in water ingress, deformation, degradation of surrounding asphalt or loading which is concentrated at the bottom of the ERS unit or at the edge of the asphalt construction. This makes it even more important to maintain good quality construction joints.

3.3.2.2 Load distribution

ERS apparatus placed within the road construction will disrupt the homogenous nature of the structure. This will affect how traffic loading is distributed downwards into the substructure and might result in a concentration of loads at the bottom of the ERS apparatus. In certain circumstances, it is possible that the ERS apparatus will be greater in depth than the thickness of the asphalt construction layers. The ERS apparatus will transfer load directly onto the pavement's unbound layers, which might cause severe deformation.

Solutions for such problems is to only install techniques in the upper centimetres of the road surface. Suggestions are also to create fundamentals underneath the rails to distribute pressure evenly along the intermediate road layers. This might however be a costly solution if materials such as concrete are used. Other suggestions that are under development is to make a stepped back construction of either the rail construction itself or the different road construction layers adjacent to the rail as shown in Figure 24. This may also be a way to collect water that might seep through the road construction. Such solutions are further elaborated in the full report of this work [77].

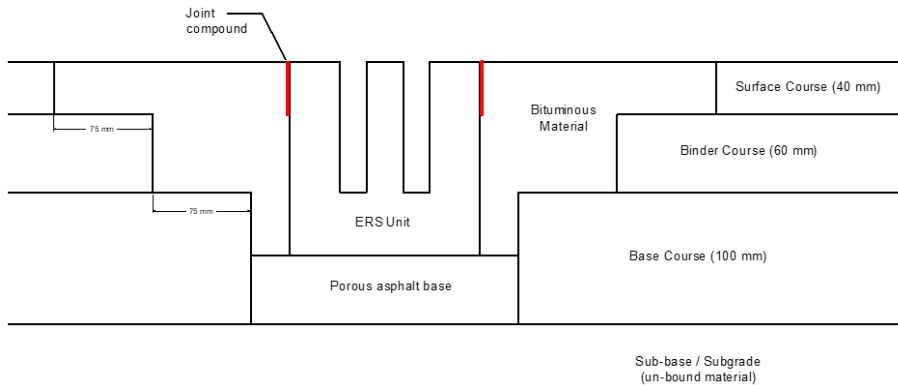


Figure 24: Proposed Construction Detail – Load Distribution Improvements.

During the two years of demonstration at eRoadArlanda there has thus far not been any apparent signs of settlements or loading damage of the rail. The project team have approximated that there are about 200 truck passages every day along the road and according to the Annual Average Daily Traffic (AADT) there are about 1500 vehicles passing every day. This is however not enough when it comes to analyzing long term effects of loading and settlements in the road where there are rails installed in the road. Accelerated and full-scale tests are needed to be able to know how such a construction might impact the bearing and construction layers.

3.3.3 Road construction challenges - Inductive technique

The inductive techniques are interesting in the way that they will not interfere with the road surface hence no extra sealing routines are needed. It is however important to consider what happens with a technique that is installed within the road construction.

The main challenge for inductive ERS are the wireless power transfer efficiency which, according to [83], varies between 70 % to 95 %. They mentioned that inductive ERS will induce electric fields, which are small but that might cause electric energy losses and small conduction in the materials around the installed technique. They furthermore investigated the well-known fact that moisture could increase this kind of electric loss in pavement materials.

As with all techniques that transfer energy, there will be heating of materials. If such electric loss would cause conductive heating of road materials it might affect the layers within the road construction. According to [84] the mechanical characteristics of a pavement can be affected by changes in e.g. strength, skid resistance, waterproofing and surface profile. This might lead to increased deterioration and it will be important to make sure that the embedded system will not be too warm or exceed the ambient temperatures of the pavement.

Excess heating during wintertime might cause possible thawing mechanisms within the road construction during the same time as the road surface and surrounding road construction is frozen. This is something that needs to be further investigated.

Generally, there are three different construction methods for embedding inductive systems in the roads. The trench-based construction method, the micro-trench-based construction and the full-lane width construction. Each of those methods are further

described in the full report of work package 3 of the FFI FOI platform for electric roads [77].

3.3.3.1 Pavement joints

Installation of the charging units inside the existing pavements requires excavation. Any kind of excavation in existing pavements results in the formation of both longitudinal and transverse joints. Depending on the width of the excavation, these longitudinal joints can form near the middle or on the edge of the lane. To be able to connect power supply to the charging units, excavation or utility cuts are needed, causing transverse joints at regular intervals along the road stretch. The distance between them varies depending on type of charging system.

The pavement joints must be carefully constructed since poor construction can trigger different types of failure in the roads. Water ingress, unevenness, poor horizontal load transfer, crack propagation etc. are some of the reasons that makes the careful construction of pavement joints very important.

3.3.3.2 Material change within the pavement structure

Any material or stiffness change within the road can cause concentration of stresses when the pavement is exposed to the traffic and environmental loads. Such a stress concentration is very much likely to cause premature failures such as reflective cracks at the asphalt pavement surface.

De-bonding at the interface between a concrete and asphalt layer can, furthermore, trigger the premature failures in the pavement structure [85], [86]. Such premature failures may take place where there is a discontinuity between an asphalt layer overlay and its concrete bottom layer due to a combination of traffic and environmental loads [87]. Hence, for ERS concepts where concrete shells are used for protecting the charging units, such problems are likely to happen and there is a great need to carry out preventive actions to reduce such risks.

3.3.3.3 Geometry

The geometry of the protecting shells of the charging sections can have a prominent impact on the quality and life span of the road. Any sharp edges at the interface between the asphalt and concrete layers is a potential distressing zone under the braking and accelerating tires. This could result in inducing pavement surface damages for the eRoads. Chen et al. [88] showed with finite element modeling the potential of using charging units with optimized geometries for providing a better stress distribution within the eRoads.

3.3.3.4 Construction challenges of inductive techniques

As described by the comprehensive report by there is little available information on long term impacts of ERS techniques. When scoping through existing literature it is the finite element analysis that seems to provide best indications of long-term impacts.

Chen et al [88] used finite element models (FEM) to investigate how traffic load on ERS roads with embedded inductive techniques might impact road construction. They showed that increased load from heavy braking or acceleration would cause premature

damage to the road construction. They furthermore suggested that this could be delayed if the bonding at the contact interfaces would be sufficient.

Balieu et al [89], performed finite element simulations and concluded in their study that increasing the depth at where the inductive ERS technique is embedded from 5 cm to 8 cm the stress concentrations within the road structure would decrease while the extent of permanent deformation and damage instead seem to be increasing. They hence urge for precaution and a more holistic view before changing depths. So far, there is no documented information about monitoring and damages induced on existing ERS test sections or static inductive systems. However, the large number of pavement joints and material change etc. on ERS makes them very susceptible to damage and therefore carrying out a systematic inspection is vital. It is, furthermore, expected that ERS require more maintenance actions throughout their service lives. This is further elaborated in [77].

Trench-based construction

Using the trench-based construction can lead to cracking near the wheel paths as well as cracking at the transverse joints where the coil is connected to the roadside power supply.

If the construction is surface-flush, the different materials on the road surface may result in changed skid resistance. The formation of asphalt and concrete interfaces at the road surface can, furthermore, act as weakness points of the pavement. If the charging system for some reason needs to be replaced, this method will be very challenging to replace. This means that depending on the severity or type of the damage there might be the need to do the full depth excavation which can make this method very costly during its service life.

Micro-trench-based construction

Like the previous method, the micro-trench-based construction method provides two longitudinal as well as transverse joints on the road. The challenge is to fill the micro-trenches with materials that can protect the embedded cables and resist against rutting and water infiltration. The depth of the embedded charging unit in the pavement is very important as well as using highly resilient tubes for protecting the coils and cables.

The depth of the embedded charging unit in the pavement is very important due to the limited allowed distance between the charging unit and the receiver to uphold an efficient energy transfer. Hence, the system cannot be buried deeper than a certain depth, which make the cables prone to receive high stresses and strains from the traffic loads [Fabric].

It was furthermore shown in a study by [90] that the concentration of stresses due to embedding utilities or any other discontinuity would, instead, damage the asphalt pavements due to the shear and large deformations. This is also expected to happen around the wireless power unit embedded within the asphalt pavement layer. Van Vilet et al [91] suggested that the minimum depth of embedment of utility cables should be at least 50 mm.

The micro-trench-based method is also prone to different damages; however, comparing to the previous method the accessibility to the embedded coil in this method is higher which makes the volume of the waste materials limited.

Full-lane-width reconstruction

With the full lane-width construction method the full depth of the bound layers in one lane is completely removed and the unit is installed either with in-situ, pre-cast or prefabricated units. A thin concrete layer is constructed after the excavation, if the stability of the bottom layers were not sufficient to provide a stable ground, free of possible bottom intrusions.

Electromagnetic fields interface/electromagnetic fields shielding plates must be placed under the unit locations for further protection. The coils are connected to the feed located at the side of the roads and later to the roadside cabinets. The units are covered by a concrete pavement. Finally, an asphalt layer with the thickness of 60-100mm is laid at the top of the concrete pavement.

Due to its slow installation, this method is expected to have more traffic disturbances during the construction phase. Since the slab lengths are limited, the number of transverse joints in this method are also very high. Transportation of the slabs is an additional issue of concern and very disruptive to traffic.

ERS built with the full-lane-width method seem to be more robust than the other two methods but requires more maintenance and inspection on its large number of transverse joints. Furthermore, any kind of maintenance which, for instance, might require the excavation of the full-lane-width, may have large impact on the adjacent lane as well.

3.3.4 Maintenance and operations

The daily maintenance and operations of the national roads are today procured, where the Swedish transport administration is responsible for the roads and the procured contractor is making sure that the roads are operable and kept at proper standard. Specific contracts are set up to ensure that the same standards can be expected along the whole stretch of a road even though it might run through several different contract areas. Operations that are included in such base contracts [92] are winter road maintenance, sweeping, ditching, clearing of side verge area, cleaning of rest areas, sealing, graveling etc. Some operations are performed regularly and others, such as pothole repair or sealing are performed when needed.

When discussing the different roles of a deployment of ERS the role of the road maintenance and operations contractor and the procurement of the road contract area will be crucial. It is suggested by Andersson et al [93] that the proposed operator role of the electric road should also be responsible for the maintenance of the road. However, this role is barely discussed in terms of road maintenance but rather focuses on the electrical operational activities.

According to [93] it is important to have as few boundary layers as possible between different actors, to be able to secure good operational safety. This is for instance crucial to be able to diminish the risks of damage or disruption such as having a cable for traffic flow measurements running a cross a conductive ERS rail without the ERS

operator's knowledge. Nevertheless, communication between different parties will be of huge importance.

Andersson et al. [93] also suggests the possibility of have a specific ERS operator focusing on the ERS infrastructure and let the STA concentrate on the road maintenance. This solution will however not discuss the differences between different ERS techniques. For the eHighway project on E16 outside Sandviken, the road maintenance contractor mentioned the risks of touching the overhead catenary cables with the lifting arm when emptying trash at the rest area. The same risks appeared when cutting grass, as the cutting arm needed to be lifted every time they passed one of the poles that holds up the catenary cables, again risking to pull down the cables [94].

The inductive techniques will on the other hand, possibly not pose as many daily interactions between road and ERS as would conductive techniques, until there are cracks, resurfacing or ditching activities with risks of cutting or damaging the electric cables or techniques within the road surface or road area.

Looking the other way around the ERS operators need to follow safety regulations when working along the roads. During installation procedures within road as well as roadside areas for cables etc, they need to follow the rules and regulations regarding where and how to install electrical components within the road [78], [95].

As the safety of a road is the most important part of the activities within a maintenance contract and the knowledge of keeping roads at good standard levels it seems as it would be better if the ERS parts of the roads are included in the road maintenance contract as well. Either way there is an eminent need for upgrading the road maintenance contracts regarding ERS and related roads to include safety regulations concerning electrical work or work close to electrified part such as cables etc.

3.3.4.1 Electricity issues – supply, safety, electric work regulations, installations

ERS will introduce electrical components that even though constructed in such a way that they are only electrically live conductors when a vehicle is using that specific part of the ERS, they still pose a safety risk if something unexpected goes wrong. This means that when working close to or with those electrical parts as well as if there is an accident it should be evident how to act.

It will be of importance to produce safety regulations to prevent all plausible risks. It could be useful to consider the technical regulations that are used in work on railways [96], [97]. These basically considered the use of machines in close proximity to live conductors. If they have lifting arms such arms should be provided with height limiter, they should not be closer to live conductors than 1 meter, or they should have protective earthing. There should, furthermore, always be an electrical work supervisor taking part of the work. As with all discussions concerning ERS, such regulations will depend on type of ERS technique used.

3.3.4.2 Pavement structure reinstatements

Electric supply cables and drainage ducts will need to be installed across the carriageway for all ERS concepts that incorporates some sort of charging devices in or

on the roads. Tracks or utility cuts will be excavated at regular intervals along the length of the ERS installation. The distance between such cuts will vary depending on the type of ERS system and longitudinal low points.

It is difficult to construct utility cuts that are sustainable. Pavement structure reinstatements should be laid flat and flush with the adjacent surfaces - no significant depression or crowning should be apparent. However, it is difficult to compact a reinstatement to the same levels as the surrounding pavement structure which might lead to post compaction from traffic loading.

A survey from seven cities in Iowa, USA [98] indicated that utility cuts often lasted two years or less. It all depended on how the cut was restored, materials used in the repair, climate and traffic. Several studies indicate that such cuts might reduce the life length of the road [99], [100].

This indicates that the ERS roads possibly might need to be resurfaced more often than a regular road. In some areas it might even be as often as every two to three years, but such indications should be tested. It is, however, important to remember that such deterioration could be reduced if the transverse connections are installed further down in the road construction and possibly also include new sub-layers to create an as sustainable road construction as possible.

When discussing maintenance activities such as resurfacing of ERS roads with rails installed in the middle of the lane it will be important to also consider the extra efforts in time and new types of machinery needed, to be able to remove pavement materials adjacent to the rail without damaging the rail. Pavers might have to be smaller or new techniques might be needed. The resurfacing activity will also have to be done at the two sides of the rail separately. Such maintenance activities might cost more in time but also cause longer traffic delays than what a regular resurfacing activity would

3.3.4.3 Comfort Levels

An amount of surface level variation will be acceptable to Road Authorities provided it is within specified tolerance levels. This means that certain levels of edge depression, surface depression, and surface crowning could be apparent after a track has been reinstated. This will be experienced by motorists as a type of local unevenness.

To try and quantify the extent of this unevenness, international roughness index (IRI) values were calculated along simulated longitudinal profiles with repetitive surface irregularities. The results were presented during a poster session at the Electric Roads conference in Frankfurt in May, 2019, and is further described in the full report of Workpackage 3 [77].

Even though IRI levels would still be within the prescribed standard, it is likely that the level of discomfort will increase. Driving over repetitive road surface irregularities will influence the motorists perceived level of comfort. At a speed of 110 km/h, the local unevenness will be experienced every 3.2 seconds. If local unevenness adversely affects comfort levels, motorists will reduce speed until similar levels of comfort are experienced.

From a visual recording done by a motorcyclist researcher at VTI, driving along one of the ERS road stretches, it was clear that the transverse joints where the electrical cords

or drainage are installed, causes the suspension and damper of the motorcycle to work hard. The driver also mentioned that the unevenness was felt while driving. This indicates that such utility cords will need to be pushed below the base layers at least 1.5 metres below the road surface as is suggested in [78]. Apparatus that is installed in the road construction may also be vulnerable to damage from works carried out in the road such as resurfacing activities etc.

It is not allowed, according to [78], to install utility cords at such depths that they may cause settlements or elevation in the surface. It is furthermore not allowed to cause uneven freeze and thaw lifts or install utility that will heat the road surface locally, as this might cause local slipperiness.

The fact that such settlements, caused by utility cuts are not allowed in the road makes the forthcoming years of ERS very interesting. It seems as if both rails and inductive techniques thus far have used transverse joints to connect power to the ERS apparatus in the road. This might cause damage and settlement and such transverse connections need to be installed at a higher depth than what has previously been done. Collaborations between manufacturers, road construction technicians and researchers are needed to solve these issues.

3.3.4.4 Wear and tear

There are so far very few studies regarding the wear and tear of ERS. The two demonstration projects in Sweden have performed some studies on the wear and tear of their respective techniques but those tests are for a few passages of their own test equipment and not to be compared with a full-scale implementation with wear from regular traffic. References have therefore been made to similar transportation modes to be able to get an understanding of what kind of wear that might occur in various ERS.

Catenary

For the catenary solution the wear and tear will be in the wear of the pantograph collector strips and contact wire. If such wear is large it could become very costly [101].

When objects or substances such as ice interrupts the energy transfer from the wire to the collector strips, arcing appears as a bright light in the contact between collector and wire. This kind of energy outburst will increase the wear of the strips [102]–[104] and it is hence important to keep the wires as well as rails free from obstacles and ice.

Wu [105] investigated the influence of electric current on contact resistance in wires on contact pantograph. This sliding electric contact plays an important part when it comes to the operation life of pantograph/wire systems. From their study, it is clear that when there is a current in the wire, the wire gets heated up which increases the wear of the wire. They also mention that arcing causes small pits or craters on the wire that in turn might increase the risk for damaging the carbon strip of the pantograph.

This increased wear of the carbon strip with increased temperature was also shown by Ding [106], which makes it even more important to consider in terms of the suggested heating of the wire as a means of winter maintenance to melt frost or ice on the wires. In such case it might be more efficient to add anti-icing agents on wires before morning rush.

Conductive rail

To the right in the figure there are clearly visual scraping marks in the sealing material surrounding the rail, and if looking closely there also seem to be marks in the rail. This calls for assumptions regarding particles as well as wear of the rail, and the suspicion whether the energy transfer will be impaired if the rail is worn down too quickly. The energy transfer is however hidden from the surface and the pick-up will transfer energy from contact surfaces further down in the track of the rail. The question regarding emission of particles from the wear still remains to be answered.



Figure 25: Wear on the ERS conductive rail.

Inductive techniques

It might seem that the inductive technique is the best choice when it comes to wear and tear of the road and the equipment. It is however unclear how efficient such techniques will transfer energy if snow and ice are covering the road surface. It is furthermore unclear if there will be excess heating during the power transfer that will increase the deterioration of the road surface or how often coils etc need to be changed.

Some inductive techniques that has been in use for a few years such as the OLEV and CIRCE installations have shown increased reflective cracking in the asphalt. New inductive ERS techniques might be better suited for this but as long as there are parts within the road construction that differs from the rest of the material of the sub-base there is an increased risk of reflective cracks as compared to a homogenous road construction. This is typically seen during freeze and thaw cycles. Further studies and accelerated tests are needed to understand how much impact such techniques might have on road construction and durability.

Chen et al. [88] showed, using finite element simulation, that embedded inductive techniques might also cause damage within the road structure. If the technique is embedded in a box-like installation beneath the surface layer, pressure from traffic load will put tension to the construction which in turn might lead to cracking and additional

and different maintenance costs than maintenance costs for the overhead catenary technology. [88] used the finite element simulation to investigate the difference between embedding the technique at a depth of 5 cm compared with 8 cm. They concluded that even though the stress concentrations within the road structure would decrease if the embedded section would lay at a depth of 8 cm, and the extent of the damage together with permanent deformation of the road would increase instead. They hence urged for precaution and a more holistic view before changing depths of the installations.

3.3.5 Increased maintenance operations due to ERS

The various kinds of ERS concepts will affect road maintenance operations in different ways. It will be more important to keep bonds between joints intact. This will be important for both conductive rails and inductive techniques.

3.3.5.1 Conductive rail

Drainage is an importance maintenance operation. Water on or in the road may cause damage to the road both on the surface as well as in the construction. It is therefore important to keep roads as free from water as possible. The contractor needs to remove obstacles that causes water to dam up at the road surface, if the pool is wider than 40 cm from the road edge. This may affect the ERS and maintenance connected to it. Rails installed in the road surface might pose as small barriers if they shot up over the road surface with only a few millimeters, causing water to dam up. It will be of extra importance to inspect the road segments and rails to detect irregularities.

Some of the conductive rails within the road surface layers will combine the inground power supply cables with drainage pipes to drain the rails of excess water. These pipes are buried in the road construction as transverse joints every 50-100 meters. There is however a risk that what goes down into the rail will settle in the drainage pipe and eventually clog it. Before any full-scale tests have been performed, it is, however, difficult to know how often such pipes will need to be rinsed.

Maintenance activities connected to the rails in tramways can be used as reference when trying to compare with the conductive rail technique. Such maintenance could for instance be the rinsing of the rails to remove dirt and particles that get stuck in the rails. For tramways in Gothenburg the rails are rinsed twice every day [107]. Rinsing of ERS rails will probably also occasionally be needed and add to the maintenance activities that will differ between the different techniques.

3.3.5.2 Catenary

All vegetation in the roadside area is to be cut to a width of 10 meter from the road during summer and again to a width of 1.6 meter before winter. This is a very costly maintenance activity [108]. With poles or other obstacles in the way, the time to do this is markedly increased. In a study by Bäckström [108] measures were made regarding roadside harvesting. The tests showed that it took 17 min/km to cut grass using regular technique along roads with no safety rails compared to 35 min/km on roads with safety rails.

The intention in Sweden is to employ ERS in rural areas. Roads in rural areas are often built with safety zones where no safety rails are needed. Since the poles in the conductive overhead techniques are placed within the safety zone, there will be a need for extra safety rails along these roads. Such rails would not usually be needed along these road stretches since there is normally no road lighting along the roads in rural areas [109], [110]. This indicates that costs for harvesting along ERS roads with overhead conductive techniques might increase by 50%. According to Bäckström [108] the annual cost for harvesting in Sweden is close to one billion SEK, which is almost one eighth the total cost of road maintenance and operation every year.

Overhead cables will furthermore complicate maintenance operations including lifting arms that might tear down the wires or get stuck. Such arms are for instance used during cleaning of rest areas and side verge cutting.

3.3.5.3 Inductive

Daily maintenance operations will possibly not be significantly affected when considering the inductive techniques. This will however depend on the size of power switching boxes and where they will be installed. It will furthermore be important to decrease the number of transverse utility cuts as described previously.

As with all ERS concepts the regular inspection routines will need to be intensified to cope with all new aspects that ERS will bring.

3.3.6 Winter Maintenance

Winter road maintenance is another area on road maintenance and operations that might be affected in different ways depending on ERS-technique.

3.3.6.1 Catenary

Safety rails will affect snow removal in making the removal less efficient as safety rails are in the way of the pushing of the snow to the side of the road. Different kinds of rails will have varying impact on the efficiency of the snow removal. It is, however, clear from a study on the impact of different kinds of safety rails on snow ploughing efficiency, that snow will pile up even at roads with rails with an open profile [111]. The study concluded that the operators of the ploughing vehicles had to keep a distance of 30 to 40 cm from the rail to not cause damage on rails or ploughing blades.

Electrical cables in the catenary concept might need to be de-iced as well. Studies regarding tramways in Sweden shows that cables are sometimes de-iced by spraying the cables with glycerin using a specific vehicle. To get an as good effect as possible the spraying needs to be done at a speed of no more than 20 km/h. The treatment lasts for 12-18 hours [112]. Field tests of anti-icing of wires in Turkey showed that the application could reduce arc formation and in doing so also have the potential to reduce the wear of the line as well as maintenance cost [102].

This might not be an issue for ERS since several ERS manufacturers seem to intend to equip their technique with the possibility to heat the cable or rails. The heating might however increase the wear of the cables and/or carbon strip of the pantograph.

Heavy snow

Snow that falls during warmer temperatures has a higher water content and other types of snowflake structures than colder snow. This makes this snow heavier and more prone to build-up. When ploughing the roads, snow will hence build up against the poles holding the cables. If the poles are positioned too close to the road it might cause snow to spill over onto the road again.

The trails of the demonstration site also showed that snow piled up on the cantilever. There are ongoing tests regarding the design of the overlay arms to make them narrower at the top so that no snow can pile up on top.

The largest effect on the system seems to be ice build-up on the power lines. The excess weight can cause problems for the lines, overlay arms and the rest of the construction which in turn might cause operational disturbance. If the contact line is ice-covered, the contact with the pantograph might be lost for a short while as the pantograph passes over the ice. When the contact is lost, a small electric arc might be emitted which, if it happens often, increases the wear of the lines.

There are three main maintenance techniques that can be used to remove ice and snow from the lines. Mechanical de-icing is when a special pantograph is used to remove ice and snow mechanically. Chemical de-icing uses chemicals such as de-icing agents. To be able to spray the de-icing agents onto the power lines, service vehicles must be specially adapted. If such devices can be incorporated onto a regular salting vehicle it might be possible to keep de-icing procedures as close to regular operations as possible. The preferred technique is electric de-icing by increasing the heat within the power/contact lines.

3.3.6.2 Conductive rail

The winter operations on roads with the conductive technique installed within the road construction poses other types of challenges for the road maintenance personnel as well as risks for road users.

In addition to transferring power to the vehicle, the pick-up – which is placed underneath the vehicle - will act as a rail-cleaner as it will force dirt and material out of the rail as the vehicle passes [45]. The same principle goes for snowfall, especially during consistent traffic flow. There might, however, be small risks of slipperiness connected to this type of procedure, as debris, ice or snow might will be forced out of the rails and transferred onto the road. Such issues as well as any possible impact from snowploughing activities that might be packing snow into the rails can only be addressed during full-scale tests.

In case of ice formation, it is possible to heat the rails by using a heating strand installed within the rail construction. There are also plans for developing a specific snow plough for the rails [45]. As with the solution for de-icing overhead cables, any technique that can be incorporated onto the regular maintenance vehicle and included in regular operations are to prefer rather than a special modified vehicle only maintaining the ERS parts of the road.

Every 50 m, the rails have drainage to drain the rails from excessive precipitation. During heavy rains the rails might be filled with water, but since water is a good isolator it will still be possible to transfer energy. In case there is brine within the rails,

the impedance needs to be measured in each rail segment. If the impedance is too low, the power will not be switched on [79].

There is however an issue regarding salting and saltwater seeping through the construction. If saltwater is percolated in the joints between two segments of the rails the saltwater may transfer energy between the two rails consequently energize two segments of the rail instead of just the one that the vehicle is passing over.

3.3.6.3 Conductive on road rail

Elonroad has developed a technique that includes rail that are installed on the road surface. A specific type of snow plough will be needed, possibly with a softer middle part, when ploughing over the rail. A specific adapter for this purpose is developed which needs to be changed before ploughing the road. This kind of snow plough and its efficiency and possibility of clearing the rest of the road from all kinds of snow and ice, needs to be further investigated.

The manufacturer also suggests replacing salt with the de-icing agents used on airport runways to reduce the corrosive action. This is, however, a solution that needs further investigations. Previous studies regarding anti-icing agents have shown that salt is the most viable anti-icing agent for road usage in Sweden, both in terms of costs and environmental impact.

3.3.6.4 Inductive technique in road

Since the inductive technique is installed within the road construction, under the road surface, regular winter road operations should be enough to uphold safe road conditions in winter. It might however be extra important to keep roads clear of snow and ice as the appearance of such obstacles might interfere with the power transfer between the coils in the road and the receiver in the vehicle. The efficiency of inductive power transfer depends on distance between the primary coil in the road and the secondary coil in the vehicle. With an ice and snow cover on the road this distance is increasing. Rutting might also cause the vehicle to tilt or laterally move its position to increase the distance between the coils. Such interference is probably very small but should be further investigated.

It should also be interesting to see if there will be enough excess heat from the power transfer to warm materials in the road construction. If such signs are appearing some sections of the roads might become warmer than others and cause problems with uneven temperature distribution on the road.

Most studies or simulations concerning inductive techniques are based on embedded rigid structures that might cause stresses and refraction cracks within the more flexible road construction. The new demonstration project called Smart Road Gotland seems to be using rubber coated plates instead to make the construction more flexible and similar to the flexible road construction. The question is however what happens to water ingress that might either seep through from above and stay on top of the embedded technique or below. When this water freezes this might cause damage to the technique or the road. This should be tested before making any assumptions on damage.

3.3.7 Summarized discussion

There are different aspects to consider when comparing between ERS concepts. They will all impact the construction and maintenance of the roads but in different ways and to a various extent. Knowing which technique will be the best is difficult to know at this time since there have not been any long-lasting full-scale tests. There are some accelerated tests performed but more are needed to be able to predict future impact of for instance embedded techniques, both rails and inductive.

It will therefore be a few very important years to come where several accelerated tests need to be performed before a full deployment of an ERS should take place.

To get an overview between the possible impacts on road construction, maintenance and operations that each ERS concept might have they were compiled in three tables in Appendix_WP3. These are compiled from what is known today but further tests are needed, performed in similar ways for all techniques, preferably following specific standards.

3.4 Publications and other dissemination

- The work in WP3 was presented together with WP2 at Transportforum, Linköping, January 2018.
- An assessment of the effects ERS might have on the road infrastructure has been carried out.
- The developments and results were presented together with WP2 at Transportforum in January 2019.
- “Changes to road maintenance and operations on electric roads” was presented at the Electric roads conference in Frankfurt in May 2019. [113]
- “Increased Road Surface Unevenness after the Installation of an Electric Road System” was presented as a poster at the Electric roads conference in Frankfurt in May 2019.[114] This was based on a case study where longitudinal IRI profiles with surface irregularities at 100 m intervals were simulated.
- Two students from the University of Gothenburg performed a GIS study on how to develop a model to geographically analyze where different concepts of ERS would be best suited.
- Compilation of possible changes or impact on road construction, maintenance and operations of the road [77].

4 Architecture and business ecosystem

The work in this work package has been done by KTH Royal Institute of Technology and RISE Research Institutes of Sweden.

4.1 Scope

This work package charts the ERS architecture as a way to show the connections and interfaces between the different systems and subsystems within an ERS. How the actors present in these systems can relate to each other is then discussed from a business model ecosystem perspective. Furthermore, different ownership constellations and their potential impact are analysed. Finally, strategies for ERS funding and investment are presented.

This work package presents the results regarding ERS business models originally planned to be presented in work package 7 due to its similarities and connections with the rest of the ERS business ecosystem discussed below.

4.2 Activities

The work on ERS architecture in this work package has been done by interviews and workshops with different actors in the ERS ecosystem. Illustrations of the ERS architecture has been done using the MagicDraw modelling tool.

The research done with regards to ERS business models, ownership models and investment models has been done by KTH in a variety of academic ways through student projects, thesis work and scientific articles etc. From this, a large number of potential business- and ownership models are presented from different central ERS actors' perspectives.

Following tasks and activities have been carried out within WP5:

- Literature review and conceptual development of potential business models for ERS
- Literature review and conceptual development of potential Public-private partnership models for ERS
- Development of a function-based assessment framework for business modelling, applied on the ERS-case of eRoad Arlanda (reported in Mokhtar, 2018)
- 16 Master student projects inquiring into management theories constitution a knowledge basis for business models and systemic innovation related to ERS.
- Development of a draft system architecture of ERS
- Development of ERS-specific capital investment appraisal models
- Workshops with different system actors to construct the ERS architecture

A major activity during 2018 has also been to support the study performed by EY on behalf of the Swedish Transport Administration.

4.3 ERS architecture and involved actors

This work package consists of an analysis of the general structure and architecture of the electric road system, who should be responsible for what and which interfaces should be further analysed. Furthermore, how the involved system functions and actors can interact through various business model setups, partnerships and investment strategies is investigated.

4.3.1 Architecture

The architecture has been developed during workshops and a next step is to share these first results with industrial actors and make improvements. The presentation of the architecture is, therefore, one step toward the goal of having a common architecture among all stakeholders. ERS will over time evolve from a system to a system-of-systems and it is therefore very urgent to clearly specify the architecture of the system. When the architecture gains acceptance it can be used to identify critical interfaces, which needs to be standardized and thereby improve interoperability.

As shown below in Figure 26, ERS is divided into five different subsystems; electricity supply, road, power transfer, road operation and vehicle. The purpose of each subsystem is defined throughout the following sections. Examples of how each subsystem interplays in the ERS are provided using the MagicDraw modelling tool.

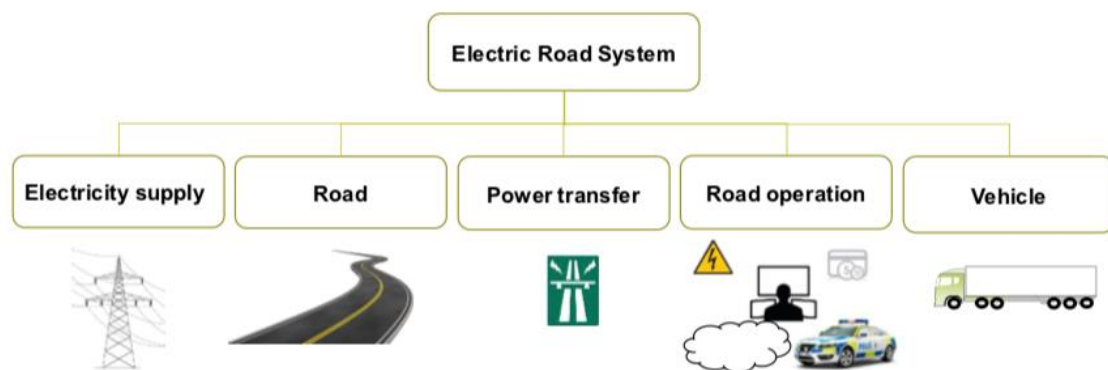


Figure 26: ERS and its subsystems.

Other than defining their operational purposes and necessary components, each subsystem needs to include maintenance to some extent. Today, there are established business models for operation and maintenance of our road networks (mainly by the Swedish Transport Administration). However, as new players are now added to this system, it is important to consider whether maintenance of ERS can be included in the existing maintenance model, or if each subsystem should be responsible for maintenance within their own boundaries. To learn more about how the installation of different types of ERS would impact operation and maintenance, we refer to Section 3 “Construction, Operations, and maintenance”. Moreover, we refer to the [www-site electricroads.org](http://www.electricroads.org) for presentations on potential architectures for ERS maintenance.

4.3.1.1 Road operation subsystem

The road operation subsystem controls the energy management of the overall system, provides user information and handles payment and billing. This subsystem also handles access and lane control of the road based on vehicle identification, as shown in Figure 27. Responsible actors for road operations is yet to be decided and will likely differ depending on the scale or type of deployment. Apart from handling energy management and keeping track of payments or road access, some sort of interface towards the current traffic management system might be required. Whether the traffic management responsible (like the Swedish Transport Administration) can extend their expertise to include electric road operation or not, needs further investigation.

Continued reasoning about this role is introduced as Electric Road System Operator (or ERSO) in section 4.3.2.

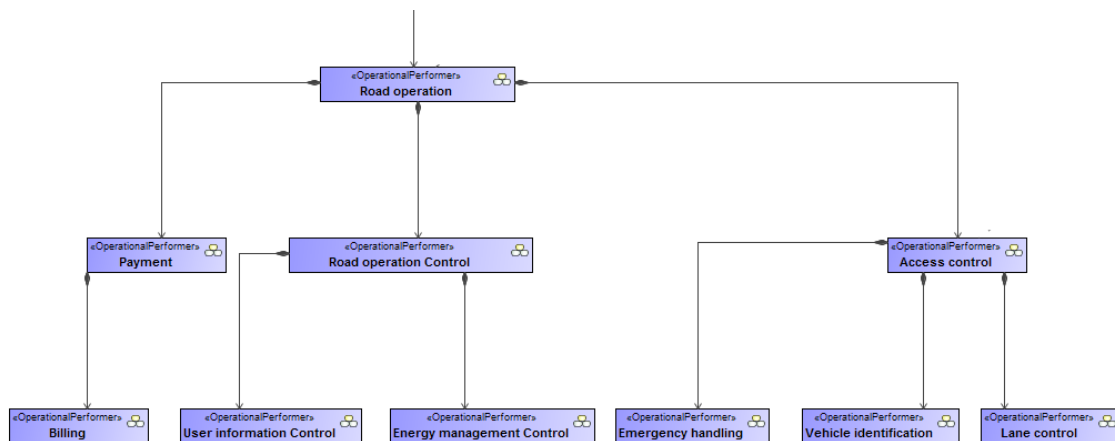


Figure 27: Example of how the road operation subsystem could be described using MagicDraw modelling tool.

4.3.1.2 Vehicle subsystem

The vehicle subsystem includes the necessary components to convert the power from the power transfer subsystem into either propulsion of the vehicle or to energy storage, depicted in Figure 28. A control component provides user information, fleet management and vehicle positioning.

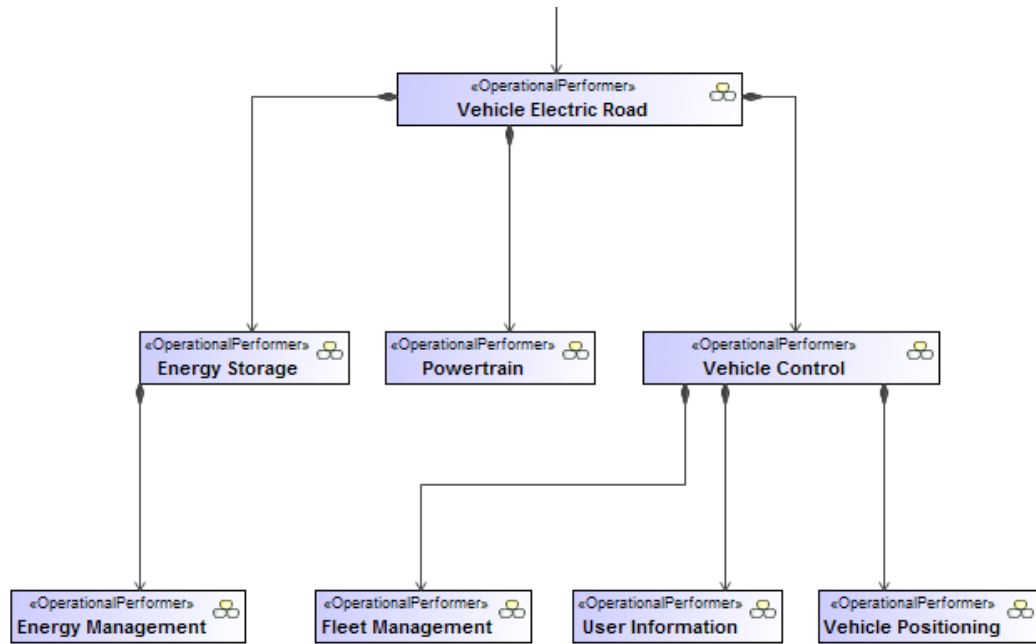


Figure 28: Example of how the vehicle subsystem could be described using MagicDraw modelling tool.

4.3.1.3 Power transfer subsystem

The power transfer subsystem is divided into three components: road power transfer, vehicle power transfer and control, shown in Figure 29. The road power transfer component handles vehicle detection and transmission of power from the road. Vehicle power transfer controls safe activation and operation of the pick-up, and measures transferred energy after a successful acknowledgement. The control component monitors the energy handover and system operation.

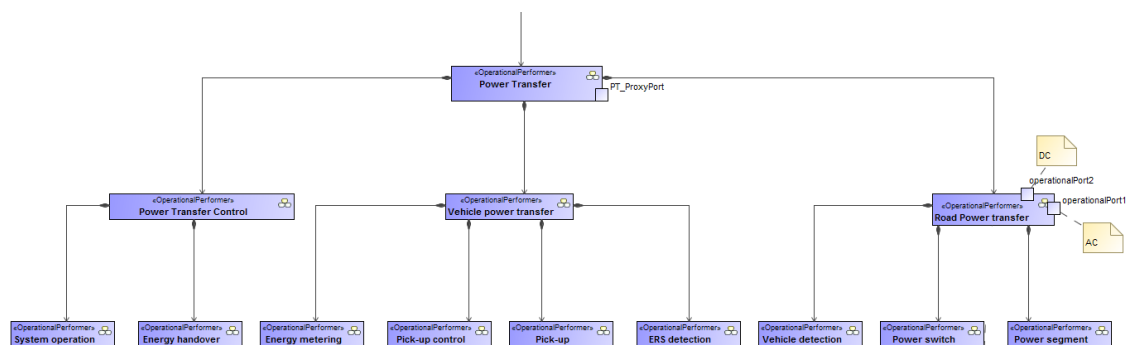


Figure 29: Example of how the power transfer subsystem could be described using MagicDraw modelling tool.

4.3.1.4 Road subsystem

The road subsystem consists of the components pavement, barriers and auxiliary, shown in Figure 30. The pavement includes the actual structural road body and road markings. The barriers component includes both safety and sound. Roadside components are e.g. road signs and other necessary components outside of the road bank.

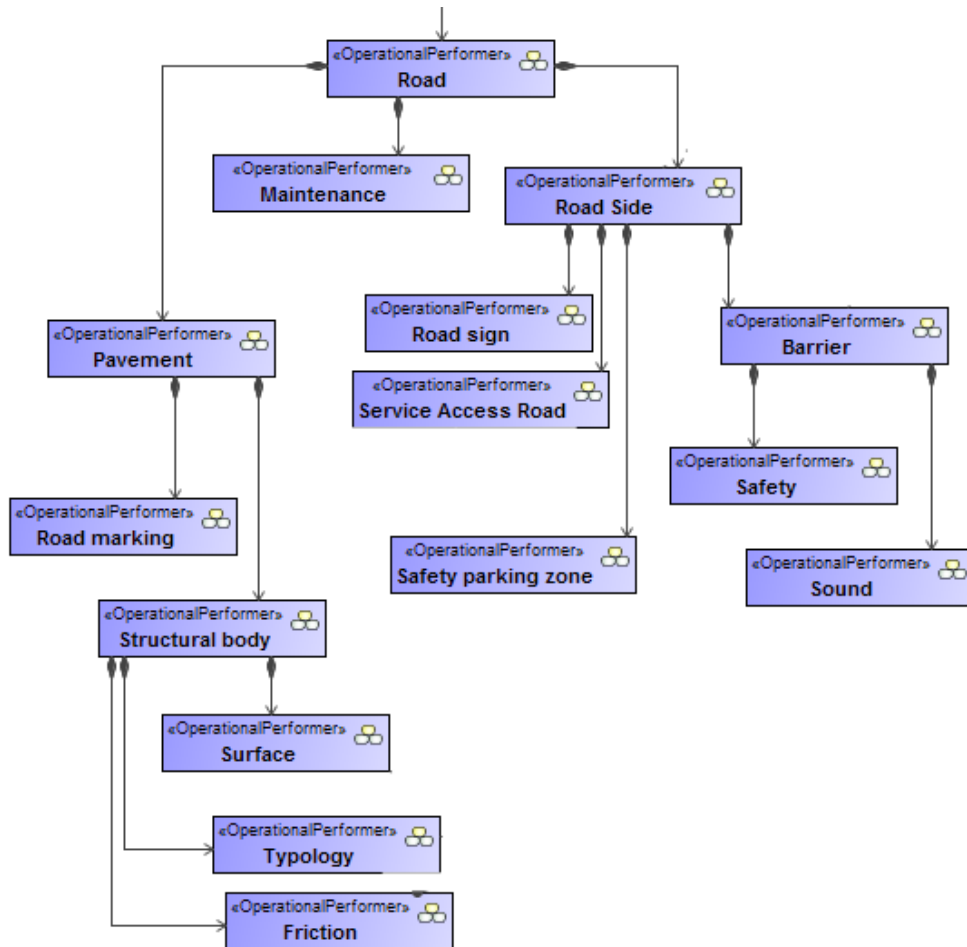


Figure 30: Example of how the road subsystem could be described using MagicDraw modelling tool.

4.3.1.5 Electricity subsystem

The electricity subsystem consists of the components production, transmission, distribution and management, shown in Figure 31. The component transmission includes how the power flows from the generation source through the national grid. The distribution is how the power flows through the regional grid to the power transfer subsystem. The management component controls the operation and balances the energy supply.

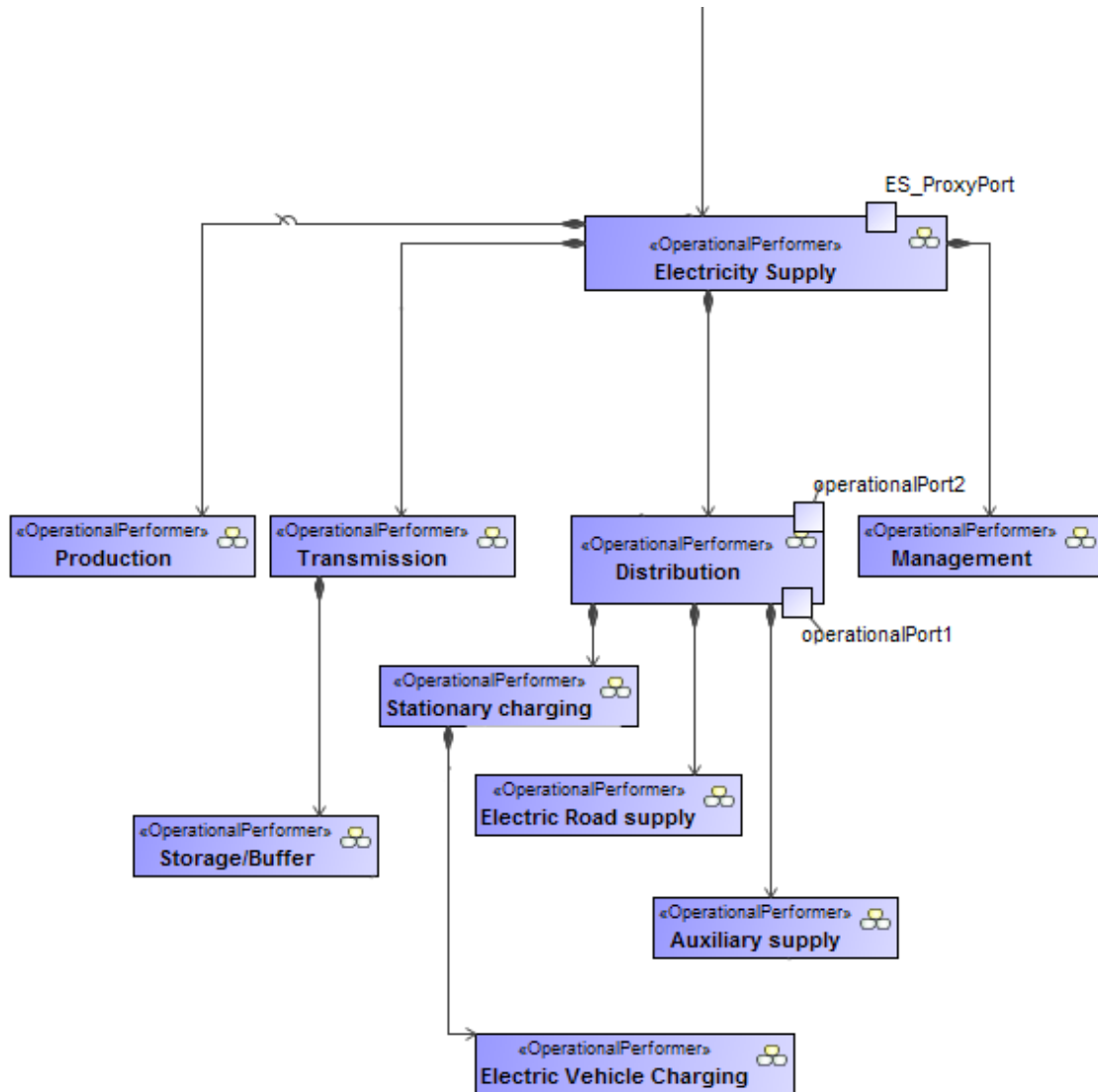


Figure 31: Example of how the electricity subsystem could be described using MagicDraw modelling tool.

4.3.2 Electric Road System Operator (ERSO)

Since ERS changes the type of fuel, from liquid (fossil) fuel to electric (renewable) energy, and how the fuel is consumed, from statically standing still to dynamically on the move, it causes major implications for users and the business models of today. Surprisingly, there has been very little attention to how users will pay for using ERS. In fact, an implemented ERS could require an operator that handles the interface between users and suppliers of ERS, working as a link between the different subsystems. We term this operator role as ERSO (Electric Road System Operator) and define it as the role that connects the users with energy supply from the electric road. The architecture of ERSO and the interfaces it relates to are described in Figure 32. It shows that ERSO has two types of relationship, one with suppliers and one with users of ERS. On the suppliers' side, ERSO operates the electric road which consists of many electric road segments. The Local power grid then provides electricity to each segment individually. ERSO then contracts electricity from the energy provider. On the user side, ERSO is the

handler of the subscription for the electric road and is responsible for contracting them to the transported goods owner or the Haulage contractor [115].

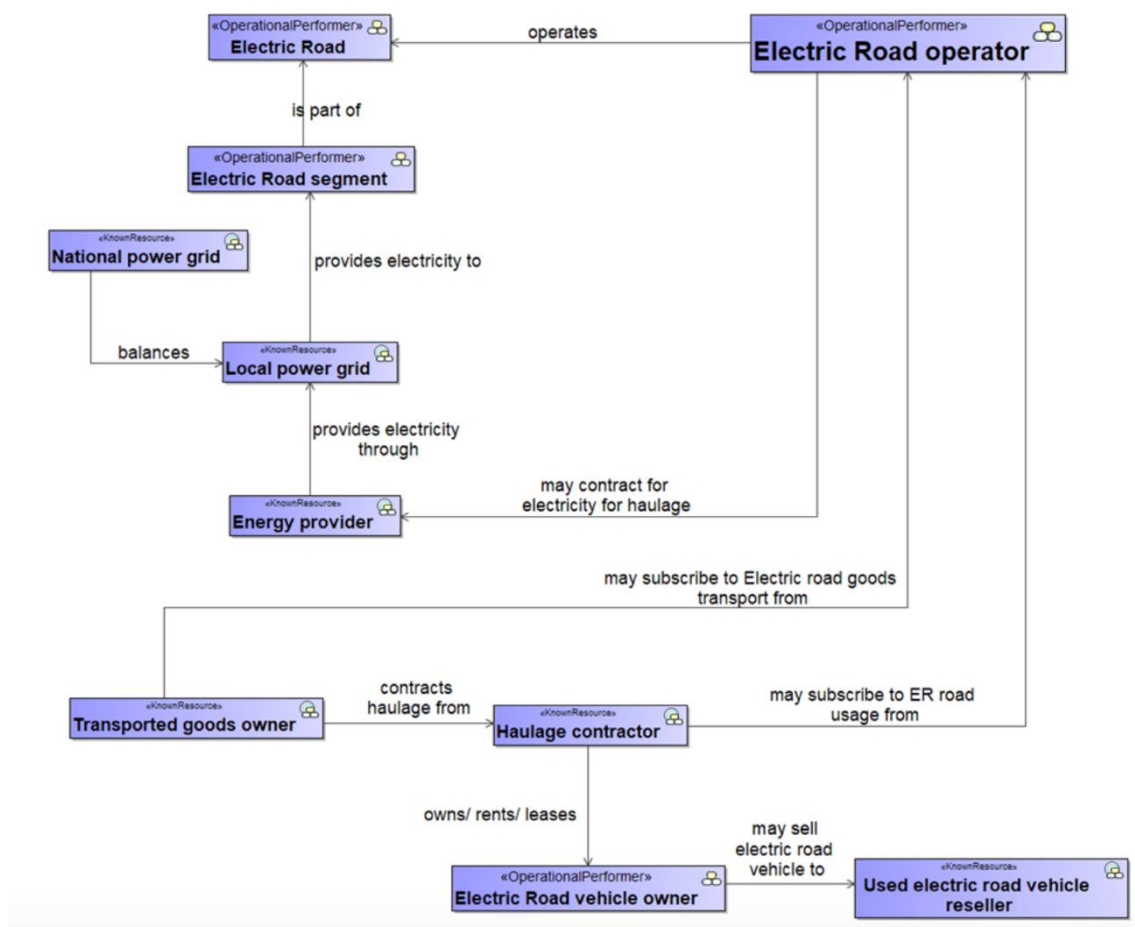


Figure 32: Relationship between logical elements and the electric road system operator.

Since the potential transition to ERS could be depicted through different phases, each with different types of user cases, the role of ERSO will change over time. Section 5.3.3.4 gives an analysis on small-scale deployment and large-scale deployment of ERS and include the ERSO perspective for different implementation strategies.

4.3.3 Communication and technical interfaces between ERS subsystems

How power transfer is performed through the different components and between the different subsystems is illustrated in Figure 33 below, from the electricity supply to the vehicle as well as critical interfaces along this path. The critical interfaces represent points in the system architecture where technical solutions are not yet fully developed and tested, both within a subsystem and between subsystems.

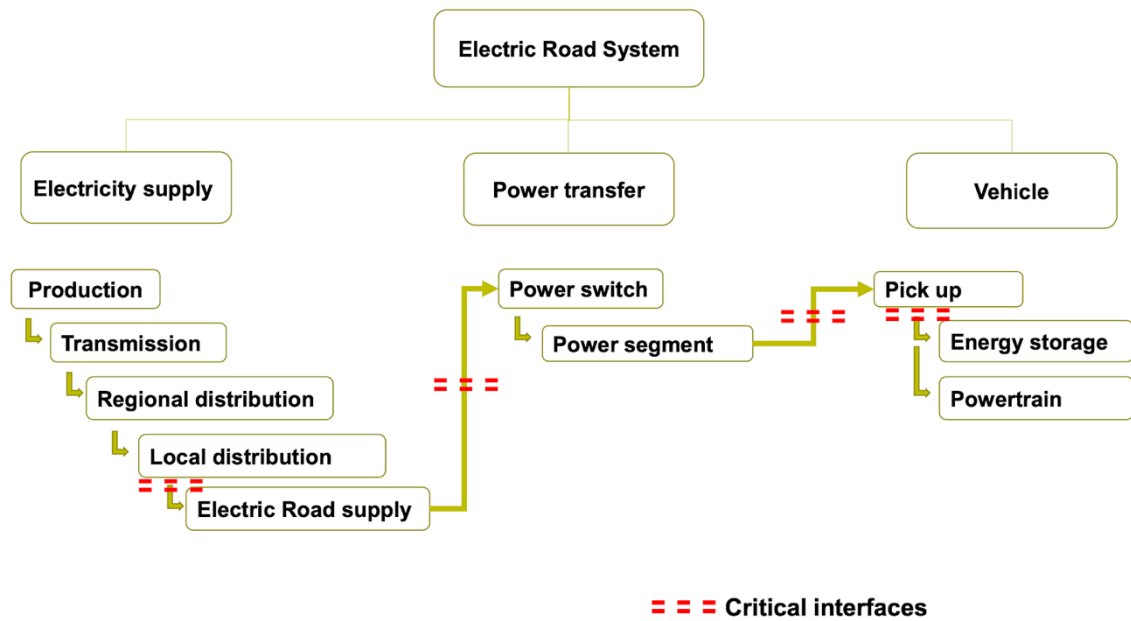


Figure 33: Power transfer through ERS and critical interfaces.

As evident in Figure 33, a solution to deliver electricity from the local grid to the ERS is still being developed and its design discussed (for example adequate grid voltage level and dimensioning). The same goes for the interface between the ERS itself and its individual power switches (discussed in detail in Section 6.3.1.1), how the ERS power segments should deliver electricity to the vehicle pick-up (as evident by multiple ongoing ERS pilots testing different technologies that aim so solve this problem) and between the vehicle pick-up and its on-board storage and powertrain systems.

The answer as to how to successfully design the solutions to these critical interfaces is twofold: partly ERS-specific technical solutions need to be invented and partly a functioning ERS actor network with proper communication pathways and clear responsibilities for each actor is needed. There are some theories on possible ERS actor setups and communication pathways that may prove adequate. However, continued work is needed to create a dialogue between road management, haulage and electricity supply representatives on the utilization of electric roads as well as identification of possible areas of responsibility for service providers and agree on a joint proposal. Figure 34 shows an architectural design of communication including the interplay of different activities in the ERS: service provider, power transfer, billing and service offerings.

By service provider we mean someone with, for example, responsibility for procuring electricity, charging infrastructure and electricity usage, operation and maintenance, supplementing truck centres with regard to major transport assignments, etc., and offering new innovative services (comparable with the idea of ERSO described above).

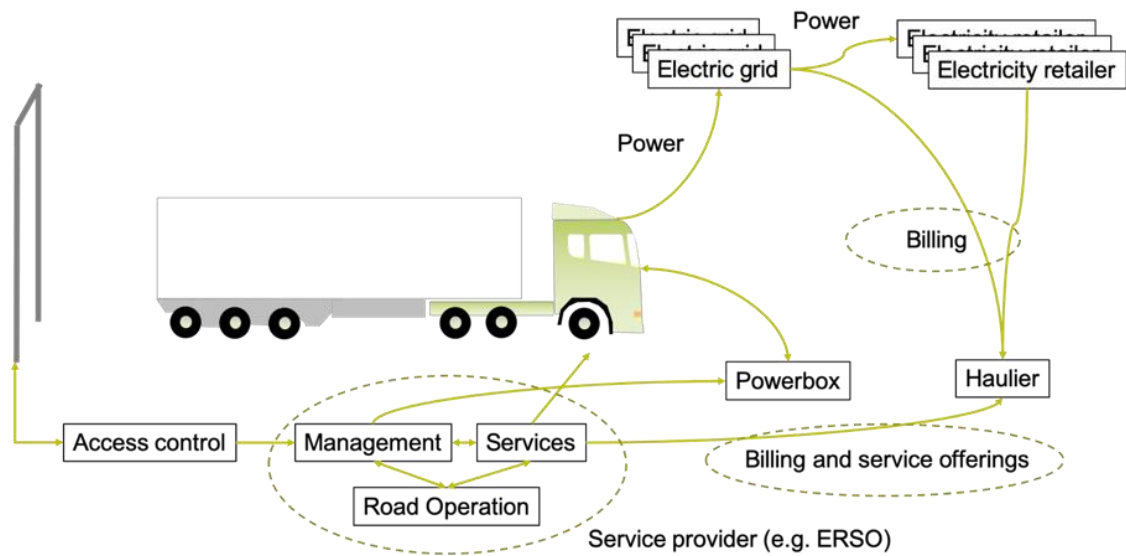


Figure 34: Communication interfaces of different activities in the ERS.

One can imagine several alternative setups of roles and responsibilities regarding electric road operation, wayside infrastructure and electricity supply to manage billing and usage of the ERS:

1. The service provider is responsible for both road operation and wayside infrastructure, and the electric grid fee is decided without any influence from the Swedish Energy Markets Inspectorate (Ei). An electricity supplier is chosen specifically for this ERS, meaning hauliers will get one bill including road usage, electric grid fees and electricity consumption. This setup is in analogy with the current railway system in Sweden.
2. The road operator and the power grid operator are separate service providers of their respective subsystems. The power grid operator is charged by the road operator for prevailing ERS services which is then transferred to hauliers for their road usage, including power grid fees. Furthermore, unlike previous setup, each haulier chooses their own electricity suppliers (similar to how individuals homeowners choose electricity subscriptions in Sweden today).
3. A fully decentralised system including one actor responsible for road operations, several power grid operators along the electric road stretch and free choice of electricity supplier for each haulier. Consequently, the hauliers are billed separately for the road usage, various power grid fees and electricity consumption without an intermediary. This setup could be a tool to split investment costs between many service providers who might see long-term profitability in managing operations and billing of ERS usage. However, the transport industry would need service providers who are really good at managing and selling package solutions on larger transport assignments than today as the payment system becomes much more complicated. One thought is that payments could be handled smoothly with blockchain technology, eliminating needs of a third party to handle financial transactions, which can instead be done automatically and instantaneously between two actors. Contracts can also be managed in a similar way to be able to quickly switch

electricity suppliers "during the journey". However, much remains to be done if this is to become a reality.

A mix of these setups can certainly occur along an electric road stretch, depending on different conditions and ambitions of the parties concerned. Work package 7, Access and payment systems look further into the specifics of ERS fees and payment systems, what to include and how to keep track of usage.

4.4 Business, ownership and investment models

There are multiple definitions of the business model concept as well as what the label “business model” refers to. Even if the exact elements of a business model are under debate, there is a strong consensus that it plays a significant role in the competitiveness of a firm. The definition has been approached from several directions historically, but in general, a business model describes the firm’s value proposition to its customers, the orchestration of resources and activities to create that value, and how the firm captures parts of that value created. However, the application of these values might differ depending on the question at issue for a specific use-case (i.e. how to earn money from the values produced, what market segments the company targets and the value it creates for what customers).

Although the business model concept is criticized for being ontologically vague and developed in silos, it does direct our attention toward the backbone of any successful business, that is, the activities connecting the firm’s technological core to the fulfilment of its customers’ needs. The business model as an analytical concept composes a unit of analysis that explicitly spans the traditional boundaries of the focal firm and relates internal value-creation activities to significant features of the firm’s business environment.

Consequently, in spite of prevailing disagreements, there is an emerging consensus among scholars that the core framework of a business model comprises the following three elements:

- Value proposition, i.e., the value that the company offers to its customers through its products and services;
- Value creation, i.e., how this value is created at the company and together with the customer; and
- Value capture, i.e., how the company appropriates parts of the value it has created for its customers.

Moreover, a business model is always related to a specific organization (e.g. a firm or a business unit) or an organization providing a specific product or service. Therefore, it is impossible to discuss business models when expanding the analysis across the juridical boundaries of the focal firm for aggregates of organizations, such as an industry, a sector, or a business ecosystem. A business model always has a focal point, i.e. a specific point of departure.

Table 1: A framework for business model design with respect to ERS.

| System function | Value Proposition | Value Creation Cost | Value Capture Revenue |
|-----------------|---|---|--|
| Energy | Generation, distribution, and provision of electrical energy | Capital investments and operating costs: Power generation Power distribution R&D New substations and power line infrastructure | Subscription agreements |
| Road Operation | Planning, provisioning, and monitoring of ERS Production, installation, and maintenance of electricity delivery components ERS operation Managing and balancing system energy | Internal operating cost Procurement of external services Infrastructure investment Technology investment Increased maintenance Road electricity | Government budget allotment ERS operator fees ERS user fees ERS construction and maintenance services fees |
| Power Transfer | Monitoring and operating of ERS Provision of safe, controlled, and efficient dynamic electric charging technology | Capital investments and operating costs: Physical component production Component control programming R&D Energy handover monitoring | Technology licensing agreements Sale of products and services |
| Vehicle | Transport as a service Recycling and reselling of reusable material waste transported Personalized delivery services Vehicle electrification components products and services Provision of electric trucks Aftermarket spare part provision Leasing and fleet management services | Capital investments and operating costs: Recycling operation Transport operation Electrified trucks Delivery services Electric road usage Vehicle production Logistics and distribution R&D Services Development and standardization of the conversion process and components | Direct sale of recycling products Direct sale of products and services New customer acquisition Licensing agreements Engineering services Aftermarket sales Sale of electric trucks Leasing of electric trucks Transport service fee |
| Road | Planning, provisioning, operating and maintaining of road infrastructure Energy provision to auxiliary road functions | Procurement of external services Infrastructure investment Increased maintenance | Road construction and maintenance service fees Sale of energy |

Following the above conceptualization, Mokhtar [116] evaluated potential ERS business models for the stakeholders involved in the Elways Arlanda demonstration project with respect to the elements of value proposition, value creation, and value capture. The study resulted in a function-based business model evaluation framework for ERS and

its findings are summarized in Table 1. The table is structured according to five major system functions; *Energy*, *Road operations*, *Power transfer*, *Vehicle*, and *Road*. Depending on the division of labour between stakeholders involved in an ERS, the table summarizes significant factors to consider for business model configuration.

4.4.1 Business models in infrastructure projects

Hypothetically, there are many potential alternatives for how to structure an ERS-investment. Given that a business model always is anchored in the perspective of one specific actor, there is a need to analyse the alternative roles that the primary stakeholders can fulfil in an ERS-project. Different ways of structuring a project create different possible divisions of labour, which, in its turn, have a direct impact on potential business models.

For instance, the road does not necessarily have to be constructed and operated by a public agency like the Swedish Transport Administration. Instead, these functions could be undertaken by an *independent road operator*, a company designated to operate this specific ERS-road, i.e. an ERSO (see Section 4.3.2). Such a road operator could be a private or public company, a consortium of private companies with interests in the road or organized as a public-private partnership. If the road is a public highway, it could be leased to the road operator on specific conditions. In such a case, the revenues of the road operator would either be based on road tolls, or some sort of long-term contracts (subscriptions) with transport operators using it for truck transports.

Arlanda Express/Arlandabanan is one example of a public-private infrastructure project with a built, operate, and transfer (BOT) setup (discussed further in Section 4.4.2). The fast speed commuter train Arlanda Express is owned and operated by the private company A-train AB, which also financed, planned, and constructed the railroad track Arlandabanan running to Arlanda Airport north of Stockholm. When the track was completed in 1999, the company handed it over to the Swedish state. In return, A-train AB leases back the track from the state with an exclusive concession to operate the train traffic until the year 2040.

Another example is the Øresund link, the bridge between Denmark and southern Sweden. The construction of the Øresund link was financed through loans, which should be repaid by tolls for road traffic and train operators. By the year 2040, the entire bridge, including auxiliary roads and tracks, should be repaid. The connection opened in 2000 and is both owned and operated by the Öresund Bridge Consortium, a company owned in equal parts by the Swedish and Danish state.

In the traditional setup for the transport of goods, independent haulage companies own and operate the vehicles. However, considering ERS infrastructure projects, one could imagine a division of labour between *provisioning the trucks* for the ERS and *operating the trucks* within the system. Already today, truck manufacturers such as Scania and Volvo operate extensive fleets of trucks for leasing. Thus, the provisioning of ERS-trucks could either be undertaken by an independent company (such as a manufacturer) but could also be fulfilled by the road operator managing the ERS-road, or an energy company renting ERS-trucks to independent transport operators.

A third alternative is that an *energy company* integrates vertically and takes responsibility (finances, constructs, owns and operates) for all the fixed facilities of the

ERS, i.e. the power supply system, but also the road-based charging system, as well as the road in itself. In this way, the energy company would primarily gain revenues from increased energy sales (and possibly also from road tolls). An even more speculative model is that the energy company acts as a telecom company providing routers to subscribers and provides the ERS-vehicles almost for free, given that the transport operator subscribes to use the ERS for a specified period of time.

To gain some perspectives, a set of business model configurations based on system components and activities will be investigated throughout the next sections, followed by a deeper dive into the discussion of how to balance between public and private ownership and responsibilities in ERS projects, and finally a look at how different investment cost appraisal models could look for different actors.

4.4.1.1 Project configuration model

In a very simplistic model of alternative project configurations, a road system could be structured into three main system *components* and three major system *activities*. The main components are physical road, vehicles utilizing the road, and fuel provided for feeding those vehicles; while the main activities are funding, owning, and operating. Thus, by putting them together, we get a 3×3 matrix, where each of the three activities is related to each component, as in Figure 35. Consequently, each of the main components needs to be **funded** (including produced and procured), **owned** by an actor (which does not necessarily mean the same actor who funds it) and **operated** in the system (but not necessarily by the same actor who funds and/or owns the component).

| | Fund | Own | Operate | |
|----------|------|-----|---------|----------------------------|
| Road | | | | road administration |
| Vehicles | | | | transport operators |
| Fuel | | | | oil companies |

Figure 35: A generic project configuration model for a traditional highway.

For a traditional, public highway serving automotive vehicles with internal combustion engines and primarily fed by gasoline and diesel, the typical division of labour is depicted in Figure 35 according to:

- A public road administration funding (which often also means deeply involved in design and construction), owning and operating the road.
- Various self-governing transport operators funding, owning, and operating the vehicles driving on the road.

- Oil companies funding, owning and operating the fuelling infrastructure of gas stations, etc., serving the vehicles trafficking the road.

Applied for an ERS, this model reveals a number of, more or less plausible, alternative business model configurations.

4.4.1.2 ERS business models for a road operator

From the perspective of road operations, ERS provides four principal business model configurations, here labelled:

1. **Classic Road**

Constituted by the road only.

2. **Integrated Transport System**

Constituted by the road integrated with operations of all transports of the electric road system.

3. **Transport System with Independent Transport Operators**

Constituted by the road in combination with the provisioning of ERS-vehicles, but either (a) subcontracting the ERS transports to independent transport operators or (b) leasing ERS-vehicles to transport operators, which use the vehicles for their own operations.

4. **Transport System with Service Purchase Agreements**

Constituted by the road in combination with provisioning of ERS-vehicles to transport operators and including a subscription to use the road for a specified period in time.

1. **Classic Road**

The Classic Road model follows the division of labour of the traditional highway described above. The difference is that the road component is electrified and contains the road-based charging equipment, physically installed into, on the side of, or above the road. Following this model, one and the same road operator funds the construction and installations of the electric road, owns the road, and takes care of the road operations (Figure 36). The ERS-compatible vehicles utilizing the road as well as the electric infrastructure feeding the road with electric power are funded, owned, and operated by other actors.

| | Fund | Own | Operate |
|-------------------------|------|-----|---------|
| Electric road | | | |
| ERS vehicles | | | |
| Electric infrastructure | | | |

Figure 36: ERS as a Classic Road.

There are two versions of this model:

- ERS with **free access**, like most public roads in Europe, meaning that any vehicle that is technically compatible, able to use the system and pay the energy bill afterwards is permitted.
- ERS with **limited access**, like a US turnpike or the motorways in e.g. France, Italy and Spain, where the transport operators have to pay a fee (road toll, subscription or a pass) to use the ERS.

2. Integrated Transport System

In the *Integrated Transport System* model, the road operator takes care of all system activities from the physical road to transport operations (but not the electrical power supply), depicted in Figure 37. In other words, the road operator builds and operates the road as well as operates all transports within the ERS. Thus, the ERS is, in this case, a closed system, not open to other transports than those operated by the road operator.

| | Fund | Own | Operate |
|-------------------------|------|-----|---------|
| Electric road | | | |
| ERS vehicles | | | |
| Electric infrastructure | | | |

Figure 37: ERS as an integrated transport system.

Designed as an integrated transport system, the ERS resembles public-private railway projects, like Arlandabanan between the airport and the city of Stockholm, or Heathrow

Express in London. ERS as an integrated transport system could also function as an extended harbour or airport; i.e. that the harbour or airport operates a remote logistics terminal, from which the harbour or airport itself takes care of the on-land transport to the ships or aeroplanes.

3. Transport System with Independent Transport Operators

In the *Transport System with Independent Operators* business model, a road operator takes care of every function related to the physical road, as well as the funding and ownership of the ERS vehicles, but not the very operations of the vehicles, as shown in Figure 38.

| | Fund | Own | Operate |
|-------------------------|------|-----|---------|
| Electric road | | | |
| ERS vehicles | | | |
| Electric infrastructure | | | |

Figure 38: ERS as Transport System with Independent Transport Operators.

There are two versions of this model. In the first version, the ERS is a **closed system**, where a road operator funds, builds, and operates the system as a whole, but outsources the actual transport operations to one or several external contractors. Designed in this way, the ERS resembles, for instance, the operations of the Stockholm Subway, where the public Stockholm Transport (SL) owns and operates the subway system and owns the subway trains, while the Hong-Kong based company MTR operates the subway traffic.

In the second version, the ERS is an **open system** with free or limited access. The road operator builds and operates the ERS as well as provides ERS vehicles for leasing to independent transport operators, e.g. private haulage companies. In this case, the ERS resembles the classic road model above, but with the difference that the road operator has integrated forward and provides ERS-vehicles as a service (this business model can also be combined with the classical model).

4. Transport System with Service Purchase Agreements

In the *Transport System with Service Purchase Agreements* business model (Figure 39), a road operator builds, funds, owns and operates the road, but also provides independent transport operators with ERS-vehicles, free or for a low price. In exchange, the transport operators are contracted to use the ERS for specified periods of time. This model resembles the model of telecom companies, or cable tv companies, where a phone or a router are provided to a customer for a low price, while the customer is bound to subscribe to a provider's services for e.g. 24 months.

| | Fund | Own | Operate |
|-------------------------|------|-----|---------|
| Electric road | | | |
| ERS vehicles | | | |
| Electric infrastructure | | | |

Figure 39: Transport System with Service Purchase Agreements.

4.4.1.3 ERS business models for a transport operator

From the perspective of a transport operator, there are three possible business models:

1. **Classic Product Purchase**

Constituted by the purchase and ownership of ERS vehicles in operations.

2. **ERS Vehicle Leasing**

Constituted by a leasing contract for the ERS vehicles in operations.

3. **ERS Vehicle Service Purchase Agreement**

Constituted by one actor providing the ERS vehicle in exchange for a subscription to use the system during a specified period of time.

1. **Classic Product Purchase**

In the *Classic Product Purchase* model, the transport operator funds, purchases, owns and operates the ERS vehicles, as seen in Figure 40. Potential revenues originate in sales of transport services.

| | Fund | Own | Operate |
|-------------------------|--------|--------|---------|
| Electric road | Grey | Grey | Grey |
| ERS vehicles | Yellow | Yellow | Yellow |
| Electric infrastructure | Grey | Grey | Grey |

Figure 40: ERS Vehicle Product Purchase.

This is the typical setup for a haulage company. For e.g. an incumbent haulage company to reinvest in its fleet and choose ERS-trucks instead of diesel trucks, the business case has to show a positive net margin (i.e. lower costs or higher revenues). Consequently, a transport operator changing from oil-based vehicle propulsion to ERS-vehicles needs to consider the following items in its business case:

- The difference in the **investments** between purchasing ERS-vehicles rather than conventional vehicles, including vehicle-based equipment for charging and energy storage.
- Differences in **fuel costs** (electricity vs. diesel) as well as in other costs for operations and maintenance of the vehicles.
- Potential differences in **revenues** from sales of transport services due to ERS instead of oil-based transports.

2. ERS Vehicle Leasing

In the *ERS Vehicle Leasing* model, a transport operator leases its vehicles from a provisioning company, typically an OEM or a third-party ownership company (often a financial actor), depicted in Figure 41. This is a common set up for product leasing.

| | Fund | Own | Operate |
|-------------------------|------|------|---------|
| Electric road | Grey | Grey | Grey |
| ERS vehicles | Grey | Grey | Yellow |
| Electric infrastructure | Grey | Grey | Grey |

Figure 41: ERS Vehicle Leasing model.

3. ERS Vehicle Service Purchase Agreement

In the *Service Purchase Agreement* model, the transport operator is provided with the ERS vehicle at low cost in exchange for subscribing to utilize the ERS-system during a specific period of time as illustrated in Figure 42.

| | Fund | Own | Operate |
|-------------------------|------|--------|---------|
| Electric road | Grey | Grey | Grey |
| ERS vehicles | Grey | Yellow | Yellow |
| Electric infrastructure | Grey | Grey | Grey |

Figure 42: Service Purchase Agreement.

4.4.1.4 ERS business models for an energy company

From the perspective of an energy company, investing in ERS could be regarded as an extension of already existing energy businesses. There are at least seven possible business model setups for an energy company (Figure 43 compilation).

In its simplest form, the energy company continues with business-as-usual, i.e. it provides energy to the ERS system (alternative **1a** in the compilation). This could, however, be extended to a model where the energy company either funds and provides ERS-vehicles for free (**1b**), or leases the vehicles, to transport operators (**1c**).

Another, more speculative alternative, is that the energy company integrates vertically and invests in electric roads in order to extend its business (**2a**). This could also be combined with funding and provisioning (**2b**) and/or leasing of ERS-vehicles (**2c**).

Furthermore, an even more speculative alternative is that the energy company create a completely integrated ERS, encompassing both the road, vehicles and electric infrastructure (**3**).

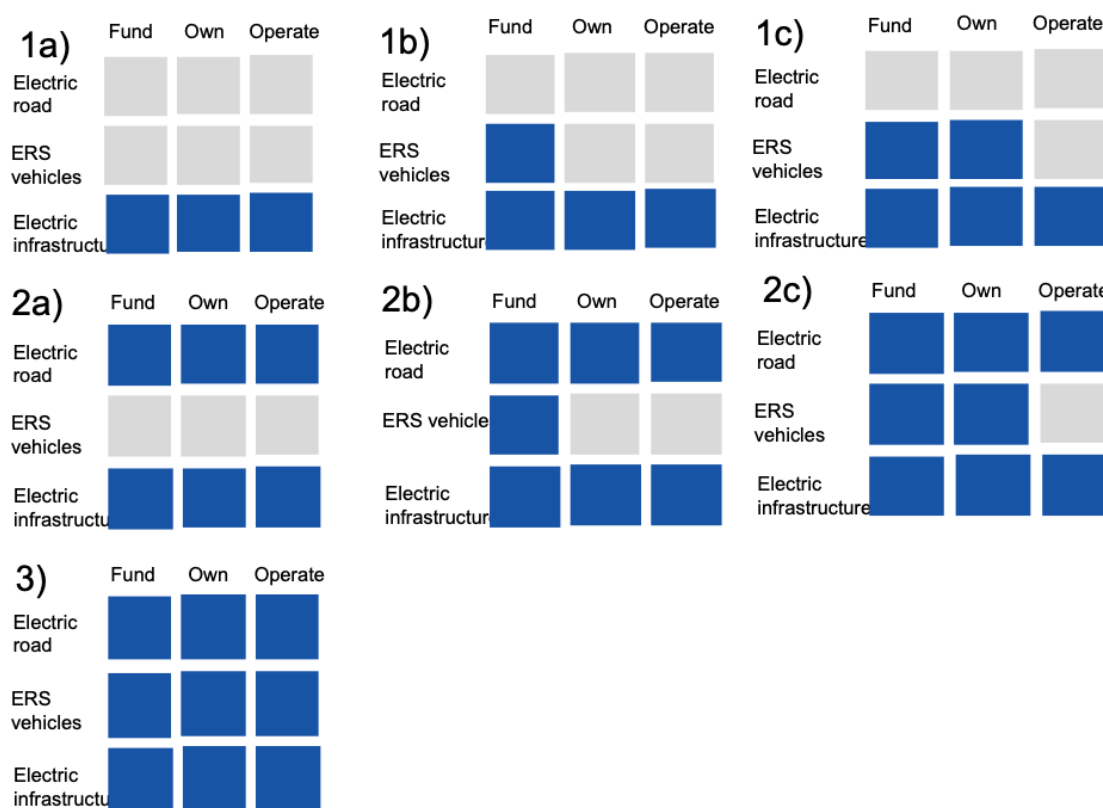


Figure 43: ERS Business Models for an energy company.

The above presented selection of business models, as well as the next chapter covering public-private partnerships, was done from an academic perspective, where the presented material is based on scientific literature where possible and plausible solutions have been chosen in line with what is relevant for ERS.

An important next step in developing these areas would be to gather the central ERS actors and for them to pick one or a few business and partnership models best suited for further research (or even actual implementation) specifically related to implementing, scaling up and commercializing ERS technology between them and possibly other actors in the ERS stakeholder ecosystem.

4.4.2 Public-private partnerships

Several of the project configurations above is based on some sort of public-private partnership (PPP) where parts of the financing of the infrastructure come from private actors. In spite of often being politically controversial, PPPs have emerged to be a likely solution for the financing of ERS outside the state budget [117].

Governments around the world are cooperating with private actors in PPPs in order to improve the efficiency of public investments and to cope with insufficient government funding [118], [119]. Political obstacles are however a major factor for why PPPs aren't widely adopted. Examples of such obstacles are the need for special legislation but also the danger of public disapproval [115], [120]. According to [121], advantages of PPPs compared to traditional public procurement include, among other things, financial risk-sharing between the public and the private partner, efficient use of resources, and reduced lifecycle costs (the positive impact on lifecycle costs has however been disputed

by other scholars, c.f. [122]). However, when problems occur within PPP-projects it is often the government that has to take the hit and ends up paying the extra costs generated [121].

Since ERS requires users to purchase a new kind of vehicle, and users may not be willing to purchase one until it can be used widely, it is possible that it will take a couple of years until a desired ERS-utilization of the roads is reached. This might lead to a vicious cycle, where the private party of the PPP may urge for higher user fees in the early phases in order to compensate for low utilization; and the high user fees might lead to users searching for alternatives for ERS since they consider it too expensive to use. This has been the case for several infrastructure BOT projects, e.g. the Cross-City Tunnel in Sydney and the Western Harbour Crossing in Hong Kong [123].

To make sure that end-users are not punished for low utilization, it may become necessary for the government to reimburse the consortium for their losses at the beginning [124]. However, to allocate tax money to this purpose, with no guarantees that the utilization will increase in the future, might be controversial politically. Furthermore, the negative reputation of PPPs in Sweden can also have negative effects on the public support for using a PPP for financing ERS. A vast majority of all newspaper articles written about PPPs, most of them about the New Karolinska Hospital (NKS) in Sweden the last couple of years has given the PPP a negative reputation, regardless of model or application. NKS has become commonly known as a PPP project which has used a large amount of taxpayers' money, and the public perception of PPPs can be considered to be damaged. Thus, if chosen, it will be important to communicate that the success of PPPs depend on the application and the contract, and that the financing of ERS will not necessarily mean that the situation with NKS will happen again.

Consequently, transparency will become significantly important in the case of ERS. In order to gain support, it will be important to clarify why the previous problems of PPP projects won't be repeated for ERS. Furthermore, transparency is also important in order to build trust between the public and private parties of the arrangement which, in turn, may constrain the risk of opportunistic behaviour, asymmetric information, and risk-aversion [125].

However, there are a number of different PPP models available and, if applied, it has to be decided which model is most favourable for ERS. The various PPP-models consist of different combinations of the following components: build, design, develop, lease, own, operate, maintain, and transfer. The components relevant for this paper are defined as follows:

- *Build*: A private partner builds a physical asset, typically a physical infrastructure and equipment. The infrastructure in the case of ERS consists of the electric lines as well as other components needed for transmission, distribution, and management of energy.
- *Own*: A private partner owns the physical asset. With ownership comes e.g. responsibility for maintenance of the infrastructure.
- *Operate*: A private partner has full operating rights of the infrastructure. For example, the partner controls access to the infrastructure and its pricing.

- *Transfer*: The ownership and/or operating rights are returned to the public partner of the PPP.

These four components can be combined into three different PPP models seen in Table 2: Build-Operate-Transfer (BOT), Build-Own-Operate-Transfer (BOOT), and Build-Own-Operate (BOO). Among these, BOT and BOO are the most commonly used PPP model during the last decade.

Table 2: The components of the different PPP models.

| Model | Build | Own | Operate | Transfer |
|-------|-------|-----|---------|----------|
| BOT | X | | X | X |
| BOOT | X | X | X | X |
| BOO | X | X | X | |

Build-Operate-Transfer (BOT)

A private partner finances, builds, and operates the physical asset for a specific concession period (usually between 30 and 40 years), while the public authority owns the asset. The private partner is given the concession to operate and gain revenues from the asset during a specified time period, but after that, the operating rights are transferred back to the public. During the concession, revenues from the operations are typically used to reimburse loans, pay operational costs, and finance maintenance of the infrastructure. In addition, user fees are generally collected by the private partner as return on investment. Responsibilities are typically balanced between the private and public partners. Thus, BOT is the PPP-structure with the least degree of privatisation and the model allows the government to transfer financial and technical risks to the private consortium.

Build-Own-Operate-Transfer (BOOT)

This model is similar to BOT, with the exception that the private partner also owns the asset during the concession period. During the concession period, the private partner has the right to collect revenue in order to pay back the investment and get a return on investment. The concession period must be long enough for the private partner to be able to do this. There is often no distinction made between BOOT and BOT since the difference is small. They are considered equivalent if the control and cash flow rights are the same. However, the choice often depends on the legal system that is regulating the PPP-contract.

Build-Own-Operate (BOO)

Even though BOO is the second most used PPP model (following BOT), research on the BOO model is far less comprehensive and there are fewer case studies reported. The BOO model is similar to BOT except that the private partner builds the infrastructure, owns it, and solely operates it with no obligations to return it to the government. Thus, BOO is similar to conventional private investments. The private partner holds most of the responsibility but is often subject to regulatory constraints, e.g. on the operations and pricing. It may be politically difficult for the government to exercise administrative

power in order to help the private partner in owning a facility with the intention to promote public welfare.

The strengths and weaknesses for each of these three models are summarized in Table 3.

Table 3: Comparisons of strengths and weaknesses of PPPs from a governmental perspective [126].

| | BOT | BOOT | BOO |
|-----------|---|--|--|
| Strengths | <p>Decreased risk of conflicting interests due to incentivization of interests made easier</p> <p>Easier to protect the government's interests since they retain control after the concession period ends</p> <p>Lower degree of privatization can protect the government's interests from risk-positivism</p> <p>Easier to acquire strong private consortiums due to high government involvement</p> <p>Suitable for strategic and large infrastructure projects</p> <p>Will gain political support due to lowest degree of privatization</p> <p>May gain higher political support due to transfer occurring</p> <p>Can lead lower end-user fees which can increase public support</p> <p>Better prerequisites for being transparent</p> | <p>Decreased risk of conflicting interests due to incentivization of interests made easier</p> <p>Easier to protect the government's interests since they retain control after the concession period ends</p> <p>Lower degree of privatization can protect the government's interests from risk-positivism</p> <p>Easier to acquire strong private consortiums due to high government involvement</p> <p>May gain higher political support due to transfer occurring</p> <p>Better prerequisites for being transparent</p> | <p>Reduced risk of moral hazard since the private partner may have incentives to guarantee high quality since no return to the government will occur</p> <p>May gain political support since it requires the smallest public investment</p> <p>Can gain public support due to high degree of privatization</p> |

| | BOT | BOOT | BOO |
|------------|--|--|---|
| Weaknesses | <p>Increased risk of moral hazard since the private party may prioritize increased profits rather than maintenance</p> <p>Can lead to reduced public support due to the bad reputation of NKS and Arlandabanan and a large public investment</p> | <p>Increased risk of moral hazard since the private party may prioritize increased profits rather than maintenance</p> | <p>Increased risk of conflicting interests due to a higher degree of privatization</p> <p>More difficult to protect the government's interests since no transfer occurs</p> <p>The private consortium may be risk-positive, which the government cannot afford to be</p> <p>More difficult to acquire strong private consortiums due to high degree of privatization</p> <p>May receive lower public support due to no transfer occurring and a high degree of privatization</p> <p>Can result in the highest end-user fees</p> <p>More difficult to be transparent due to higher degree of privatization</p> |

Regardless of which model is chosen, the contract between the public government and the private consortium has to be written carefully. Consequently, with respect to ERS, the next step is to conduct a detailed analysis of the risks related to ERS- investments and how the contract can be framed in order to avoid or mitigate these risks. Once the risks, and how they should be handled, are identified, a decision about the appropriate PPP model can be made.

4.4.3 Models for capital investment appraisals

The deployment of ERS is related to large investments in physical infrastructure. There are a number of estimates of the capital expenditures reported. So far, however, all these estimates suffer from high uncertainties. Furthermore, estimates of the capital expenditures are also highly dependent on the actor, i.e. from which perspective the estimate is calculated. Given the different configurations discussed in Section 4.4.2 above, the investment models to be adopted and utilized by these actors are expected to be different and context-specific.

Throughout the following sections, four models for principal capital investment appraisal of ERS are outlined from a business perspective. It follows the categories in

Figure 44: **(1)** for an *energy provider*, **(2)** for a *road operator*, **(3)** for a *haulage company*, or **(4)** for an *internal system operator*, i.e. when a company uses an ERS for its internal logistics operations.

Actor-specific investment cost appraisal models are presented and broken down according to every cost or revenue element that each specific actor is affected by when part of an ERS venture. The relation between costs and revenues for different actors (and how they change with different ERS actor setups) is important to understand when discussing the monetary implications of investing in an ERS, both for the system at large and for its subsystems. As ERS is considered both a novel technology and a system-of-systems, it can be argued that the investment and payoff equation needs to show a reasonable result both for the entire system and for each system actor individually before an ERS will be constructed and able to compete with existing fossil-based technologies.

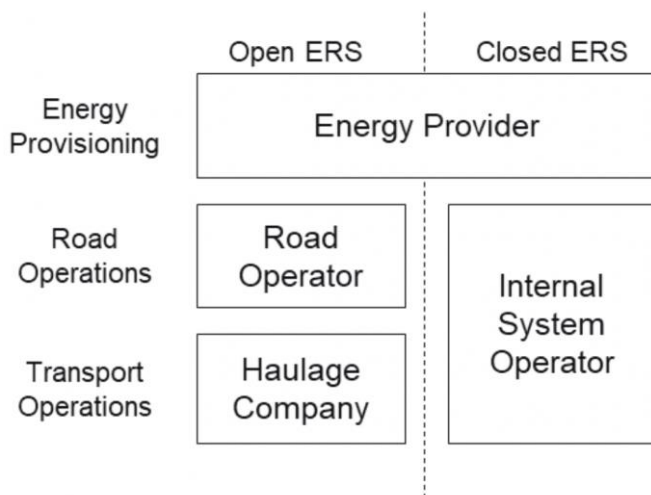


Figure 44: ERS Categories.

4.4.3.1 Energy Provider

The energy sector includes construction of generation, transmission & distribution capacities. Consequently, the investment appraisal model for an energy provider involves a Net Present Value (NPV) assessment that is subject to the assumptions, variables, and factors outlined below:

- The model spans the entire value chain: generation, transmission & distribution, and storage.
- The model includes all types of energy technologies to be used (e.g. Solar, Wind, etc.).
- The structure of the model is similar for both the open and closed ERS setups with elements removed or values changed to correspond to the needs of the particular scenario setup.
- The time span of analysis assumes that the ERS is operational at year $t=1$.
- The analysis takes only economic factors and excludes monetization of externalities.

Model

$$NPV = -OI_{t=0} + \sum_{t=1}^T \frac{EI_t + GI_t + RV_t - CE_t - OM_t}{(1 - CC)^t}$$

when the cashflows and values are assumed to be different every year, and

$$NPV = -OI_{t=0} + PV([EI + GI - OM - CE], CC\%, T) + PV(RV, CC\%, T)$$

when the cashflows and values are assumed to be constant every year.

Variables and Factors

Revenues

- Energy Income (EI)
 - System Usage Charges
 - Price of Electricity
 - Electricity Consumed
 - System Connection Charges
 - Energy System Installation

EI = System Usage Charges + System Connection Charges + Energy System Installation

System Usage Charges = Price of Electricity × Electricity Consumed

- Potential Government Income (GI)
 - Policy Grants
 - Subsidies

GI = Policy Grants + Subsidies

- Equipment Residual Value (RV)

Costs

- Original Investment (OI)
 - Construction
 - Engineering Services
 - Land Purchase
 - Equipment

OI = Construction + Engineering Services + Land Purchase + Equipment

- Additional Capital Expenditure (CE)
 - Construction
 - Engineering Services
 - Land Purchase
 - Equipment

$CE = \text{Construction} + \text{Engineering Services} + \text{Land Purchase} + \text{Equipment}$

- Operations & Maintenance (OM)
 - Operations
 - Labour
 - Land Lease
 - Insurance
 - Fuel
 - Equipment (Control services)
 - Engineering Services
 - Maintenance
 - Periodic
 - Breakdown
 - Overhaul

$OM = \text{Operations} + \text{Maintenance} + \text{Engineering Services}$

$\text{Operations} = \text{Labour} + \text{Land Lease} + \text{Insurance} + \text{Fuel} + \text{Equipment}$

$\text{Maintenance} = \text{Periodic} + \text{Breakdown} + \text{Overhaul}$

Cost of Capital (CC)

- Financing Structure
- Inflation
- Risk-Free Interest Rates

Time (T)

- Economic Life

4.4.3.2 Road Operator

The investment appraisal model for a road operator also utilized an NPV assessment. With an overall increase in the number of toll road projects, it follows that the accuracy of forecasts for revenue and cost associated with such projects becomes a paramount element to their success [127]. Therefore, the assessment exams two scenarios when it comes to ERS operations: road with tolls and road without tolls. The distinction is made by outlining the revenue, cost, and discount factor variables and factors that are general for both scenarios and the variables and factors distinct to a particular scenario.

Assumptions:

- A road operator will only operate an open ERS.
- The two potential scenarios are whether the road will be with tolls or without tolls.
- The road operator considers only the conversion of existing roads into ERS and not the construction of new roads.
- The time span of analysis assumes that road is operational at year $t=1$.
- The analysis taking only economic factors and excludes monetization of externalities.

Model

$$NPV = -OI_{t=0} + \sum_{t=1}^T \frac{ES_t + GI_t + *RT_t + RV_t - CE_t - OM_t}{(1 - CC)^t}$$

where cashflows and values for the variables are assumed to be subject to change over time, and

$$NPV = -OI_{t=0} + PV([ES + GI + *RT_t - OM - CE], CC\%, T) + PV(RV, CC\%, T)$$

when the cashflows and values are assumed to be constant every year.

Variables and Factors

Revenues

- ERS Service (ES)
 - Price of Charging
 - Number of ERSVs
 - Electricity Consumption
 - Distances Travelled

ES = Price of Charging × Electricity Consumption × Number of ERSVs

- Potential Government Income (GI)

- Annual Budget Allotment

GI = Policy Grants + Subsidies

- Equipment Residual Value (RV)
- *Road Tolls (RT)

Costs

- Original Investment (OI)
 - Construction
 - Charging Equipment
 - ERS Technology License
 - Intelligent Traffic System
 - Grid Connection
 - Road Works
 - Engineering Services
 - Land Purchase

OI = Construction + Engineering Services + Land Purchase

Construction = Charging Equipment + Grid Connection + Road Works

- Additional Capital Expenditure (CE)
 - Construction
 - Charging Equipment
 - ERS Technology License
 - Intelligent Traffic System
 - Road Works
 - Engineering Services
 - Land Purchase

CE = Construction + Engineering Services + Land Purchase

Construction = Charging Equipment + Grid Connection + Road Works

- Operations & Maintenance (OM)
 - Operations
 - Labour
 - Land Lease

- Insurance
- Electricity
- Engineering Services
- Maintenance
 - Periodic
 - Breakdown
 - Overhaul

OM = Operations + Maintenance + Engineering Services

Operations = Labour + Land Lease + Insurance + Electricity

Maintenance = Periodic + Breakdown + Overhaul

Cost of Capital (CC)

- Financing Structure
- Inflation
- Risk-Free Interest Rates

Time (T)

- Economic Life

4.4.3.3 Haulage Company

As transport operators in open ERS-systems, haulage companies are to mainly focus on the investment in the vehicles. As such, it is important to take into account the comparative decrease in fuel consumption costs and reduced maintenance costs. Consequently, the analysis from a haulage company perspective takes on a comparative outlook between the potential investment in ERS vehicles and the conventional diesel vehicles (DVs) over the time span in which the vehicles are to be utilized.

The payback period method is commonly used for assessing fuel-saving technology investments and more generally for comparisons of newer technologies with their older counterparts. Thus, the investment appraisal model for haulage companies when comparing alternative vehicle technologies when expanding or replacing their vehicle fleet involves a comparison of payback periods with a focus on comparative total costs of ownership. However, a haulage company can either (1) own the vehicles or (2) lease them, which affects the choice of an appraisal method. The payback method is utilized for the scenario involving the purchase and ownership of the vehicle given the presence of original investment value to payback.

A net value (NV) based assessment was utilized for the scenario that haulage companies are to lease the vehicles in order to understand the comparative difference between ERS vehicles and diesel vehicles (DVs).

The variables and factors are outlined below, based on the following assumptions:

- Haulage companies will only operate in an open ERS.
- DVs and ERS vehicles are comparable in terms of load capacity and revenue generating ability.
- Vehicle lifecycle assessment for the total cost of ownership period starts at acquisition and ends at the disposal of the vehicle.
- The analysis takes only economic factors and excludes monetization of externalities.

General Variables and Factors:

Revenues

- Sale of Transport Services (TS)
 - Price
 - Demand
 - Capacity
 - Fleet Size
 - Load Capacity
 - Distances Travelled

$$TS = \text{Price} \times \text{Demand}$$

Costs

- Operations & Maintenance (OM)
 - Operations
 - Labour
 - Insurance
 - Registration Fees
 - Maintenance
 - Periodic
 - Breakdown
 - Overhaul

$$OM = \text{Operations} + \text{Maintenance}$$

Operations = Labour + Insurance + Registration Fees

Maintenance = Periodic + Breakdown + Overhaul

- Vehicle Taxes (VT)

Cost of Capital (CC)

- Financing Structure
- Inflation
- Risk-Free Interest Rates

Time (T)

- Economic Life

Scenario-Specific

Own Vehicle Model:

Δ Payback Period (DV – ERSV, T): Δ OI(DV – ERSV)_{t=0}

$$= \sum_{t=0}^T TS_t + \Delta RV(DV - ERSV)_t - \Delta OM(DV - ERSV)_t + \Delta VP(DV - ERSV)_t - VT_t$$

Variables and Factors:

- Original Investment (OI)
 - Diesel Vehicle (DV)
 - DV Purchase
 - Number of DVs
 - ERS Vehicle (ERSV)
 - ERSV Purchase
 - Number of ERSVs

Δ OI(DV – ERSV)

$$= (\text{DV Purchase} * \text{Number of DVs}) - (\text{ERSV Purchase} * \text{Number of ERSVs})$$

- Vehicle Residual Value (RV)
 - Vehicle economic life

- Number of decommissioned vehicles
- Vehicle Powering (VP)
 - Distances Travelled
 - DV Fuelling
 - Number of DVs
 - Price of Diesel
 - Diesel Consumption
 - ERSV Charging
 - Number of ERSVs
 - Price of Electricity
 - Electricity Consumption

$$\begin{aligned} \Delta VP(DV - ERSV) &= (\text{Number of DVs} * \text{Diesel Consumption} * \text{Price of Diesel}) \\ &\quad - (\text{Number of ERSVs} * \text{Electricity Consumption} * \text{Price of Electricity}) \end{aligned}$$

Lease Vehicle Model

$$\text{Net Value (NV)} = \sum_{t=0}^T TS_t + \Delta VP(DV - ERSV)_t + \Delta OM(DV - ERSV)_t + \Delta VL(DV - ERSV)_t - VT_t$$

Variables and Factors:

- Vehicle Powering (VP)
 - Distances Travelled
 - DV Fuelling
 - Number of DVs
 - Price of Diesel
 - Diesel Consumption
 - ERSV Charging
 - Number of ERSVs
 - Price of Electricity
 - Electricity Consumption

$$\begin{aligned} \Delta VP(DV - ERSV) &= (\text{Number of DVs} * \text{Diesel Consumption} * \text{Price of Diesel}) \\ &\quad - (\text{Number of ERSVs} * \text{Electricity Consumption} * \text{Price of Electricity}) \end{aligned}$$

- Vehicle Lease (VL)
 - DV Lease
 - DV Lease Fee
 - Number of DVs
 - ERSV Lease
 - ERSV Lease Fee
 - Number of ERSVs

$\Delta VL(DV - ERSV)$

$$= (\text{Number of DVs} * \text{DV Lease Fee}) - (\text{Number of ERSVs} * \text{ERSV Lease Fee})$$

4.4.3.4 Internal System Operator

Since an internal system operator will have exclusive access to and control over its ERS, the investment model variables and factors are highly analogous to a combination of those variables and factors incorporated in the models for a road operator and a haulage company. An internal system operator is subject to similar analysis scenarios as those of a haulage company. An internal system operator will analyse the comparative difference between ERSVs and DVs through the owning or leasing of the vehicles when considering a replacement or expansion of the vehicle fleet. Unlike the haulage company assessment, the internal system operator assessment needs to include the investment in the ERS infrastructure as part of the comparative assessment. Thus; the models, variables, and factors will be outlined in a similar manner to that of the haulage company.

A distinction between general variables and factors and context-specific variables and factors is provided. Followingly, the two scenarios (own and lease) require making distinctions between the factors and variables to be included along with the general ones in a comparative NPV assessment. The assumptions, variables, and factors for an internal system operator investment appraisal assessment are outlined below.

Assumptions:

- An internal system operator will only operate a closed ERS for company-related transports.
- The analysis consists of a comparative fuel saving costs given lack of revenue from transport service.
- Vehicle lifecycle assessment for the total cost of ownership period starts at acquisition and ends at the disposal of the vehicle.
- The analysis takes only economic factors and excludes monetization of externalities.

General Variables and Factors:

Revenues

- Residual Value (RV)
 - Vehicle economic value
 - Number of decommissioned vehicles
 - ERS components

Costs

- Original Investment (OI)
 - ERS Construction (ERSC)
 - Charging Stations
 - Local Energy Generation
 - Local Energy Storage
 - ERS Technology License
 - Engineering Services
 - Land Purchase

$OI = ERSC + \text{Engineering Services} + \text{Land Purchase}$

$ERSC = \text{Charging Stations} + \text{Local Energy Generation} + \text{Local Energy Storage} + \text{ERS Technology License}$

- Additional Capital Expenditure (CE)
 - ERS Construction (ERSC)
 - Charging Stations
 - Local Energy Generation
 - Local Energy Storage
 - ERS Technology License
 - Engineering Services
 - Land Purchase

$CE = ERSC + \text{Engineering Services} + \text{Land Purchase}$

$ERSC = \text{Charging Stations} + \text{Local Energy Generation} + \text{Local Energy Storage} + \text{ERS Technology License}$

- Operations & Maintenance (OM)
 - Operations
 - Labour

- Insurance
- Registration Fees
- Equipment
- Maintenance
 - Periodic
 - Breakdown
 - Overhaul

OM = Operations + Maintenance

Operations = Labour + Insurance + Registration Fees

Maintenance = Periodic + Breakdown + Overhaul

Cost of Capital (CC)

- Financing Structure
- Inflation
- Risk-Free Interest Rates
- Vehicle Taxes (VT)

Time (T)

- Economic Life

Scenario-Specific Models

Own Vehicle Model:

$$\begin{aligned}
 &NPV \\
 &= \Delta OI(DV - ERSV - ERSC)_{t=0} \\
 &+ \sum_{t=0}^T \frac{RV_t + \Delta CE(DV - ERSV - ERSC)_t + \Delta OM(DV - ERSV - ERSC)_t + \Delta VP(DV - ERSV)_t - VT_t}{(1 - CC)^t}
 \end{aligned}$$

Variables and Factors:

- Original Investment (OI)
 - Diesel Vehicle (DV)
 - DV Purchase
 - Number of DVs

- ERS Vehicle (ERSV)
 - ERSV Purchase
 - Number of ERSVs

$$\Delta\text{OI}(\text{DV} - \text{ERSV}) = (\text{DV Purchase} * \text{Number of DVs}) - (\text{ERSV Purchase} * \text{Number of ERSVs})$$

- Additional Capital Expenditure (CE)
 - Diesel Vehicle (DV)
 - DV Purchase
 - Number of DVs
 - ERS Vehicle (ERSV)
 - ERSV Purchase
 - Number of ERSVs

$$\Delta\text{CE}(\text{DV} - \text{ERSV}) = (\text{DV Purchase} * \text{Number of DVs}) - (\text{ERSV Purchase} * \text{Number of ERSVs})$$

- Vehicle Powering (VP)
- Distances Travelled
- DV Fuelling
 - Number of DVs
 - Price of Diesel
 - Diesel Consumption
- ERSV Charging
 - Number of ERSVs
 - Price of Electricity
 - Electricity Consumption

$$\begin{aligned} \Delta\text{VP}(\text{DV} - \text{ERSV}) &= (\text{Number of DVs} * \text{Diesel Consumption} * \text{Price of Diesel}) \\ &\quad - (\text{Number of ERSVs} * \text{Electricity Consumption} * \text{Price of Electricity}) \end{aligned}$$

Lease Vehicle Model:

$$NPV = -OI_{t=0} + \sum_{t=0}^T \frac{RV_t + \Delta VP(DV - ERSV)_t + \Delta OM(DV - ERSV - ERSC)_t + \Delta VL(DV - ERSV)_t - CE(ERSC)_t - VT_t}{(1 - CC)^t}$$

Variables and Factors:

- Vehicle Powering (VP)
 - Distances Travelled
 - DV Fuelling
 - Number of DVs
 - Price of Diesel
 - Diesel Consumption
 - ERSV Charging
 - Number of ERSVs
 - Price of Electricity
 - Electricity Consumption

$\Delta VP(DV - ERSV)$

= (Number of DVs * Diesel Consumption * Price of Diesel)

– (Number of ERSVs * Electricity Consumption * Price of Electricity)

- Vehicle Lease (VL)
 - DV Lease
 - DV Lease Fee
 - Number of DVs
 - ERSV Lease
 - ERSV Lease Fee
 - Number of ERSVs

$\Delta VL(DV - ERSV)$

= (Number of DVs * DV Lease Fee) – (Number of ERSVs * ERSV Lease Fee)

The general revenue side variable is the Residual Value (RV), and the general cost side variables are Original Investment (OI), Operations & Maintenance (OM), Additional Capital Expenditure (CE), and Vehicle Taxes (VT). The general discount factor variables are the same as the three previous actor analyses. For the vehicle owning

scenario, the variables include more specific OI and CE factors and Vehicle Powering (VP). The vehicle leasing scenario variables include VP and VL.

Given that the investment is for internal operations, there is no distinct revenue stream other than the potential residual value of system components or the vehicles in the case of owning them. Moreover, the variables consist of the difference in costs that are assessed to identify whether an investment in an ERS and its compatible vehicles will lead to accrued savings.

An example of concrete use of such capital investment appraisal models for ERS can be found in the Slide-In 2 report, chapter 6, where the highways connecting Stockholm - Jönköping - Gothenburg and Borås - Gothenburg were evaluated in regard to investment cost and ability for economic recoupment [128].

4.5 Publications and other dissemination

Lemos, Camilla and Mats Engwall (2018) Evaluating Public-Private Partnership Models for Electric Road Systems, KTH Royal Institute of Technology, TRITA-ITM-RP ISBN 978-91-7873-305-7 [126]

Mokhtar, Luay and Mats Engwall (2018) Proposed ERS Investment Appraisal Models, KTH Royal Institute of Technology, TRITA-ITM-RP ISBN 978-91-7873-306-4 [116]

Engwall, Mats (red.) (2019) A Business Model Perspective on Electric Road Systems (ERS): Master student essays in technology strategy, KTH Royal Institute of Technology [117]

Nunez-Morales, Christian (2019) Reaching Commercial Deployment of Electric Road Systems: Barriers and Opportunities from the Perspective of eRoadArlanda, KTH Royal Institute of Technology [118]

Cameron, David (2019) Batteries and the Electrification of Heavy-Duty Transportation: Battery Development and its Impact on the Provision of Charging Infrastructure in Sweden, KTH Royal Institute of Technology [119]

S. Tongur, H. Sundelin, "Defining ERSO The Electric Road System Operator". 3rd Electric Road Systems Conference Frankfurt am Main, Germany, 7th to 8th of May 2019. [115]

H. Sundelin, "Architecture of Electric Road System". EVS32 Proceedings Lyon, France, May 19-22, 2019. [120]

5 Business impact and implementation strategies

The research done in this work package has been performed by RISE Research Institutes of Sweden, Chalmers University of Technology, and Institute of Transport Economics (TØI). The work has been led by RISE Research Institutes of Sweden.

5.1 Scope

The aim and scope of this work package is to present broader implications of a future ERS implementation in the form of different social and economic effects, the important aspects tied to such an implementation and to give insight as to how to manage this correctly. Potential socio-economic and business-economic effects have been studied in detail. Possible future implementation scenarios and roll-out strategies have also been studied.

This section describes in detail:

- A socio-economic analysis of ERS and its implementation
- The perspective, economic situation and possible role(s) of the electricity industry
- The perspective, economic situation and possible role(s) of the transport industry
- Different ERS implementation scenarios based on use case, actor setup etc.
- A first approach to disseminate and use heavy duty vehicle GPS-data to incorporate into possible implementation strategies
- A concrete ERS implementation case study and its economic consequences

5.2 Activities

In this section, much of the necessary information has come from interviews with industry actors inherent in the ERS ecosystem, such as actors within the transportation industry (hauliers, logistics operators etc.) and electricity sector (electricity generation, suppliers, grid owners etc.). Several studies have been done in order to analyse the economic and societal viability of ERS. Scientific literature and new data-based methods have been used as a base to conduct both general and specific cost-benefit analyses with different perspectives.

Following tasks and activities have been carried out:

- Interviews and dialogue with the transport industry.
- Interviews and dialogue with the electricity industry.

- A preliminary study of a business case for ERS has been improved and presented.
- Development of a draft implementation strategy.
- A study on data-based roll-out scenarios for ERS (ROSE) by Johnsson et al., 2019 has been done within the project and presented.
- Compiled results and syntheses in a memorandum (PM).

A major activity during 2018 has also been to support the study performed by EY on behalf of the Swedish Transport Administration. The study of different possible pilot stretches performed by the Swedish Road Administration has also been supported.

5.3 Results

The implementation of ERS at national and international levels will be associated with large investments and it is therefore important to study the economic impact and benefits for the society. The present work describes an initial dissection of prioritized issues on large-scale deployment of ERS in Sweden as well as a methodology for conducting socio-economic analysis on electrification of an existing road infrastructure.

5.3.1 Socio-economic analysis of ERS

A few prioritized issues on ERS have been identified resulting from the dialogue and interviews with members of parliamentary committees on Transport and Communications, Environment and Agriculture, and Industry and Trade, as well as with civil servants at the Ministry of Enterprise and Innovation.

The interviewed members of the Riksdag have all been cautiously positive to electric roads as a means of reducing dependence on fossil fuels in the transport sector. The perception of their own knowledge has ranged from “well-informed” to “moderate” and impression from study visits. No member has stated that there anything that crucially divides the political parties concerning ERS.

There has been a fairly broad consensus on which issues that are prioritized for a large-scale deployment of electric road systems in Sweden:

- Experience from ongoing demonstration activities is very important. Alternative technologies need to be evaluated.
- Viable business models must be developed, and it is important to investigate which actors will do what in the future business ecosystem.
- It is crucial that electric road systems are included in the Government’s infrastructure budget and national plan for infrastructure.
- European cooperation is very important, partly to ensure that Swedish companies can operate on an international market and partly for a joint EU work to achieve climate goals.

The implementation of ERS at national and international levels will be associated with large investments and it is therefore important to study the economic impact and

benefits for the society. The present work describes a method for conducting socioeconomic analysis on electrification of an existing road infrastructure.

The business ecosystem for the transport sector when an ERS has been adopted will involve several actors and roles. There will be familiar actors, e.g. goods owners (industries), haulage contractors and road operators; and there will also be new actors, especially from the energy sector that will handle power distribution; as well as new roles for existing actors such as road operators and government on local, regional and national levels. This overall view of the future business ecosystem for electric road systems is illustrated in Figure 45: Business ecosystem for electric road systems with several actors and roles. [129].

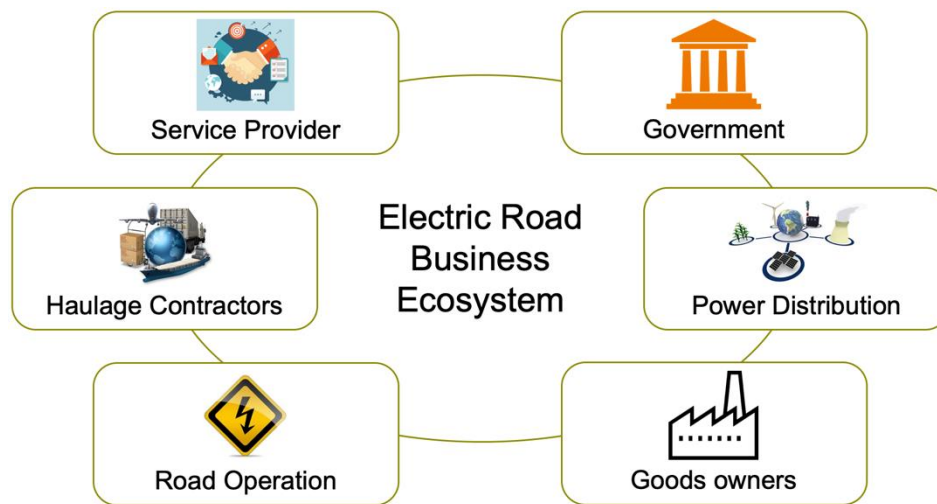


Figure 45: Business ecosystem for electric road systems with several actors and roles.

Electrification of roads can take place either as a separate deployment to existing road infrastructure, or in connection with a major infrastructure development. Socioeconomic analyses – often including a cost-benefit analysis (CBA) – are widely used in transport planning, especially when investigating large investment projects [130]. The presented work is based on the situation where the investment is made as an electrification of an existing road and not infrastructure development in general.

5.3.1.1 Method for socio-economic analysis of ERS

The question of socio-economic surplus is largely the same as the question for a private investor would be: How large are the gains in terms of cost savings compared with the cost of investing in new infrastructure and new vehicles? However, a cost-benefit analysis will follow a slightly different structure and include some more elements. The main differences are:

- **Break-even vs. net benefits:** When considering private profitability, the question is often whether the investment is profitable or not (break-even), and not how profitable or unprofitable (net benefit). Sensitivity analyses are based on changing one prerequisite (e.g. number of vehicles) and showing how much another prerequisite (e.g. the proportion of driving on the ERS) must change in order for the electric road to be profitable. In cost-benefit analysis, it is more common to change one assumption at a time and show how much profitability changes.

- **Net present value:** In cost-benefit analyses, a present value of net benefits is calculated from a discounting and summation of all future benefits and future costs. In the study of business models, one has instead used the annuity method, which gives the cost per year throughout the lifetime. Both methods are based on discounting, and it is easy to calculate the net present value from annuity costs.
- **Taxes and fees:** In a cost-benefit analysis, taxes and fees do not constitute a net cost to society, only a transfer from private individuals or firms to the government. However, it is customary to include taxes and fees in the calculations in order to show how the benefit of the measure is distributed between the public and other groups (e.g. road users).
- **External impact:** A cost-benefit analysis should include the cost of greenhouse gas emissions, local pollution, noise and accidents. It is uncertain whether an ERS investment will affect the two latter outcomes, but this must be investigated.
- **Demand effect:** In a cost-benefit analysis, it should be taken into account whether the saved transport costs make it more profitable to increase the transport volume. (It may also be considered profitable to distribute the transport on several and possibly smaller vehicles.) In practice, demand is often considered fixed, for simplicity.

There are not necessarily major differences between business and socio-economic analyses, at least not in the case of a closed transportation systems, e.g. bus loops or mining transportation applications where the routes are predictable and relatively easy to service and maintain. However, open systems, e.g. along a highway, are more interesting as it is easier to achieve large traffic volumes and there is a clearer role for the public sector.

Compared to other types of infrastructure projects, analysing open ERS cases involve some specific challenges for traffic modelling:

- Railways are used by only one type of vehicle, and the capacity utilization is regulated by the government.
- Conventional roads are used by several types of vehicles (including private electric vehicles) and access to the road is open, but the infrastructure does not affect the choice of vehicle.
- For an open ERS case, the project will affect whether private business invest in electric trucks that can operate on the ERS, which again is crucial for the socioeconomic impact.

Moreover, private profitability and socioeconomic benefits will also depend on the existing ERS network. An electrified road link that is not profitable by itself could be profitable if it is close to an existing ERS network, because (i) trucks that use the existing network can now drive an even longer distance on electricity and (ii) using electric trucks now become profitable on distances that previously were served by conventional trucks.

5.3.1.2 Results for socio-economic analysis of ERS

For an analysis of a public investment in an ERS system, the following data are needed for both a reference case and the ERS development case:

- Costs of road construction.
- Cost for deployment of ERS infrastructure.
- Cost of maintenance.
- Amount of traffic with heavy vehicles, electrical (development case) and conventional, distributed along the road network. This should preferably be based on a suitable demand model.
- Distance-dependent driving costs for heavy vehicles of both types.
- Non-distance-dependent capital costs (investment and maintenance) for vehicles of both types.
- Local emissions (and possibly noise) costs from heavy vehicles of both types, segmented by geographical area.
- Costs of greenhouse gas emissions from heavy vehicles.
- Other external costs, if applicable.

The analyses should be structured such that it is shown how the different costs are divided between different actors. This implies that taxes and fees are included as an expense for private actors and as an income for the public sector.

As to how many transports will be transferred to electric vehicles, the assumption should be that the companies choose electrification as long as the saved driving costs outweigh the additional costs of such vehicles (difference in purchase price and possibly maintenance costs). The decisive factor here is the proportion of transport distances that take place along the electric road. A simplified procedure would be to assume that this percentage is fixed. A more sophisticated approach will be to also take into account that the consolidation pattern changes so that a greater extent utilizes the ERS (such as for rail) and this requires a logistics model.

If the ERS route is built on an existing route without great gains in terms of driving time savings, it is in our view not necessary to analyse wider economic impacts of the investment. If electrification occurs in combination with a project that also involves substantial transport time savings, one should also assess these effects. In all cases, one should follow developments in this field within the transport economics.

In addition, the following general prerequisites are required:

- Analysis period and life of the investment. The analysis period should preferably be equal to the lifetime of the electric road, but one may possibly operate with a calculative residual value of the investment.
- Discount rate.

The recommendations above are quite general. They must be adapted to the specific case that is subject to a socioeconomic analysis. This particularly concerns the simplifications that can be made in the analysis as to which transports are affected and how the companies adapt. For cases where a single operator or a type of transport dominates heavily, a socioeconomic analysis will require less resources.

5.3.2 Business-economic analysis of ERS

A preliminary study focused on the business ecosystem likely to be built up alongside an electrified road, initially by interviewing interested parties and a thorough review of previous publications [131]. On the basis of this background information, a computation model has been developed to be able to analyse the influence of various parameters. This computation model is further described and applied to a specific case study in Section 5.3.4. Within this section, we instead start by exploring a main question for the present work:

“What is required for electric roads to be desired and used by actors within the transport and electricity industries?”

5.3.2.1 Transport industry: role and economy

Interviews and workshops were conducted with different actors within the transport sector: trade organizations and business associations, forwarders (that offers end-to-end logistics), and haulage contractors (also known as hauliers or trucking companies). In addition, the diversity among the haulage contractors needs to be considered: they have various kinds of customers and different kinds of contracts, the hauliers conduct their business with or without their own vehicles (and thus in the latter case depends on individual truck owners), and only one of the interviewed hauliers has experience of using an electric road [129].


From a technology-neutral perspective – i.e. no preference towards overhead line, rail and wireless solutions – the interviews and workshops were based on the following questions:

1. What is required for hauliers and forwarders to use ERS?
2. Can ERS bring competitive advantages to forwarders and hauliers?
3. What is required for transport buyers and goods owners to order transportation that utilizes ERS?
4. Can ERS represent competitive advantages for transport buyers and goods owners?
5. Will ERS bring new benefits and opportunities?
6. Is there a need for providers of additional services?

The current industry is characterized by small and medium-sized companies, and many of them are still one-man companies. It involves several actors with different responsibilities and assignments, where one is the haulier. The industry consists of about 10 000 hauliers (reference Swedish Association of Road Transport Companies, SÅ).

Interviews and dialogues performed with representatives from the Swedish transport industry have resulted in the following main findings:

Table 4: Main findings from the Swedish transport industry.

| | |
|---|--|
|  | <ul style="list-style-type: none"> • The total cost of transport must be lower than today, or at least not more expensive. • The investment costs for hybrid or electric trucks is subordinate. Rather, a good total cost of ownership (TCO) is required. • Need for new investments in pantographs with service agreements. • A switch to electric vehicles means reduced fuel costs. • A fee for using the electric road is accepted. • Some letter of intent (LoI) from major industries to order electric road transport is required. • The trucks must have the same loading capacity as today. • A positive joint marketing opportunity with the merchants is seen. The industry is under competition with foreign hauliers and the ERS can bring opportunities to influence the situation in different ways for the better of those involved. Large merchants might have sustainability policies and emphasize the importance of the end customer's requirements/demand that push for delivery to happen in terms of sustainability. • ERS can bring increased control of the condition of transport vehicles etc. • Good electric road access control is required. |
|---|--|

A general positive opinion regarding electric roads has been expressed several times. However, the representatives from the transport sector have in particular emphasized the importance of a declaration of intent from large goods owners (e.g. industries) and transport buyers to order transports utilizing electric roads. The customer side must become willing to pay for sustainable transport and regulatory measures should help making this a more viable option.

The transport sector seems to be willing to pay a fee to use an electric road, provided that it does not eliminate the potential for cost reductions and better margins. The total cost of operations is key and investments in new trucks and add-on power collector devices are subordinate to a considerable extent, or even negligible.

There is a tough competition among forwarders and hauliers as well as pressure from transport buyers. ERS could, therefore, provide opportunities to positively influence the situation for forwarders and hauliers that are apt for utilizing innovative technology and business models. Novel kinds of partnerships could also occur with, for example, electricity companies. The willingness among forwarders and hauliers to make investments include new vehicles and add-on technology, but they are unwilling to finance the large-scale investments needed for the ERS infrastructure. This is expected to be financed by other actors such as the government or large business actors. In a recent study [132], several hauliers were asked what their criteria would be in order to buy ERS compatible vehicles, assuming that an actual ERS would exist along their current operational route. Other than economics, the reliability and predictability of the infrastructure were repeatedly mentioned. It's important that weight, payload volumes or range does not become limiting factors, and that the haulage companies must be certain that an ERS network is large enough not to risk them having to drive detours in order to find charging. A suggestion from one of the actors was to initially get leasing offers for the ERS vehicles with short binding periods, meaning they could test and

evaluate whether the technique is suitable for their operations before making larger investments. Furthermore, the importance of having the same system between adjacent countries was mentioned. If the electric road solution differs, like having road embedded rails in one country and overhead wires in another, it will be very difficult to find hauliers with trailers/trucks that can utilize both techniques. Another challenge is the fact that drivers are sometimes hard to find, and thus many hauliers currently prioritise utilization of other intermodal transport modes like railways or ferry to suit their driver's working times. One actor emphasise that this issue could be solved if autonomous ERS vehicles were available.

Hauliers could become the best advocates of ERS and influence individual truck owners that need to prioritize current day-to-day business before strategies. The hauliers also have an influence through the dialogue with their customers, such as major transport buyers and goods owners with sustainability policies.

Actors within the transport sector begin to recognize future opportunities where ERS has a given role. Exciting technology development and large-scale implementation of ERS would greatly affect the transport business. Ideas on new logistics solutions that make benefits of electrical roads and strengthen competitiveness have begun to spire.

Forwarders and hauliers would like to avoid, for natural reasons, intermediaries that reduce the potential for cost savings and better margins. External service providers may be accepted if they add value to the existing actors in the transport sector.

5.3.2.2 Electricity industry: role and economy

Other than the transport industry, several representatives from the electricity industry were interviewed to understand current structures and collect thoughts on ERS from their point of view. The interviews were based on the following research questions:

1. Which of the electricity market roles are affected by electric roads?
2. Which of the three scenarios (from Section 4.3.3) are possible and attractive?
3. Is it interesting for an electricity company to invest in electric roads? If so, what kinds of investments?
4. What is required for electricity companies to invest in electric roads?
5. Will electric roads bring any new benefits and possibilities to the electricity industry?
6. Are there any needs for service providers?
7. Who do you see as suitable service providers?

From the production of electricity to the final use of electricity, there are five different roles with different responsibilities and assignments: electricity producers, electricity retailers, electricity grid companies, balance responsible and transmission system responsible organisations.

Electricity grid companies own the power grid that transport electricity to customers and are responsible for the connections and measurement. In Sweden, there are about 170 electricity grid companies of different sizes. Within each geographical area, only

one company (“site concession”) is authorized to operate. Figures 6.3a and 6.3b illustrates how Sweden is divided into four different electricity areas (where the prices of electricity can vary) as well as an example of how the grid companies are responsible for smaller sections of those. Vattenfall, Ellevio and E.ON are the largest electricity grid companies that also own regional power grids, but there are also municipal companies and economic associations.

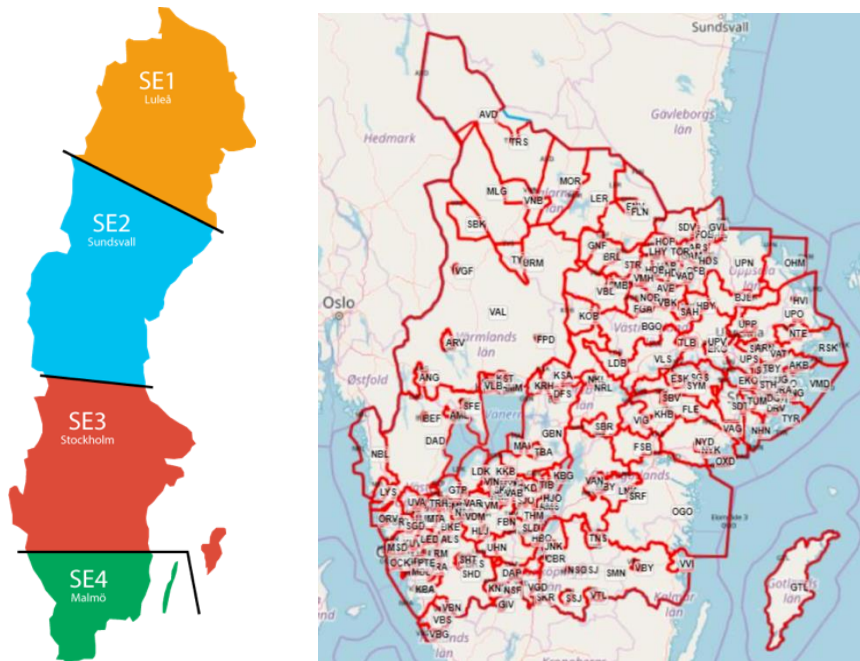



Figure 46: The left picture shows the four Swedish electricity areas. The picture to the right shows power grid areas in one part of four in Sweden.

Interviews and dialogues performed with representatives from the Swedish electricity industry have resulted in the following findings:

Table 5: Main findings from the Swedish electricity industry.

| | |
|---|---|
|  | <ul style="list-style-type: none"> • Electric roads can be introduced without affecting the different roles in the overall power grid. But where connection to the grid occurs and who connects is important to know. • Investments in parts of the electric road network that is closest to the existing grid may become relevant for the electricity industry and therefore a part of the local grid. • Some form of written Lol agreement is required. • It's important to have a dialogue with the Energy Market Inspectorate and to investigate law permits. • ERS can result in better utilization of existing networks, people and equipment as well as generate new businesses. • It should work smoothly and easily for the users! Get started easily. • The ERS should not include too many players/roles since it risks creating very split responsibility. Responsibility follows ownership. |
|---|---|

The most attractive scenario for the electricity industry is what most resembles what the electricity market is today. The electric roads will pass a large number of local power grid areas and therefore need to be connected to some of these via transformer

stations for power supply. They are best connected to local area power grids or regional power grids in some cases.

Everyone earns on electric roads in the form of extended business and replacement business. It can also be coupled with grid extensions for (locally produced) renewable electricity. The utilization rate of the existing grid is also improving.

The electricity grid companies are prepared to invest in the electric road that goes through their respective grid areas, but then the existing revenue framework needs to be reviewed politically to create the space to invest. And there is a need for some kind of written letter of intent to take the risk. The investment in an electric road is seen as part of the power grid within the area of the concession.

The electric grid companies are best equipped for service, operation and maintenance of electric roads. The question remains if there is also a service provider in addition to themselves that can complement and add value. It may be retailers who take more and more of the direct customer contact already today or someone else may be accepted if they add value to the existing actors in the electricity sector.

The electricity industry is one of the known (private) actors who can imagine investing in electrical roads, especially the grid companies. They see it as reasonable to in the first place invest in their own power grid, including the transformer stations, and possibly even further in the actual electric road technology infrastructure.

5.3.2.3 Continued analysis

The idea of ERS has seen rapid development since the research and innovation platform first begun, from a somewhat unknown concept to a position where the involved actors are more aware of what their roles and responsibilities might become in different roll-out scenarios. This means that the interviews done with the transport and electricity industries in an early stage of our project might already have changed to some extent.

An updated analysis was done in 2019 for the transport industry within the project “Swedish-German research collaboration on Electric Road Systems (CollERS)”. Transport operators from Sweden, Denmark and Germany were interviewed on their criteria for investing in ERS compatible vehicles. The main takeaways from those interviews were:

- Total economy, it must pay off to invest in this new technology.
- The customer side must become more willing to pay for sustainable transport and regulatory measures should help making this a more viable option.
- It’s important that weight, payload volumes or range does not become limiting factors, and that the haulage companies must be certain that an ERS network is large enough not to risk them having to drive detours in order to find charging.
- A suggestion is to initially get leasing offers for the ERS vehicles with short binding periods, meaning they could test and evaluate whether the technique is suitable for their operations before making larger investments.

- It's important to have the same technique for all countries. If the electric road solution differs, like having road embedded rails in one country and overhead wires in another, it will be very difficult to find hauliers with trailers/trucks that can utilize both techniques.

Some of the standpoints are similar to those seen in the research and innovation platform, but continued insight is gained as more interviews are conducted. Thus, more updates are probably necessary for a continued progress of ERS, as the involved actors learn more about what the technology means in various implementation scenarios and user perspectives.

5.3.3 Implementation strategies

From an overall sustainability perspective, electrification is a central part of ERS. This applies to both economic and environmental sustainability, but also to political economics where a national comparative advantage is our ability to drive and implement changes in multidisciplinary complex societal systems. In this context, the sustainability issue also has to do with our ability to implement, extend and utilize climate-smart road infrastructure. It combines technology, financing, flexibility and consideration with the need for specification, decision, extension and implementation; i.e. ultimately about leadership in multidisciplinary innovation systems, which is very difficult but where Sweden has proven to be among the best over the years. It is a very important responsibility for politics and the authorities to manage this balance in a good way. The balance requires dialogue and collaboration, along the entire value chain, from research to commercial use. The coming years will be an exciting challenge for balancing public and private roles quickly, safely and at a reasonable cost so that competitiveness, procurement, innovation and development are combined with responsibility, safety and sustainability. A key part of the development is that the business ecosystem that surrounds electric roads is identified, defined, developed and to some extent implemented [133].

In conclusion, when deciding on implementation strategies it is crucial to discuss ownership and responsibility as well as how a balance between the public and private could be embodied.

Fully private solution

It may be appropriate to consider completely private solutions in some cases, for example in closed industrial areas, adjoining roads from large factories, individual road transport solutions and small-scale solutions that do not require permanent infrastructures such as an inductive charger on their own parking space or short charging plates/rails in taxi rows.

Fully governmental solution

A fully governmental solution, where the Swedish Transport Administration owns and manages both the road and the electrical systems along the roads, similar to today's rail solution. The advantage of this setup is that the Swedish Transport Administration finances and manages the revenue and is responsible for safety, operation and maintenance. This is a safe and stable solution, but the pressure on change is low, the costs are probably higher than for a mixed solution, and the flexibility for innovation or

development of new business models is relatively low. The momentum and interest that exists today from transport buyers, freight forwarders, suppliers of infrastructure and vehicles as well as the growing innovative industry that sees this as a profitable industry, where many disciplines are combined, is likely to be cooled down with a completely state-owned solution. Despite the drawbacks, there may be exceptional cases and applications where this solution is preferred for various reasons.

Public-private partnership

The benefits of public-private partnerships (PPP) are to maintain state control and stability while increasing the opportunity to push for development through financial incentives, innovations and competitive prospects. Properly executed, a public-private solution can lower public costs and balance investment and operating costs against future revenues. The disadvantage is that public-private collaboration is complex. The interface between the state and the private must be clearly defined. Risks must be priced correctly, while costs, revenues and responsibilities - combined with requirements for security and low costs - must be defined for infrastructure facilities with difficult to understand service life. Development must also often be catalysed to get started, subsidized to grow and then risk collapsing as these efforts disappear and increasing taxation is introduced.

As of now, a PPP model is probably the most useful model for an electric road ecosystem as described in Section 4.4.2.

To further investigate and understand the complexity and system design of ERS in commercial operations, two hypothetical scenarios are illustrated below. These scenarios are based on the purpose description and goals of many of the ongoing projects.

5.3.3.1 Future use-case scenario: Mining operation

The Norwegian mining company NorthStar was one of the first in the world to invest in and use electric roads for iron ore transport between the mine and the harbour. The mine is located 600 meters above sea level and the operation runs 24/7 with 15 trucks at all times. The empty trucks weigh 30 tons and carry 60 tons of iron ore when fully loaded (see Figure 47).

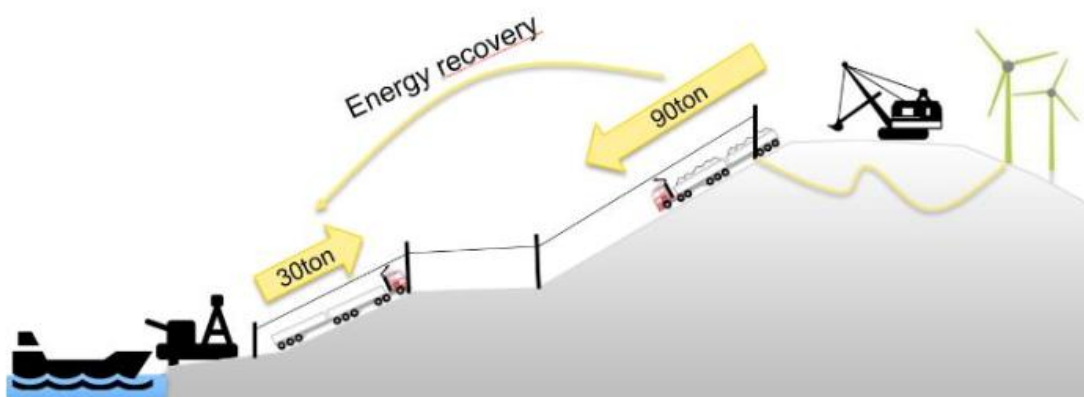


Figure 47: Use-case scenario of ERS for mining operations.

The need for an electric road emerged when NorthStar investigated the options to reduce emissions and fuel costs from traditional diesel trucks. Truck transportation was seen as the only solution, as operations would start within a year and building a railway was more costly and would delay the production start. By using ERS, NorthStar could reduce fuel cost by 50 % with only modest investments in existing road infrastructure. In addition, an existing transmission line was installed near the road, making it relatively easy to supply power to traction substations along the electric road. The energy needs could be calculated based on the predicted operations to avoid under- or over- dimensioning the power system.

The power transfer system (designed as an inductive, rail, or overhead-line solution) would be designed to be cost-effective and optimal for the operation needed. In places where it was deemed impossible to build electric road infrastructure, for example, in the mining unloading and reloading centre, the trucks would run on batteries or a small ICE fuelled with biofuel. Furthermore, as only authorized trucks would operate on the electric road and no pedestrians would be present, the safety and control system requirements were predictable and relatively easy to accommodate.

The mining company has contracted a single truck operator, Transportation Solution Provider, to manage all transportation on the electric road, so only a single energy bill is required for all vehicles. The operator is a large truck OEM that supplies the mining company with a transportation solution and bills the mining company by tonne/km, making this case what we refer to as a fully private solution. The trucks are specified, and the drivers are trained for NorthStar's specific electric road operations to be as fuel-efficient as possible and to reduce the need for maintenance. The trucks have an integrated pick-up to transfer the electricity and a hybrid powertrain to use electricity as energy. Furthermore, the height difference enables the recovery of much of the braking energy, making the overall transportation very fuel-efficient.

5.3.3.2 Future use-case scenario: Highway operation

The Swedish government has decided to implement ERS along the major Stockholm–Helsingborg–Gothenburg road triangle. The main purpose is to achieve the goal of fossil-free transport and improved air quality by replacing imported fossil fuels with domestically produced renewable energy. The installed road infrastructure includes communication technology, which will enable autonomous vehicles.

If the electric road is based on an overhead wire solution, it will be dedicated to trucks and buses. Operators and users support the deployment of electric roads because electric energy increases their energy efficiency and thereby lowers the energy cost, which is important in an industry with very low margins.

Different vehicle configurations can be used depending on the particular operation context (see Figure 48). All major OEMs offer ERS as an option, enabled through standardizing the interfaces. A bus route (A to B) from a town near the electric road to an airport also near the electric road will have a pure electric driveline with a small battery that enables electric propulsion when it leaves the electric road. Long-haul operation between two industries (C to D) located relatively far from the electric road will need a larger range extender, batteries not being an option due to the considerable energy needed; hybrids with a combustion engine using domestically produced biofuel are a popular choice.

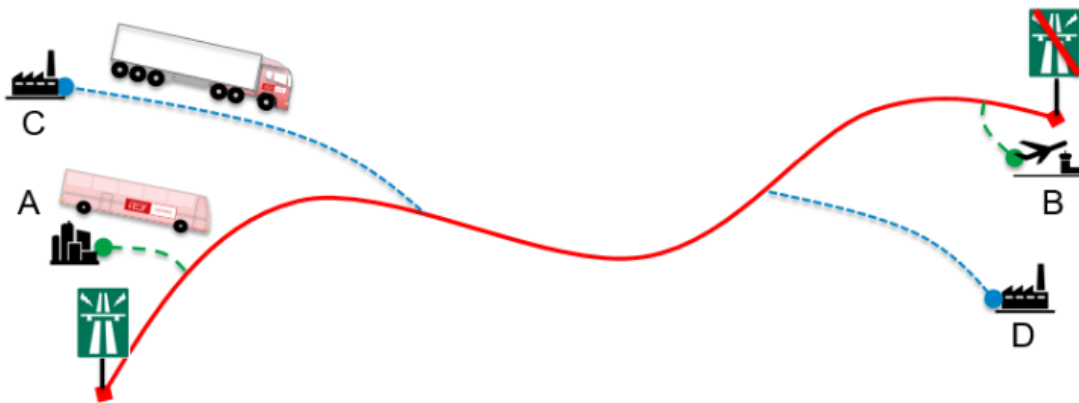


Figure 48: Use-case scenario of ERS for highway operations.

The safety and control system requirements are very stringent because the electric road will be used by various vehicle types and users. The command and control of the system are centralized in control centres like those used for rail traffic. Each vehicle is checked before being allowed to connect to the electric road. In the case of conductive solutions, the pick-up quality is checked to reduce infrastructure wear.

In both static and dynamic power transfer system, energy payment is made to a single ERS operator, although many ERS networks may exist nationally. This arrangement is made possible by the same roaming setup as is used in telecommunications. Advanced fleet management systems have been shown to reduce the total cost of ownership for large fleet operators by using the appropriate configuration for a given operation.

To distribute the load on the energy system, lower off-peak energy costs will encourage increased off-peak deliveries. Lower sound and air pollution emissions will make roadside areas more attractive and enable deliveries by night.

Traditional heavy transport often involves a fleet-management system that coordinates the vehicles in a specific fleet. In a full-scale ERS, the system becomes much more complex. Before entering the electric road, a vehicle needs to identify itself and its payment credentials need to be verified. The power transfer system continuously supplies the vehicle with electric energy from the energy system. The safety and control system continuously monitor the power transfer to prevent overloads or illegal activity.

When leaving the electric road, the cost of the energy consumed will be charged through a payment system. Depending on whether this ERS is owned and managed by the Government or to some extent financed by private actors, it can be considered either as a fully governmental solution or a PPP. Details about different configurations for PPPs can be viewed earlier in Section 4.4.2.

5.3.3.3 Development steps

The development of ERS has, so far, largely been supported by public funding with the participation of industrial firms. A few demonstration projects have already illustrated the feasibility of different technologies. More demonstration projects are currently under construction in various parts of the world to determine whether ERS should be implemented on a wider scale to achieve sustainable transportation. As ERS requires investment in both infrastructure and vehicles, substantial funding and support of the system is needed if it is to enter the commercial market.

For first pilot operations, when the systems are still immature, the systems will be more suitable for closed transportation systems such as point-to-point shuttle operation. In a pilot operation, the routes are predictable and relatively easy to service and maintain. When ERS has been proven to operate in pilot operation at the same level of quality as traditional systems and when the market uncertainties have decreased, commercial ERS operations could be evolved and suitable for deployment, either in small-scale (i.e. the mining operation scenario) or large-scale (i.e. the highway operation scenario). This development perspective is illustrated in Figure 49.

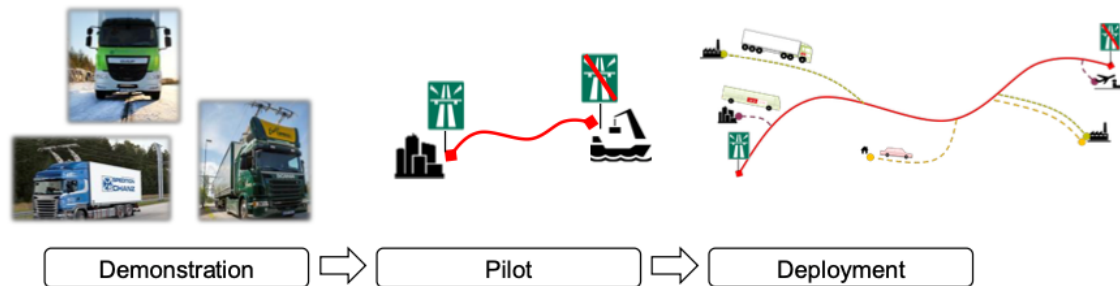


Figure 49: Development steps from first demonstrations, on to pilots with predictable operations and lastly commercial deployment in larger road networks.

5.3.3.4 Future roles of the Electric Road System Operator (ERSO)

In a **small-scale deployment**, the role of ERSO could be assumed by one of the ERS suppliers. This could reduce the number of actors involved in the ERS market which could initially help to reduce technical risks and increase incentives for actors to integrate forward and to develop new business models. For example, ERSO could be one of the following actors;

- Supplier of power transfer technology (e.g. Siemens, Alstom or Electreon etc.),
- Vehicle OEMs with a vehicle as a service offer to users (e.g. Scania or Volvo),
- Energy suppliers that offer subscriptions to users and possibly also pick-ups (e.g. Vattenfall, Eon, Elevio, EnBW)

The relationship between ERSO and transport goods owners will be very important in a small-scale deployment of ERS. Goods owners that have rather fixed transportation, e.g. from a factory to a rail yard or harbour could decide to support investment in an ERS if it allows them to decrease their transportation cost and their environmental impact. Thereby they could collaborate with haulage companies, by writing longer transport contracts and by sharing some of the higher costs in ERS trucks. Thus, the risks for establishing an ERS is reduced. The metering and billing could be done through deposition for the single electric road and be contracted with haulage company, which in turn has a contract with the transport goods owner.

The relationship between ERSO and ERS suppliers is rather simple in a small-scale deployment. Since the electric road network is limited, there will be one electric road provider and probably one (or maybe two) energy providers. This decreases the number of suppliers that the ERSO must collaborate with and simplifies access control and metering.

In a **large-scale deployment**, such as regional and long-distance transportation, electric road coverage will have to be extensive over regions and nations. This assumes that the interfaces between various subsystems are standardized at regional and international levels.

In this case it is likely that ERS technologies have been standardized and that the ERS market has moved into efficiency and new business models that enable value creating services for users. This could pave the way for establishment of new operators from similar markets, e.g. from telecom, energy industry or petroleum companies. Furthermore, there will probably be multiple of ERSO actors on the market, possibly different operators in different regions. These ERSOs could develop unique business models to compete on the ERS market.

In a large-scale deployment, goods transport owners could choose and calculate on using a large ERS network. ERSOs relationship will thus be stronger with the forwarding market, rather than single haulier companies and goods owners, since they control international logistic chains with high volumes. Furthermore, given that the forwarding market consists of multimodal transportation, e.g. using train, shipping and road transportation, the ERSO might play an important role in facilitating future improvements of the logistic chains. One example is that ERSO could integrate autonomous technology with ERS and thereby facilitate efficient and sustainable logistic chains over international markets.

In this market scenario, the ERSO must be able to handle multiple ERS suppliers and owners. Thereby they must have standardized contracts and metering systems that could enable roaming e.g. supplying and billing energy to ERS users over different regions and from different suppliers. Furthermore, there could also be different ERS technologies (that co-exist) and thereby different types of ERS trucks (with different pick-ups). Hence, the ERSO must be able to facilitate interoperability between different transportation modes and ERS alternatives.

5.3.3.5 Data-based evaluation of ERS roll-out scenarios

In a large-scale deployment of ERS technology there is a need to have an evaluation method as to which roads or road networks will be economically, environmentally and socially profitable to electrify, and which roads to prioritize to maximize the desired effects of road electrification through ERS. One such method was analysed [134] with the aim of examining the possibility of using detailed GPS data from heavy trucks (obtained from Scania) to develop a better basis for identifying road stretches suitable for ERS. Previous studies [132] and [8], on roll-out scenarios have relied on showing the traffic intensity of different roads by using Average Annual Daily Traffic (AADT) data and to some extent hourly traffic data. By using detailed GPS data there is a possibility to show not only the traffic intensity of certain roads, but also how specific vehicles will be affected by and interact with the implementation of an ERS, for example how far and when trucks of a certain size and with certain loads travel on different roads and with identification of their Origin of Destination (OD).

There are, however, some challenges to a road evaluation method based on GPS-data:

- Detailed GPS-data is typically the property of the vehicle manufacturers or freight companies and thus not readily accessible to the research community (as opposed to for example AADT data)
- In order to link the GPS-data to the roads on which the trucks travel a map-matching procedure needs to be carried out

The map-matching process is based on combining multiple datasets and done through different map-matching algorithms. Stated by the authors of the study [134], this was a complex and challenging task, and to effectively do this in the future, a methodology on how to use GPS data to assess ERS should first be developed.

The use of Scania GPS data was used to create a cost-optimization model, that together with a traffic intensity analysis (based on AADT-data) resulted in an optimized road-network map for large-scale ERS deployment in northern Europe, depicted in Figure 50. The cost-optimization model is based on the profitability of converting each vehicle to an ERS-truck from both the vehicle owner and ERS constructor perspective. The model can find an optimal length of roads to electrify with ERS based on two relationships: If too few kilometres are electrified, it will not be profitable for vehicle owners to invest in converting their vehicles to use electric roads, and, if too many kilometres are electrified, there will not be enough vehicles using the electric road to cover its construction cost.

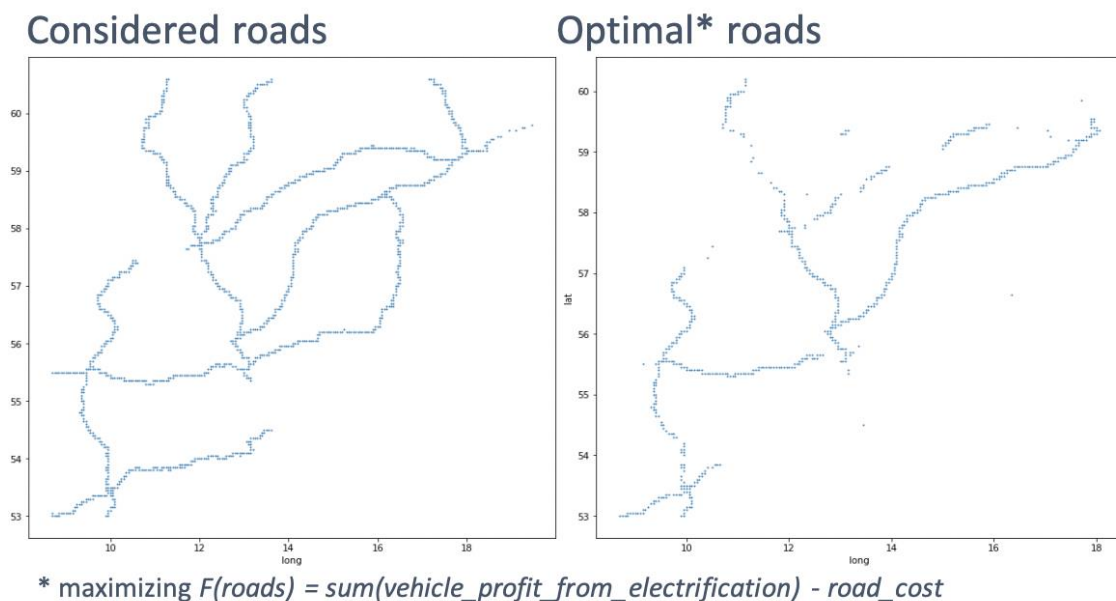


Figure 50: Left hand map represents the roads with the highest traffic intensity based on AADT-data. Right hand map shows the roads suitable for ERS optimized by the GPS-data based cost-model.

The left map shows a possible deployment of ERS based on traffic intensity from the map-matching and selection of the roads with highest AADT. The right-hand map shows the results from applying the cost model to the GPS base data. Thus, the roads are those for which the average vehicle profit is the highest. As can be seen the preliminary analysis shows that for Sweden the most profitable roads for electrification are the main roads connecting Stockholm, Gothenburg, Malmö, Copenhagen, Kolding and Hamburg. More details about the project can be viewed in Appendix C.

5.3.4 ERS business case

As mentioned, a preliminary study was performed which focuses on the business ecosystem likely to be built up alongside an electrified road, initially by interviewing interested parties and a thorough review of previous publications. On the basis of this background information, a computation model has been developed to be able to analyse the influence of various parameters.

The stretch of the 120-kilometre-long road between Gävle and Borlänge has been used as a case study but an attempt to find other applicable stretches has also been undertaken. The model has a solid footing with the parties involved in the project and with people who have good insight into financial computations previously undertaken in relation to electrified roads.

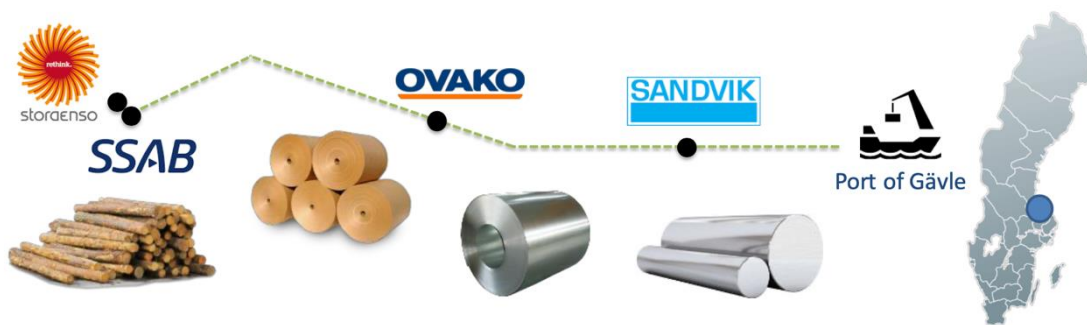


Figure 51: Transport buyers along the route Gävle-Borlänge.

The computation model that has been developed is primarily thought of as a model for overall surpluses or deficits for all stakeholders in the business ecosystem. It is not, therefore, a complete socio-economic model, which would include considerably more consequences for society at large, such as the influence on local and national businesses, increased employment and so forth. However, as this is a closed transportation system, there are not necessarily any major differences between business and socio-economic analyses as explained in Section 5.3.1. The model has been developed on the assumption that all prices and values are given for a point in time when the solution is in an 'early commercialisation phase'.

In the analysis we have chosen not to estimate the costs for an electrified road system's component from scratch. A large number of reports have been written presenting such figures, mostly based on statements or estimates from companies hoping to supply such components in the future. This means that all figures included in our analysis come from such sources.

5.3.4.1 Computational model equation

In order to evaluate the economic feasibility of electrified roads for trucks, we prepare alternatives for comparison (e.g. road systems based on diesel) and estimate all costs that differ between the systems. The alternatives for comparison we have looked at are partly diesel and partly bio-synthetic diesel (HVO) as energy sources by means of internal combustion engines. In the short term, diesel is often the most relevant comparison alternative for private actors since that is what is mostly used today. But from a societal perspective, biofuels are possibly a more relevant alternative

considering the Swedish government's stated objective of achieving a fossil independent vehicle fleet by 2030. Our calculation is primarily intended to serve as a calculation of the total profit or deficit for all actors involved in the business ecosystem. The equation which describes the relative attractiveness of electrified roads is therefore based on the differences in costs of the terms below. More information about examined cost components and their additional assumptions can be viewed in the original article [131].

$$\Delta\text{costs} = \Delta\text{road costs} + \Delta\text{grid costs} + \Delta\text{vehicle costs} + \Delta\text{energy costs} + (\Delta\text{environmental costs}) + (\Delta\text{taxes})$$

The differences thus refer to the difference in the respective cost type between electrified road systems and diesel and biofuel road systems. Generally, the first three terms are much higher for electrified road systems, while the remaining terms are lower for electrified road systems than for the two alternative road systems.

5.3.4.2 Sources for cost estimates

We tried to get hold of figures related to costs from an actual pilot project – i.e. real, historic costs which had already arisen during the installation of an electrified road. These figures could then form a credible ceiling – highest value – for the cost estimates. But we were not able to get hold of any such figures. The closest we got was estimates related to a short section (2 km) at Sandviken, between Gävle and Borlänge (E16) in Sweden. A pilot section for electrified roads has been built there, in cooperation between the Region Gävleborg, Swedish Transport Administration, Siemens and Scania. However, we have not used those figures for the initial, short section there in any of our cost scenarios as we did not get access to sufficiently detailed calculations in order to be able to properly separate the different cost sources in this case. Based on an oral source familiar with the in-company calculations, we assessed that the overall cost was not applicable to our purposes, seeing that so much would be done manually (for example monitoring).

The method for selecting reports to examine was an ad hoc search which was successively expanded using a so-called snowballing search – meaning that one source led us to other sources. An ad hoc search seemed justifiable as several of the project's members had been doing research on electrified roads for many years and were very well-versed with the literature and phenomenon. In total, we have reviewed estimates and argumentations on the costs for electrified road components in some 30 different reports. Many of these overlap in their underlying sources and assumptions. Ultimately, we elected to use figures from 16 sources. Furthermore, we have been in contact with a number of experts in the project group and at Vattenfall, Circle K, SPBI, Volvo and Scania by mail and phone in order to get input for best assumptions concerning the costs for electricity grids, price strategy and efficiency for biofuels, or the price for current collectors, respectively.

As the spread of the cost estimates is so wide and actually implemented road sections so few, the costs for electrified roads are still extremely uncertain. The estimates used is the one we ourselves consider as being the most likely of the previously reported cost estimates and which we take as a basis in the analysis. This estimate was reviewed at a workshop with experts from Scania, Siemens, KTH, Region Gävleborg and Stockholm

School of Economics in August 2016. Although, we would like to emphasise that the uncertainty is significant.

5.3.4.3 Results for cost estimates

In comparison with diesel routes, it generally applies for electrified roads that every kilometre of road and every vehicle adds extra costs and that every kilometre driven creates earnings. Thus, for an electrified road system to be profitable, the stretch of electrified road must comprise a significant percentage of the overall distance driven by a truck. Nor must the stretch of the road be too short, for then too much time is spent loading/unloading and too few kilometres (where the earnings occur) are driven. Following familiarisation with various scenarios, a coherent, highly qualitative judgment, based on the electrified road computation model, would suggest that the suitable characteristics for such roads would be:

- A distance of at least twenty kilometres
- Annual average daily traffic (AADT) for electrified road trucks should be around two times as many as the number of electrified kilometres
- The electrified stretch should comprise 60 % or more of the trucks' overall distance driven each year.

For the case of Gävle-Borlänge (120 km), it appears that the stretch will be able to pay for itself, for example, when 190 electrified trucks complete the stretch an average of 4 times per day throughout the year (back and forth twice a day 365 days a year), amounting to 92 % of the vehicles' overall distance being driven on electrified road.

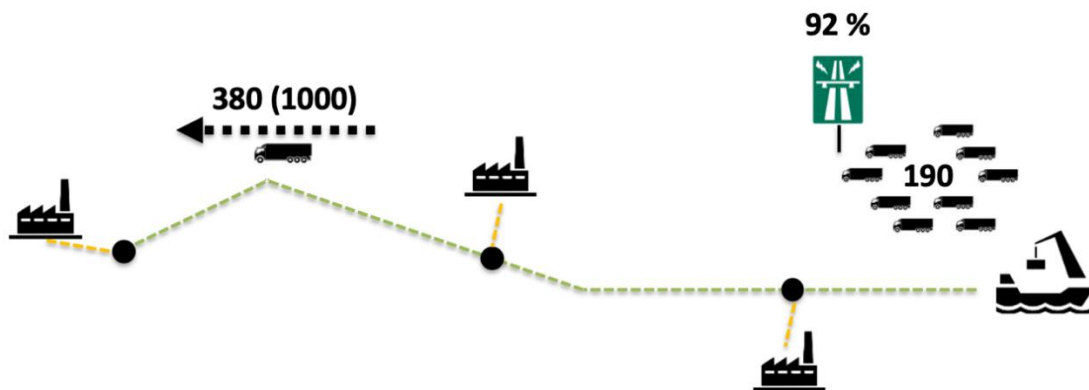


Figure 52: One case when an electric road goes break-even.

The possibility to experiment with routes, the number of vehicles and AADT makes it possible to identify potentially profitable routes and continue in-depth studies. The next step is to give the actors that come into question for the selected route/system a calculation basis for their own participation. This calculation sheet shall be prepared bottom-up and be able to be adjusted to the individual actor's business administration economic conditions. It is primarily intended to facilitate decisions regarding participation for individual players.

5.3.4.4 Updated cost estimations

Since the above study was performed, new estimations have been derived from several reports [84], [128], results from ongoing ERS pilots and in dialogue with different ERS actors. These estimations are, as of today, the most actual to use for future cost calculations of ERS until new figures are provided through upcoming pilot projects or specific technical developments.

Table 6: Projected cost of deploying the infrastructure of an ERS network is based on a number of current cost estimates. Costs per km is for bidirectional electric road.

| | |
|---|---|
| Construction of wayside ERS infrastructure, for example, connections between the ERS and the regional electricity grid. | <i>Estimated cost:</i> 0.75 M€ ₂₀₁₉ /km |
| Construction of in/on-road ERS infrastructure, for example, ERS power transfer technology between the road and the vehicle. | <i>Estimated cost:</i> From 0.94 to 1.87 M€ ₂₀₁₉ /km |
| Construction of roadside ERS infrastructure necessary for safe operation, for example, road guardrails. | <i>Estimated cost:</i> From 0.05 to 0.47 M€ ₂₀₁₉ /km |

The most recent estimates of the infrastructure cost of ERS (for these three areas) thus lie in the range from 1.73 to 3.1 M€₂₀₁₉/km according to the Swedish Transport Administration. The range of the expected investment of ERS infrastructure depend on some uncertainty factors, what degree of the road in question is electrified (certain ERS setups are designed to only electrify for example 50 % of a given road stretch) and choice of ERS technology (catenary, conductive rail or inductive).

Table 7: Apart from infrastructure, some further cost estimations have also been updated.

| | |
|--|--|
| Investment in vehicle conversion for ERS compatibility (in terms of heavy trucks). Including an as-of-now proposal for a state subsidy between 40 and 60% of the ERS vehicle cost, for a maximum of 400 000 SEK/vehicle. | <i>Estimated cost:</i> From 140 000 to 328 000 € ₂₀₁₉ /vehicle (short time horizon with specialized ERS vehicles) and between 9 300 and 14 000 € ₂₀₁₉ /vehicle (long time-horizon with established production of ERS vehicles). |
| Fuel costs for heavy trucks. | <i>Estimated cost:</i> 0.11 € ₂₀₁₉ /km for electricity and 0.43 € ₂₀₁₉ /km for diesel. These values are from a short time perspective in Sweden. In a longer time-perspective, it is likely that the cost for both electricity and diesel will increase. |

ERS cost parameters are constantly updated and new information is gained as the development process continue. Therefore, it should be pointed out that some of the conclusions throughout the report might be out-of-date by now. However, as the groundwork and general reasoning around ERS have been done within the research and innovation platform, some things will be easy to update in the future, whereas other things will require more work. No quick fixes are prioritized at this stage as ERS is still in an early phase and new information is gained frequently. Instead, we emphasize the need for updating methods and models developed within the platform throughout upcoming research.

Note, costs per km is for bidirectional electric road.

5.4 Publications and other dissemination

Conny Börjesson and Martin G. H. Gustavsson. User Perspectives on Electric Roads. *Proceedings of EVS31 International Electric Vehicle Symposium*, Kobe, 1–3 October 2018. [129]

Håkan Sundelin, Marcus Linder, Ann-Charlotte Mellquist, Martin Gustavsson, Conny Börjesson, and Stefan Pettersson. Business case for electric road. *Proceedings of 7th Transport Research Arena TRA 2018*, Vienna, 16–19 April, 2018. [131]

F. Johnsson, A. Al-Shishtawy, L. Thorsson (2019). ROSE: Roll Out Scenarios of Electric Roads, Phase 1. [134]

Jan Nylander, Håkan Sundelin and Martin Gustavsson. Elvägars utveckling – Från demonstratorer till storskalig utbyggnad. RISE Research Institutes of Sweden, 2017. [133]

6 Access and payment systems

The research in this chapter has been performed by RISE Research Institutes of Sweden.

6.1 Scope

The scope of this chapter is to give insight into the importance and function of both access and payment systems for ERS. This analysis covers both digital system solutions and physical components and describe how such parts may look when designing necessary digital and physical infrastructure for ERS solutions. Furthermore, there is also an analysis on where certain components and functions fit into the electric road system at large.

Originally, the scope of this work package also included analysis on possible ERS business models. These results have been reported in work package 5, together with the rest of the work done on ERS business ecosystems.

6.2 Activities

To understand how similar systems and solutions for access and payment have been used in neighbouring sectors, and to realize how they might be adaptable for use in ERS, multiple interviews were conducted with companies in various sectors, for example the telecom industry and companies designing and constructing various electromechanics components. The access and payment systems for ERS have been studied as a whole but also broken down into deeper examination of crucial parts and components.

Thus, this work package contains an outlook for potential solutions rooted in current technologies in neighbouring sectors, necessary and auxiliary components for access- and payment systems specifically made for ERS, their desired functions and a look at relevant companies suited for further dialogue as ERS matures.

Following tasks and activities have been carried out within WP7:

- Paper published about access system architectural design for ERS.
- Interviews and dialogue with the telecom industry.
- Interviews and dialogue with the electricity components industry.
- Contacts with region Västra Götaland and region Jönköping about demonstration on RV40.
- Participated in ELinGO project meetings and done presentations. <https://www.sintef.no/projectweb/elingo/english/>
- Established good contacts with Utah State University with regards to inductive technology. Member of Center for Sustainable Electrified Transportation SELECT <https://select.usu.edu/>

- Compiled results and syntheses in a memorandum (PM).

6.3 Results

In this section, the technical components for the access- and payment systems for ERS are presented. There are currently no tailor-made solutions for either an access- or payment system for ERS applications, there are however similar solutions in both areas that can serve both as a technical foundation and inspiration for technology-specific ERS solutions in the future. Thus, this chapter contains an outlook for potential solutions rooted in current technologies in neighbouring sectors, necessary and auxiliary components for access- and payment systems specifically made for ERS, their desired functions and a look at relevant companies suited for further dialogue as ERS matures.

6.3.1 Access system for ERS

For an ERS to function properly, there needs to exist a system to identify and give access to the vehicles that wants to connect to it. Simultaneously, this system also needs to monitor and hinder any unauthorized vehicles to be able to connect to the ERS. Within the system there is also a need for necessary data to be handled correctly, for example, to log where and when a vehicle connects and disconnects to the ERS.

When a vehicle enters the ERS, the access system should be able to tell whether the vehicle is approved to use the ERS or not. This process will probably contain several checks, for example:

- That the vehicle is registered to use the ERS
- That the vehicle is within the technical boundaries necessary to use the ERS
 - That the vehicle is travelling above the minimum speed and below the maximum speed required
 - That the electricity pick-up unit is in proper condition
- That the vehicle is within the legal boundaries necessary to use the ERS
 - That the vehicle is approved for operation on public roads
 - That the logistics operator has a valid commercial traffic licence
- Auxiliary functions
 - That the driver has the right license to operate the vehicle
 - That the driver is wearing his or her seatbelt

To be noted is that the central part of the access system is based on controlling the identity of the vehicle (and that it is approved to connect to the ERS) and that it has the technical capabilities to do so. The legal and auxiliary parts of the process can be seen as optional or bonus features. The above listed (and probably further) auxiliary functions could be attained by integrating the ERS access system with the in-vehicle or fleet manager control system, which could be a way to make ERS technology more attractive in the future.

It is only after a vehicle has entered the ERS and the access process is completed that the vehicle may connect to the road and electricity be delivered to the vehicle. One central part of the access system is to also ensure that the right segment is turned on and powering the right vehicle on the ERS. A conceptual design of how the access system can look, and what subsystems are necessary can be seen in Figure 53.

Naturally, the access process requires some data inputs (most of which are available today) along with an integrated communication between some existing systems and registers from the vehicle and logistics operator. Interviews with logistics operators indicate that they see positively on this process and access system, as it is a way to ensure fair competition in their business sector.

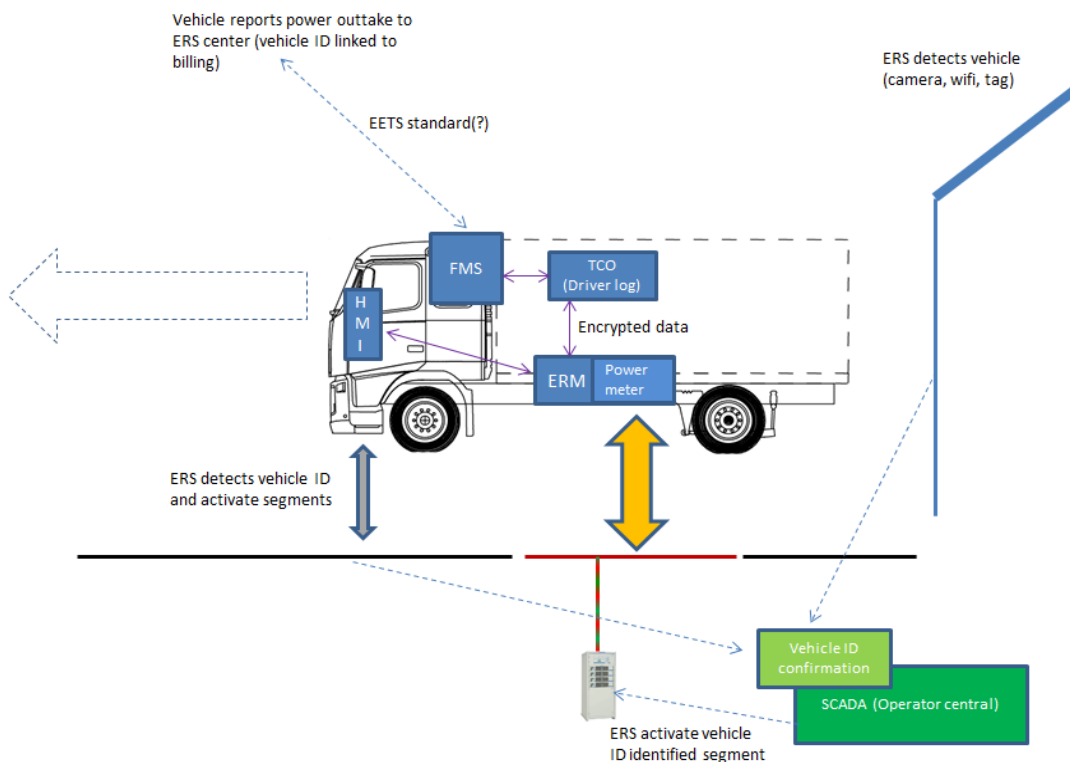


Figure 53: A concept design of the access system for an ERS and its subsystems. Source: Richard Sebestyen and Håkan Sundelin.

6.3.1.1 Access process and parameters

An important underlying activity for accessing electric road usage is the *Power Consumption Monitoring* activity. Power Consumption Monitoring activity is described in Figure 54 and focuses on the connection of vehicles to the electric road, the usage during the ongoing connection and disconnection from the electric road system. The signal for access approval to the electric road must be received before the monitor can engage in metering activities. The start metering parameter is an on-off switch to start recording power usage during the period when the metering is switched on. When it is turned off, the total effect use is sent to the requested outer activity.

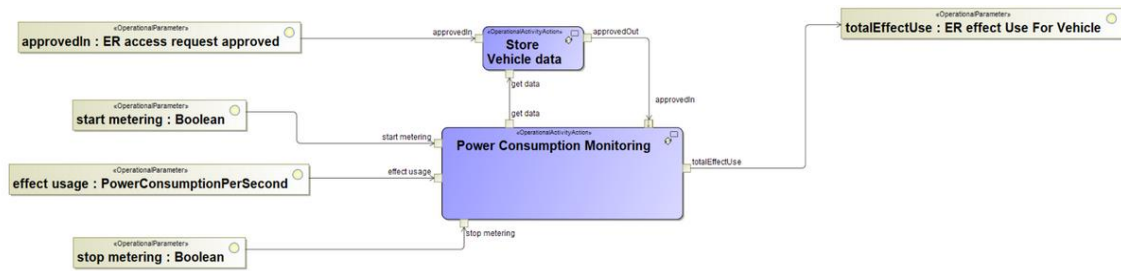


Figure 54: Power Consumption Monitoring activity.

To enable the connection to the electric road, a sequence of events is needed starting with the electric road vehicle requesting access for the usage of the electric road. This must be approved by the electric road operator and if the request is denied the whole process will end there. If the request is accepted, the operator will then activate the segments, one at a time, which the approved electric road vehicle will drive on (Figure 55). The power consumption monitor will thus start logging the power consumption for invoice and monitoring purposes.

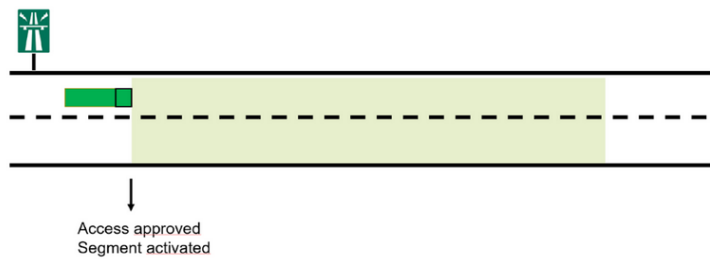


Figure 55: ER connection start.

At highway speed, if a segment is 20 meters in length or less, it seems unlikely that more than one electric road vehicle could make use of that individual segment simultaneously. Furthermore, each segment needs to be activated in advance as the electric road vehicle progresses through the ERS, which creates challenges for shorter segments. An electric road vehicle travelling at 36 km/h will pass 10 meters in one second. 72 km/h means 20 meters in one second and 108 km/h means 30 meters. How quickly a segment can be activated or deactivated will therefore matter in determining how far in advance it will need to be switched on to prepare for the arrival of an electric road vehicle.

It is assumed that the vehicle can periodically transmit its speed and position to the electric road operator, making it possible for the operator to determine how fast the electric road vehicle is progressing through the segments and then deactivate or activate segments in advance to make the transition between segments easy. Obviously, if there are several vehicles present on the road, the activation and deactivation segments may overlap and this needs to be considered, i.e. a segment cannot be deactivated if another electric road vehicle is already using it.

Thus, major challenges for shorter segments are both the ability to cope with timing issues as well as a high number of switches needed between segments. For longer segments, the challenge is instead to identify possible unauthorized usage which could lead to a lack of payment, but also a more serious risk of damage to the infrastructure due to uncertified and checked power receivers [135].

The access system for ERS will probably be closely intertwined with the payment system that will handle the economic transactions in the system. Both access and the price to use the ERS can through these systems be controlled, which in turn gives an opportunity to control or steer traffic intensity and load on the electricity grid if needed. For example, the system can give access only to the vehicles on the road with a low state of charge in their batteries that need to charge when the system is strained, or the system can give access to enough electricity consumption in the vehicles to propel them, but not to charge the internal battery as well. This may prove useful in a number of different circumstances as the total strain on the electricity grid and ERS system may vary by yearly season, time of day, during public holidays and so on. It may also prove useful as more renewable electricity is added to the electricity mix, as these intermittent generation sources play well with demand-side management solutions.

6.3.2 Payment system for ERS

No matter what technology solution for energy transfer chosen for future ERS, there will be a business ecosystem with several actors and commercial relationships between different roles such as goods owners (industries), haulage contractors, road operators, electric power distributors etc. Although a single actor may take care of more than one role, it will likely be a complex situation where multiple actors will split expenses and revenues. Since it is presently not known to what extent ERS will be used and which business models that will be used, an ERS revenue management system should have an open and scalable architecture that enables interoperability and different business models.

Rate of development, competition and especially the need to adapt to different business models has caused revenue management systems used by communication service providers (telecom companies) to often be flexible and configurable in order to cope with changing commercial situations with multiple actors and roles, which corresponds with what the revenue management for an ERS needs to handle. Trading of electricity for railway transport affects fewer roles than what is expected to be the case for ERS and its revenue management system is therefore not deemed possible to reuse directly for ERS, but it is highly relevant to note the trend to calculate energy consumption based on distance reading of power consumption.

From the information that was gained by conducting industry interviews, together with the inspiration from state-of-the-art revenue systems from the telecom industry, a solution proposition has been determined for an ERS payment system consisting of the fundamental design, crucial functions, necessary dataflows and possible suppliers.

Currently, there are pre-developed management systems that are able to handle very complex revenue streams that would be suited to implement in an ERS with some modification. Interviews with several suppliers indicate that it would take about two weeks to design a prototype and approximately six months to fully configure and deploy a system to be used for ERS and that can be expanded with services as they occur. Future adjustment of revenue management should be possible by changing the configuration.

6.3.2.1 The ERS fee

No matter the scale or technology design of the ERS, its payment system will need to account for use of both energy and the underlying infrastructure. The fee for the ERS user may consist of several dependent or independent parts:

- Fee for electricity
- Fee for road infrastructure
- Fee for wayside infrastructure
- Fee for potential add-on services

How parts of the total fee will look for the customer of the ERS or the recipients of the fee payments should be constructed in accordance with the chosen ERS business model. There are different fee compositions that can ultimately affect the success and adoption rate of ERS. One such example is the underlying measurement factor for the main part of the fee, i.e. for a vehicle using the ERS:

Should the payment system measure the kilometres travelled on the ERS, time spent on the ERS or the amount of electricity consumed?

The fee can also have both fixed and variable parts, e.g. a fixed fee depending on what kind of vehicle is using the ERS (light/heavy), and a variable fee depending on multiple deciding factors such as time of utilization (this would take into consideration the variable electricity price over time) and geographical location (which would take into account the prices of different electricity grid areas). Different parts of the fee could then be split differently between the actors that deployed and are managing the ERS.

In the design of a system that should measure and register ERS kilometres for the payment system, there are existing investigations for inspiration on both national and international level, for example, [ARENA](#) and [EETS](#).

The total amount of the fee itself should be kept to a cost-competitive level where one example is to keep it equal to (or slightly lower) than what it would cost to fast-charge along the given route instead. This way, the advantage of charging dynamically (and thus saving time by not standing still to be able to charge) would give ERS an important edge to gain users. Interviews with logistics operators also indicate that they would not accept a total price higher than what is available by fossil fuels, which would indicate a top limit equal that of the current diesel price.

6.3.2.2 The ERS payment system

An ERS payment system will have some core functions that will be crucial for a successful interface between actors and communication systems. Currently, the most important functions for the system are predicted to be:

- Dynamic multi-identification (vehicle, electricity grid area and road segment)
- Date and time of vehicles entering and exiting the ERS
- Metering of consumed electricity

- Flexible and reconfigurable system
- Modularized and interoperable
- Handle complex cases regarding multiple actors and split revenue streams
- Integratable with current electricity grid metering and communication systems
- Integratable with vehicle sensors and logistics operator's communication systems

The design of the payment system will be interdependent with the design of the ERS business model, as the business model determines which and how many actors that are present in the network as well as how their economic relationships are constructed. As the business model for ERS is not yet determined, the design of the payment system cannot be fully determined either, hence the need for a flexible and reconfigurable system design. For example, there is a possibility of a business model dependent on one central actor (ERSO, see Section 4.3.2 for description) to handle all the information exchange and interaction with the rest of the actor ecosystem. Having such a central actor in the ERS would probably mean that a payment system would also have to be designed according to a centralized information exchange, meaning data and payments would be processed and sorted between different parts of the ERS actor-network through the ERSO. On the other hand, there is a possibility of an ERS business model without such an actor as well, meaning the payment system would probably have to be designed to connect certain actors in the ERS actor-network directly to each other depending on what kind of data or payment transaction is in question. One example of such a connection would be to connect the consumer of electricity (logistics operator or haulier) directly to the electricity supplier for payment of the electricity consumption part of the ERS fee, while another connection may need to be implemented to the ERS infrastructure operator for use of the infrastructure.

From industry interviews, a number of companies were identified as suitable to deliver a billing/revenue management system for ERS:

- Ericsson
- Props Utility Solutions
- Enghouse Utility Billing
- Tieto
- NetSuite / Oracle

6.3.2.3 Electricity metering

If the vehicle using ERS should be billed for the exact amount of electricity used, the electricity consumption for the vehicle will need to be measured correctly in terms of location, time and amount as it is entering, using and exiting the ERS. To correctly measure the consumed electricity there will need to be present an electricity meter either in each vehicle or in each ERS road segment. If the meter is present in the vehicle it will be tied to the identity of that specific vehicle and meter when the vehicle is receiving power from the ERS. If the meter is instead present in each ERS road

segment, there will be a need to tie each specific reading of electricity consumed by the meter to the correct vehicle connected to the ERS. How this identification process will work will mainly depend on the segment length. For in-road ERS technologies (conductive rail and inductive solutions) the segment length is short (maximum a few meters), meaning there is a very low probability that more than one vehicle is activating the same segment. Thus, the identification process, in this case, could be tied between the active segment and the vehicle that activated said segment. If the segment is long (catenary solutions, up to a few kilometres long) there needs to be another way to tie specific vehicles to the correct amount of electricity flowing through the segment. From current system designs, there seems to exist more advantages in placing the meter in the vehicle rather than the ERS segment, although this might change as the ERS technology matures.

Both the EU and the Swedish Energy Markets Inspectorate (Ei) currently have some regulations regarding electric meters, but the most important body in this context is the Swedish Board for Accreditation and Conformity Assessment (SWEDAC), who is responsible for the functional regulation of electric meters in Sweden and how they are categorized. If electric meters are to be introduced in an ERS context, it should be done in dialogue with SWEDAC as to how it is done correctly and efficiently.

There currently exists multiple companies that manufacture and sell different electric meters within the electricity sector that could work as a good first point of contact to develop electric meters specifically for ERS applications, such as [Kamstrup](#), [Tillquist](#), and [EMH/LEEM](#).

It may fall upon the electricity grid owners to meter the electricity that is consumed by the ERS and its respective vehicles, depending on if they will own the ERS infrastructure connecting the road to the electric grid. If not, it is likely that they will only concentrate on measuring the total amount of electricity consumed by the ERS in the transfer points between the ERS and their grid. If so, it falls upon another actor to facilitate the measuring of the individual vehicles and to bill them correctly, probably the ERSO or the proprietor of the specific ERS transfer technology (i.e. Siemens for catenary ERS and so on).

6.3.2.4 Suggestions

With the current state of ERS development in mind, there are some visible ways forward in terms of measuring and payment systems for ERS.

For metering systems, existing solutions for similar applications are already available on the market. A current electricity metering solution should serve as a good foundation to meter consumed electricity in future ERS pilots. Simultaneously, it is recommended to investigate how current solutions can be adapted according to ERS-specific use cases, for example how the meter and its measurements can be integrated into road vehicles and possibly their Fleet Management System (FMS).

For payment systems, a suitable first point of conduct could be to investigate how current companies delivering complex and flexible payment systems for the telecom sector can tweak existing solutions toward an ERS. The payment system should be compatible with the electricity metering system if that becomes the chosen basis for the ERS fee. The payment system should also be integrable with current or future

communication systems for OEMs, logistics operators, electricity grid companies and electricity suppliers.

6.4 Publications and other dissemination

H. Sundelin & S. Tongur. (2019) Architectural description of ERS: Analyzing implications of short and long electric road segments. 3rd Electric Road System Conference 2019. Frankfurt am Main. Germany. [135]

M. Gustavsson, C. Börjesson and H.K. Dahlgren. “Revenue Management for Electric Road Systems”. EVS32 Symposium Lyon, France, May 19-22, 2019. [136]

Two memorandums (PM) covering this topic were written in Swedish and disseminated by Conny Börjesson, RISE.

7 Standardisation

The results presented in this section are the joint efforts of VTI, RISE, the Swedish Institute for Standards (SIS), the Swedish Transport Administration, and ÅF. VTI has been the work package leader and has planned and overseen three integral parts created for the purposes of this work. These parts, which form the basis of the current report, are themselves reports commissioned by VTI, and were written by handpicked experts in close collaboration between VTI, RISE, SIS, the Swedish Transport Administration, and ÅF. As the results substantially builds on these reports, this chapter will frequently refer to the reports, also appended as Annex 1-3.

Since the start of the Research & Innovation Platform for Electric Roads, a change of working group has occurred regarding regulations. Late 2018, Mohammed Hoseini, VTI, took over as acting work package leader from Wanna Svedberg, VTI. During the beginning of 2019, the role as permanent work package leader was handed to Philip Almestrand Linné, VTI.

As a result, the work on regulations was modified to focus exclusively on standardisation of electric roads, hence the updated and abridged title “Standardisation”.

7.1 Scope

Although there has been a change in scope from the original WP 8 by excluding legislative aspects in favour of focussing solely on standardisation issues, an overarching objective for WP 8 has been to contribute with knowledge that might influence ERS in terms of development, creation, design, function, and administration. For instance, factors affecting these areas could be standardisation of matters like security, safety, environmental, and technical requirements for ERS.

The aim of this revised work package was more precisely to:

- review standards that directly or indirectly cover electric roads
- analyse and recommend standards that are essential or need to be developed for the establishment and potential expansion of electric roads

7.2 Activities

The main activities of WP 8 have been:

- Setting up a consulting agreement between VTI and SIS for mapping relevant standards for ERS, standardisation in progress, and identification of obstacles
- Drafting a report on the mapping of standardisation together with SIS, and accompanying Excel-“database” on standards relevant for ERS and standardisation in progress
- Establishing a working group for the standardisation task (RISE, VTI, SIS & the Swedish Transport Administration)

- Presenting preliminary results of WP 8 in the form of an extended abstract at the 3rd Electric Road Systems Conference, Frankfurt Am Main, Germany, May 2019
- Setting up a consulting agreement between VTI and ÅF for making a more refined user-friendly Excel-“database” of standardisation. The database can be used as a “work in progress” document for regular circulation among stakeholders, for continuous mapping of relevant standards for ERS, and to keep track of standardisation in progress

The main results presented below were achieved through combining the findings in all the integral parts drafted for the purposes of WP 8 (see further Appendix 1-3).

7.3 Results

Initially, it must be noted that a general statement applying to the following results is that standardisation of ERS is still in an early phase. With this said, the current section now proceeds to present an overview of the results from examining the work done so far in standardisation of ERS from an international to a national (Sweden) level. The more detailed results can be found in Appendix 1-2.

7.3.1 The First Work Items for Standardisation of ERS

The first two work items regarding standardisation of electric roads were initiated at the European standardisation level late 2018, in the European Committee for Electrotechnical Standardization ([CENELEC](#)) [137].

At present, there are still no specific published standards for electric road systems, but the drafting of standards is under way. Current standardisation discussions revolve around standards that were initially created for other and related purposes, such as, for example, railway and rail operations [138], [139].

Recently, the CENELEC technical committee TC9x has proceeded to working with both of the ERS-related work items in working group (WG) form instead of survey group (SG) form. Currently, TC9X is working on two draft *technical specifications* (TS) covering aspects of ERS [139], [140]. Typically, technical specifications are drafted in areas of evolving technologies and can be prepared with a faster, less extensive, voting process than is required for a full standard. Technical specifications may act as trial or pre-standards and can later be transformed into full standards if suitable. As to yet, the standardisation work with technical specifications for ERS in TC9X among other things considers the important interfaces of vehicle and road infrastructure [139]. Additionally, it should also be mentioned that the CENELEC SC9X subcommittee has recently added an informative annex with relevance for ERS in a standard *not* specifically dedicated to electric roads, but which all the same mentions electric roads in its informative (non-binding) Annex C [141]. Moreover, the IEC TC69 technical committee is working with a new work item proposal that is also relevant for ERS when it comes to inductive charging solutions for vehicles [142].

7.3.2 Standardisation Mapping

As mentioned above, a mapping of standards and standardisation in progress was made for WP 8 on commission by SIS for VTI. The work included making a preliminary Excel list/"database" [141] of standards potentially useful for ERS. The list was then circulated for comments to the following reference group, especially regarding the applicability to ERS and any missing standards in the Excel list:

Table 8: Reference group, stakeholders for each category.

| Vehicle | Electric power supply | Infrastructure | Overall |
|----------|----------------------------------|----------------------------------|----------------------------------|
| Scania | Alstom | NCC | Swedish Energy Agency |
| AB Volvo | Elonroad | Swedish Transport Administration | Swedish Transport Administration |
| | Elsäkerhetsverket | | |
| | E.ON | | |
| | Fortum | | |
| | Siemens | | |
| | Swedish Transport Administration | | |
| | Vattenfall | | |
| | Elways | | |
| | Bombardier | | |
| | Ellevio | | |

After the completed period of review, comments from seven stakeholders were received, mainly focusing on electric power supply. The stakeholders commenting represented OEM's, energy market actors, as well as Swedish public authorities.

The main findings from the standard review show that a number of published standards and standards under development within three different thematic categories (vehicle, infrastructure, electric power supply) covering four different applications (general, conductive transmission by rail in road, conductive transmission overhead, inductive power transmission) can be considered useful in the context of ERS.

In numbers, this means that 96 standards out of a total of 244 listed standards were preliminarily classified as "applicable" to electric road systems within the thematic categories and the different applications [138], [141]. For the time being, this quantification of "applicable" standards can at most give an indication of where the relevant standards for ERS could be found. It is therefore not an indicator of "a leading" technology, but rather reveals where the formal standardisation work has started as to yet. Immediately below, we will for instance see that so far, work items with a clear ERS focus have been initiated in a railway setting.

| Standard Number | Standard Title | Status | Scope | Limitations | Applicable to ERS |
|---------------------------------|---|-----------|--|--|-------------------|
| ISO 6469-1:2009 (ed.2) | Electrically propelled road vehicles – Safety specifications – Part 1: On-board rechargeable energy storage system (RESS) | Published | This part of ISO 6469 specifies requirements for the on-board rechargeable energy storage systems (RESS) of electrically propelled road vehicles, including battery-electric vehicles (BEVs), fuel-cell vehicles (FCVs) and hybrid electric vehicles (HEVs), for the protection of persons inside and outside the vehicle and the vehicle environment. Flywheels are not included in the scope of this part of ISO 6469. | This part of ISO 6469 does not apply to RESS in motorcycles and vehicles not primarily intended as road vehicles, such as material handling trucks or fork-lift trucks. This part of ISO 6469 applies only to RESS in on-board voltage class B (see 3.18) electric circuits for vehicle propulsion. This part of ISO 6469 does not provide comprehensive safety information for manufacturing. | Yes |
| ISO/FDIS 6469-1 (proposed ed.3) | Electrically propelled road vehicles – Safety specifications – Part 1: Rechargeable energy storage system (RESS) | Draft | This document specifies safety requirements for rechargeable energy storage systems (RESS) of electrically propelled vehicles for the protection of persons. | It does not provide comprehensive safety information for manufacturing, maintenance and repair personnel. NOTE Requirements for motorcycles and mopeds are specified in ISO 13063 and ISO 18243. | Yes |
| ISO 6469-2:2018 ed.3 | Electrically propelled road vehicles – Safety specifications – Part 2: Vehicle operational | Published | This document specifies requirements for operational safety specific to electrically propelled road vehicles, for the protection of persons inside and outside the vehicle. | It does not provide comprehensive safety information for manufacturing, maintenance and repair personnel. It does not consider specific aspects of driving automation | Yes |
| ISO 6469-3:2018 (ed.3) | Electrically propelled road vehicles – Safety specifications – Part 3: Electrical safety | Published | This document specifies electrical safety requirements for voltage class B electric circuits of electric propulsion systems and conductively connected auxiliary electric systems of electrically propelled road vehicles. | It does not provide comprehensive safety information for manufacturing, maintenance and repair personnel. | Yes |
| ISO 6469-4:2015 | Electrically propelled road vehicles – Safety specifications – Part 4: Post crash electrical safety requirements | Published | It specifies electrical safety requirements for protection of persons against electric shock and thermal incidents. | It does not apply to motorcycles and mopeds. It does not specify any crash test procedure. It does not provide comprehensive safety information for first responders, emergency services, maintenance, and repair personnel. | Yes |

Figure 56: Screen print from Excel-“database” of standards for ERS.

Generally, it must still also be recalled here that standards considered “applicable” in the list are *potentially applicable* to ERS, changing what needs to be changed. Therefore, standards marked as “applicable” should only be considered as candidates for being relevant for ERS, as the field of technology develops. The only certain way of judging standards as truly applicable will be when standards (or technical specifications) have passed the proper drafting procedure and explicitly apply to ERS.

For the moment, there are only two explicit work items applicable to ERS, plus the additional informative (non-binding) annex, briefly mentioned above [141], and the new work item proposal in the IEC [142]. The two technical specifications drafted for ERS, mentioned above, are currently being prepared in TC9X. In the standardisation mapping for WP 8, these have been sorted under the theme of electric power supply and apply to conductive rail in road, and conductive overhead solutions respectively:

- CLC/prTS 50XXX “Technical Requirements for Current Collectors for ground-level feeding system on road vehicles in operation” (conductive rail in road) [139], and
- CLC/prTS 50712 “Railway applications - Current collection systems - Technical criteria for the interaction between pantograph and overhead lines on electrified roads” [140].

From the standardisation mapping, it can therefore be noted that there are presently only two standards (technical specifications) that explicitly apply to ERS. The rest of the standards that have been preliminarily listed as “applicable” have been added to this list by merit of their closeness in application or technical area. Thus, it is possible that standards that have a technical or thematic proximity may prove helpful for further standardisation work as standardisation of the field of ERS progresses.

The following list provides some examples of preliminarily “applicable” standards with adjacent technical or thematic closeness, although without explicitly referring to ERS:

For vehicles

Possibly useful standards for conductive rail in road applications regard:

- Electrical safety aspects,

- Conductive charging,
- V2G CI (Vehicle to grid communication interface), especially the wireless communication parts,
- Voltage classes,
- Environmental conditions and testing of the exposed parts on the vehicle,
- To some extent, test specifications for the electric propulsion components,
- To some extent, voltage class B specifications and voltage class B testing of components.

Possibly useful standards for conductive overhead applications:

- The most closely related are for electric bus (static) charging with an automatic mechanical overhead device, similar to a pantograph.
- Safety and other aspects on the charging station side is under development
- Standards in the area of railways, and specifically urban transport systems such as trams and trolleybuses

Possibly useful standards for inductive applications:

- A standard that covers passenger cars and light vehicles only (static charging)

For electric power supply

Possibly useful standards for conductive rail in road applications regard:

- Standards for the electric charging station (AC and DC charging), including communication and EMC requirements;
- Standards for charging plugs and sockets (not directly applicable to electric roads, but contains some relevant information);
- Standards for charging communication between vehicle and infrastructure.

Possibly useful standards for conductive overhead applications regard:

- Several standards for electric overhead contact lines and pantographs for train application
- Safety requirements and current collection systems for trolley buses

Possibly useful standards for inductive applications regard:

- Standards on the electric power supply side

For infrastructure

Possibly useful standards generally regard applications for:

- Product standards for the performance of road materials products (although considered as *not applicable* to conductive overhead solutions)

As a round off, it can be added that the Excel-“database” [141] can be used to analyse other headings than has been considered in the above (e.g. Applicable to ERS, Technical Committee, SE mirror committee, ...). The list can therefore be used when looking for relevant standards by “slicing” with many different parameters, as well as for identification of missing standards for ERS. On the note of standardisation, gaps, and identifying possibly useful standards among standards that do not yet apply to ERS, but could be changed in the future to do so, it should be known that the work in progress Excel-“database” [143] contains several standards marked as TBD, to be defined.

In numbers, around 51 % (124 out of 244) standards are currently marked as TBD. Admittedly, this could be seen as a weakness of the listing of standards. However, it also testifies the current uncertainty regarding possibly applicable standards for electric road systems. Additionally, the relatively high frequency of standards marked as TBD, is a result of waiting for proper peer review of the preliminarily categorised standards by SIS. Among the stakeholders asked for feedback regarding the standardisation listing, 7 out of 22 persons returned comments.

While a low answering frequency in surveys is no major surprise, a suggestion to improve further research where stakeholders in reference groups are involved could be to engage them even more with a known person that has well-established contacts and credentials, for example the project leader in the research project.

For any future analysis work, it would also be highly desirable to involve the competence from SEK Svensk Elstandard, as its work includes an extensive part of standardisation within the electrotechnical area.

Although there are currently no dedicated published standards covering the specific technology of ERS, this will probably change in the coming years. As noted above, by the end of 2018, the first dedicated ERS work items were started and Sweden have representatives following the work. It is expected that there are good opportunities for proposing new standardisation work for ERS and taking a Swedish lead.

Finally, when it comes to recommending standards that are essential or need to be developed for the establishment and potential expansion of electric roads, it can be concluded that work is under way, currently in a railway setting. It is likely that the number of standards with a connection to ERS will expand in the coming years, but for now, the standardisation work that has the most concrete shape, the technical specifications prepared by TC9x in working groups, seem to focus on a problem that several stakeholders have raised as a key for the development of ERS; namely the standardisation of important interfaces like vehicle and road infrastructure [144].

7.3.3 Possible Further Research

As possible further research, it would be desirable to involve stakeholders even more and to have a close cooperation with both SIS and SEK.

More precisely, this could be done by involving further expertise from standards organisations within the electrotechnical area and with continued stakeholder dialogue. Moreover, further aspects and links of ERS as a system of systems [143] could be examined. The latter is important considering the potential relevance of telecommunication standards, which were not examined in this work package, especially for payment technologies in ERS, but likewise for other foreseen ‘megatrends’ besides electrification of transport, like autonomous/automated and shared vehicles [144].

7.4 Publications and other dissemination

P. Almestrand Linné, M. Hoseini, L. Casselbrant, P. Claeson, Standardisation of Electric Road Systems – An Inventory of Standards for Vehicles, Electric Power Supply, and Infrastructure. 3rd Electric Road Systems Conference 2019 Frankfurt am Main, Germany, 7th to 8th of May 2019, 2019. (Extended abstract) [144]

P. Almestrand Linné, M. Hoseini, L. Casselbrant, P. Claeson, Standardisation of Electric Road Systems – An Inventory of Standards for Vehicles, Electric Power Supply, and Infrastructure. 3rd Electric Road Systems Conference 2019 Frankfurt am Main, Germany, 7th to 8th of May 2019, 2019. (Poster) [144]

P. Claeson, L. Casselbrant, Y. Kadoura, A. Almqvist, Research and Innovation Platform for Electric Roads – WP 8 – Standardisation, SIS Swedish Institute for Standards, 2019. (Report commissioned by VTI for WP 8) [138]

P. Claeson, L. Casselbrant, M. Hallberg, WP 8 Standards Compilation – Ver. 3.0 - 2019-09-16, SIS Swedish Institute for Standards/ÅF, 2019. (Excel-“database” commissioned by VTI for WP 8) [143]

M. Hallberg, PM AP8 – Excelhantering, ÅF, 2019. (User manual for Excel-”database”, commissioned by VTI for WP 8, Swedish version) [145]

P. Almestrand Linné, Standardisation of Electric Road Systems - Report from Workshop at FIRM 19, 28 March 2019, Brussels, Swedish-German research collaboration on Electric Road Systems, 2019 [144]

8 Knowledge spread

8.1 Scope

A specific work package with the project has focused on objectives that are helpful for all other project efforts such as developing a common architecture, identifying essential interfaces within and between various systems within electric road systems as well as organising information meetings. This work package is also responsible for arranging the international conference where researchers in the platform as well as external researches, authorities and other stakeholders get together to share their knowledge around ERS.

8.2 Global spread of knowledge

The area of Electric road system has grown significantly since the research and innovation platform was launched, partly due to the work done within the platform. The participants have been spreading the knowledge around the world with presentations in, for example China, Japan, Korea India, US, Israel and several European countries. The www-site <https://www.electricroads.org/> have been a useful tool in the dissemination.

8.3 Publications

In each of the individual WP there is a list of journal publications, reports and presentations. In total, more than 40 scientific papers and reports have been published.

8.4 Conference

For the dissemination of the research and innovation platform for electric roads an international conference on electric road system was initiated. The first conference was held in Sandviken 14-15 June. Sweden was the first country in the world to demonstrate electric road systems for heavy duty trucks on the public road network. A visit to the two-kilometre demonstration site on the E16 was the first point of the program when 80 experts and researchers from seven countries got together at Högbo Bruk outside Sandviken.

Sweden, the Swedish Transport Administration and the Region of Gävleborg received many praises for enabling this, together with the technology suppliers Siemens and Scania. “I feel proud every time I go this way and pass the test facility. It has been realized thanks to enthusiasm and cooperation between all involved”, the Director of Strategic Development at the Swedish Transport Administration, Agneta Wargsjö, said when she opened the conference.

At the conference several additional ERS projects were presented. In Sweden there will be another demonstration by the consortium eRoadArlanda, on public roads outside the airport of Arlanda, with a conducting rail in the road surface. Elonroad presented their technology and the plans for a test with a conducting rail placed on the road surface.

On the international arena participants from Germany presented both research and plans for at least two demonstrations on public highways, each about 5 km of electrified road in each direction. In Israel and USA, developments are ongoing on inductive systems whilst the companies Alstom and Bombardier presented their respective technologies. Jakob Teter of the International Energy Agency (IEA) believes that electric road system has a key role to play in reducing CO₂ emissions from road transport, as also included in their reports and the IEA strategies.

At the first conference there was a strong focus on technology. However, a few presentations dealt with policies, effects and cost such as Julius Jöhrens of the Institute for Energy and Environmental Research in Heidelberg who stressed that work must start now. He compared the electrification of the German railway, which took 20 years. "The roadway electrification is much more complicated and can take at least as long. We do not have time to keep up with technical evaluations for ten years if we are to meet global climate targets. Political action is needed due to the high investment cost" Julius Jöhrens said.

The international community is growing, which was evident at the second international conference on electric road systems held in Stockholm Arlanda 13-14 June. The number of participants grew to 119 participants from 11 different countries, including India, Japan and the United States, besides a large crowd from Sweden and Germany. The number of presentations increased from 15 to 22. Based on the evaluations of the first conference the focus was changed toward non-technical challenges associated with the development of an electric road network. "From vision to reality" was the slogan for the second conference, which was included in various presentations. However, as the Community is still relatively small, so all subjects have been taken into account. All abstracts were peer-reviewed by an international scientific committee, which this year had Swedish members from KTH, RISE, VTI, the Swedish Transport Administration, and German members from the OEKO Institute and the Institute for Energy and Umweltforschung Heidelberg GmbH. The mixed group led to different perspectives, and the contact was a good start to the recently initiated initiative "Swedish-German cooperation on ERS".

The conference took place from lunch to afternoon the day after. On Day 1, there were two sessions: "Decision processes and stakeholders" and "Energy and environment". In addition, there were key notes from Jan Pettersson (Swedish Transport Administration) and Gina Ytterborg (National Road Administration, Norway), Takamitsu Tajima (Honda, Japan) and Michael Lüken (VDI / VDE Innovation + Technik GmbH, Germany). Day 2 consisted of two sessions "Tests and demonstration" and "Network and large scale deployment" as well as key notes from Stefan Tongur (KTH) and Hans Säll (NCC and eRoadArlanda). There was also a panel discussion and the conference was concluded with a visit to the eRoadArlanda electric road demonstration site outside the airport of Arlanda.

In 7-8 May 2019 the third ERS conference was held in Frankfurt, Germany. The ERS community had grown even larger with more than 200 participants and 40 contribution divided between eight scientific sessions. Besides the scientific sessions the ERSC2019 also included round table discussions with key stakeholders, poster session and a visit to the ERS demo site on A5 outside Frankfurt. The scientific session was divided into the following topics (1) Interaction with energy system, (2)

Stakeholder / Acceptance, (3) Status of test tracks (planning / implementation), (4) Business models / framework conditions, (5) Techno-economic analysis, (6) Simulations along test tracks, (7) New technologies beyond traditional ERS, OEM strategies and (8) Large-scale implementation.

The plenary sessions were rather focused on the activities ongoing in Germany, but keynote presentations from for example India and China broadened the scope. The overall topic of the conference was “Paving the way to large-scale implementation”. Jens Deutschendorf, Secretary of State at the Hessen State Ministry of Economics, Energy, Transport and Housing said “The full decarbonisation is an ambitious goal, but has to be achieved. In the future, we will likely see a mix of propulsion types on the roads. An efficient use of renewables in the transport sector is required as renewable energy is also limited. The direct use of electricity is the preferable way”.

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Appendix A: Electricity supply

Table A1: Parameters used in the simulations of a single truck with a total payload of 60 tonnes for the E6 and E4 roads.

| Notation | Value | Description |
|----------|--------|--|
| m | 60 000 | Total payload of the truck (kg) |
| Cr | 0.0055 | Rolling friction coefficient (dimensionless) |
| Rho | 1.2 | Air density (kg/m ³) |
| Af | 10 | Cross sectional area of the truck (m ²) |
| Cd | 0.53 | Drag coefficient (dimensionless) |
| g | 9.82 | Standard acceleration of gravity (m/s ²) |

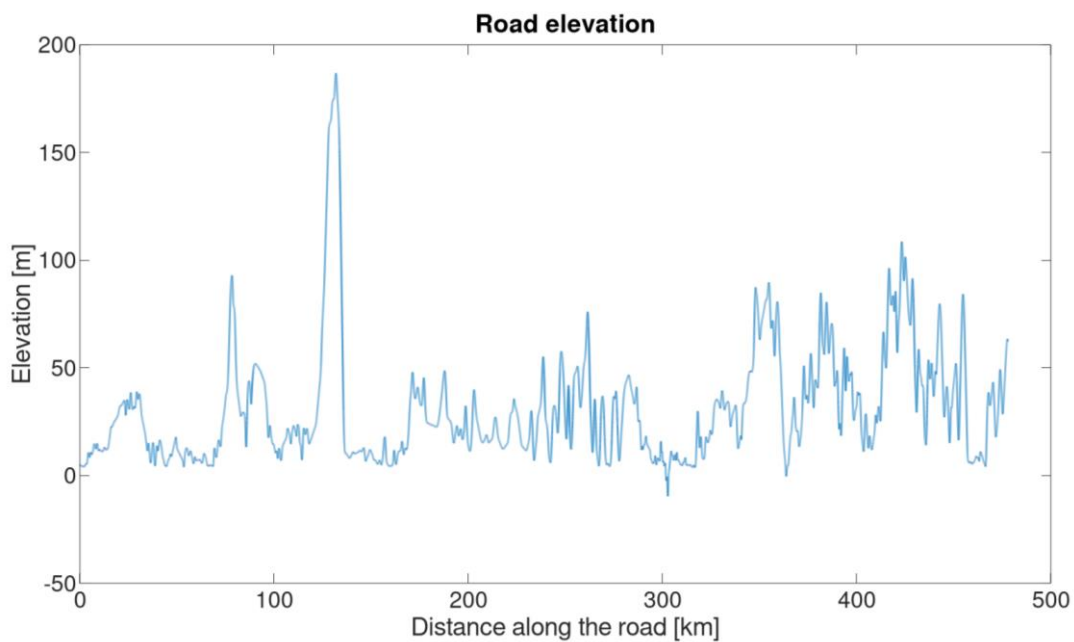


Figure A1: Road elevation of the road E6, from Trelleborg to Svinesund. Note that the road at Svinesund has a higher elevation than the road at Trelleborg, leading to a slightly higher average power needed to transport a truck from Trelleborg to Svinesund than the reverse.

Appendix B: Impact on road construction, maintenance and operations

Table B1: Possible impact on road construction – Comparison between different ERS concepts.

| | Catenary | Rails in road surface | Rails on road | Inductive |
|-------------------------------|----------------------------------|--|--|--|
| Loading in base layers | No | Yes | No | Yes |
| Need for other infrastructure | Yes – safety rails | Power switching boxes etc | Power switching boxes etc | Power switching boxes etc |
| Electrical cables in the road | No | Yes Degradation of the road from utility cuts in road surface, may cause irregularities, might also be problem with resurfacing risking to damage cables | Yes Degradation of the road from utility cuts in road surface, may cause irregularities, might also be problem with resurfacing risking to damage cables | Yes Degradation of the road from utility cuts in road surface, may cause irregularities, might also be problem with resurfacing risking to damage cables |
| Electric cables in sidearea | Yes – cables in the air | Yes – cables in side area might cause problems during ditching operations risking to damage cables | Yes – cables in side area might cause problems during ditching operations risking to damage cables | Yes – cables in side area might cause problems during ditching operations risking to damage cables |
| Increased rutting | Little risk | Some risk | Some risk | Little risk |
| Sustainability of apparatus | Weather sensitive | Wearing of pick-up, debris on road, snowplow etc. | Wearing of pick-up, debris on road, snowplow etc. | Maybe frost heave or flooding |
| Thermal expansion | Yes, overhead wiring will expand | Yes | ? | ? |
| Frost heaving issues | No | Yes some | No | Yes some |

Table B2: Possible impact in road maintenance and operations – Comparison between different ERS concepts

| | Catenary | Rails in road surface | Rails on road | Inductive |
|---|--|--|--|---|
| Maintenance contract | Yes, needs to be adjusted to cover maintenance concerning electrical parts as well as road maintenance that risks damaging ERS | Yes, needs to be adjusted to cover maintenance concerning electrical parts as well as road maintenance that risks damaging ERS | Yes, needs to be adjusted to cover maintenance concerning electrical parts as well as road maintenance that risks damaging ERS | Yes, needs to be adjusted to cover maintenance concerning electrical parts as well as road maintenance that risks damaging ERS |
| Cracking | No additional risks | Some impact as the steel construction might expand differently than surrounding asphalt | There could be some additional risks if the rail is lowered into the road surface. | Yes some, depending on how the technology is behaving in the sublayers of the road. |
| Regular maintenance activities in sub-base layers or asphalt layers such as resurfacing | There could be increased risks with lifting arms or raised flatbeds of trucks risking damaging catenary wires | Yes, every resurfacing activity or other maintenance activities concerning irregularities or cracks etc. | If the rail is glued on the road surface it can be easily removed and will not cause problems, unless there need to be electrical wiring installed underground | Electrical wiring might be damage during regular maintenance activities such as resurfacing, crack sealing etc. There are unsolved issues regarding the efficiency of power transfer if an extra layer of asphalt should be laid on top of the surface. |
| Maintenance operations in sidearea | Yes, Safety rails will have impact on side verge cutting, and snow ploughing. The overhead wires might be a risk for emptying trash, or cutting grass as the lifting arm will risk touching the wires. | Some if there are switching boxes | Some if there are switching boxes | Some if there are switching boxes |
| Maintenance or repair of electric parts | Some - Will need to close the lane during installation of new parts. | Some - Will need to close lane during repair, this will have a large impact on the road as the surface needs to be cut or milled | If the rails are glued to the road surface they are easily removed during repairs and a new segment could be easily replaced if damaged. | Yes, the road surface will probably need to be cut open (Plane off) for the operator to get to the damaged section of electric infrastructure. |

| | Catenary | Rails in road surface | Rails on road | Inductive |
|-------------------------|--|--|---|--|
| Wear of electric wiring | Yes, the overhead is open to weather as well as salt and wear from pantograph, and exposed to sabotage | Electrical wiring in road construction should be protecting using protective pipes or other standard techniques for protecting wires installed in the road construction. | Electrical wiring in road construction should be protecting using protective pipes or other standard techniques for protecting wires installed in the road construction | Electrical wiring in road construction should be protecting using protective pipes or other standard techniques for protecting wires installed in the road construction. |
| Rutting | No particularly increased risk | Yes, some increase risk | Yes some increased risk | No particularly increased risk. |

Table B3: Possible impact in winter road maintenance – Comparison between different ERS concepts.

| | Catenary | Rails in road surface | Rails on road | Inductive |
|-----------|--|--|--|--------------------------|
| Ice/frost | Road: No Cables: Yes | No – anti-icing as usual, salted water might however pose a risk of electrifying two sections at the same time, as salt water might cause leakage of electricity between two segments. | Anti-icing as usual but might affect corrosive parts of technology | Anti-icing as usual |
| Snow | Snow ploughing as usual. Poles might be damaged from snow or ploughing blades and safety rails may impair the winter operations along ERS roads. | Ploughing as usual but with caution coming from a crossing road. The rails will need to be cleared from snow or other debris. | Need a new type of plough. Will it work in all types of snow? | Snow ploughing as usual. |
| Friction | No particular impact | There might be an increased risk of decreased friction when driving on the rail. | Some, if driving on top of the rail. | No particular impact. |

Appendix C: Roll Out Scenarios of Electric Roads – ROSE

This appendix describes an activity that was added to the Research & Innovation Platform for Electric Roads. The main authors are Filip Johnsson, Chalmers; Ahmad Al-Shishtawy, RISE; and Ludwig Thorson, Chalmers.

C.1 Aim

The aim of this additional project was to investigate if detailed GPS data available at Scania and Volvo could be used to get a better basis for identifying road stretches suitable for Electric Road Systems (ERS). This, since Average Annual Daily Traffic (AADT) only gives the traffic intensity but does not give any information on the actual routes of individual vehicles such as how far different vehicles drive on certain road stretches. ERS would preferably require a certain number of vehicles driving sufficiently long distances on a road for it to be of interest for ERS (unless it is a “closed system” with dedicated transportations between two points for which shorter road stretches may be feasible). In the first phase of the project, the aim was to investigate to what extent data at Scania can be used to assess which road stretches can be suitable for ERS. The aim is then to use the data in the R&D platform work with the aim to present a map of suitable stretches for electrification in Sweden (hopefully Europe) using vehicle positioning datasets.

C.2 Route analysis of trucks

Route mapping

In order to assess the conditions for Electric Road Systems (ERSs), there is obviously a need for detailed data on truck movements in order to obtain route estimations. This requires information on truck travel times, freight tonnage distribution, transported commodity and truck trip stops and paths (including Origin of Destination (OD)). At present, data is mostly limited to such that can be derived from pneumatic tube measurements, i.e. counting vehicles from which the AADT can be determined as well as estimates of vehicle types and traveling speeds.

Today's trucks are equipped with GPS sensors, which together with on-board computing, provide real-time monitoring of vehicle position and speed together with vehicle data such as fuel consumption and other engine parameters (e.g. RPM). This opens up for a complete analysis of detailed mapping of routes of the trucks along all roads used by the trucks. Thus, not only can roads with high AADT be identified but also how far trucks of a certain size and with certain load travel on different roads and with identification of their OD. Such information is important for a more detail assessment of the conditions for ERS than can be obtained from AADT-based analysis or theoretical simulations of the transportation work, with exogenously given assumptions on the truck movements. There are two challenges to use truck-GPS data:

1. These are typically a property of the vehicle manufacturers or freight companies and,

thus, not readily accessible to the research community and 2. In order for these to be linked to the roads on which the trucks travel a map-matching procedure needs to be carried out. Thus, the map-matching translates a sequence of vehicle locations into the correct route in a road network.

Quddus et al. (2007) provides a comprehensive review of map-matching algorithms. They point to that map-matching algorithms span over a wide range of types from “simple search techniques” to more advanced techniques such as Extended Kalman Filtering and fuzzy logic (see Quddus et al. and references therein). Algorithms presented in the literature are typically used to improve the performance of systems that support the navigation function of intelligent transport systems (ITS). This will generally require a higher sampling frequency than what is required for evaluating routes suitable for ERS. Quddus et al. (2007) categorize map matching algorithms into four groups: geometric, topological, probabilistic and what they refer to as other advanced techniques.

According to Shoman (2019) there are a number of free open source codes and services for map-matching, based on published scientific papers (several of them belongs to the advanced techniques group of map matching algorithms). Examples are:

1. TrackMatching, which is a cloud-based web service. This web service matches GPS data to the OpenStreetMap road network. It is accessible through a REST API. This is a free service but it is not clear to what extent there is a limit to the dataset. See van Winden (2014) and <https://mapmatching.3scale.net/tutorial> for an example.
2. ST-matching based on Lou, et al. (2009), which provides map-matching for low-sampling-rate GPS trajectories.
3. Offline-MapMatching Q-GIS tool, which is based on Jung (2019).
4. LeuvenMapMatching open code python code, based on Wannas & Verbeke (2018).

GPS-based route analysis for trucks

There is a limited number of works in literature dealing with route identification of trucks. These works are focused on route planning and prediction, i.e. not as a basis for an evaluation of ERS. Examples of works in which map-matching algorithms are assessed and applied are given by Pinjari et al. (2014) in a report prepared for the Florida Department of Transportation and by Green and Mitchell (2018) applied to different areas of Australia. Pinjari et al. (2014) provide estimates of a number of driving parameters for trucks, including average driving distances for the state of Florida. Pinjari et al. conclude that a majority of trips between any OD pair tend to follow similar routes and Figure 1 exemplifies one of their results in the form of the distribution of average driving distances and a map with a sample of truck GPS records. Other works developing map-matching algorithms for study of truck routes are by Liao, (2014) and Flaskou et al. (2015) but they provide no results from the analysis.

As pointed out by Pinjari et al., using the GPS data for freight flow analysis will require that a truck trip database is developed which requires that a number of parameters are determined: truck starting and ending instances and locations, trip distance, total trip

duration, and duration of intermediate stops in the trip (such as traffic signals and rest stops). This required separation of valid pickup/delivery stops from congestion stops, stops at traffic signals, and stops to meet hours of service regulations. Thus, as described by Pinjari et al. (2014) it is a rather complex task to identify trips from raw GPS data, discarding short trips and define the points of origin and end destination. An example of a challenge is to identify trips for which origin and destination locations are close to each other, although the distance traveled by the truck on the network along the route is long enough to represent a trip of length long enough to be relevant, i.e. such as would be relevant for ERS. As can be seen from Figure C1, there is a significant share of the trips which are within a 50 miles (80 km). It is likely that the truck logistics in Florida differ from Sweden and perhaps also from continental Europe and, therefore, the results have a limited application to Swedish and European conditions.

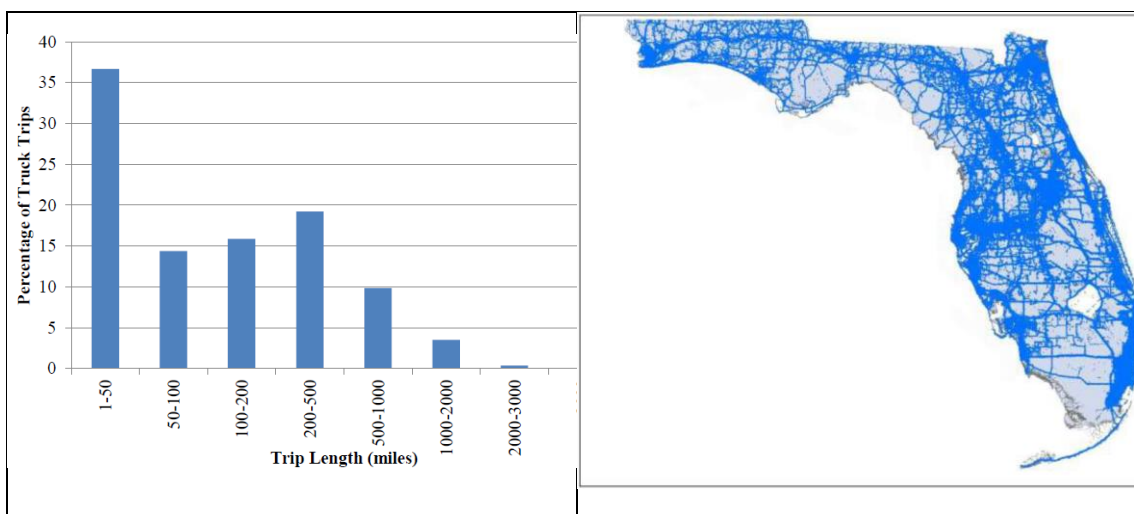


Figure C1: Distribution of average truck trip length distribution (in miles) derived from all data (entire USA) analysed by Pinjari et al. (2014) and a sample of truck GPS record positions for Florida. From Pinjari et al. (2014).

Figure C2 shows the time-of-day profile of trip starting as obtained by Pinjari et al. (2014). As can be seen, the majority of trips starts during the morning hours. Thus, this single peak distribution differs from the bi-modal peak behavior which is typically observed for passenger travel, representing morning and evening peak periods.

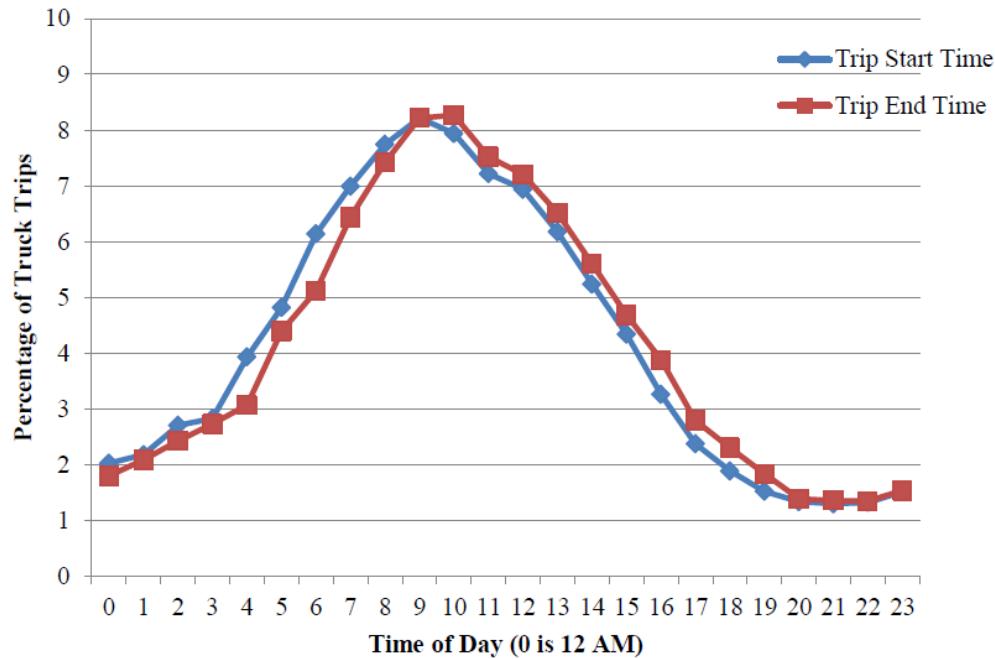


Figure C2: The time-of-day profile of trip starting in Florida. From Pinjari et al. (2014).

Phase 1 assessment of datasets

The aim of the Phase 1 work was to assess the Scania GPS data and if successful to apply the data in a cost analysis with the aim to identify roads with favorable traffic conditions for ERS (later also using GPS data from Volvo), i.e. to apply a cost model to estimate the economic conditions for ERS. More specifically, the work aimed at the following activities:

- Improve and evaluate the analysis performed by Scania
- Define suitable vehicle configurations to test
- Define suitable infrastructure configurations to test i.e. electrification level
- Perform analysis by using Scania and Volvo positioning datasets.
- Investigate what data sources are available to compensate for the biases in the data i.e AADT and sales statistics.

The main work was spent in map-matching. Due to the restricted scope of the work it was decided to improve a map-matching routine already developed at Scania. This was of a fuzzy logic type.

GPS raw data from Scania trucks across Europe

Figure C3 shows GPS traces from Scania trucks for Europe. The work included the past three years of data and only vehicles for which the position was sampled at least every couple of minutes. Some filtering was performed to remove GPS samples which were believed to be outliers (based on thresholds of parameters such as distance to adjacent

position, speed, and fuel consumption). Each of the positions was resampled using linear interpolation into new points with 100-meter separation, using a PySpark script.

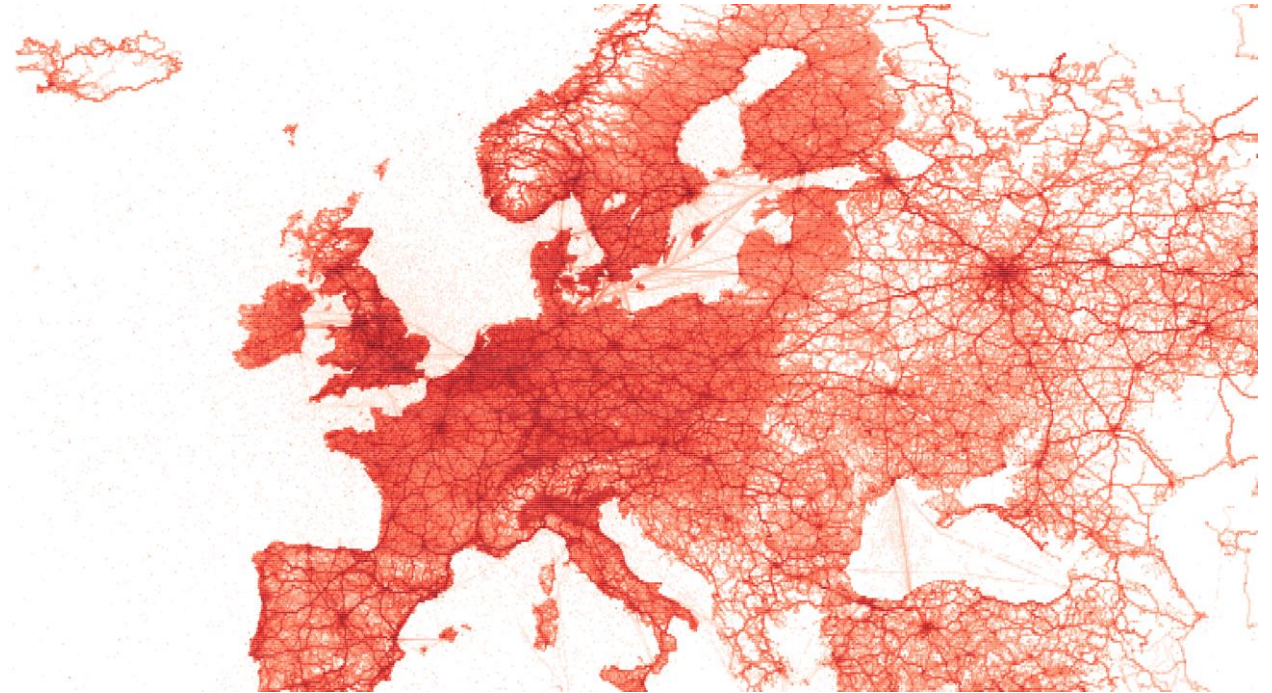


Figure C57: Heatmap of the raw GPS traces for selected Scania trucks.

Building datasets from the GPS raw data

For the GPS traces, a large precomputed Hive table was established that contains:

- vehicleid (INT)
- timestamp (TIMESTAMP)
- latitude (DECIMAL, degrees)
- longitude (DECIMAL, degrees)
- heading (SMALLINT, 0=north, clockwise)
- time_delta (BIGINT, time difference since previous sample, in seconds)
- geo_delta (DECIMAL, earth mover distance since previous sample, in meters)
- odometer_delta (BIGINT, distance driven since previous sample, in decameters)
- fuel_delta (BIGINT, fuel spent since previous sample, in centiliters)

Annual Average Daily Traffic (AADT)

The AADT data is used to match the Scania dataset with the total amount of trucks driving on the roads, thereby obtain the share of Scania trucks on the road stretches. Thus, the comparison is made to find the potential for all trucks. The data is collected

from the transport administrations and contains values for light and heavy vehicles. The details differ from country to country, where Sweden has very high resolution for all roads. Germany and UK contain only values for a few points along roads and is therefore used to extrapolate to the other road segments to connect all roads. The AADT data is also joined together with OpenStreetmap ID to be able to connect the Scania and the AADT data set to same road segments. Figure C4 illustrates AADT data for Sweden.



Figure C58. Example of heat map of AADT data for Sweden and Norway

OpenStreetMap Highway Network

For OpenStreetMap, the analysis started with the “node” and “way” tables imported to Hive from a recent dump of the map database.

The Node table contains (* are used in the computation):

- id* (BIGINT)
- version
- timestamp
- changeset
- uid
- user_sid
- tags
- latitude* (DOUBLE)
- longitude* (DOUBLE)

The Way table contains (* are used in the computation):

- id* (BIGINT)
- version
- timestamp
- changeset
- uid
- tags* (array<struct<key:string,value:string>>)
- nodes* (array<struct<index:int,nodeid:bigint>>)

From these Hive tables, the OSM roads that correspond to main roads (motorway and trunk) in Europe were extracted. The nodes of these roads are then again resampled into 100 meter intervals using linear interpolation. Figure C5 illustrates the roads (highways) used in the analysis.



Figure C59. OpenStreetMap Highways used in the analysis

Other datasets

Other data from Scania to be used in the analysis include:

- market share data (% of vehicles per country that are Scania vehicles)
- sampling ratios (% of Scania vehicles per country for which we have good positioning data)
- vehicle-country mappings.

Cost Model

The profit of an electric road can be computed with the following equation (simplified, more detailed computation in the code section given in section C3 below):

$$\bullet \text{ Road profit per year} = \text{Road income} - \text{Road cost} \quad (1)$$

where:

- $\text{Road income} = \text{displaced fuel} * \text{SEK saved per liter} * \text{ratio to road owner}$
- $\text{Road cost} = \text{length} * \text{cost per km}$
- $\text{Displaced fuel} = \text{sum}(\text{fuel on road})$, for all participating vehicles
- $\text{Participating vehicles} = \text{vehicles that are profitable to convert to electric vehicles given a set of electric roads}$

The profitability of a vehicle is calculated from the difference between the fuel savings and the initial cost of converting the vehicle. The profit clearly depends on the length of ERS on the vehicle route. Figure C6 illustrates this relation. Too few kilometers of ERS on a vehicle route will not result in enough fuel savings to motivate the investment in electrifying the vehicle. Only if a sufficiently long distance of ERS on the vehicle route will start giving profit from using ERS. Figure C7 below depicts the relation between the length of the electrified road and the profitability of the road. Looking at the two extremes, if we electrify few road kilometers, it will not be profitable for vehicle owners to invest in converting their vehicles to use electric roads (as discussed in the vehicle profit), thus there will be only road cost and no income. On the other hand, if we electrify too many road kilometers, there will not be enough vehicles using the road (produce road income) to cover the cost. In between the two extremes, there is an optimum length of ERS that maximizes the road profit.

The code for the analysis is given in section C3 below.

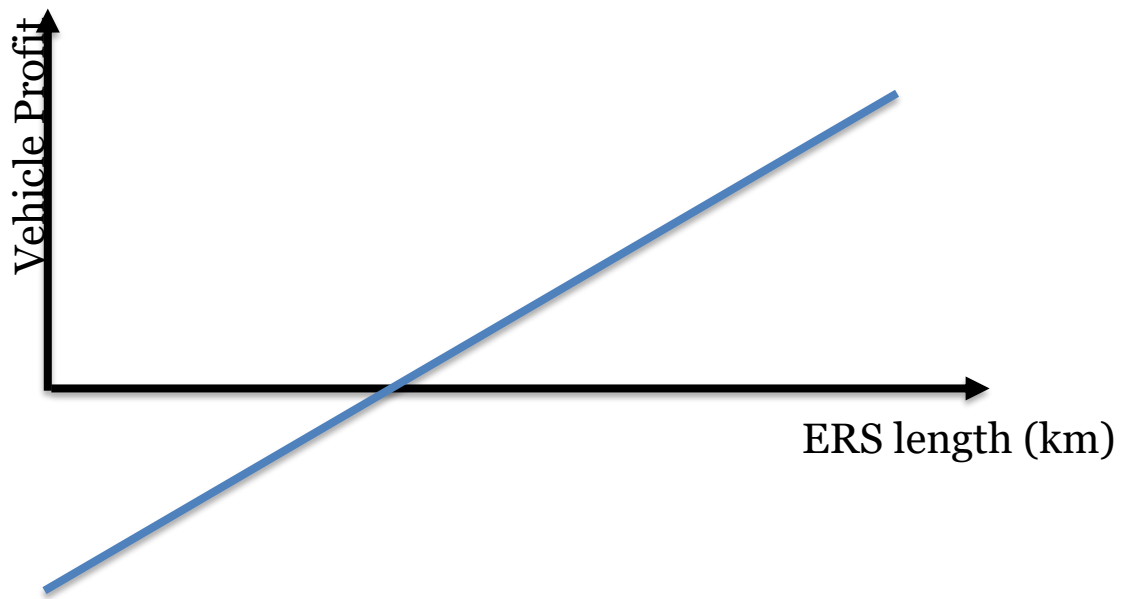


Figure C6: Vehicle profit versus ERS length of its route

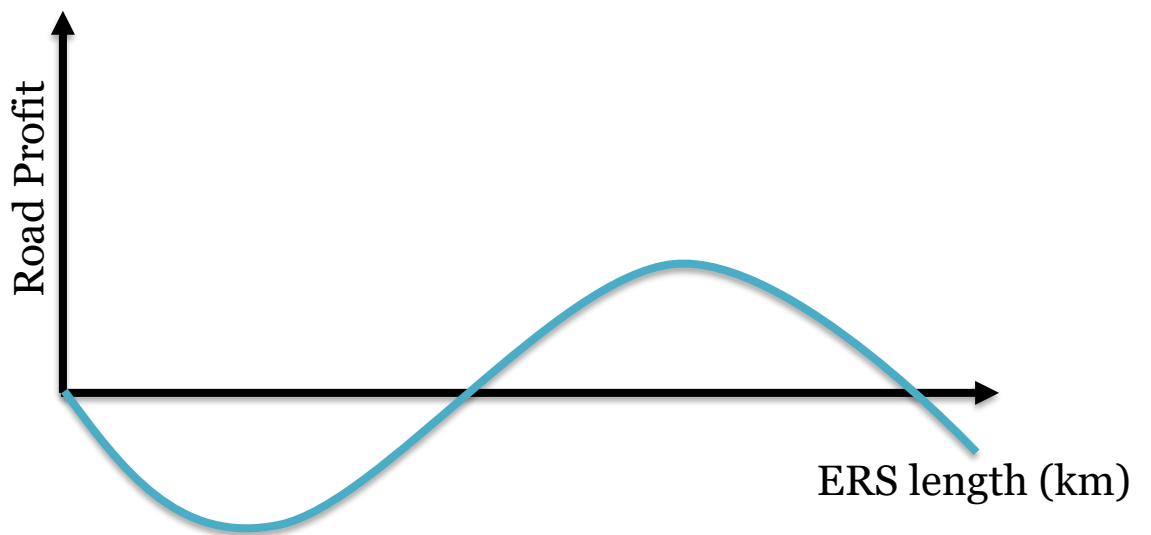


Figure C7: Road profit per ERS km length

C.3 Computation

Preprocessing

As described in the Datasets section, we provide Python Spark code (PySpark Notebooks) to preprocess the raw GPS traces and OpenStreetMap Ways and resample both using linear interpolation into new points with 100 meter separation.

Joining GPS data with OpenStreetMap main ways

A fuzzy join is then performed on the two point sets using another PySpark script, to arrive at a new table that contains:

- vehicleid
- wayid
- yearly fuel
- yearly distance

Market shares are weighted together into a per vehicle weight ($\text{weight} = 1 / (\text{market_share} * \text{sample_ratio})$), which is further adjusted based on AADT data (estimates of annual heavy vehicle passages per road taken from public sources).

These two tables are the basis for computation of what:

1. How profitable it would be to electrify a stretch of road
2. What roads to electrify

Road Scoring Function

The function used for scoring roads using a more elaborated cost model

```
def score_road(self, segment_ids_to_electrify):
    s = segment_ids_to_electrify

    v_fuel = self.vehicle_road_fuel[s].sum(axis=1)
    v = v_fuel.index[v_fuel > conf.min_annual_vehicle_fuel_on_road_to_invest]
    fuel_displaced_per_vehicle = v_fuel.loc[v]

    road_length = self.segment_lengths[s].sum()
    road_cost = self.segment_costs[s].sum()
    total_fuel_displaced_obs = fuel_displaced_per_vehicle.sum()
    total_fuel_displaced_norm = (fuel_displaced_per_vehicle *
self.vehicle_scale_factors[v]).sum()

    taxable_vehicle_income = fuel_displaced_per_vehicle *
self.conf.electric_saved_kr_per_liter_diesel -
self.conf.vehicle_electrification_cost_annualized_kr

    environment_gain = total_fuel_displaced_norm *
self.conf.environment_savings_kr_per_liter

    income_from_vehicles = (taxable_vehicle_income * self.vehicle_scale_factors).sum()
```

```

    break_even_tax_rate = 1 if income_from_vehicles == 0 else min(1, (road_cost -
environment_gain) / income_from_vehicles)
    tax_from_vehicles = income_from_vehicles * break_even_tax_rate
    road_income = tax_from_vehicles + environment_gain
    participating_vehicle_count_obs = len(v)
    participating_vehicle_count_norm = sum(self.vehicle_scale_factors[v])
    median_vehicle_income = 0 if len(v)==0 else np.median(taxable_vehicle_income)
    median_vehicle_profit = 0 if len(v)==0 else np.median((1-break_even_tax_rate) *
taxable_vehicle_income)

    print("Road length electrified:", int(road_length), "of",
int(sum(self.segment_lengths)), "km")
    print("Annualized net road cost:", int(road_cost), "kr")
    print("Break even tax rate:", round(100*break_even_tax_rate), "%")
    print("Annualized road income, vehicles:", int(tax_from_vehicles), "kr")
    print("Annualized road income, emissions:", int(environment_gain), "kr")
    print("Annualized road cost after income:", int(road_cost - road_income), "kr")
    print("Vehicles electrified (obs):", participating_vehicle_count_obs, "of",
len(self.vehicle_scale_factors))
    print("Vehicles electrified (norm):", int(participating_vehicle_count_norm), "of",
int(sum(self.vehicle_scale_factors)))
    print("Fuel displaced (obs): ", int(total_fuel_displaced_obs), "liters")
    print("Fuel displaced (norm): ", int(total_fuel_displaced_norm), "liters")
    print("Median vehicle income:", int(median_vehicle_income), "kr")
    print("Median vehicle profit after tax:", int(median_vehicle_profit), "kr")

```

Parameters

When the return on investment of electrifying a particular road stretch is computed, assumptions about pricing of several components is needed. The following was used in the work:

- Euro per kr = 0.096
- Annualized road electrification cost kr per km = $(10000000 / 10) * 2$ # Annualized to 10 years, and assume fuel data is for bi-directional traffic
- Annualized vehicle electrification cost kr = $150000 / 3$ # Annualized to 3 years
- diesel_kr_per_liter = 11
- diesel_liter_per_km = 0.3
- electric kr per kWh = 0.55
- electric kWh per km = 1.5
- kg_co2_per_liter_diesel = 2.65
- co2_price_per_kg = 0.03 / conf.euro_per_kr

- environment savings kr per liter = 1 # The road is expected to be publicly funded. This is the indirect value society gains due to cut emissions.
- Max vehicle scale factor = 100

Table C1 lists estimates for ERS road costs including grid and installation. Maintenance cost is not known at the moment. Most estimates are around 1-3% of the cost of a new road. Most likely there will also be an increased maintenance cost compared to a conventional road. The present work applies the estimates for the Siemens ERS.

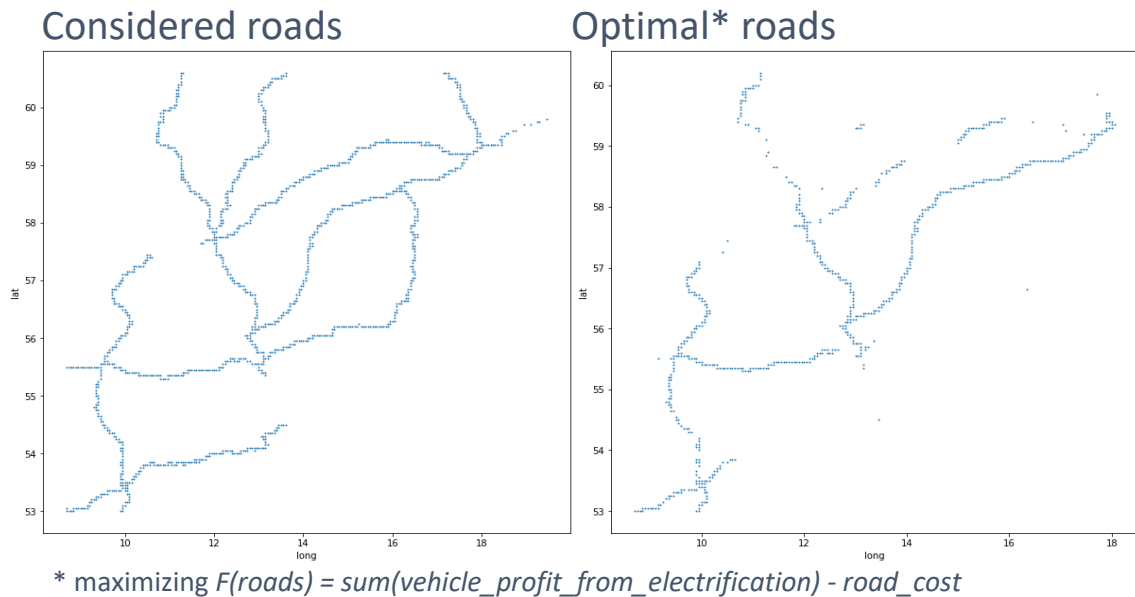
Table C1. Estimates of ERS costs (in Msek/km)

| | Grid | ERS | Installation |
|------------|------|------|--------------|
| Siemens | 3.85 | 9 | 2.6 |
| Elways | 3.85 | 7.25 | 0.5 |
| Alstom | 3.85 | 10 | 2.9 |
| Elonroad | 3.85 | 10.5 | 0.1 |
| Kaist/OLEV | 3.85 | 5 | 0.8 |
| Bombardier | 3.85 | 5.15 | 1.2 |
| Electreon | 3.85 | 5 | 0.8 |

C.4 Results and conclusion

Figure C8 exemplifies first results from the analysis. Thus, the left map shows the results from the map-matching and selection of the roads with highest AADT (cf Figure 5). The right hand map shows the results from applying the cost model to the GPS base data. Thus, the roads are those for which the average vehicle profit is the highest. As can be seen the preliminary analysis shows that for Sweden the most profitable roads for electrification are the main roads connecting Stockholm, Oslo and Hamburg.

A general experience is that the task of applying the above analysis to the GPS data was a challenging task and, therefore more work is required to develop an efficient methodology which is required in order to explore how GPS truck data can be used to assess ERS. It seems, however, obvious that in principle, GPS truck data should make it possible to determine important parameters such as average driving distance for different vehicle types. Due to the complexity of the task, it is recommended that continued work should first assess the state-of-the-art in map-matching algorithms. Then selecting an algorithm and, if possible, apply on a restricted set of GPS data to try out the methodology. The assessment may also require access to such a dataset to be part of the evaluation work. It is likely that the best is to apply the road network in OpenStreetMap since this dataset contains connected road segments without the need to generate ways or nodes.



Impact analysis

| | |
|---|-----------------------------|
| Road length electrified: | 3 813 of 7 346 km |
| Break even tax rate: | 61.0% |
| Annualized net road cost: | 7 627 220 924 kr |
| Annualized road income, vehicles: | 5 927 843 558 kr |
| Annualized road income, emissions: | 1 699 377 365 kr |
| Annualized road cost after income: | 0 kr |
| Vehicles electrified (obs): | 6 364 of 42 768 |
| Vehicles electrified (norm): | 144 139 of 1 550 281 |
| Fuel displaced (obs): | 95 791 389 liters |
| Fuel displaced (obs %): | 61% |
| Fuel displaced (norm): | 2 052 078 328 liters |
| Fuel displaced (norm %): | 56% |
| Median vehicle profit: | 45 682 kr |
| Median vehicle profit after tax: | 17 830 kr |

Assumptions

| | |
|---|---------------------|
| annualized_road_electrification_cost_kr_per_km: | (10000000 / 10) * 2 |
| vehicle_electrification_cost_ | |
| annualized_kr: | 150000 / 3 |
| diesel_kr_per_liter: | 11 |
| diesel_liter_per_km: | 0.3 |
| electric_kr_per_kWh: | 0.55 |
| electric_kWh_per_km: | 1.5 |
| kg_co2_per_liter_diesel: | 2.65 |
| co2_kr_per_kg_diesel: | 0.0377 |
| → environment_benefit_kr_per_liter: | 1 |
| max_vehicle_scale_factor: | 100 |

Figure C8: First results from the GPS analysis of this work

C.5 References

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Appendix D: Standards compilation

This appendix is the result of a request to SIS – Swedish Institute for Standards for compiling published standards and standards under development, having a relationship to electric road technologies.

The authors are Peter Claeson, Linnéa Casselbrant, Yamen Kadoura and Annika Almqvist at SIS – Swedish Institute for Standards.

The following appendix is a slightly revised version of a report commissioned by VTI, and performed by SIS in close collaboration with VTI, RISE, and the Swedish Transport Administration. With regards to a revision of the work on standards after this commissioned report was finished the following can be added: What is said in this and following section about laws and regulations does not apply to the final version of the work package as described in Chapter 7. See further the introduction in the main report to which the current report is appended.

D.1 Summary

The work package 8 (WP 8) covers "Laws, regulatory system, and standardisation". One of the main objectives with WP 8 is to contributing knowledge that might influence the legislative content in terms of the development, creation, design, function, and administration of electric roads. It requires review of existing regulation and strategies on EU-level and considering national and international regulatory framework to identifying areas where adaptation is needed. WP8 is also including standardisation.

This report covers the later part: standardisation. The purpose and goal were to identify, analyse and recommend areas where standards are missing, or there is need of adaptation of existing standards to ERS.

The work has been carried out by SIS – Swedish Standards Institute, in close collaboration with VTI and RISE. Parties from the reference group were engaged in the later part of the work for review and commenting on the list of standards and drafts, resulting from the mapping of standards and ongoing standardisation work.

The main findings from mapping standards related to ERS are presented in three categories; vehicle, electric power supply and infrastructure. The core information from the investigation is presented in an Excel compilation (Appendix 1) having provisions for filtering of the results on different parameters.

The standards compilation is helpful in the work with developing ERS since it provides a reference for where there are standards available. When a specific need for standards has been identified, this can be checked for in the reference list. If it does not appear in the list it can be brought up for further discussion and appropriate action. There is a good chance that there is a similar item that can serve as a basis for a dedicated ERS work. The compilation shows the standardisation groups in charge of the respective items, which helps guiding any requests for new ERS work items.

There are, so far, no dedicated published standards covering ERS. However, a number of published standards and standards under development are considered useful in the context of ERS. These have been specially indicated (in green and marked as applicable

to ERS) in the compilation. Several of these may possibly also serve as an appropriate starting point for developing future standards more dedicated to using electric roads as the power supply for the vehicle.

In the end of 2018, CENELEC TC9X decided to start a Survey Group for the French new work item proposal (NWIP) *Current Collectors for ground-level feeding system on Commercial Road Vehicles in Operation*. The group held a kick-off meeting in November 2018 and a Swedish representative attended. This together with the work on *Current collectors on commercial road vehicles in overhead contact line operation*, also within CENELEC TC9X, are the first two work items in the specific area of ERS.

It would be of great value to, together with the stakeholders, continue identifying critical areas, where standards are needed. This should be investigated from the point of view of the different techniques, related to conductive transmission by rail in road, conductive transmission overhead, inductive power transmission. Further work can be helpful in the decision of how to prioritize the future standardisation work.

D.2 Scope

Identification of standards directly or indirectly covering ERS, in need for adaptation. The list should be able to use for identification of missing standards.

In accordance with the request, the standards were divided into three different categories (vehicle, infrastructure, electric power supply), which in turn are divided into four different applications (general, conductive transmission by rail in road, conductive transmission overhead, inductive power transmission).

Missing/needed standards could be identified with help of participants in the reference group for FoI Platform for Electric Roads, including the Swedish Road Administration plus developers of electric road technologies.

D.3 Standardisation – General introduction and approach of the study

Standards organisations and standards application

Global standards are developed within [ISO](#), [IEC](#) (electrotechnical area), having the appointed national standards bodies (NSBs) as the national members. In addition, [ITU](#) covers the telecommunication area. It is a main task of the NSBs to organize and coordinate the national expertise into the global standardisation work. This is usually done two ways – by having experts participating directly in the ISO and IEC work in developing standards, and by having national mirror committees as reference for the work – to obtain a national consensus in the voting on standard proposals subjected to nation-wise ballot.

Global standards are by definition voluntary to apply, although regulations can prescribe the use of a specific standard as a means to fulfil the regulation.

The European standardisation works in a similar way, with [CEN](#), [CENELEC](#) (electrotechnical area) and [ETSI](#) (ICT area). A main purpose of the European standards

is to facilitate the free trade within Europe, and many standards are having a relationship to EC directives or regulations. They may alternatively be independent of the latter and merely reflecting best practices within Europe. In many cases as a European implementation of a global standard, but also as "pure" European standards developed to meet the needs within Europe.

For the European countries (EU and EES) the European standards (EN) have a preference over the global standards. When an EN standard has been adopted, it is mandatory to implement it as national standard in the European countries, and no "alternative" standard is allowed to co-exist. This also includes the "original" ISO or IEC version of the standard in case a global standard was adopted as an EN standard. Because of the lead time in implementing the European standard, a more recent version of a standard may exist within ISO or IEC for some time, until it has become processed and implemented as an EN standard. This is the case for a few of the standards mentioned in the Excel compilation.

In Sweden, [SIS](#) is the national member of ISO and CEN, [SEK](#) is the national member of IEC and CENELEC and [ITS](#) is the national member of ITU and ETSI. The relationship is shown in Figure D1. The telecom standardisation has not been part of the investigation of standards/drafts related to electric road systems.



Figure D1: Global and European standards organizations, and their respective Swedish members.

An illustration of global and European standards, and their application in the context of regulations, is shown in Figure D2.

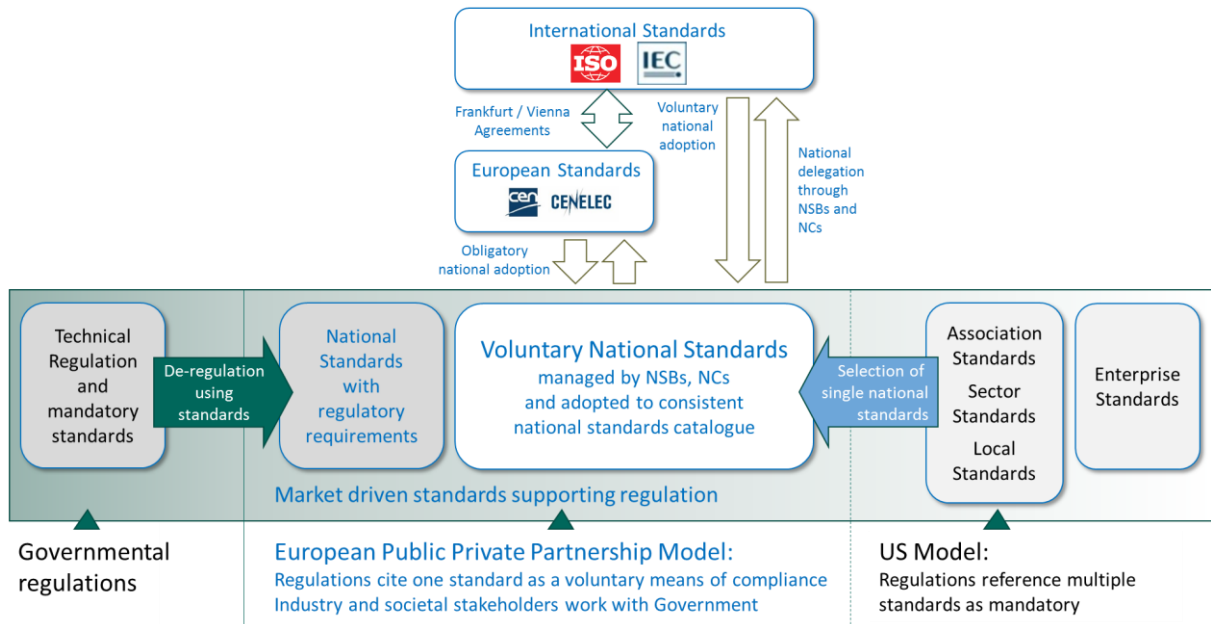


Figure D2: Global and European standards application.

Approach for determining ERS related standards and standards work

General approach for the study

The following approach has been applied in this study:

1. Setting a template (in Excel) for the information requested, in agreement with VTI;
2. Identification of relevant standards committees working on subjects related to electric vehicles, electric power supply and infrastructure of electric roads;
3. Review of scope for published standards and work programs of these committees;
4. In some cases, review of current reports and in-depth project information, e.g. preliminary work items and early working drafts;
5. Listing of the relevant information about the published standards and drafts, including scope where relevant, categorization, responsible committee, related Swedish committee, etc. in the Excel sheet;
6. Preliminary judgement of applicability of each standard/project to ERS;
7. Enquiry to the reference group for comments and viewpoints, especially regarding the applicability to ERS and any missing standards in the Excel list;
8. Finalization of the Excel sheet, taking into consideration the responses from the reference group members.

Enquiry to the reference group

To verify the results in the compiled Excel file (bullet point 7 in the general approach for the study), members of the reference group were asked to review it from their perspective as a stakeholder and expert in the field of ERS. Each stakeholder was given their category but had the possibility to review also the other categories. Table 1 show the stakeholders for each category.

Table D1: Reference group, stakeholders for each category.

| Vehicle | Electric power supply | Infrastructure | Overall |
|----------|-----------------------------|-----------------------------|-----------------------------|
| Scania | Alstom | NCC | Energimyndigheten |
| AB Volvo | Elonroad | Swedish Road Administration | Swedish Road Administration |
| | Elsäkerhetsverket | | |
| | E.ON. | | |
| | Fortum | | |
| | Siemens | | |
| | Swedish Road Administration | | |
| | Vattenfall | | |
| | Elways | | |
| | Bombardier | | |
| | Ellevio | | |

After the completed period of review, comments from seven stakeholders were received, mainly focusing on electric power supply. The review period was ongoing for three weeks in December 2018, which might have influenced the number of answers. In most cases one person was identified as the reference member for the stakeholder organization, this person was encouraged to gather opinion internally before providing the comments.

All comments received from the reference group members have been reviewed and considered in the final Excel sheet.

D.4 Vehicle

General

Global standards related to road vehicles with electric propulsion are developed by ISO and IEC, and European standards by CEN and CENELEC.

Historically, ISO is responsible for standardisation of road vehicles (mainly within ISO/TC 22 *Road vehicles*) and IEC covers all aspects of electric power supply.

With the renewed interest in electrified vehicles, the related standardisation activities became intensified around 10 years ago, both within ISO and IEC. Some overlap in the activities became obvious and called for an agreement to be taken. After negotiations an MoU agreement was signed in 2011, allocating the work as follows:

- [ISO/TC 22](#) (and mainly its [SC 37](#) *Electrically propelled vehicles*) is responsible for all aspects regarding the vehicle itself, including the electric charging inlets

and electric safety within the vehicle, and the battery packs as designed for use in vehicles. It also includes wireless power transfer on the vehicle side.

- [IEC/TC 69](#) is responsible for most aspects of the electric supply for charging of electric vehicles, including safety and other requirements on the charging station, and wireless power transfer, on the supply side.
- [IEC/TC 23/SC23H](#) is responsible for all aspects regarding the charging connectors.
- [IEC/TC 21](#) is responsible for the performance and safety of batteries (but not the vehicle battery packs).
- [IEC/TC 64](#) is responsible for the electrical installations and supplies for electric vehicles (not including the specific electric charging station).
- The standardisation work related to V2G CI (vehicle to grid communication interface) is done in close cooperation between ISO and IEC, and the standard is the common ISO/IEC 15118 series.

Sweden has been actively participating in the ISO work on electrically propelled vehicles since 2008, when the mirror committee [SIS/TK 517](#) *El- och hybridfordon* was formed. Sweden has also been actively participating in IEC/TC 69 through members of [SEK/TK 69](#) *Elbilsdrift*. Also, the other IEC TCs mentioned above are monitored through the corresponding SEK TKs.

The European standards work is to actively follow up the ISO and IEC work and to implement the appropriate standards as EN standards. For the corresponding EN standards the respective ISO or IEC standards number is maintained, adding the EN prefix.

Besides the global ISO and IEC standards, and their EN implementations, some SAE standards may be applicable and of interest in the context of ERS, and these have also been included in the compilation. The SAE standards are originating from the USA but are to some extent applied also in other countries, and there are also non-US members participating in the SAE work.

Conductive, rail in road

There are, so far, no dedicated standards on the vehicle side covering the specific application where the power supply comes from and electric road (rail in road).

However, a number of published standards and standards under development are considered useful and may be partly applicable for the electric vehicle with this type of power supply. Hence, these have been included in the compilation. They may possibly also serve as a starting point for developing future standards more dedicated to using electric roads as the power supply for the vehicle.

The standards considered useful in this context are mainly those covering

- Electrical safety aspects,
- Conductive charging,

- V2G CI (Vehicle to grid communication interface), especially the wireless communication parts,
- Voltage classes,
- Environmental conditions and testing of the exposed parts on the vehicle,
- To some extent, test specifications for the electric propulsion components,
- To some extent, voltage class B specifications and voltage class B testing of components.

A few more standards that do not belong to electric vehicles, but for the regular 12/24 V electric systems, might also be taken into account. Examples of such standards are ISO 26262 regarding *functional safety*, and ISO 20653 regarding *IP classes for road vehicles*.

Part of the above text is also applicable to Conductive overhead.

Conductive overhead

There are (so far) no dedicated standards for conductive overhead power supply to a road vehicle. The most closely related are for electric bus (static) charging with an automatic mechanical overhead device, similar to pantograph. Standards in this area is of great importance for a broad introduction of electric buses in cities and is priority subject for electric bus manufacturers. Safety and other aspects on the charging station side is under development as part 23-1 in the IEC 61851 series. For the interface to the vehicle (e-Bus), positioning etc, a work item is in preparation within CEN. This will probably be based on the preparation work within the [OppCharge](#) consortium.

The other way to find standards/drafts applicable to "conductive overhead" relative to the vehicle is through the area of railways, and specifically urban transport systems such as trams and trolleybuses. See the below section on electric power supply for conductive overhead.

Inductive

For inductive charging of vehicles, on the vehicle side, there is one ISO standard under development (and almost finalised) – ISO 19363. The current standard covers passenger cars and light vehicles only, and it is still for the static charging. It may later on be extended to cover heavy vehicles and possibly dynamic charging.

D.5 Electric power supply

General

Relative to electric power supply for road vehicles, the IEC committees involved are [IEC/TC 69](#), [IEC/TC 23/SC23H](#), [IEC/TC 64](#). See also 4.1. Relevant standards to take into account from these committees have been included in the SIS compilation.

On the electric supply side, however, it is also important to check the standards and work programmes of IEC and CENELEC committees for railway and urban rail to find

standards that might be relevant for electric roads. The following IEC and CENELEC committees have been checked in the SIS compilation:

- [IEC/TC 9](#) Electrical equipment and systems for railways
- [CLC/TC 9X](#) Electrical and electronic applications for railways

Conductive, rail in road

In the end of 2018, CENELEC TC9X decided to start a Survey Group for the French new work item proposal (NWIP) *Current Collectors for ground-level feeding system on Commercial Road Vehicles in Operation*. The group held a kick-off meeting in November 2018, with Swedish participation. There are several different technical solutions and work has started to define interfaces. This can become a crucial dedicated standard to enable power supply from the road to the vehicle. Swedish experts have been nominated to take part in this work. Only internal committee documents exist so far.

On the electric supply side, and for charging of electric road vehicles, the following important standards have also been reviewed and included:

- The IEC (EN) 61851 series for the electric charging station (AC and DC charging), including communication and EMC requirements;
- The IEC (EN) 62196 series for charging plugs and sockets (not directly applicable to electric roads, but it contains some relevant information);
- The ISO/IEC 15118 series for charging communication between vehicle and infrastructure.

On the railway and urban rail side, there are some other standards that may be applicable, or at least of interest, for the electric road power supply. See Excel list.

Conductive overhead

As mentioned under 4.3, for the electric power supply of road vehicles, there is one standard draft applicable to overhead charging of electric buses at fixed charging stations: Draft IEC 61851-23-1, *DC electric vehicle charging station with an autoconnect charging device*.

In this context, there is also an SAE draft J3105: *Electric vehicle power transfer system using a mechanized coupler*.

Standardisation in the area of electric power transmission with overhead line and pantograph is developed by IEC and CENELEC within their committees for railway.

There are several standards for electric overhead contact lines and pantographs for train application, e.g. EN 50119, EN 50206.

Within the railway standardisation, CLC TC 9X has developed EN 50502 *Safety requirements and current collection systems for trolley buses*.

In 2018, CENELEC TC9X started the work on *Current collectors on commercial road vehicles in overhead contact line operation*.

Inductive

On the electric power supply side, the IEC 61980 series is applicable.

The IEC 61980 parts (supply side) and ISO 19363 (vehicle side) are developed in close cooperation, to ensure compatibility and interoperability.

D.6 Infrastructure

General

In the context of road infrastructure, SIS has identified product standards developed by [CEN/TC 227 Road materials](#).

These standards have all been published but some of them are under revision to comply with the construction product regulation (CPR). They are all candidates to become harmonised standards.

A harmonised standard is developed by a standardisation body based on a directive or regulation, in this case CPR. These standards express the performance of road materials products.

When the revisions have been published by CEN, and approved by European Commission, by being published in the Official Journal of the European Commission, the manufacturers of road material will be able to draw up a declaration of performance and provide CE marking based on the standards. These product standards refer test methods or determination methods for different characteristics in the products standards. Those standards have also been included in the Excel list of standards and could be relevant for electric roads.

The road materials have been considered for power transmission by conductive, rail in road and inductive. It is considered that the road material is of less importance for power transmission by conductive overhead.

Conductive, rail in road

There are several factors to take into account while looking at the relevance of standards regarding road material. This can include the method used for routing/milling contact lines and regarding chosen method, the time and cost. It is assumed that different countries within Europe have different road material for the time being and, in that case, a future timeframe need to be taken into account regarding for example maintenance.

Product standards for road material set out how the different characteristics of the material shall be tested. These tests are also standardized (European standards). ERS might then lead to new or/and additional testing with regard to the power transmission by rail in road. Test for friction is one example that has been mentioned by the reference group for this project.

Conductive overhead

The road material standards are considered not applicable.

Inductive

There are several factors to consider while looking at the relevance for standards regarding road material. Some of them are the method used for installation of inductive coils and regarding chosen method, the time and cost. It is assumed that different countries within Europe have different road material for the time being and, in that case, a future timeframe need to be taken into account regarding for example maintenance.

Product standards for road material set out how the different characteristics of the material shall be tested. These tests are also standardized (European standards). ERS might then lead to new or/and additional testing with regard to the power transmission by rail in road.

D.7 Results

The mapping of standards and standardisation related to ERS has been compiled in an Excel file that is published together with this report.

It is possible to filter the data into three different categories (vehicle, infrastructure, electric power supply) and four different applications (general, conductive transmission by rail in road, conductive transmission overhead, inductive power transmission). Filtering can of course be applied to any other heading (Applicable to ERS, Technical Committee, SE mirror committee, ...).

The list can be used when looking for relevant standards, as well as for identification of missing standards, for ERS.

It is not always obvious that a standard is belonging to one single category. In these cases, we have chosen to put them in the category that we have identified to have the closest relationship to the standard.

In the end of 2018, the reference group got the opportunity to review and give comments on the results of the mapping. Many valuable comments were given, and we have tried to address these in the best possible way in this report and in the Excel file. One outcome was that additional standards were added on the electric power supply category, and some "TBD" became classified as "applicable to ERS".

For any future analysis work, it would be highly desirable to involve the competence from the SEK work in addition to that of SIS, as the work includes an extensive part of standardisation within the electrotechnical area.

The findings show that a number of published standards and standards under development can be considered useful in the context of ERS. 96 standards (out of a total of 244) have been classified as "applicable".

Although there are currently no dedicated standards covering the specific technology, this will probably change in the coming years. By end of 2018 the first dedicated ERS

work items were started and Sweden have representatives following the work. There are good opportunities for proposing new standardisation work for ERS and taking a Swedish lead.

D.8 Next steps

The Excel file of compiled standards is a starting point that can be subsequently updated and refined, for instance via a deepened and broadened further analysis of standards. It is not always obvious that a listed standard belongs to a single thematic ERS architecture category. In the Excel list, standards are put in the category that they have the closest relation to. It should further be recalled that the identification and listing of standards as applicable in this study is a snapshot of the current status; there are still no dedicated published or draft ERS standards, only standards that have relevant substance to potentially be adapted to and be used for ERS.

In a next step it is desirable to involve stakeholders even more and to have a close cooperation with both SIS and SEK.

More precisely, this could be done by involving further expertise from standards organisations within the electrotechnical area and continued stakeholder dialogue, but also by examining further aspects and links of ERS as a system of systems. The latter is important considering the potential relevance of telecommunication standards, which were not examined in this study, for payment technologies in ERS, but likewise for other foreseen 'megatrends' besides electrification of transport like autonomous/automated and shared vehicles.

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